

ATMOSPHERE OF FREEDOM: 70 YEARS AT THE NASA AMES RESEARCH CENTER

70TH ANNIVERSARY EDITION

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Foreword

Ames is the coolest place to work in the federal government. That was true when one of us (Jack) joined the laboratory in 1947, true when the other (Pete) joined in 2006, and true today. Our offices are nearby, and we often trade stories about how well Ames' heritage supports our vision of the future of space exploration. Part of what makes Ames so cool is the constant dialogue between past and future, between capabilities and potential, between the science fiction of yore and the realities of what we do today, and between those giants of aerospace engineering who walk our campus and those young folk who seek to learn from them.

One of ten NASA field Centers around the country, Ames is located at the heart of Silicon Valley. The organizational culture of NASA Ames reflects that of Silicon Valley: collaboration to leverage proven strengths, a desire to nurture new disciplines, a willingness to work cheap and fast, a need to match demonstration with theory, a longer view into the future of space exploration, and the belief that we can change the world.

During its earliest days, Ames researchers broke new ground in all flight regimes (the subsonic, transonic, supersonic, and hypersonic) by building increasingly sophisticated wind tunnels, arc jets, research aircraft, and methods of theoretical aerodynamics. Extending its expertise in human factors and pilot workload research, Ames became NASA's lead center in basic life sciences research, which included radiation biology, adaptability to microgravity, and exobiology. Some Ames aerodynamicists explored the complex airflows around rotorcraft and devised the first tilt-rotor aircraft, while others modeled airflows using new supercomputers and internetworking to create the field of computational fluid dynamics. Building upon its expertise in computational chemistry and materials science, Ames pioneered the field of nanotechnology. Ames research in air traffic management helped make air travel safer and more energy efficient. Ames engineers and planetary scientists managed a series of airborne science aircraft, of planetary atmosphere probes, and robotic explorers like the Pioneer spacecraft and Lunar Prospector. Ames pioneered the "virtual institute" to develop the disciplines

of astrobiology and lunar science. More recently, NASA Ames is innovating in the engineering of small and modular spacecraft.

Some of Ames' greatest contributions to America's aeronautics and space program include the swept-back wing concept that is used on all high-speed aircraft today; the blunt body concept, which is used on every spacecraft to prevent burning upon planetary entry; the management of the Pioneer planetary spacecraft, which was the first human-made object to leave the solar system; the disciplines of computational fluid dynamics and astrobiology; the Kepler mission to find exoplanets, which was one of the first astrobiology-driven missions, and the Lunar Prospector and LCROSS missions, which confirmed the presence of water at the poles of the Moon.

Ames has emerged as NASA's leading center in supercomputing and information technology, astrobiology and the space life sciences, earth and planetary science, materials science and thermal protection systems, and small spacecraft engineering. We've drawn new types of researchers into space exploration by creating the NASA Research Park, a premier space for collaborative corporate research and innovative educational facilities to train the future aerospace workforce. With more than \$3 billion in capital equipment in 2010, a research staff 2,400 people strong, and an annual budget of more than \$800 million, Ames plays a critical role in virtually all NASA missions in support of America's space and aeronautics programs.

We dedicate this book to the many women and men who have dedicated their careers to the success of the NASA Ames Research Center, and who make our Center so cool.

A stylized, handwritten signature in black ink, featuring a large, looped 'P' and 'W'.

Pete Worden

A handwritten signature in black ink, written in a cursive style that reads 'Jack Boyd'.

Jack Boyd

Preface

As the NASA Ames Research Center approached its 70th anniversary in December 2009, there was interest in updating the 60th anniversary history *Atmosphere of Freedom: Sixty Years at the NASA Ames Research Center* (NASA SP-4314). Much had happened in the decade from 1999 to 2009. Ames stayed focused on its historical mission of basic research and forward-thinking technologies—in information technology, aeronautics, reentry systems, space life sciences, and planetary science. Still, the Center confronted new challenges and new programs emerged. Notable was the growth of astrobiology, the birth and death of nanotechnology, the establishment of the NASA Research Park, the LCROSS mission to the Moon and the Kepler mission to hunt for Earth-sized planets. Perhaps the most important challenge was NASA's Constellation program, a full-bore effort to create a transportation system for human space flight to replace the Space Shuttle and return America to the Moon. Furthermore, events of the most recent decade shed new light on parts of NASA Ames' legacy. The renewed emphasis on small spacecraft, for example, prompted renewed interest in Ames' historical strengths in spacecraft engineering dating back to the 1960s. The renewed emphasis on NASA research to resolve the common concerns of commercial space, likewise, prompted renewed interest in Ames work to support the information technology industry.

This update also allowed for a reconfiguration of the text. The story here starts in 1958 when the National Advisory Committee for Aeronautics (NACA), of which Ames was a part, was incorporated into the new National Aeronautics and Space Administration (NASA). The first twenty years of Ames' history—back to 1939, its NACA years—remains relevant. The NACA culture is firmly fixed within Ames and often colored its work in the NASA years, especially in its continuing efforts in aeronautics and in how it provides research support to firms and other Centers pursuing larger projects. For those interested in Ames during the NACA years, that story is told well in Edwin P. Hartman, *Adventures in Research: A History of the Ames Research Center, 1940-1965* (NASA SP-4302, 1970).

The 60th anniversary edition of *Atmosphere of Freedom* was organized largely chronologically, with topical areas broken into large swatches of time. This 70th anniversary edition begins with a history of the Center from the perspective of the Center directors—there have been ten since 1958. This ties the history of Ames into its larger context of space policy and politics, and addresses the impact of leadership on the history of the Center. Then the chapters are organized by the subjects that persisted throughout Ames' history: spacecraft projects, human exploration, planetary sciences, space life sciences, information technology, and aeronautical research. Each of these stories has a history dating back to at least 1958, so issues of overlap in the narrative remain—in that what Ames has done best is explore the fruitful interchanges of disciplines and capabilities. Computational fluid dynamics, for example, developed from iterative advances in aerodynamics, supercomputing and software development, and so will be addressed in various chapters. Astrobiology, likewise, grew along the shifting border between the space life sciences and planetary science.

However, the larger themes relevant on its 60th anniversary remain relevant on the 70th anniversary of NASA Ames: the complex and constant intermingling and convergence of people, tools and ideas. Ames people value the perpetual reinvention of their careers and the cross-fertilization of ideas. Ames stands as an extraordinary repository of high-tech equipment, research laboratories, and facilities. That physical infrastructure supports what Ames truly is—a growing and evolving community of researchers and support staff who have given birth to new technologies, and thus enabled the human conquest of the atmosphere and the exploration of space.

CHAPTER 1

Administrative History

Ames contributed much of the technology that helped NASA succeed in the mission that most preoccupied it during the 1960s—that of sending an American to the Moon and returning him safely to Earth. Ames people defined the shape, aerodynamics, and ablative heatshield of the reentry capsule. They mapped out navigation systems, designed simulators for astronaut training, built magnetometers to study the Moon and instruments to explore the landing sites, and analyzed the lunar samples returned. Still, compared with how it fueled growth at other centers, NASA's rush to Apollo largely bypassed Ames.

Ames' slow transition out of the NACA culture and into the NASA way of doing things, in retrospect, was a blessing. Under the continuing direction of Smith DeFrance, then Harvey Allen, Ames people quietly deepened their expertise in aerodynamics, thermodynamics, and simulation, then built new deep pockets of research expertise in the space and life sciences. They sat out the bureaucratic politics feeding the frenzy toward ever more elaborate and expensive spacecraft. DeFrance's gentle refocusing of Ames' NACA culture during the 1960s meant that Ames had nothing to unlearn when NASA confronted its post-Apollo years—an era of austerity, spin-offs, and broad efforts to justify NASA's utility to the American public.

This chapter addresses the history of NASA Ames from the perspective of the Center directors and of the staff who managed the operations of the Center. It was in Ames' headquarters building (now called N200) that the Center's relations with the larger agency were mapped out, funding argued for, and new organizational processes imposed. The work done there set the context for all the research and engineering work done on Center.

DEFRANCE ALIGNS HIS CENTER WITH NASA

President Dwight Eisenhower signed the National Aeronautics and Space Act into law in July 1958, and its impact was felt most immediately in redefining Ames' relations with its headquarters. The NACA was disbanded, and all its facilities incorporated into the new National Aeronautics and Space Administration (NASA) that opened for business in October 1958. Eisenhower wanted someone in charge of NASA who would take bold leaps into space—bolder than NACA leadership had been willing to take—and appointed as administrator T. Keith Glennan, then president of the Case Institute of Technology. Hugh L. Dryden, who had been NACA chairman, was appointed Glennan's deputy. Glennan first renamed the three NACA "Laboratories" as "Centers," though kept Smith DeFrance firmly in charge of the NASA Ames Research Center. DeFrance had directed the Center since its founding in 1939.

Perhaps the first sign that the transition into NASA would disrupt DeFrance's management style was the appearance of organization charts. DeFrance hated them, and never did them for Ames. "The director believed," remembered Ames engineer Jack Boyd, "that when you put a man in a box you might as well bury him."¹ DeFrance wanted everyone at the Center to move easily between research projects, and he already knew whom to call on when he needed an answer. NASA headquarters staff, though, wanted an easier way to directly discover who at Ames was responsible for facilities or research projects. So for the sake of headquarters Ames put their organization charts on paper.

DeFrance went a year without making any organizational changes to reflect NASA's new space goals. At the end of 1959, he announced that Harvey Allen was promoted to assistant director, parallel to Russell Robinson. Robinson continued to manage most of Ames' wind tunnels, some of which were mothballed or consolidated into fewer branches to free up engineering talent to build newer tunnels for space-oriented research. Allen had participated in many of the NACA subcommittees focused on manned exploration of space, and understood the research needs of the new NASA. Allen was named assistant director for astronautics. Allen's theoretical and

applied research division was reconfigured so that he now managed an aerothermodynamics division and a newly-established vehicle environment division, both focused on studying the interior and exteriors of spacecraft. In addition, DeFrance formed an elite Ames manned satellite team, led first by Alfred Eggers and later by Alvin Seiff, who helped define the human lunar mission that soon became NASA's driving mission.

Another major cultural shift in the Center came with the departure of Harry Goett. NASA had also inherited the various space project offices managed by the Naval Research Laboratory—specifically Project Vanguard, upper atmosphere sounding rockets, and the scientific satellites for the International Geophysical Year. These offices had been scattered around the Washington, D.C. area, and Glennan decided to combine them at the newly built Goddard Space Flight Center in Beltsville, Maryland. Goddard would also be responsible for building spacecraft and payloads for scientific investigations, and for building a global tracking and data-acquisition network. Glennan asked Harry Goett, chief of Ames' full scale and flight research division, to direct the new Goddard center. Goett had been the architect of Ames' work in subsonic flight and large-scale testing. To replace Goett, in August 1959, DeFrance turned to Charles W. "Bill" Harper. Fortunately, Goett resisted the temptation to cannibalize colleagues from his former division, and instead built strong collaborative ties between Ames and Goddard, especially in the burgeoning space sciences.

The flood of money that started flowing through NASA only slowly reached Ames. The NACA budget was \$340 million in fiscal 1959. As NASA, its budget rose to \$500 million in fiscal 1960, to \$965 million in fiscal 1961, and earmarked as \$1,100 million for fiscal 1962. Staff had essentially doubled in this period, from the 8,000 inherited from the NACA to 16,000 at the end of 1960. However, most of this increase went to the new Centers—at Cape Canaveral, Houston, Goddard, and Huntsville—and to the fabrication of launch vehicles and spacecraft. Ames people had little engineering experience in building or buying vehicles for space travel, even though they had devised much of the theory underlying them. Glennan, in addition, followed a practice

from his days with the Atomic Energy Commission of expanding research and development through contracts with universities and industry rather than building expertise in-house. The competition for engineering staff grew intense, and most firms paid more than NASA could. Thus, between 1958 and 1961, the Ames headcount actually dropped slightly to about 1,400, and its annual budget hovered around \$20 million.

The disparity between what NASA got and what Ames got grew greater in early 1961 when President Kennedy appointed James E. Webb to replace Glennan as administrator. Glennan had pursued a technology development program to move NASA quickly into space, but across many fronts—human space flight, robotic explorers, and Earth observation and communication satellites. Kennedy had campaigned on the issue of the missile gap and Eisenhower’s willingness to let the Soviets win many “firsts” in space. So in Kennedy’s second state of the union address, on 25 May 1961, he declared that by the end of the decade America would land a man on the Moon and return him safely to Earth. Ames people had already planned missions to the Moon and pioneered ways to return space travelers safely to Earth. But they had expected decades to pass—and essential infrastructure built—before these plans were pursued. Kennedy’s pronouncement dramatically accelerated their schedules and brought a compellingly clear focus to NASA’s mission. Kennedy boosted NASA’s fiscal 1962 budget by 60 percent to \$1.8 billion and its fiscal 1963 budget to \$3.5 billion. NASA’s total headcount rose from 16,000 in 1960 to 25,000 by 1963. More than half of this increase was spent on what Ames managers considered the man-to-the-Moon space spectacular.

Again, Ames grew little relative to all of NASA, but it did grow. Ames’ head count less than doubled, from 1,400 in 1961 to 2,300 in 1965, while its budget quadrupled, from about \$20 million to just over \$80 million. Almost all of this budget increase went to research and development contracts—thus marking the greatest change in the transition from NACA to NASA. Under the NACA, budgets grew slowly enough that research efforts could be planned in advance

and personnel hired or trained in time to do the work. Under NASA, however, the only way to get skilled workers fast enough was to hire the firms that already employed them. Furthermore, under the NACA, Ames researchers collaborated with industrial engineers, university scientists, and military officers as peers who respected differences of opinions on technical matters. Under NASA, however, these same Ames researchers had enormous sums to give out, so their relations were influenced by money. Gradually, Ames people found themselves spending more time managing their contractors and less time doing their own research.

Organizationally Ames continued to report to what was the old NACA headquarters group—guarded by Dryden, directed by Ira S. Abbott, and renamed the NASA Office of Advanced Research Programs. The four former NACA laboratories—Ames, Langley, Lewis, and the High Speed Flight Research Station—continued to coordinate their work through a series of technical committees. Even though the organizational commotion left in NASA's wake centered in the East, throughout the 1960s Ames found itself an increasingly smaller part of a much larger organization. Gradually the intimacy of the NACA organization faded as NASA's more bureaucratic style of management took over.

Four examples displayed the cultural chasm opening between Ames and the new NASA headquarters. First, in 1959, on the day Bill Harper reported to work as Harry Goett's successor in full-scale research, NASA headquarters told Ames to send all its aircraft south to the NASA Flight Research Facility. Harper insisted that research on VTOL flight (vertical take-off and landing) could not be done without the aircraft to support it, so those remained, along with one old F-86 used by Ames pilots to maintain their flight proficiency. Thus started decades of debate, and disagreements, over how aerodynamicists got access to aircraft for flight research. More specifically, Ames continued to have access to the great runway at Moffett Field and Navy hangars, and would continue to acquire aircraft used for a variety of flight programs. NASA headquarters, though, would continue to yield to arguments that aircraft could be more cheaply based at Rogers Dry Lake.

Second, NASA headquarters asserted its new right to claim the 75 acres of Moffett Field on which Ames sat as well as 39 acres of adjacent property that was privately held. DeFrance argued that there was no need to change Ames' use permit agreement with the Navy, and he negotiated a support agreement that showed he was happy with Navy administration. NASA headquarters, however, had money and chose to assert control over its assets.

Third, NASA renumbered the NACA report series and, more importantly, relaxed the restriction that research results by NASA employees first be published as NASA reports. With NASA engineers building special purpose spacecraft for their own use, it was less important that they share the results with everyone. Newer employees, especially in the space and life sciences, with more academic inclinations, preferred to publish their work in disciplinary journals rather than through the peer networks so strong in the NACA days. The result was less cooperation between the NASA Centers on shared research interests—in that they would continue to fight for funding but not over the validity and utility of the results. On the other hand, cooperation with university-based researchers was more clearly reflected in the published results.

Finally, NASA headquarters wanted Ames to leap into the limelight. DeFrance had encouraged Ames staff to shift public attention to the sponsors of its research, and Ames' biggest outreach efforts had been the triennial inspections when industry leaders and local dignitaries—but no members of the public—toured the laboratory. NASA headquarters encouraged DeFrance to hire a public information officer better able to engage general audiences rather than technical or industry audiences. Bradford Evans arrived in August 1962 to lead those efforts, and soon Ames was hosting tours by local school groups. DeFrance and his leadership staff remained disinterested in advertising themselves, so Evans went directly to individual researchers to find intriguing work to write about and younger researchers learned the value of self-promotion.

The rise of public outreach, the decline of internal peer review and publication, the distance growing between wind tunnels and flight test aircraft, and central control of assets—all displayed a cultural

shift as the NACA laboratories assimilated into NASA. Ames explored organizational ways of integrating itself into the Apollo program, and in the process demonstrated the skills NASA Ames people would display in reinventing their careers, and reinventing their Center, to enable changes in how America chose to explore space.

The first organizational change to meet the needs of the Apollo program came in August 1962, when Harvey Allen, who had been active in the early NASA committees planning a manned space program, formed a space sciences division and hired Charles P. Sonett to lead it. Sonett was among the most experienced spacecraft builders in the country. He had worked for Space Technology Laboratories (later part of TRW Inc.) building space probes for the Air Force, including Pioneer 1 and Explorer VI. Then from 1960 to 1962 he led the lunar science program office at NASA headquarters. Notably, Sonett chaired a scientific working group on how to incorporate science into the Apollo program and report they wrote served as a road map for space science over the next decade.² At Ames, by leveraging the extant expertise in instrumentation for the wind tunnels and arc jets, Sonett established Ames as the leader in solar plasma studies—especially with the Pioneers 6 to 9 spacecraft. Later he devised the lunar surface magnetometers flown on Apollo 12, 15 and 16, and managed the team that led the science on the Pioneers 10 and 11. Sonett left Ames as its director of astronautics in 1972 and moved to the University of Arizona to establish its planetary science department. Largely through his efforts, Ames grew directly involved in how NASA pursued its solar and lunar research effort, and extended its expertise in instrumentation into space experiments.

The second organizational change was the start of life science research at Ames. Like Sonett in the space sciences, Clark Randt had worked at NASA headquarters dreaming up biological experiments to be carried aloft into space. He wanted to build a laboratory to validate the experiments on the ground prior to flight, and run control experiments parallel to the flight experiments. Randt sent Richard S. Young and Vance Oyama to work at Ames and build a

small penthouse laboratory atop the instrument research building. In the Bay area, they had contact with some of the world's best biologists and physicians and, at Ames, they got help from a well-established human factors group in its flight simulation branch. With encouragement from headquarters, Ames established a life sciences directorate and, in November 1961, hired world-renowned neuropathologist Webb E. Haymaker to direct its many embryonic activities. Haymaker proved too focused on his own research on radiation affects to be a program builder. In 1964 DeFrance hired Harold P. "Chuck" Klein who would lead the Ames life sciences division for two decades. Klein broadened the types of space life science work done—notably into exobiology and the engineering of biology payloads—while bringing organizational focus. By 1963, the three major directorates at Ames were defined as aeronautics, astronautics, and life sciences. The Johnson Space Center asserted dominance over biomedicine and risk reduction related to astronaut activity in space, though Ames remained NASA's lead Center on fundamental life sciences.

In addition to giving Ames expertise in a new discipline within NASA, the life scientists also shifted the culture of the Center. This new cohort of life scientists shared much with the aeronautical engineers who inhabited the Center since the NACA days: polyglots in scientific theories, driven to design the apparatus to prove their theories, practitioners in rigorous peer-review, and aware of their place in the networks that generated usable knowledge. Yet these biologists seemed awkwardly grafted onto the Center. They inhabited different disciplines, procedures and languages. Many of Ames' leading biologists were women, when women scientists were still sparse on Center. Now, Ames people addressed different intellectual communities and reorganized themselves accordingly. Whereas Ames had historically organized itself around research facilities—wind tunnels—by 1963 DeFrance organized his staff by either missions or disciplines.

The third organizational change happened at headquarters. In November 1963, NASA headquarters reorganized itself so that Ames as a Center reported to the Office of Advanced Research and

Technology (OART) while some major Ames programs reported to the other headquarters technical offices. DeFrance could no longer freely transfer money around the different programs at his Center. Headquarters staff had grown ten times since the NACA days, and from Ames' perspective countless new people of uncertain position and vague authority were issuing orders. Some of these newcomers even bypassed the authority of the director and communicated directly with individual employees on budgetary and engineering matters. Virtually all of them wanted to know how Ames was going to help get a human on the Moon, and return him safely to Earth. Ames' NACA culture was under pressure.

HARVEY ALLEN AS DIRECTOR

In October 1965, DeFrance retired after 45 years of public service, with elaborate ceremonies in Washington and in San Jose so his many friends could thank him for all he had done. DeFrance planned well for his retirement and had cultivated several younger men on his staff to step into his role. Harvey Allen was the best known of the Ames staff, and had the most management experience. The director's job was his to refuse which, initially, he did.

Alfred Eggers then loomed as the front-runner. Eggers and Allen were both friends and competitors. The two had collaborated in the early 1950s on the pathbreaking work on the blunt body concept, but Allen made his work more theoretical whereas Eggers explored more practical applications like the lifting body spacecraft and design of facilities like the 3.5 foot hypersonic wind tunnel.

In January 1963, Eggers convinced DeFrance to assign him to the newly created post of assistant director for research and development analysis and planning, a platform from which he could move Ames more directly into human space flight. A year later Eggers went to headquarters as deputy associate administrator in OART. He persuaded his boss, Ray Bisplinghoff, to create a group to design missions of interest to OART. This mission analysis division (MAD), established in January 1965, reported directly to headquarters, was located at Ames, and staffed by scientists on loan from the OART Centers—Ames, Langley, Lewis and Dryden. The MAD was also

tasked to manage the OART advanced studies program, a grant-giving program which funded futuristic studies at universities and corporations. But this MAD never got support from the other Centers, and within a year, OART abandoned plans for assigning a complement of fifty scientists to it. Soon the disarray began to spread through the Ames directorate for R&D planning and analysis that was originally created for Eggers to manage. Bob Crane assumed control of program management and John Foster of systems engineering. Clarence Syvertson remained in charge of a much smaller, though very active, MAD focused on defining missions specific to Ames (which would be dissolved in 1972). A new programs and resources office was created under Merrill Mead to plan and fight for Ames' budget. All this organization-building and space flight emphasis left Eggers as the headquarters choice to become director. But Allen was not convinced so dramatic a shift in direction was best for Ames. To prevent Eggers from being named director and to keep Ames largely as it was—distant from Washington, with a nurturing and collaborative spirit, and focused on research rather than projects—in October 1965 Allen took the directorship himself.

Allen did not distinguish himself as Ames director as he had in his other promotions. In personality, Allen differed from DeFrance. DeFrance was distant, fatherly, safety-minded and inclined to remind Ames people that they were spending the hard-earned money of the American taxpayers. Allen was warm, benevolent, close to the research, inspirational in his actions and words. Allen, like DeFrance, kept Ames as a research organization and worked hard to insulate his staff from the daily false urgencies of Washington. Jack Parson had served as associate director to DeFrance since the founding of the Center, and Allen convinced him to stay to handle the internal administration of the Center. Allen asked Loren Bright and Jack Boyd to fill the newly created positions of executive assistant to the director and research assistant to the director. It would be their jobs to review and vet the various research proposals emanating from Ames staff. Allen often sent Ames' ambitious young stars in his place to the countless meetings at headquarters. And every afternoon at two o'clock, when headquarters staff on Washington time left their

telephones for the day, Allen would leave his director's office and wander around Ames. He would poke his head into people's offices and gently inquire about what was puzzling them. "Are you winning?" he would ask.³ Eventually he would settle into his old office and continue his research into hypersonics.

Ames suffered a bit during Allen's four years as director. Ames' personnel peaked in 1965 at just over 2,200 and dropped to just under 2,000 by 1969. Its budget stagnated at about \$90 million. For the first time a support contractor was hired to manage wind tunnel operations—in the 12 foot pressurized tunnel—and there was a drop in transonic testing and research on aircraft design. Tunnel usage actually increased to support the Apollo program and studies of supersonic transports, and there was dramatic growth in Ames' work in airborne and space sciences, especially from the Pioneer program. But overall, not much new was happening on Center.

HANS MARK

Two events made 1969 the year to mark the next era in Ames history. First, Apollo 11 returned safely from its landing on the Moon, signalling the beginning of the end of the lunar landing missions that drove NASA almost from its start. NASA had yet to decide what to do for its second act, and a flurry of strategic planning took place against an uncertain political backdrop. Much of the American public—including political conservatives concerned with rampant inflation and political liberals concerned with technocratic government—began to doubt the value of NASA's big plans. NASA had downplayed the excitement of interplanetary exploration as it focused on the Moon. Congress and the American aerospace industry, under pressure from a resurgent European aerospace industry, began to doubt if NASA really wanted the aeronautics part of its name. Into the 1970s NASA had to justify its budget with quicker results, better science, and relevance to earthly problems.

The second major event of 1969 was the arrival of Hans Mark as Ames director. Mark, himself, displayed a force of personality, a breadth of intellect, and an aggressive management style. More importantly, Mark arrived as rumors circulated that Ames would

be shut down. Thus, Ames people gave him a good amount of freedom to reshape their institution. An outsider to both Ames and NASA, Mark forged a vision for Ames that nicely translated the expertise and ambitions of Ames people with the emerging shape of post-Apollo NASA. Mark fashioned Ames to epitomize what NASA called its OAST Centers—those reporting to the Office of Aerospace Science and Technology (previously the OART). Mark left Ames in 1977, following eight active years at the Center, and then became in effect an ambassador for the Ames approach to research management during his posts at the Defense Department and at NASA headquarters.

Into the 1970s, NASA increasingly focused its work on the Space Shuttle, assuming they would soon render routine human access to low Earth orbit. Ames responded to NASA's mission, first, by creating the reentry technologies and control systems that might make the Shuttle truly routine and second, by showing that there was still a need within NASA for the extraordinary in aeronautics and space exploration. This was a time for Ames when what mattered most were entrepreneurship, reinvention, and alliance building. Ames reshaped itself, so that its key institutional structures crossed divisional boundaries, like the Ames Basic Research Council, the Ames strategy and tactics committee, quality circles, and Ames-university consortia agreements. Ames more consciously developed its staff, so that Ames people played ever more prominent roles in NASA administration.

Like Ames directors tended to be, Hans Mark was a practicing researcher. But, other than Chuck Klein, he was the first senior executive at Ames who did not come up through its ranks. Mark was born in June 1929 in Mannheim, Germany, and emigrated to America while still a boy. He got an A.B. in 1951 in physics from the University of California and a Ph.D. in 1954 in physics from the Massachusetts Institute of Technology. He then returned to Berkeley and, save for a brief visit to MIT, stayed within the University of California system until 1969. He started as a research physicist at the Lawrence Radiation Laboratory in Livermore and rose to lead its experimental physics division. He also rose through the faculty ranks to become

professor of nuclear engineering at the Berkeley campus. In 1964 he left his administrative duties at Lawrence Livermore National Laboratory to become chair of Berkeley's nuclear engineering department as it shifted its emphasis from weapons to civil reactors.

When he arrived at Ames, Mark applied many of the management techniques he had witnessed at work in the nuclear field. He created a strategy and tactics committee that allowed for regular discussions, among a much broader group than just senior management, about where Ames was going and what would help it get there. As a result, Ames people became much better at selecting areas in which to work. Tilt rotor aircraft, for example, brought together diverse researchers at Ames to tackle the problem of air traffic congestion. Ames deliberately pioneered the new discipline of computational fluid dynamics by acquiring supercomputers and merging scattered code-writing efforts into a coherent discipline that benefitted every area at Ames.

Similarly, Mark created the Ames "murder" board. This board was a sitting group of critics who questioned anyone proposing a new project or research area, to toughen them up for the presentations they would make at headquarters. His style was argumentative, which he thought Ames needed in its cultural mix. In a period of downsizing, Mark wanted Ames people to stake out "unassailable positions"—program areas that were not just technically valuable but that they could defend from any attack.

From his experience at Livermore, Mark also understood the power of matrix organization, the predominant management idea then underlying all research and development in the military and high-technology industry. Though formal matrix organization fitted Ames badly—because of its structure around disciplinary branches and functional divisions—Mark used the murder board to get people thinking about the on-going relationship between functional expertise and time-limited projects. Ames took project management more seriously, using the latest network scheduling techniques to complement its tradition of foreman-like engineers. And Ames bolstered the functional side of its matrix, by getting its scientific and facilities staffs to more consciously express their areas of expertise.

Ames people insisted that Mark understand that they were each unique—willing to be herded but never managed. Mark compromised by mentally grouping them as two types. Some wanted to become as narrow as possible in a crucial specialty that only NASA could support, because academia or industry would not. Mark admired these specialists, but took the paternal attitude that they were incapable of protecting themselves. The other type warmed to the constant and unpredictable challenges of space exploration, and constantly reinvented themselves. So Mark created an environment of opportunities, perhaps unique in NASA, where both types of researchers flourished. And Mark adopted the Ames custom of motivation and management by meandering. Like Harvey Allen before him, Mark poked his head randomly into offices to ask people what they were up to, and took it as his responsibility to understand what they were talking about. When he did not have time to stride rapidly across the Center, he would dash off a hand-written memo (dubbed Hans-o-grams) that concisely presented his point of view. When scientists like R.T. Jones and Dean Chapman suggested Mark could know a bit more about the work done at the Center, they convened a literature review group that met every Saturday morning after the bustle of the week. While at Ames Mark learned to pilot an aircraft just so he could talk shop with aerodynamicists and flight mechanics. Mark made enemies too. After a spat with John Dimeff, he dissolved Ames' renowned instrumentation division and scattered those researchers around the Center.

Mark treated NASA headquarters in the same informal way. He encouraged Ames people to see headquarters as more than an anonymous source of funds and headaches. Mark showed up every morning at six o'clock so his workday was synchronized with Eastern time. He travelled constantly to Washington D.C., taking a red eye flight there and an evening flight back. He attended every meeting he thought important and told anyone who would listen how Ames was shaping its future. There, too, he would poke his head randomly into offices to chat about how to shape NASA strategy. To head the Ames directorates of aeronautics, astronautics, and life sciences, Mark picked entrepreneurs who were likewise willing to travel

and sell. Their deputies stayed home and manage daily operations. From Mark, headquarters got the impression that Ames was more involved in deciding how its expertise would be used. They also got the impression that Mark had a “stop me if you can” attitude toward headquarters and shared little respect for chains of command.

Mark also made Ames collaborate with broader communities. “Ames has always been better at looking outside the Agency than inside,” he reflected.⁴ NASA headquarters was often too rule-bound or unimaginative to fund every program Ames wanted to accomplish. Collaboration increased the opportunities for direct funding. Collaboration also made Ames people think about the larger scientific and educational constituencies they served, and increased the chances that the best people would aid Ames’ efforts. Mark broke open the fortress mentality that DeFrance had inculcated, and encouraged everyone to build bridges in whatever way they thought appropriate.

During Mark’s tenure Ames forged on-going ties with universities. While Ames had long used individual contracts with area universities for specific types of help, in 1969 Ames signed a cooperative agreement with Santa Clara University that was open-ended. Negotiated by Ames chief counsel Jack Glazer, it pushed the limits of the Space Act of 1958. The agreement defined an on-going infrastructure of collaboration so that Ames and university scientists only needed to address the technical aspects of their work together. Furthermore, students could come to Ames to write their dissertations, and many did in the fields of lunar sample analysis and computational fluid dynamics. Some students came to write papers on the law of space, research, or intellectual property, since Glazer had made his office the only legal counsel office in NASA with a research budget. Rather than operating under a contract with research bought solely for NASA’s benefit, collaborating universities shared in the cost of research. Ames signed collaborative agreements with universities around America so that in June 1970, when President Nixon tried to appoint a government czar of science to keep university faculty out of the pockets of mission-oriented agencies like NASA, Ames stood out as exemplary on the value of

collaboration at the local level. In 1971 headquarters let Ames award grants as well as administer them; by 1976 Ames' university affairs office could administer the grants independent of the procurement office. By 1978, Ames administered 260 grants to 110 universities with annual obligations of more than \$11 million.

Mark also encouraged Ames researchers to interact more freely with engineers in industry, and allowed them more freedom to contract with the firms most willing to help build products for NASA's needs. Paul Yaggy, of the Ames full-scale and flight research group, in 1965 had formalized Ames' relationship with the U.S. Army air mobility research and development laboratory. Encouraged by Yaggy's success in building a research effort on helicopter handling qualities and the reliability of propulsion systems, Mark encouraged the Army to augment its rotorcraft research office at Moffett Field and broaden it to encompass two other NASA centers. He opened dialogue with the Federal Aviation Administration (FAA) on joint programs in aircraft safety. Mark put the Illiac IV supercomputer on the Arpanet to encourage a wider community to author its code. He was especially proud that people nurtured in Ames' atmosphere were named directors at Lewis and Goddard (John M. Klineberg), director at Langley (Richard Peterson), associate administrator for management at headquarters and deputy director at Dryden (Jack Boyd).

Mark left Ames in August 1977, having guided Ames through the years of uncertainty between the end of the Apollo program and the start of Space Shuttle operations. He also guided Ames people to shape a long-term vision, which is still evident today. He helped match their creative energy with NASA's larger and ever-shifting ambitions. The next three directors of Ames shaped the Center in much the same way, but with an evolving palette of personnel against a changing canvas of scientific progress and international politics. Although none hit Ames with the same amount of youthful energy and cultural dissonance, each of these directors learned his approach by watching Mark at close range. In fact, Mark's very first decision as director was to confirm the decision by NASA headquarters that his deputy should be Clarence Syvertson.

CLARENCE A. SYVERTSON

Clarence “Sy” Syvertson understood the NACA culture that had made Ames so great. He arrived at Ames in 1948, after taking degrees at the University of Minnesota and after a stint in the Army Air Forces, to work with Harvey Allen solving the problems of hypersonic flight. Syvertson then worked with Al Eggers in the 10 by 14 inch wind tunnel until 1959, when he was named chief of the 3.5 foot hypersonic tunnel that he and Eggers designed. By pioneering theories that could be tested in Ames’ complex of wind tunnels, Syvertson outlined the aerodynamic limits for some aircraft that NASA still hopes to build—a hypersonic skip glider, direct flight-to-orbit aircraft, and hypersonic transports. For the North American B-70 bomber, he defined the high-lift configuration later incorporated in other supersonic transport designs. Syvertson also managed the design and construction of the first lifting body, the M2-F2, a prototype wingless spacecraft that could fly back from orbit and land at airfields on Earth. A successful series of flight tests in 1964 with the M2-F2 guided the configuration of the Space Shuttle orbiter.

In 1964 Syvertson led the NASA mission analysis division, based at Ames, which charted dramatic ways to explore the outer planets. In 1966 he succeeded Harvey Allen as director of astronautics, then in 1969 became deputy director of Ames. Syvertson was awarded NASA’s Exceptional Service Medal in 1971 for serving as executive director of joint policy study by NASA and the Department of Transportation on civil aviation research policy that made key recommendations on civil aviation and helped move Ames into air traffic issues.

As Mark’s deputy, Syvertson was the inside man. He managed the internal reconfiguration of Ames so that Mark could focus on its future and on its relations with Washington. He managed renovation of the main auditorium so that the Ames community had a better setting for lectures. Syvertson was known as a consensus-builder—able to step in, forge compromise, and resolve the conflict that Mark encouraged, be it policy battles with headquarters or argumentation internally. When Mark decided to leave Ames in July 1977, NASA

headquarters advertised the job of Ames director. In April 1978, the “acting” was removed from Syvertson’s title and he was made director because of the superb, quiet job he had done. Plus, many people noted, Ames could not survive another Mark.

Ames grew more slowly during Syvertsons’ tenure, and the pace of contracting out support services accelerated. But Syvertson broke ground for some important new facilities at Ames—like the crew-vehicle systems research facility and the numerical aerospace simulation facility—and extended its collaboration in new areas. Syvertson accelerated Ames’ outreach efforts, especially to pre-college students. The teacher resource center, for example, archived slides, videos and other media that science educators could borrow to improve their classes. Class tours grew more frequent, so Syvertson helped form a hands-on teaching museum, which opened in October 1991 as the Ames Aerospace Encounter built in the old 6 by 6 foot wind tunnel.

Perhaps the biggest challenge to Syvertson and Ames management came in 1981 with Ames’ consolidation of the Dryden Flight Research Center. Soon after headquarters had sent Ames’ aircraft to Rogers Dry Lake in 1959, Ames started adding aircraft back to its fleet at Moffett Field—first helicopters and VTOL aircraft, then airborne science platforms. When the Reagan administration demanded that NASA cut its staff by 850, acting administrator A. M. Lovelace responded with a plan to make Wallops Flight Center an administrative unit of Goddard and Dryden an “operational element and component installation” of Ames.⁵ The merger, effective October 1981, formalized an already strong relationship. Ames aerodynamicists already performed most of their test flights at Dryden; and most of Dryden flight test projects originated at Ames. Both of the Ames-based tilt rotor aircraft had been flying at Dryden, and Ames willingly transferred more research aircraft there with its staff ultimately in charge.

Louis Brennwald implemented this consolidation, as Ames director of administration, with consolidation planning led by Jack Boyd, then Ames’ associate director and a deputy director at Dryden from 1979 to 1980. Both aeronautics and flight systems

directorates were reorganized, without requiring reductions in force or involuntary transfers. Consolidation meant that Dryden administered flight operations locally, where it was ostensibly cheaper and safer, and Ames provided technical leadership and policy guidance. NASA Ames researchers had done much of the basic research on the reentry and landing systems for the Space Shuttle orbiter and their insights would help as Dryden (which had little experience in spaceflight) was prepared as the landing site for the early shuttle flights.

The renamed Ames-Dryden Flight Research Facility sat on the edge of Rogers Dry Lake, a vast, hard-packed lakebed near the town of Muroc in the Mojave desert of southern California. Its remote location, good flying weather, exceptional visibility, and 65 square mile landing area all made it a superb test site. Edwards AFB managed the entire lakebed, and NASA's Western Aeronautical Test Range provided the tracking and telemetry systems to support research. The Ames-Dryden Facility also ran the world's best laboratory for remotely piloted flight, and its flight loads research facility allowed ground-based structural and thermal tests of aircraft, as well as calibration of test equipment. With better access to Dryden facilities, Ames researchers more efficiently moved innovative designs from concept to flight. To move from concept to flight, Ames had computational power for aerodynamic design and optimization, wind tunnels for measuring loads and fine-tuning configurations, simulators to study handling qualities, and shops to build the proof-of-concept vehicles. The best examples of Ames' abilities to move ideas in to flight quickly and cheaply were the AD-1 oblique wing aircraft, the HiMAT remotely piloted high-G research vehicle, and the F-8 digital fly-by-wire program.

Eventually, Ames itself had to address the Reagan administration's demand for staff cuts. In 1983 a program review committee led by deputy director Angelo "Gus" Guastaferrro decided to cut back on new space projects to support existing ones, and to mothball several research facilities—like the 14 foot tunnel, the 3.5 foot hypersonic tunnel, the transportation cab simulator, and the vertical acceleration and roll device. Yet Ames continued to pursue the same broad areas

it had staked out as unassailable in the early 1970s. Aeronautical research focused on testing methods, safety studies, and slow-speed technologies and VTOL aircraft. Space research focused on thermal protection and spacecraft configurations, adding infrared astronomy and airborne sciences, as well as extending the Pioneer efforts into probes of planetary environments. All Ames research efforts were infused with its ability to build unique laboratory tools—wind tunnels, test models, and motion and work simulators. Supercomputing permeated everything so that computer codes seemed to replace the scientific theory that had earlier guided so much of what Ames did. By Syvertson's retirement in January 1984, Ames had bolstered its prominence within NASA and among wider research communities.

WILLIAM F. BALLHAUS, JR.

The inculcation of supercomputing into everything Ames did accelerated when Bill Ballhaus, a leader in computational fluid dynamics (CFD), became Ames' next director. By 1984, Sy Syvertson had directed Ames for six years, and the Center had flourished under his guidance. But the death of some close friends on the Ames staff, a series of heart problems, and the tragedy and inquiry following an accident in the 80 by 120 foot wind tunnel, all caused him to think it was time for younger leadership. He encouraged headquarters to look at Bill Ballhaus, who at a young age had already distinguished himself as a leader.

Ballhaus received his B.S., M.S. and Ph.D. degrees from the University of California at Berkeley in mechanical engineering, studying with CFD pioneer Maurice Holt. His father was a senior vice president for Northrop Aerodynamics and Missiles in Los Angeles, and introduced him to the emergent importance of computing in aerospace. Ballhaus served in the U.S. Army Reserve from 1968 to 1976, earning the rank of captain. He arrived at Ames in 1971 as a civil service engineer with the U.S. Army Air Mobility Research and Development Laboratory. When Ames decided to form an applied computational aerodynamics branch, the Army staff was delighted to let Ballhaus become a NASA employee as branch chief. It proved

how close a working relationship had developed between the Army and Ames. After less than a year as a branch chief, and without having served as a division chief, in 1980 Ballhaus became Ames' director of astronautics, succeeding the legendary Dean Chapman. CFD underwent explosive growth in the 1970s, and Ballhaus honed his leadership skills through almost constant recruitment. Along with his younger colleagues in the field—Paul Kutler and Ron Bailey—Ballhaus kept abreast of work done in industry and academia, learned to quickly size up whether a researcher wanted time to do basic research or the excitement of engineering application, and teamed them with the best colleagues.

Jack Boyd met with him a few days before Christmas 1983, and said NASA administrator James Beggs wanted Ballhaus to write a brief strategic plan for the Center. Without ever referring again to that plan, Beggs named Ballhaus director of Ames in January 1984. Ballhaus' first memory of the Center, as a graduate student on a tour, had been of the wonderful research facilities. As director, Ballhaus helped bring about several new facilities that were key to its research future, like the numerical aerospace simulation facility and the national full-scale aerodynamics complex. He secured funding for the human performance research laboratory and the automation sciences research facility, and for the integrated test facility at Ames-Dryden. Ames' budget grew by fifty percent during his tenure, including \$300 million for renovation of facilities.

Ballhaus initiated Ames' first comprehensive strategic planning exercise, published in March 1988, that suggested information technology could inject new life into every research area at Ames. And Ballhaus was skilled in reading headquarters, helping Ames people sell their research efforts by describing their ultimate contributions to the International Space Station. Funding for Station-oriented projects was then relatively easy to secure, and the Ames budget grew quickly in the late 1980s. John Billingham, as chief of the Ames life sciences division in the 1980s, broadened its purview into all dimensions of the study of life in the universe. Billingham advocated an integrative vision for the space life sciences, encompassing exobiology, gravitational biology, biomedical research, ecosystem

science and technology, life science flight experiments, and advanced life support systems. During Ballhaus' tenure the Ames life sciences effort increasingly set the agenda for space biology.

Four years into his directorship, in February 1988, Ballhaus was called to Washington to serve fourteen months as acting associate administrator for NASA's Office of Aeronautics and Space Technology. This made him responsible for the institutional management of the Ames, Langley, and Lewis Research Centers. Once NASA named a permanent associate administrator of OAST, Ballhaus returned as Ames director, but stayed less than six months; in July 1989 he officially resigned. He insisted the press release about his resignation cite "inadequate compensation for senior federal executives and vague new post-government regulations as factors in his decision."⁶ This referred to a 1989 ethics law that barred federal contractors from hiring federal employees who had supervised their competitors' projects. Ballhaus was one of several NASA officials to leave the agency in the week before the new law took effect, prompting the newly appointed NASA administrator Richard Truly to call a press conference to decry the law as "a crying shame."⁷

Throughout his tenure as Ames director, Ballhaus amplified a concern expressed by all previous directors—that Ames needed the freedom to hire the best people. Back in October 1961, when vice president Lyndon Johnson asked Smith DeFrance what he could do to help Ames, DeFrance asked for freedom from civil service hiring ceilings. The ceilings remained an issue, and Ames was never so constrained by funds or resources as it was by civil servants to manage them. By the 1980s, Ames still suffered under the ceilings, but now lacked the freedom to pay potential hires competitive wages. Ballhaus fought to secure special salary rates that applied to half of the Ames workforce, he got limited approval to match industry salary offers, and approval to test a more flexible compensation and promotion plan. He led his staff in improving the quality of life around Ames—opening a child care center, working more closely with the local union of the National Federation of Federal Employees, getting everyone involved in a regular strategic planning process, and

encouraging diversity so that Ames was awarded the NASA trophy for equal employment opportunity in both 1984 and 1989. Statutes limited what he could do with executive pay, however, and when Congress defeated the Reagan administration proposal for a pay raise many in Ames' senior executive service left prematurely. "I would have preferred a more graceful exit," Ballhaus wrote to announce his departure. "The Center's success in the future will depend upon our ability to continue to recruit and retain the high-quality people that Ames is noted for. In leaving, it is the close association with the outstanding people who make up this Center that I will miss most."⁸ From there Ballhaus joined the Martin Marietta astronautics group in Denver as vice president of research and development, then rose steadily up the ranks of Lockheed Martin Corporation, and retired in 2007 as president of the Aerospace Corporation. In retirement he joined the NASA Advisory Committee and proved a steady voice for the "seed corn" investment in basic research that had made NASA so great in its earlier years.

DALE L. COMPTON

Dale Compton, who had served as acting director when Ballhaus moved to Washington, replaced him as Ames director. Compton, too, was a product of Ames. He came to the Center fresh out of Stanford University with a master's degree in 1958, one of the first students taught by former Ames aerodynamicist Walter Vincenti. He returned to receive his Ph.D in 1969. Compton worked as an aeronautical engineer with a penchant for participating on project teams—as an aerothermodynamicist for ballistic missiles and NASA's Mercury, Gemini and Apollo human space programs, and as manager of the infrared astronomical satellite program (IRAS). In the mid-1970s, he reinvented himself in space science. He entered management ranks in 1972 as deputy director of astronautics, became chief of the space sciences division, then director of engineering and computer systems, and was named Ballhaus' deputy in 1985. Compton was officially named director on 20 December 1989—at his request to honor Ames' past—at ceremonies marking Ames' fiftieth anniversary.

Victor L. Peterson joined Compton as deputy director in 1990. Peterson, too, was a product of Ames. He had joined Ames in 1956 upon graduating from Oregon State University, and distinguished himself through research in aerodynamics, high-temperature gas physics and flight mechanics. He was known internationally as an advocate of large scale computing across all scientific disciplines, especially in computational fluid dynamics.

Compton, like Ballhaus before him and Syvertson before him, understood how Ames nourished innovation and personal reinvention. Each had grown his own career at Ames, and each knew how to let those under his direction shift and blossom. And NASA headquarters provided new opportunities and resources for myriad Ames researchers to flourish as the first Bush administration looked to space adventures—following the end of the Cold War in 1989—to once again display America’s technological prowess.

In April 1989, early in his term as president, George Bush appointed Admiral Richard H. Truly—a former Shuttle astronaut and the person most responsible for restoring the Shuttle to viability after the Challenger accident—as the new NASA administrator. Then, on 20 July 1989, the 20th anniversary of the Apollo 11 lunar landing, Bush made a Kennedy-esque announcement dubbed the Space Exploration Initiative, about America’s commitment to return to the Moon “this time to stay,” for a human mission to Mars, and for the expanded internationalization of the Space Station Freedom. These long-term, complex space projects made good use of the basic research done at Ames in microgravity, robotics, and planetary science, and Ames’ budget grew apace modestly into the early 1990s.

Yet Compton was seen by some around Ames as too conservative in his vision—as a “tunnel hugger”—one who thought Ames’ standing within NASA depended on the immovability of the wind tunnel infrastructure around Ames. Compton had seen the more project-oriented NASA Centers go through booms and busts as Congress approved and disapproved major projects and thought Ames—fundamentally a basic research organization—would be especially disrupted by such cycles. He had doubts about what sort of institutional follow-on would come from any of the projects

emanating from Ames' space scientists, and he understood that if the Jet Propulsion Laboratory needed work that NASA headquarters would send Ames-originated space projects there to be managed. He had fought hard for SIRTf (the space infrared telescope facility), the Mars Observer, and the Magellan Venus all initiated at Ames, but lost to JPL. Moreover, the various wind tunnel and simulator restoration projects added \$300 million to Ames' budget in the late 1980s, so Compton made sure these efforts were managed well.

Beginning in the late 1980s and continuing through the mid-1990s, NASA headquarters put Ames through a series of roles and mission exercises. The goal, ultimately, was to make all NASA Center directors more agile in modifying their Centers' expertise to support changing national needs. While the strategic plans emerging from these exercises always reiterated Ames' interest in aeronautical research, the plans seemed a bit empty. A great many people at Ames, especially those in life sciences and information technology, began to wonder how they fitted into that picture of Ames. Into the 1990s, Ames began to directly address the relationship between its future and its past.

Ames underwent more profound change in the mid-1990s than in any period since the end of the Apollo era and the arrival of Hans Mark. With the demise of the Soviet threat and shrinkage in federal research spending, Ames people once again had to face the rumors that their Center might be shut down. "Ames has never had a secure place in this agency," Compton reflected. "All directors have tried to secure a place; some have succeeded, some not. My years as director were not easy."⁹

Like NASA as a whole, Ames was swept up in changes imposed by headquarters: downsizing, quality reengineering, program shifting, and outsourcing. However, Ames people took this dark period as an opportunity for self-discovery—of asking what was unique about Ames' historic strengths in science and engineering. They focused on expansive new missions in astrobiology and intelligent systems, and cleared away inherited structures to get at the essence of their work. By the end of the decade, as NASA as a whole reconfigured itself to shape America's aerospace future, the Ames approach—its

cultural climate, managerial empowerment, collaborative spirit, and fundamental scientific curiosity—increasingly stood as the model for what NASA as a whole wanted to become.

THE GOLDIN AGE

Three years into the Bush administration, Congress insisted more firmly that all federal laboratories, especially those in the departments of energy and defense, rethink their roles for the political realities of the post-Cold War era. Compared with the rest of NASA, Ames had lost little as Congress started cutting defense funds. Ames had already planned to mothball non-essential tunnels and simulators. Half of Ames' remaining tunnel time went to test military aircraft, though civil projects stood in line to buy any time freed up from the cancellation of military tests. What military work that remained at Ames went toward technologies—like helicopters and navigation systems—needed to fight the now-expected strategic scenario of many smaller conflicts on many fronts. In fact, the decades of quiet collaboration between Ames and the Soviets in life sciences through the Cosmos-Bion series of biosatellites was a key resource for the rest of NASA as it pursued a wider array of cooperative projects with the Russian space agency, especially surrounding the international space station.

NASA headquarters, however, showed no inclination to squeeze out a peace dividend from the NASA budget. Concepts for a Moon colony and a human mission to Mars were abandoned slowly with the realization that the technology was too premature to do either safely or cheaply. Congress grew impatient as NASA let the space station, the key cooperative project, soak up any funding liberated from NASA's defense-oriented projects. In March 1992 George Bush made a surprise announcement—that he had nominated Daniel Goldin to replace Richard Truly, whom he had asked to resign as NASA administrator.

Goldin was a vice president and general manager of the TRW Inc. space and technology group in Manhattan Beach, California, which specialized in commercial, early-warning and spy satellites. During Goldin's five year tenure in that group, TRW had built thirteen such

spacecraft—for the Tracking and Data Relay satellite network, the Air Force Defense Support program, and the Brilliant Pebbles and Brilliant Eyes projects of the Strategic Defense Initiative Office. For NASA, TRW had built the Compton Gamma Ray Observatory, and parts of the Advanced X-ray Astrophysics Facility. TRW won NASA's 1990 Goddard Award for Quality and Productivity and was a finalist for the George M. Low Trophy for quality. Those who bought spacecraft from TRW knew Goldin as a capable manager. Those in space policy knew nothing about him.

Goldin's early pronouncements showed him supportive of a smaller space station, a human landing on Mars, and reliable operation of the Shuttle. But mostly, he talked about applying an industrial perspective to shake up NASA. "He's a faster, cheaper, better kind of guy," said a Bush administration official. "He's obviously outside the NASA culture."¹⁰

"My challenge," Goldin proclaimed in his first address to NASA employees, "is to convince you that you can do more, do it a little better, do it for less, if we use more innovative management techniques and if we fully utilize the individual capabilities of each and every NASA employee." Goldin also voiced, Ames people noted, distaste for how he perceived NASA's recent work in aeronautics: "We have to perform world class aeronautics research. Not leave it on the back-burners, not enjoy all the fun we're having writing TRs and TNs [technical reports and technical notes], but what we have is an obligation for America. The American aeronautics industry is counting on us and let's ask ourselves, have we really lived up to the expectations of American aeronautics?"¹¹ He was obviously a man of energy, different views and, Ames people soon discovered, of strong personality.

Not the passage of time, nor the eventual respect for Goldin's leadership—nothing softens the horror when Ames people tell the story of Goldin's first visit to Ames. There is no videotape that recorded what actually happened, so stories are told. Articles criticizing Goldin's intentions had just appeared in Bay Area newspapers and Goldin, one Ames manager remarked, "seem to show up loaded for bear."¹² Rather than listen to welcoming speeches, he counted

the number of women and minorities in a photograph of Ames executives, remarking on how few he found. Goldin challenged those he happened upon to defend their programs. People hid their name badges. In a meeting in the director's conference room, Goldin sent to the perimeter all those sitting around the table—mostly senior white males—and asked those sitting in perimeter chairs to take their place. Then Goldin heckled director Dale Compton as he reviewed Ames' strengths and goals, until Compton walked silently from the room, halfway through his presentation, to compose himself. Only then did Goldin's wrath subside.

Goldin himself has turned philosophical about how NASA people reacted to the force of his personality. One of his first decisions as administrator, for example, was to return NASA to the round blue "meatball" logo of its glory days. Individuals at Ames quickly started removing "worm" logos (the red, linked letters introduced in the 1970s), because they saw how Goldin reacted when he saw it. Goldin denied that finally burying the NASA worm logo was some personal obsession, "but if people think it is and it helps to stimulate positive change, I'm all for it."¹³ Goldin's visit, in fact, foreshadowed that he really would push for a diverse workplace, for opening up the NASA facilities to scientists outside the usual groups, for imposing total quality management, and for tightening the NASA organization. But clearly, there was more than that to his displeasure with Ames.

NASA headquarters sent a surprise security review team that descended upon Ames on the evening of 31 July 1992. They sealed buildings, changed locks, searched file cabinets, took computers, interrogated more than a hundred scientists, and sent ten researchers home on administrative leave. Only Compton was told, the day before, who they were, what they were looking for, and what prompted the raid. The team pointedly asked everyone about "management's judgment" on technology transfer matters.¹⁴ Rumors circulated that they targeted scientists of Asian descent, especially those in the aerophysics directorate. In the end, the team discovered nothing illegal, and Ames altered some minor security procedures. But some good people decided to quit, and the Center was left with deepened concerns about the attitudes toward Ames that prevailed in NASA headquarters.

Whenever Goldin talked of Ames he used the word “revitalize,” which Ames people considered better than “shut down.” During the summer of 1992, as Bill Clinton made gains in the polls, Ames people thought a change in administration might remove Dan Goldin from their list of worries. But Albert Gore, as senator from Tennessee, chaired the committee that oversaw NASA matters and liked what he saw in Goldin. When Gore became vice president, he asked Goldin to stay on as administrator.

MOFFETT FIELD AND CULTURAL CLIMATE

Compton won the next round of tensions between Goldin and Ames—over the reconfiguration of Moffett Field. The Navy had managed Moffett Field since 1931—except from October 1935 (following the crash of the dirigible *Macon*) to April 1942 when the Army Air Corps ran it. In the 1950s, the Navy based supersonic fighters there until the community objected to the noise. In 1962, propeller-driven P-3 Orions arrived on base to fly patrols over the Pacific in search of Soviet submarines. With the collapse of the Soviet Union in 1990, the Navy said it no longer needed Moffett Field. The Base Realignment and Closure Commission (BRAC), an independent board reporting to Congress, agreed.

The Bay Area congressional delegation, led by Norman Mineta, a San Jose Democrat who chaired the Congressional Space Caucus, stepped into the fray. They convinced the BRAC that, even if the Navy left, Moffett should remain a federal airfield. Efforts in 1990 to declare fifty acres at Moffett as protected wetlands, and to chart the presence of protected species like the burrowing owl, least tern, and peregrine falcon limited other developments at the field. In the October 1991 recommendations approved by Congress and the president, the BRAC said that NASA, as the next biggest resident agency, should become Moffett’s custodian. The Navy had subsidized Moffett operations at \$6 million per year, a cost NASA then would have to include in its budget unless it found other ways to generate revenues from field operations. NASA administrator Richard Truly understood the opportunities for Ames. Goldin inherited a decision, however, that was not initially in line with his change agenda. NASA

headquarters was already planning to further trim Ames' flight operations. Furthermore, if Congress ever imposed a BRAC-type process on NASA, headquarters might want nothing to get in its way of shutting down Ames. Compton and his executive staff understood this, marshalled the substantial goodwill toward Ames from its local community, and wrested control of the property on which Ames sat. Not until December 1992, in a subdued signing ceremony at Ames, did Goldin concede that NASA would step up as custodian agency when the Navy officially decommissioned its station in July 1994. It would be four years after that, though, before NASA Ames could move forward with any plans for redeveloping the base.

"Over the past five years in my prior job, I've become a true believer in the value of total quality management," said Goldin. "I believe deeply that if you can't measure it you can't manage it, and intend to bring this philosophy to NASA."¹⁵ Throughout the 1970s, headquarters had asked Ames to undertake consultant-driven reviews and exercises—like quality circles—to make itself more efficient, and it was entirely Goldin's prerogative to impose this latest fashion in organizational improvement. But total quality management (TQM) was confusing. It demanded a focus on the "customer," which in Ames' case proved nebulous. "The space program doesn't belong to us," Goldin would say. "It belongs to the American people. They are our customers."¹⁶ Lots of NASA people did not find that definition specific enough to clarify how they would use all the statistics and acronyms TQM demanded. But Ames people tried.

Compton called an all-hands meeting in July 1992 on the Ames flight line to say Ames would start implementing TQM beginning with a year of education and training. Meanwhile a quality improvement team, chaired by Jana Coleman and Robert Rosen and working with continuous-improvement consultants Philip C. Crosby, Inc., wrote a report on the whole TQM process. In April 1993, Ames posted everywhere its carefully worded quality statement. Ames' management council approved the report in February 1993, and set about forming process action teams to reduce the costs of non-conformance. Throughout the Center, teams defined their customers, used flow charting and process measurements, tore apart then

rebuilt all their procedures, and began to report savings in costs and time. For example, in late 1993, the Unitary 11 foot transonic tunnel applied a TQM approach to runs for the Navy's A/F-X competition by four contractor teams. By reviewing their procedures and listening to their customers, the tunnel group doubled the expected number of successful runs. Ames announced a \$2 million investment in process infrastructure—like electronic forms and purchasing, computer peripherals, and a charge-back system for technical support—that helped all teams improve their processes. Ames made good progress, even though the Crosby literature trumpeted that continuous improvement is a cultural process that takes five to seven years to change—"so don't let impatience cloud your view of progress."¹⁷ Ames undertook the Malcolm Baldrige Self-Assessment in the fall of 1993—less than eighteen months after starting TQM—because of a Clinton administration initiative to reinvent government. The survey showed that, even though Ames people thought their work was very high quality, they knew little about Ames' formal quality process. Ames lagged well behind all other organizations actively implementing TQM.¹⁸ Ames management, presumably, had not become true believers in TQM.

Another cultural review further widened the chasm between Ames management and NASA headquarters. In July 1992, Ames was visited by a NASA-wide cultural climate and practices review team, led by General Elmer T. Brooks, deputy associate administrator for agency programs. The team gave Ames a glowing report, calling it "the best" of all NASA Centers. Ames employed higher percentages of underrepresented groups than any other NASA Center; the Ames Multi-Cultural Leadership Council was a model for other Centers; participation was strong in the Equal Opportunity Advisory Groups—African America, Asian American and Pacific Islander, Disabled, Hispanic, Women and Native American; Ames won NASA's Equal Opportunity Trophy in three of the past nine years; and Ames' entire work force felt challenged and satisfied.

However, there were problem areas. The percentage of minorities employed was lower than in the culturally diverse Bay Area as a whole. Blacks were especially underrepresented, suggesting Ames

had failed to reach into the local community. Ames tended to hire experienced researchers rather than those fresh out of co-op programs. Any mentoring was too informal, and career development was haphazard. Higher wages in local industry made it tough for Ames to retain the leaders it did develop. Of forty top managers, only one was a woman and only two were minority males. Minorities and women perceived the senior executive service as a white male preserve. In fact, the Brooks team declared that all problems were caused by upper management. Despite being the best in NASA in affirmative action, the Brooks team reported, “everyone is looking to the Center director for proactive leadership.”¹⁹

Then, in October 1993, Congress pulled funding for the SETI program (the search for extraterrestrial intelligence), which Ames had nurtured for two decades and had stirred up real scientific excitement around NASA. Some Ames staff felt that Goldin failed to stand up to congressional doubts, and sacrificed SETI to secure funding for the space station and for programs at other Centers. Goldin later said that NASA would focus instead on the far more promising search for dumb, organic life in the universe by developing the discipline of astrobiology. Eight civil servants and fifty contractor staff were affected by the \$12 million cut. As other Ames projects were cut, and as Ames prepared for many years of flat or declining budgets, Ames opened a career-transition office to move its work force into a booming Silicon Valley economy hungry for such technical skills.

Compton and Peterson increasingly felt that, as the lightning rods for some unarticulated displeasure from NASA headquarters, the best thing they could do for their Center was to retire. In November 1993, both Compton and Peterson retired—after 36 and 35 years of government service, respectively. In declining to speculate on what his successor might consider Ames’ major goals and challenges, Compton replied: “The long term goals of this Center have survived many directors.”²⁰

KEN K. MUNECHIKA

In January 1994 Ken K. Munechika became director of Ames, recommended to Goldin by Senator Daniel Inouye of Hawaii. Munechika was raised in Hawaii and earned a doctorate in educational administration from the University of Southern California. He had a distinguished career in the U.S. Air Force. He started as a navigator, flew 200 combat missions in Southeast Asia, moved into training as a professor of aerospace studies, then served as chief of satellite operations to recover space capsules deorbited from space. In July 1981 he moved to Sunnyvale to command the Air Force Satellite Control Facility (later renamed Onizuka Air Force Station), where he directed contractor teams in launch operations of more than fifty defense satellites, and all the defense payloads launched by NASA's Space Shuttle. He was also responsible for planning and budgeting a global network of satellite tracking stations. He retired from the Air Force in June 1989 to become executive director of the office of space industry for the state of Hawaii (where he returned after being reassigned from Ames).

Munechika asked William E. Dean to serve as his deputy director. Dean, too, was a newcomer to Ames, having arrived in August 1991 as special assistant for institutional management. Prior to that, Dean served as president of Acurex Corporation of Mountain View, a privately held supplier of control and electronics equipment. Before then, from 1962 to 1981, Dean worked for Rockwell International, serving as group vice president responsible for the Global Positioning Satellite and for the operational phase of NASA's Space Shuttle program. Compton had hired Dean to infuse business-like thinking into Ames, and Munechika asked him to stay on.

Though he had spent his entire career managing the highest technology in the Air Force arsenal, Munechika was the first to admit he was no scientist. His first priority was addressing the lingering factionalism from the Cultural Climate and Practices Plan. "Since aeronautics and space are for everybody," Munechika wrote, "I want Ames to look like America and the community we represent....Ames

must have a work environment where everyone feels empowered, included, valued, and respected.”²¹ Jana Coleman was named to lead the newly created Center operations directorate, the first woman to head a directorate at Ames. Ames people addressed their diversity with seriousness.

Ames people also put more vigor into their outreach efforts. Every summer for two weeks thousands of students gathered for the JASON project to explore, through telepresence, the scientific mysteries of our Earth. Ames formed a docent corps to staff the Ames Aerospace Encounter, the Ames visitor center, and the Ames teacher resource center. NASA distributed internet kits to area schools, when the internet was still largely unknown, and engineers volunteered to share with students the excitement of their work. Ames expanded its relationship with the National Hispanic University (the relationship began early in 1993 with a space sciences program and would culminate in an historic collaborative agreement in October 1997). Interns and research fellows came from a wider variety of schools. Space Camp California opened just outside Ames’ main gate.

With Munechika to introduce them, headquarters staff showed up more regularly at Ames, praising its revitalization efforts. Many of the significant events and program activities that would follow—like the Zero Base Review, the information technology Center of Excellence, the astrobiology institute, Lunar Prospector, the SOFIA restart, and the absorption of Moffett Naval Air Station—were all started in a fairly short period of time after Munechika became director. Yet bolstered morale and coalescence of support from the external community only served to brace Ames people for program adjustments and structural changes still to come. The darkening funding picture and Goldin’s agenda for change set the challenges for Munechika’s leadership. The same day Goldin announced Munechika’s appointment, he also announced the appointment of three other Center directors (two of whom, like Munechika, would be gone within three years).

He further announced that the Dryden Flight Research Center would again become an independent field Center. Managing Dryden from afar had not resulted in any significant cost savings. In December

1990 NASA headquarters appointed long-time Dryden researcher Kenneth Szalai to the position of director of the Ames-Dryden Flight Research Facility. Marty Knutson, who had managed the facility for five years and guided Szalai's development as a manager, returned home to Ames. Goldin visited Dryden in September 1992 and announced that "the right stuff" still lived there and, indeed, Szalai proved adept at bringing new projects to Dryden—from industry as well as from other NASA Centers. By March 1994, after thirteen years of leadership from Ames, Dryden again became an independent NASA Center. In a note to Ames employees, Szalai wrote "Many professional associations and friendships were developed and I intend to work hard to sustain these....Please consider Dryden as your flight research center, too."²² Ames management expected that, as Dryden asserted itself in NASA planning, that programs and people would be shifted there from Ames.

Headquarters let Ames staff know that Moffett Field was their burden to bear. Countless details were ironed out in advance of the transfer, all coordinated by Michael Falarski and Annette Rodrigues of the NASA-Moffett Field development project. Change appeared gradually—access rules were rewritten, security guards wore different uniforms, the Navy's P-3 Orions left, the Navy began environmental remediation, and historic preservationists surveyed the architecture. In 1993, NASA also took control of the small naval airfield at Crows Landing in Stanislaus County—which Navy pilots had used for P-3 training flights and which NASA would use for low-speed flight research. The Onizuka Air Force Station took over the military housing that Navy families vacated. On 1 July 1994, while a Navy blimp and a P-3 Orion flew overhead, a 21 gun salute and taps sounded as Navy officers lowered their flags. "From Lighter than Air, to Faster than Sound, to Outer Space:" that's how the Navy commander described the changes seen at the Naval Air Station Moffett Field.

NASA renamed it Moffett Federal Airfield to reflect the organizational flexibility it now had to serve a wider array of tenants and customers—the Naval Air Reserve of Santa Clara, the Army Reserve, the California Air National Guard, other governmental

agencies like the Post Office and the Federal Emergency Management Agency, and private firms executing government contracts. Then Ames people started planning to make something exciting from this opportunity.

Ames started by assessing community needs, in the adjacent cities of Mountain View and Sunnyvale and in Silicon Valley region-wide. San Jose International Airport was congested, with any expansion limited by its proximity to the downtown and its location amid residential neighborhoods. Moffett Field offered a superb airfield—twin runways, 9,200 feet and 8,900 feet long, ample tarmacs, three very large hangars, aircraft fuel and wash facilities, and more than seventy structures for aircraft operations. It had 24 hour crash and rescue service, sixteen hour air traffic control, instrument landing, world-class communication links, and easy access to Highway 101. What it lacked was air traffic, so Ames facility managers suggested using the airfield for business and freight flights. The San Jose airport could no longer fit in jumbo jets ferrying electronics back and forth from Asia. Furthermore, Bill Dean, Ames' deputy director and the person most responsible for base planning, thought that Ames should keep the airfield as the Navy left it. Like so many others, he thought that some day soon Russian submarines would again patrol the Pacific and the Navy would return its P-3 Orions. Converting Moffett Field into an air cargo base, as he proposed, best kept it in mobilization shape.

But local residents had gotten used to quiet (though the P-3 and C-130 flights were never very noisy). Rather than decide themselves, the Mountain View and Sunnyvale city councils asked for a non-binding vote on the plan to make Moffett Field a freight airport. Voters advised against the plan, Munechika respected the vote, and Ames was left to devise another plan while shouldering the costs of running the base. Losing the momentum behind the Moffett Field plan was a loss, though far greater losses to the Center came in the wake of NASA's Zero Base Review.

ZERO BASE REVIEW

Goldin arrived at NASA proclaiming that NASA was bloated. He imposed a new type of discipline to NASA's budget process and, in time for the fiscal 1994 appropriations, submitted a budget that reduced NASA's five-year budget by \$15 billion. Two years later, by cancelling programs and redesigning the International Space Station, he voluntarily reduced NASA's long-range budget by thirty percent. He called this process "a fiscal declaration of independence from the old way of doing business." But by 1995 Congress asked NASA to cut an additional \$5 billion from its \$14 billion budget, starting in 1997. Goldin realized that the loss of more research programs would jeopardize NASA's leadership in aerospace. So in response to the Clinton administration's call for a national performance review, instead of cutting programs Goldin tried to streamline NASA's infrastructure through a Zero Base Review (ZBR).

Rather than starting with last year's budget to develop the next, zero base budgeting meant starting from zero every year, and asking whether each program was essential to an agency's core mission. This was different from the national laboratory review of 1992, which focused mostly on eliminating duplication of functions. A headquarters "red team" visited Ames in 1994 and asked Ames people to ponder the prospect of being shut down. The preliminary ZBR white paper of April 1995, drafted at NASA headquarters, translated this vague recommendation into a specific budget planning document. Nancy Bingham, the Ames manager on whose desk the faxed ZBR draft landed, called it "inflammatory."²³ It presented numbers that dropped Ames' civil servant cadre from 1,678 to below 1,000 within five years—below the point of viability. Aerospace facilities would be transferred to Dryden, and the space station centrifuge project would go to Johnson Space Center. What remained of Ames could then easily be shunted into a GOCO—a government owned, contractor operated facility. Ames had in the past confronted efforts, both real and imagined, to shut it down—in 1969 at the start of Hans Mark's tenure and during the 1976 reductions in

force before he left. The draft ZBR white paper made it most clear—in dollars and headcounts—that if people in Washington wanted to rebuild NASA from scratch, they would rebuild it without Ames.

To stave off the threat that the entire Center would be shut down, Ames mobilized support within the community, among California legislators and Ames' friends in Washington. Congressman Norm Mineta protested that the people of Ames "are too valuable to be left to the underestimation of NASA bureaucrats in Washington."²⁴ With the small amount of time they won, they dove head first into the challenge of zero-base thinking. NASA headquarters had started by defining its five strategic enterprises—mission to planet Earth, aeronautics, human exploration and development of space, space science, and space technology. They intended to declare each Center a center of excellence in some area to help all of NASA execute those missions. Each Center would take on lead-center programs, and administrative functions would be consolidated agency-wide. Deciding which Centers should execute a mission and which were "overlap" got intensely political.

Many at Ames believed their Center did not fare well in the grab for assignments. Ames lost its leadership in Earth sciences to Goddard, in biomedical sciences to Johnson, in space technology to Marshall Space Flight Center, and in planetary sciences to the Jet Propulsion Laboratory. Significantly, Ames lost its leadership in aerodynamics and airframes to Langley, and Langley might also manage Ames' tunnels and simulators, which were mostly staffed by contractors but made up sixty percent of Ames' budget. Ames faithfully eliminated programs declared redundant, and executed its plan for 35 percent attrition during 1996: buyouts reduced the number of civil servants by 300, layoffs almost halved the number of contractor personnel to 1,400.

Most importantly, Ames finally lost its aircraft to Dryden. In May 1995, NASA announced that for cost savings every aircraft in the NASA fleet—operational as well as experimental—would be consolidated at Dryden.²⁵ Ames had the most to lose. Of the seventy aircraft in NASA's fleet, Ames then serviced twelve of the biggest—three ER-2s, one DC-8, one C-130, one Learjet, one C-141, and five

helicopters. Moving the airborne science airplanes provoked the most controversy. Ames management argued that these airborne laboratories relied on input from an active scientific community simply not found in California's high desert, and that they used equipment made and maintained in Silicon Valley. "This consolidation could mean the end of valuable environmental programs," wrote California congresswoman Anna Eshoo, "I'm also concerned that NASA is fudging its fiscal homework on the consolidation plan. Its numbers are incomplete and its economic justifications are questionable."²⁶ The flight operations branch, the first branch ever established at Ames, was disbanded. Some support staff moved with the aircraft; some retired, like long-time flight operations chief Martin Knutson and pilot Gordon Hardy; most took new assignments at Ames. In November 1997 the last Ames aircraft flew off to Dryden, though some helicopters remained. A disconcerting quiet hung over the Ames hangars. Researchers at Ames who dedicated their careers to improving aircraft and who wanted to see them fly now had to shuttle south to the desert and back on a commuter airplane.

Amid all these program losses, though, Ames constructed a bold new strategy. Ames' active response to the ZBR fell on the shoulders of a group of mid-career technical leaders—most of whom had hired into Ames during the 1970s and had honed their advocacy skills in the strategy and tactics committees called by Bill Ballhaus and Dale Compton. Despite the mandate of zero-based thinking, they refused to consider that Ames had utterly no history. They knew the people on Center, how fluidly they worked together, and how ingeniously they used the research tools available. Ames management had not done the best job marketing these capabilities; still they existed. Coordinating efforts from the Ames headquarters building, Nancy Bingham, Bill Berry, Mike Marlaire, Scott Hubbard, and George Kidwell pulled together comments from their colleagues around Ames, and gradually a strategic response emerged. Ames polished this story by talking to community leaders, to the Bay Area Economic Forum, and the local press. Largely because of the Ames response, the final NASA ZBR white paper of May 1996 showed Ames' headcount at 1,300 and that Ames would lead NASA in information technology, astrobiology, and aviation system safety and capacity.

The Ames response to the ZBR marked another rebirth. In the same way that so many scientists and engineers had reinvented themselves to address new national needs, by the end of the ZBR exercise the Center had also redefined itself. It coincided with the arrival of a new director.

HENRY MCDONALD

Harry McDonald remembers that when he first met Dan Goldin, Goldin said that he “gave Ames one plum assignment—to become a center of excellence in information science—and that Ames hadn’t executed it well.”²⁷ Munechika’s plans for the newly-created information systems directorate were largely derailed when David Cooper, the information system director he appointed to replace Henry Lum, left and many of his staff left with him. Consolidating all of NASA’s computing and communication systems should have shown a savings of 1,200 positions agency-wide, but the systems were still burdened by disorganization and redundancy. More NASA mission revolved around newer information technologies in imaging, robotics, data crunching and internetworking, and NASA people had a hard time finding the expertise they needed. If Ames expected to grow it had to take a bold stance, especially in serving NASA’s information needs. Thus charged with implementing Ames’ information technology mission, McDonald arrived as Ames director in March 1996.

A native of Scotland with a doctorate in engineering from the University of Glasgow, McDonald had spent the previous five years as professor and assistant director of computational sciences in the Applied Research Laboratory at Pennsylvania State University. Before that, McDonald was president of Scientific Research Associates Inc., of Glastonbury, Connecticut, a company he founded in 1976 to do contract research in computational physics and gas dynamics. The state of Connecticut awarded McDonald its Small Businessman of the Year Award for high technology because of a ventilator he invented and developed. And before that he worked as a research engineer for British Aerospace and then for United Technologies where, along with colleagues at Ames, he developed software for

linearized block implicit methods for solving compressible flow equations. McDonald joined Ames on an interpersonnel agreement that allowed him to keep his university tenure, and he kept a house in Glastonbury, where his wife had her medical practice.

McDonald was an expert in computational aerodynamics, and though an outsider to the Center, people around Ames knew and respected his work. As his deputy director he appointed William E. Berry, who had built a strong reputation for management in the space and life sciences at Ames. McDonald also brought in new managers from the outside—like Robert J. “Jack” Hansen as deputy director of research. Steven F. Zornetzer, director of life sciences at the Office of Naval Research, was hired as director of information sciences and technology, and worked with Kenneth Ford to develop Ames’ center of excellence in information technology. McDonald also invited back an old hand as his advisor, Jack Boyd.

Intellectually, McDonald understood the entire range of work at the Center and could thus represent it effectively outside. He tempered what many perceived as the traditional arrogance around “Ames University.” McDonald tapped into the desire of Ames researchers to embrace change, and to reinvent themselves by applying their skills to new challenges. Most important, McDonald focused Ames on implementing the strategic opportunities posed by the Zero Base Review.

The mantra of faster, cheaper, and better fit Ames’ legacy in spacecraft management, exemplified by the Pioneer series of space probes launched in the early 1970s. This small spacecraft tradition combined well with Ames’ ability to craft cooperative arrangements with private firms and research organizations. Even in broader programs managed by other NASA Centers, Ames was named leader of important specific projects—like Lunar Prospector, the X-36 and SOFIA. Ames had established a center for Mars exploration in 1992 which, in May 1998, was reconfigured as a cross-directorate organization, the Center for Mars Exploration with Anthony Gross joining Geoffrey Briggs as co-directors. It supported a re-invigorated headquarters desire for robotic Mars exploration and for inventing ways to use materials found on Mars to build a settlement. As NASA

reshaped itself during Goldin's tenure it looked to Ames and to the leadership style of McDonald as models.

The history of Ames Research Center is reflected in the projects it did and the way it organized its scientific and technical expertise. Ames undertook ISO 9001 certification, at Goldin's insistence, to align its tradition of engineering with the international standard for quality management. In June 1996, Ames' deputy director Bill Berry saw how certification benefited work at Great Britain's closest analog to Ames, the Defense Evaluation and Research Agency. In January 1996, the leadership of the Ames aeronautical test and simulation division decided that their efforts at total quality management would be better channeled into the broader and better-defined ISO 9001 process. Bob Shiner led the effort; teams including every civil servant and contractor employee wrote the manual detailing their work processes and methods of quality assurance. This division passed their ISO certification audit in June 1998, and soon all of Ames embraced the ISO 9001 process as a chance to demonstrate categorically the quality they had so long, and often so quietly, provided to those they served.²⁸ In April 1999, after an intense review, Ames was ISO certified "without condition," a rare achievement. "When Ames needs to step up we can show superior management process," noted Harry McDonald. "We just don't want too much managerial process."²⁹

Ames people started seeing Moffett Field as the physical endowment on which to build the Center of their dreams. Led by McDonald, Berry and Michael Marlaire, Ames' director of external affairs, Ames people began to view Moffett Field not as a problem to be managed or a collection of historical artifacts from another era of science and technology to be preserved. Instead, they came to view the Moffett land as a unique opportunity—as a large, still-underdeveloped piece of land at the epicenter of the world's most dynamic industrial region. "Our Center's traditional agenda and structure were becoming fundamentally unstable because of the change in the world around us," noted Berry. "Today, no one would build huge wind tunnels here, on land this expensive, and where labor costs are so high. Nor would they surround a major research center

with a fence.”³⁰ The San Francisco Bay area was the most prosperous metropolitan area in the nation; the nation’s third leading exporter overall, producing more than one fourth of America’s high tech exports. One fifth of the hundred fastest growing global companies located there—including most of the leaders in computing, communications, and biotechnology. For Ames to continue to flourish, Center leadership realized it must be firmly rooted in that Silicon Valley community.

Ames held its first open house in September 1997. Thousands were expected; nearly a quarter million of Ames’ closest friends streamed in. Ames displayed its latest technology at sites around the Center, including demonstrations of a Mars rover and many of its wind tunnels. “Partnership” unified the 150 exhibits inside the enormous Hangar One, where local schools, companies, federal agencies, and community organizations bragged about all they had accomplished by working with Ames. Over 1,300 Ames ambassadors helped the crowd, describing the science behind the dazzling displays. “We all witnessed actions so extraordinary,” effused Lynn Harper, who coordinated the space sciences exhibits, “that we thought we’d burst with pride.”³¹ As David Morse and Donald James, the Ames external affairs co-chairs who so quickly organized the open house, walked around to check on things, people applauded.

Morale at Ames had sunk low in the early 1990s— budget cuts by Congress, the transfer of programs to other Centers, neglect and scolding from headquarters, and a lack of technical leadership within Ames. As Ames people caught glimpses of the public interest in the open house, however, enthusiasm grew. The open house displays let Ames shed the trappings of its past and embrace its future by declaring—loudly, visibly, and harmoniously—how it was stepping up to its missions in information technology, astrobiology, and aviation capacity and safety. This time Dan Goldin, who had inspired the event after he met with local leaders six months before, had to compose himself as he welcomed the throngs so fervently interested in all Ames had contributed to its community. Ames director Harry McDonald reflected:

“September 20, 1997 was a momentous day in the life of Ames Research Center—a day when we made history and recast the course of our future. Together, as we transform this incredible Center, we are reinventing ourselves in the process. Our workforce has a new sense of pride. A better, more robust Ames will be our legacy; effecting the transformation is our reward. Community Day did not initiate this process. But, as we look back, it will stand as the most visible signpost on the historic pathway of change, and the point from which all future progress will be measured. Collectively, we have changed both the perception and reality of Ames.”³²

In 1998, four years after the closure of Moffett Field as a military base, Ames signed memoranda of understanding with the cities of Mountain View and Sunnyvale that allowed planning of the NASA Research Park (NRP) to move forward. Marlaire and Trish Morrissey led creation of an award-winning re-use plan to transform part of the former Naval Air Station into a research and development center dedicated to serving the nation’s space program. In 2002, a final environmental impact report was approved, eventually allowing 4.2 million square feet of new construction. NASA Ames could act as its own master developer.

The Ames portion of the base remained fenced and operated as before. The airfield remained intact though relatively quiet. In the old Navy portion of the base—several million square feet of built space—there would emerge a new complex of research buildings. The University of California at Santa Cruz and Carnegie Mellon University needed space for extension education. UC Santa Cruz also formed a university-affiliated research center to take research and engineering contracts from Ames, and apply the intellectual horsepower of the UC system to serve NASA. Ames also brought in industrial partners—mostly start-up companies helping to transfer NASA technology—as reimbursable Space Act tenants that paid Ames fair market rents to fund base operations. NASA Ames was

also allowed to lease buildings in historic Shenandoah Plaza through authority granted by the National Historical Preservation Act of 1966. While any major construction at Moffett Field would still require substantial financing and political support, small improvements accumulated quickly.

Goldin resigned in November 2001, ten months into the administration of George W. Bush, having served three presidents and as the longest-tenured NASA administrator.³³ He was succeeded by Sean O'Keefe, who served until February 2005, and then by Michael Griffin, who served until January 2009. Both of these administrators, unlike Goldin, proved largely indifferent to Ames and moved the agency in directions that scarcely relied on Ames' traditional strengths. Bush appointed O'Keefe as administrator expecting NASA to fund the aerospace industry to build new rockets to replace the space shuttle, a policy Griffin accelerated. Thus, even lacking Goldin's initial anger, Ames people considered the tenures of O'Keefe and Griffin more trying times for their Center.

McDonald retired from NASA Ames in September 2002, soon after he turned 65. McDonald had crossed swords with O'Keefe in a personal way he never had with Goldin, and both of them sensed their working relationship was beyond repair. As a distinguished professor of computational engineering at the University of Tennessee in Chattanooga he remained quite active in his research. McDonald's deputy, Bill Berry, also retired then went on to lead the Ames-oriented efforts of the University of California at Santa Cruz. To succeed McDonald, O'Keefe selected one of the young managers who had guided Ames through its zero base review.

G. SCOTT HUBBARD

Prior to becoming director in September 2002, Scott Hubbard had spent fifteen years in leadership positions at NASA Ames. Hubbard earned his undergraduate degree in physics and astronomy from Vanderbilt University in 1970, then did graduate work in solid state physics at the University of California at Berkeley. He served as staff scientist at Lawrence Berkeley Laboratory, founded and managed Canberra Semiconductor, then worked as senior research

physicist at SRI International. During this period he authored forty papers, and did research on radiation detection and far infrared photoconductors. He joined Ames in 1987 and served as principal investigator for detector technology projects; he later served as co-investigator for the Lunar Prospector gamma ray spectrometer. As associate director for astrobiology and space programs in the early 1990s, he originated the concept behind the Mars Pathfinder, which successfully landed on Mars in July 1997. He helped create the NASA Astrobiology Institute, and served as its interim director. From 1997 to 1999 he served as deputy director of the Ames space directorate. He was also NASA manager for the Lunar Prospector mission which launched in January 1998, orbited the Moon for a year to map lunar resources, and found evidence of water ice at the south pole of the Moon. In 2000 he was called to headquarters as Mars program director, the “Mars Czar,” to reshape NASA’s efforts at the robotic exploration of Mars following the high profile failures of the Mars Climate Orbiter and the Polar Lander in 1999. Under his watch, NASA accelerated their plans for Mars Odyssey and the rovers *Spirit* and *Opportunity*. In 2001 he returned to Ames as deputy director for research—third in command—before being named director.

Four months after becoming director, though, Hubbard was called away from the Center for six months. When the space shuttle Columbia disintegrated in the skies over Texas in February 2003, NASA’s established protocol designated the director of Ames as NASA’s sole representative on the accident investigation board. The Ames director would not be as vested in shuttle program decisions as were the directors of the Centers more actively engaged in human space flight, but would still be able to marshal the NASA resources needed for a thorough investigation. Hubbard, with the help of a great many people at Ames, directed the testing that showed the cause was an insulation foam breach in the shuttle wings.

Steve Zornetzer, whom Hubbard had earlier moved up to the Ames headquarters building as director of research, served as acting deputy director during Hubbard’s absence. “In the months following the disaster,” remembered Zornetzer, “the entire agency was in a holding pattern waiting to learn what would be required

on the shuttle program. Our job was to marshal resources to help with the return to flight.”³⁴ Zornetzer, assisted by Estelle Condon as associate director for programs, led the Center through a time of great uncertainty in NASA’s direction.

When Hubbard returned to Ames full-time in September 2003, he refocused on his agenda for remaking Ames. The convergence of nanotechnology, biotechnology and information technology, he thought, could best define Ames’ place at the frontier of space exploration. He hoped to encourage the emergence of an entrepreneurial space industry, and explored new partnership ideas with Silicon Valley companies like Google. However, Hubbard increasingly found his optimism deflated at NASA headquarters.

Full-cost accounting and recovery had a major impact on how Hubbard was able to run Ames. O’Keefe’s background was in government accounting rather than space. After confronting criticism from Congress that NASA was not able to pass a financial audit, O’Keefe quickly imposed some accounting measures intended to display the full cost of the work NASA did. Full-cost accounting had been discussed within NASA since the early 1990s, as the financial equivalent of total quality management. But Goldin thought this financial precision came at too great a cost compared with traditional cost estimation. When O’Keefe moved ahead with full-cost accounting, Center directors almost completely lost control of their finances. Problems arose not simply in the precision required in the accounting reports; the problems arose because this accounting precision theoretically would allow the recovery of all expenses incurred by a particular program. Mission directors at NASA headquarters funded programs—like parts of the rocket development program—and Center directors begged those program managers for work packages that would pay their staff. Center directors could not transfer money between program funds. With little funds of their own to pay for Center maintenance, their only flexibility was in applying overhead expenses at their Centers to a program, until those program managers resisted.³⁵

At the same time Congress, wanting to assure that NASA spent money as Congress wished, moved to appropriating funds as often

as seven times a year. And NASA headquarters started releasing all funds on a task order by task order basis so they could monitor how all the funding was spent. Between the encroaching bureaucracy and the demands of the Bush administration to focus NASA on building a new launch vehicle, Center directors had no way to address the imbalances in the skills of their workforce. For example, at Ames, when the space station biological research project was cancelled, about forty civil servant life scientists found their salaries unfunded, and their skills not easily transferred to other space science programs. Their salaries were rolled into a Center overhead rate, already high at Ames because of the costs of working in Silicon Valley, and charged to funded programs. Managers bringing money into Ames to support rocket engineering resented having to carry the overhead burden of underemployed scientists; and world class life scientists either left or found themselves relegated to a pool of workers “available for other assignment.”

Furthermore, full cost accounting imposed extra costs at Ames. A human spaceflight center might manage thirty big pots of program money (known as WBS funds, for work breakdown structure funds) whereas Ames might track a couple different WBS numbers. At an operational center, an engineer might charge his entire salary to three WBS numbers; at Ames they might charge it to thirty. Lewis Braxton led Ames’ finance staff in managing and ameliorating this accounting burden, though morale suffered as it became apparent Hubbard ultimately had little power to fund Center needs.

Full-cost accounting, more than anything else, shined a spotlight the inequities in funding between the Centers. At the same time full cost accounting intensified conflict between Centers over every dollar of funding, O’Keefe proclaimed the idea of “One NASA,” of eliminating what he considered harmful competition between NASA’s ten field Centers. He moved all agency-wide program offices back to headquarters, and eliminated the idea that any one Center could be a formal center of excellence within NASA. In addition to combining infrastructure across Centers—like the shared services center which NASA located at Stennis, or the email system located at Marshall—O’Keefe wanted to see NASA people moving more freely

around the Centers. In August 2003, soon after Hubbard's return, G. Allan Flynt, a program manager at the Johnson Space Center, was appointed to a one-year assignment as Ames deputy director. Flynt's primary role was to introduce people at Ames to the program managers in the human space flight arena who had money to spend.

Hubbard also began discussion around Ames, in response to rumors from headquarters that O'Keefe hoped to shut down Ames, of converting Ames into a federally funded research and development center. FFRDCs included the Jet Propulsion Laboratory, RAND Corp., the Aerospace Corp., Lawrence Livermore National Laboratory, and the Ames Laboratory in Ames, Iowa. These laboratories did fundamental research, could take funds from any part of the federal government, and were usually managed by universities or as independent not-for-profit institutions. People at Ames thought their Center could make a superb FFRDC, but they were not yet willing to abandon their place within NASA. More importantly, as the union of federal employees at Ames stressed, there was no precedent around the legislative difficulties of transferring civil servants to a non-profit institution. The FFRDC exercise was useful, like the zero base review of a decade earlier, in getting Ames people to think about their core competencies and their role in the ecology of aerospace research. Still, it only reflected Ames' troubles with headquarters.

Hubbard was a masterful public speaker, and his all-hands and state-of-the-Center addresses were always well attended. In January 2004 Hubbard was upbeat about the changes at NASA Ames. He had streamlined operations, reducing the number of staff offices from 21 to 5: legal, equal employment opportunity, the SOFIA program office, the NASA Astrobiology Institute, and the nanotechnology center. He also announced that Cliff Imprescia would lead a new Code P, a project engineering and management directorate that would report directly to Hubbard. Comprised of elements of other codes, it would focus on hardware engineering and management of the Kepler spacecraft, the SOFIA airborne observatory, and the space station biological research project. Hubbard also opened a new business office, led by Wendy Dolci, to focus Ames efforts on writing proposals for new spacecraft projects. And he instituted new types

of training for a new generation of program managers. Leadership Boot Camp trained division directors on how Ames worked, and the Ames Project Excellence Program trained engineers in NASA methods of systems engineering and project control.³⁶ Building on the success of the Lunar Prospector mission, Hubbard wanted to emphasize Ames' skills in spacecraft engineering.

As the main conduit for news, both bad and enigmatic, from headquarters, Hubbard refined his communications with Ames staff. Hubbard hired Ingrid Desilvestre as executive officer, to assure communication of—and follow through—on planning. McDonald's tendency had been to communicate broadly. For his executive staff meetings, he packed the N200 committee room to overflowing with as many as forty directorate and division chiefs. Centerwide emails went to everyone, whether they dealt with major strategic initiatives or meetings of the ham radio club. Desilvestre focused email communication so it reached only the intended audience, created a Heads-Up to announce events to the entire Ames community, and compiled a highlights memo with input from each directorate that Hubbard referred to in detailing Ames progress to headquarters.³⁷ Hubbard's executive meetings, now twice a week rather than once every two weeks, involved only key staff and directorate chiefs, and they were expected to disseminate information through the ranks.

When communication failed and the Ames corporate culture broke, Ames employees could avail themselves of an ombuds office. In January 2004 Jack Boyd added ombud to his list of jobs. NASA headquarters asked all Centers to open an ombud office as they sought to improve NASA's safety culture in the wake of the Columbia accident. It served as a confidential channel of communication where employees could raise concerns that might affect safety or organizational performance.

That January of 2004, O'Keefe finally found a way to express his desire that NASA build a new rocket to replace the Space Shuttle. President Bush announced his vision for space exploration, and rather quickly things looked even worse for Ames. The vision focused on human space flight: completing the International Space

Station, retiring the Space Shuttle, building a new set of rockets later dubbed Ares, and preparing for crewed missions to the Moon by 2020. Robotic exploration got scant attention, as did Ames traditional work in aeronautics and space science. O'Keefe created at headquarters an exploration systems mission directorate, planned for aerospace contractors to design and build the spacecraft, and started shifting control of NASA funds toward those Centers, largely in the American southeast, working on human space flight.

Not until November 2004 was it clear if Congress would fund this vision. It did, and handsomely with a \$16.2 billion NASA budget. While NASA's plans were initially intended to demonstrate new technologies, still a stated mission of NASA Ames, little of that money was actually spent at Ames. Hubbard created an exploration systems office, led by Daniel J. Clancy, to coordinate all the research done at Ames to support the vision. NASA Ames did wind tunnel tests of rocket and capsule designs and computational fluid dynamics on the whole system. James Reuther led the multi-Center group developing new concepts in thermal protection systems for the crew exploration vehicle, and much of that work was done at Ames. David Korsmeyer led a group designing new information technologies, notably to monitor the health of the rocket systems in real-time.

In April 2005, Michael Griffin became NASA administrator, and brought a new intensity to the vision for space exploration. He oversaw an *Exploration Systems Architecture Study*, released in October 2005, that defined more precisely the technologies and timeline he needed to return to the Moon.³⁸ His goal was to minimize the five-year gap between the confirmed retirement of the shuttle and the availability of NASA's planned crew exploration vehicle. He also added a heavy launch vehicle back to NASA's planned fleet, now called the Constellation program. He decided to bring more of the system engineering work in-house to NASA, rather than leaving it to aerospace contractors, which further shifted power to the Marshall and Johnson centers. He also hoped to minimize any advanced technology design to instead use existing technologies, which further cut into research funding. The Bush administration and Congress were not, however, willing to boost NASA's budget to

fund Griffin's dreams for the Constellation program.

Hubbard repackaged Ames in order to suggest the work it did was less long-term technology demonstration and more focussed on the specific engineering needs of Constellation. Hubbard created a Code T encompassing all the groups—about a quarter of the Ames workforce—who were funded to design exploration technology. Led by Eugene Tu, the new Code T included intelligent systems, the arc jets, and the human factors group. In August 2005, Griffin also moved to Ames the robotic lunar exploration program office (RLEP). The office had been at Goddard, where the Lunar Reconnaissance Orbiter spacecraft had originated, since it was designed to serve NASA's science missions. However, under the vision, robotic spacecraft did not do science, but would serve as pathfinders for a human mission to the Moon. Griffin expected Ames to ally the RLEP with the needs of the Constellation program, and Hubbard named as chief Butler Hine who had recently served as the Ames liaison at NASA headquarters to the exploration systems mission directorate. In the short time before it was again relocated to Marshall, the Ames RLEP office brought LRO to confirmation, completed a major trade study for a lunar rover, and revised the robotic architecture presented in the ESAS study.

These were all important roles, just not ones that would cover capacity, meaning bring in funds to pay Ames salaries. Despite buy-outs of employees near retirement, Hubbard warned Center staff to expect lay-offs of up to ten percent of the workforce. "Managing our way through fiscal year 06 without major damage to our core competencies or our strategic future may be the greatest challenge in the history of the Center," Hubbard declared.

In his January 2005 state of the Center address Hubbard was again pessimistic. There was a significant decline in the Ames budget, and little hope it would improve. The Ames budget of nearly \$800 million in fiscal year 2004 dropped by about \$100 million, with aeronautics and life sciences especially hard hit. Aeronautics suffered from a number of unfunded earmarks. Budget forecasts for future years showed additional declines because more funding would be subject to competition. While Ames traditionally did well in competition, it suffered from the high

overhead burden imposed by O’Keefe’s full-cost recovery.

Perhaps most ominously, the NASA budget submitted that April eliminated all funding for the space station biological research program. As part of the vision, the space station would be completed, in part by eliminating the modules for scientific research. The shuttle flight that would have taken the SSBRP to the station, the last shuttle flight planned, was cancelled. A big portion of Ames’ budget in the early 2000s—roughly \$100 million of an \$800 million budget—came from life sciences work, most of which revolved around the SSBRP. Hubbard flew more frequently to NASA headquarters, pressing the need to restore funding for the space life sciences.

Ames had a reputation, around headquarters, and extending back decades, for telling NASA headquarters staff what they should do rather than actively aligning itself with the goals of headquarters. Back on Center, his coworkers grew concerned that Hubbard’s tendency to take credit for what was happening at Ames might tarnish their programs as Hubbard’s star waned. Hubbard was losing credibility with his message of hope.

A TIME OF TRANSITION

In January 2006 Scott Hubbard announced that he had resigned to accept the Carl Sagan Chair at the SETI Institute and continue his research in astrobiology. He also took a research position in the aeronautics and astronautics department at Stanford University. In a memo to Ames staff, Hubbard wrote: “As is often the case when there is any change of administration, the new leader wants his own team. In discussions with Mike Griffin before the holidays, we agreed that the future of Ames should be set by a Center director of the administrator’s choosing.”³⁹

It was not clear who at Ames did have the administrator’s ear. Following Allen Flynt’s year as Ames deputy director, headquarters named Stan Newberry as Ames deputy director. Newberry had served in a variety of positions around NASA, including as director of space operations at the Johnson Space Center. Both Flynt and Newberry brought insights into how the manned space centers worked, and connections to program managers at those Centers.

However, neither had enough corporate knowledge of Ames to do much more than assume some of the director's ceremonial functions. In August 2005 this experiment ended, and Steve Zornetzer was again named acting deputy director. Hubbard then named Marvin Christensen as his special assistant to supervise efforts that required program management experience.

Prior to becoming an Ames civil servant in September 2005, Christensen had more than forty years experience in space industry. He had worked at Ames for eleven years as manager of the Lockheed Martin contract—which provided engineering support to programs such as SOFIA, Kepler, the space station biological research facility, and space life sciences payloads. Before that he worked at Martin Marrietta, JPL, and NASA headquarters on a variety of spacecraft projects. Upon Hubbard's resignation, Griffin asked Christensen to serve as acting Center director with Zornetzer continuing as acting deputy director. Christensen never pretended he knew Griffin's goals for the Center. He was, though, an experienced hand in times of budget crises and workforce re-alignments. Griffin never searched for an internal candidate from Ames to become the permanent Center director.

A month into his tenure, in February 2006, Christensen delivered an all-hands address on how Ames would survive its budget shortfalls in fiscal year 2007. Hundreds of millions of dollars of NASA's budget had been shifted from more basic research done in Ohio and California to rocket design done in Alabama and Texas. Since fiscal year 2004, NASA Ames had seen its budget shrink by \$200 million, from \$865 million to \$657 million in fiscal year 2006. The Ames workforce had also shrunk, from 1,458 civil servants and 1,475 contractors in fiscal year 2004 to 1,237 civil servants and 851 contractors in fiscal year 2006. For fiscal year 2007, Ames' budget was expected to shrink further, to \$533 million. Overall, NASA's budget was up 3.2 percent over the previous year, but Ames was getting a smaller slice of the pie. Due to underfunding, 288 civil servants were facing a reduction-in-force notices (RIFs), essentially lay-offs. SOFIA had received no funding in the fiscal year 2007 budget, after a thirty percent reduction the previous year. Kepler was slightly over budget. Astrobiology funding was slashed by forty percent, and aeronautics

facilities were dramatically underfunded. NASA headquarters was reducing its efforts in education and outreach. “We still have a good thirteen months before the RIF,” Christensen noted, “to solve our problems.”⁴⁰

Christensen announced that Jack Boyd, who had moved out onto the Center to work as Ames senior advisor for history, would move back into the N200 headquarters building to help develop a strategic plan. Lew Braxton’s staff in Center operations had reduced overhead expenses by fourteen percent in one year, which improved Ames’ ability to bid on work. The Ames storage facility at Camp Parks was sold, providing \$6 million to fund other facilities, and the funds to close out the space station biological research program were ample enough to float many engineers on Center overhead funds. The NFAC was leased to the U.S. Air Force Arnold Engineering Development Center, which reduced institutional costs while keeping it available for NASA research. Christensen continued to focus Ames on small satellites, defined as those costing less than \$250 million, built that small satellite group new workspace, and promised to reinvigorate Ames’ expertise in project management. NASA administrator Mike Griffin likewise encouraged Ames to develop program management expertise in small satellites.

That April, Christensen announced that headquarters had selected Ames to build a secondary payload, called LCROSS, to launch with the Lunar Reconnaissance Orbiter. Christensen had been especially active in championing LCROSS. Joel Kearns and Carol Carroll led an Ames team responding to an independent assessment of SOFIA, and Christensen was optimistic that SOFIA funding would be restored. NASA was maintaining its Centers through “shared capabilities” funding for facilities of national-level significance. Ames’ supercomputing capabilities were already being funded through this mechanism, and Christensen hoped to get similar funding for the Ames 20G centrifuge and the vertical motion simulator. George Sarver was named Ames lead for the Constellation work. Largely, Ames was pursuing work packages—scraps—from the Centers that had funding for Constellation. Still, by cutting costs and identifying the work it could do best, Ames leadership stabilized its funding during a very challenging time.

SIMON “PETE” WORDEN

In April 2006 Griffin announced that the new permanent director of Ames would be Simon “Pete” Worden. Worden’s background was thoroughly Air Force, though suffused with space science. Worden retired in 2004 as a brigadier general after 29 years with the U.S. Air Force. He started his career in 1975 as an astrophysicist with the Air Force National Solar Laboratory in New Mexico. Over the next three decades he remained an active researcher, published more than 150 papers, and was a noted expert on speckle interferometry. He was a co-investigator for two NASA space science missions, notably working with Alan Title on the solar magnetic and velocity field measurement system deployed on Spacelab in 1985.

In March 1983 Worden flew to Washington D.C. to look for his next job, as luck would have it, on the same day that President Reagan made his speech about ballistic missile defense. He became the first full-time staffer for the Strategic Defense Initiative Office and, through 1994, in a variety of roles, he worked on every technical and political facet of the Star Wars program. In 1991, when the SDIO decided to develop a single-stage to orbit launch vehicle, Worden supervised the work that culminated in the DC-X.⁴¹ For about \$80 million, DC-X demonstrated the potential of reusable rockets able to do vertical takeoff and landing.

He twice served in the executive office of the president. While staff officer for initiatives in the National Space Council of the first Bush administration, he tried to revitalize civil space exploration and Earth monitoring, and was an architect of the “faster, cheaper, better” approach later adopted by Dan Goldin.⁴² He was an outspoken critic of NASA at the time, and played a role in Richard Truly being fired as administrator for tying NASA’s future too closely to the Shuttle.

Perhaps most relevant to his future post at NASA Ames, from 1991 through 1993 Worden served as deputy for technology with the Ballistic Missile Defense Organization, succeeding Michael Griffin. There, Worden had billions of dollars to spend on development projects. He funded the Clementine mission, a small, rapidly deployable satellite designed by a small group meeting in

a townhouse in Alexandria, Virginia. Clementine was ostensibly designed to test sensor and propulsion systems for missile intercept though, remarkably, Worden succeeded in running these tests while Clementine orbited the Moon in 1994. It became the first American mission to return to the Moon since Apollo, and made news when it detected the chemical signature of water around the south pole of the Moon. He earned a NASA Outstanding Leadership Medal for the Clementine mission.

From 1994 to 1996 Worden commanded the 50th Space Wing, the USAF Space Command, with more than 6,000 staff at 29 locations around the world, all responsible for more than sixty Defense Department satellites. From 1996 to 2002 he held various director and deputy director level positions with USAF headquarters and the Air Force Space Command in Colorado. Following the terrorist attacks on September 11, 2001, Worden was asked to start an Office of Strategic Influence within the Defense Department. When the *New York Times* labeled this a disinformation and psychological operations effort, the office was closed and Worden was ushered toward retirement.⁴³

Worden capped his career with two years as Director for Development and Transformation at Air Force Space Command's Space and Missile Systems Center in Los Angeles. "As a general in a non-job, in an office which ran pretty well itself," he managed many proposed but unfunded projects. He worked mostly for DARPA, and had time to think big thoughts about the Air Force presence in space.⁴⁴ He advocated a broader exploitation of space, like putting stations in cislunar orbit, encouraged the Air Force to develop a capability for detecting and manipulating near Earth objects such as asteroids, and suggested thinking not about weapons in space but the command and control of space. "Space is never going to be more than a supporting element of warfighting. However, it's a primary element in war prevention."⁴⁵

Worden also defined a major program called "responsive space," a new way of business and engineering that did not rely on the massive, expensive, multi-purpose satellites the Air Force had grown to rely on. Responsive space incorporated elements of "faster, cheaper, better,"

but with the goal of developing the ability to fabricate and deploy satellites quickly, in response to specific military needs or scientific opportunities. This need became obvious during the Persian Gulf War of 1990-1991, when the massive reconnaissance satellites developed during the Cold War did not always provide information needed by commanders on the ground. To be operationally responsive, rockets had to be ready to launch faster, satellites needed to be configured quickly, and people had to be equipped and trained to use the data. Worden's agenda included a wider variety of smaller rockets, able to reach orbit with eight hours warning, like the *Sprite* rocket built by Microcosm, Inc. He advocated a common aerospace vehicle, perhaps winged like the X-37B orbital test vehicle, that could loiter in low Earth orbit until called to enter the Earth's atmosphere. He started work on hyperspectral sensors, notably the Noble EYE (for Enhanced hYperspectral experiment) which could resolve a greater array of features on Earth.

After he retired from the Air Force in 2004, Worden served as research professor of astronomy at the University of Arizona, Tucson where in 1975 he had earned his doctorate in astronomy. The University of Arizona Lunar and Planetary Laboratory had long ties with NASA Ames, stretching back to Charles Sonett's work on magnetometers for Apollo. The University of Arizona hosted a leading research group in hyperspectral imaging, and Worden worked with that group. He took a detail to serve as chief advisor on space issues for Senator Sam Brownback (Republican from Kansas), and helped investigate NASA's dependence on the Shuttle.

Worden and Griffin were old friends from their days working on the Strategic Defense Initiative. Soon after Griffin became administrator, Worden talked with him about perhaps joining the NASA Advisory Council. Griffin, however, wanted Worden's help within NASA just not, because of the enemies Worden had made, too close to Washington. When Griffin asked Hubbard to resign, he asked Worden to apply for the post. Worden remembers that Griffin gave him the charge: "Fix Ames." It came as a surprise to virtually everyone at NASA Ames when Worden was announced as the incoming director.

ONCE AGAIN, RE-INVENTING NASA AMES

In Worden's first address to Ames staff in May 2006 he declared, "Ames is the coolest place in NASA."⁴⁶ So often thought, but seldom articulated, as Ames people struggled to define their "relevance" and "value," Worden's statement reflected an immediate change in tone. "Coolness" was what Worden thought Ames should aspire to, and coolness would be the best trait for Ames to have as NASA got its groove back. Hans Mark flew out to introduce Worden to Ames, reflecting that he first met Worden 28 years earlier when Worden was an Air Force captain and Mark was Secretary of the Air Force. Mark called Worden "a zen master" able to keep focus with noise all around. Worden said he wanted to rebuild Ames' expertise in science and engineering, then build new partnerships—especially with the Defense Department. "I'm interested in seeing how we can do things quickly," Worden said. "If we can do that, I think we can succeed in space exploration." When asked to describe Ames, he used the words: "Fearless, agile, responsive, creative, inventive, hands on."

Within a few weeks of arrival, though, Worden delivered some bad news that reminded him that space exploration was still a contact sport. The Marshall Space Flight Center had taken the robotic lunar exploration program away from Ames. Worden had just started a blog, to improve communication with Ames staff, and summarized his experience: "Congressional politics (read jobs) often dictates what we do more than technical excellence. My first meeting with some of the other Center directors made me feel like a little boy at the first day of school. Several playground bullies came up to me and asked if Mommy had given me any lunch money. When I nodded they suggested I give it to them for 'safe keeping.' Well one of them got some of that money called RLEP."⁴⁷ As consolation, Worden noted that the RLEP itself generated little money, but mostly passed funding on to the project offices like the LCROSS program managed at Ames.

In fact, the politics of RLEP were more complicated. The principal goal of RLEP was to measure water ice at the lunar south pole, and characterize any other resources useful for a permanent station on the Moon. Marshall wanted NASA to develop a complex lunar lander,

costing about \$2 billion, which it expected would qualify Marshall to later build the Altair crewed lander. The Marshall RLEP II robotic lander was as big as a crewed lander and used the proposed hydrogen engine.⁴⁸ It carried a rover that was nuclear powered and could sample ice from many different craters. Butler Hine and his RLEP group at Ames, by contrast, argued for an architecture built around low-cost landers, about \$200 million each, that would land at various places and test specific technologies. To deal with uncertainties about lunar dust, for example, the Ames RLEP group designed landers that could carry potential astronaut suit seal materials and operate on the Moon for a month. In the face of uncertainty, technologies are overdesigned, and the extra mass ramified through the design. Ames wanted to get data quickly so the Constellation engineers had a factual basis for their designs. Marshall won the battle for the RLEP office, but it never built the RLEP II lander. By 2008, the program office at Marshall was itself closed.

More bad news came more quietly. Griffin asked Worden to kill the Ames' nanotechnology program because its results would be too far in the future. Worden did so, cutting the staff to fewer than twenty and rebranding the remaining staff as a center for advanced materials. Aeronautics would remain important at Ames, but aeronautics represented only five percent of NASA's budget. "You can't run three Centers on 5 percent of its budget," Worden noted.⁴⁹

As a bit of bright news, in June 2006 NASA headquarters announced some new work packages that would fund Ames to work on Constellation. Ames would lead development of the thermal protection system for the crew exploration vehicle, as well as integration of all the information technology. At a second all-hands meeting, Worden predicted that there would be no RIF and that Ames would continue to find itself in the mainstream of where NASA itself was going.

Two changes in NASA's financial environment gave Worden more control over his finances than Hubbard had. First, full-cost accounting and recovery were changed throughout NASA by adding a CM&O budget, for Center management and operations. Each year Worden got funds, essentially overhead funds pulled out of program

funds before they left headquarters, that he could use for director's staff and discretionary funds. Those funds were limited, though, and Worden was seldom able to fund all the great ideas he saw emerging from Ames. Jack Boyd described Worden as open to any and all great ideas: "If you present him with three ways of doing something, he'll want to do all three." What limited his ambition was the limit of his CM&O funds.

Second, tenants in the NASA Research Park (NRP) began to return rents. The legislative mechanism behind these funds was the enhanced use lease (EUL), which Congress created to allow military bases to rent underutilized land in return for fair market rents or in-kind services. Mike Marlaire was actively involved in drafting the legislation that extended EUL authority to NASA, in 2003. Because of the value of Silicon Valley real estate, the NRP grew into a valuable source of alternative funding for Ames. When Worden arrived in 2006 NRP tenants returned \$531,000 in rents and \$150,000 in in-kind services to the Center.⁵⁰

Unfortunately, both NASA headquarters and Congress noticed Ames' success. The NRP underwent, and survived, audits from the General Accounting Office and the NASA inspector general. In 2006 NASA Headquarters asked for a formal business plan that showed how every NRP tenant would contribute solely to the Bush administration vision for space exploration. In 2007 Congress eliminated the option for NRP tenants to pay their rent with in-kind services, and required that any funds earned through EUL go back to the treasury for Congress to allocate, rather than remain under control of the Center director. Despite these setbacks, Ames was recognized as a world leader in public-private partnerships, and representatives from other NASA Centers and other government laboratories visited the NRP's Silicon Valley campus to learn how they could replicate that success.⁵¹

Worden, over the course of his career, had nurtured contacts that now helped him bring spacecraft engineering work to Ames. He used discretionary funds to bring some fresh faces to Ames. He hired in Peter Klupar and Alan Weston from the space vehicles division of the

Air Force Research Laboratory to build the infrastructure for a small satellite effort. Gary Martin, who had worked at NASA headquarters on space architecture studies, was hired to manage a new Code V, encompassing all of Ames' public outreach, education and strategic partnership efforts. Chris Kemp was elevated to the position of chief information officer. Worden brought to Ames a group of young space enthusiasts he had met during his travels, including many students of the International Space University. His long terms goals included reducing the average age of the Ames workforce, hiring more young people from around the country and around the world, and hiring students from minority universities. These young engineers were driven by the desire to get spacecraft into flight.

Many old hands remained in senior management, though. Lew Braxton managed Center operations, Eugene Tu managed Ames support of Constellation engineering, Tom Edwards managed its aeronautics portfolio, Michael Bicay led the space sciences, and Tom Berndt became chief counsel. Worden appointed Steve Zornetzer as his associate director for research, Jack Boyd as his senior advisor and Marv Christensen, who had served as acting director for more than a year, as his deputy director. After a year, though, Worden re-assigned Christensen after he interjected himself into decisions on senior staff and on relations with other Centers.

Worden quickly named Lew Braxton as his new deputy. Braxton had spent almost all of his career at Ames, rising to chief financial officer during a time of rapid change in how NASA did its accounting and then moving to take charge of Center operations. (Deborah Feng would succeed him in that role.) The division of labor within the N200 headquarters building was now clearer. Braxton took care of things on Center, leaving Worden free to finesse Ames' role in space exploration at large.

Yuri's Night symbolized Worden's efforts to stoke the space enthusiasm among a newer generation. Every April 12th, space enthusiasts around the world held parties to celebrate humankind's past and future presence in space. As a Soviet cosmonaut, Yuri Gagarin was far better known outside America, and the celebration was largely ignored by anyone with ties to NASA. Still, Ames debuted

its first Yuri's Night party in 2007, with many participants masterfully coordinated by Lew Braxton, and it attracted wide interested. More than 8,000 people attended Yuri's Night the next year. Worden wore a Soviet general's uniform, and much of his senior staff wore costumes reflecting their imagined future in space. The party appealed to a younger constituency, showed Ames' aspirations for internationalism, and it was all part of being cool. Worden's leadership style was also evident in the Great Worden Quake exercises of 2007 and 2008. These were emergency response exercises that involved the whole Center and many local communities, and highlighted the ingenuity of Ames protective services personnel. To work, it required tremendous cross-Center collaboration.

Worden also reshaped NASA Ames around the work he started with the U.S. Air Force on "responsive space," by accelerating Ames' work in small spacecraft. "Small" might mean light and volumetrically compact, like the Ames GeneSat and PharmaSat. More importantly, small meant quickly built, which equated to inexpensive. Faster, better cheaper as a phrase was no longer in vogue, since during the Goldin years it was seen to allow for failure. "Small" and "responsive" instead reflected Worden's new emphasis on spacecraft project management.

Worden reshaped the Ames Code P office into a program and projects directorate. Led by Alan Weston, it focused solely on the success of active projects, which included small spacecraft like Kepler and LCROSS. Peter Klupar led Code R, an engineering directorate, to develop new technologies and mission concepts. Over the course of his career, with the aerospace industry and the Air Force, Klupar had flown more than forty spacecraft—some big, some small. Klupar shrunk Code R to a staff of about 150, all focused on spacecraft engineering. He created a mission design division, led by Belgacem Jaroux, based on the concurrent engineering strategy of Team X at JPL but focused on smaller spacecraft. The mission design division focused on developing tools—like thermal analysis software—to support the rapid engineer of small spacecraft. The first data integrated into the mission design center was from the modular common bus built by the Ames RLEP office.

As soon as he had arrived at Ames, Worden was itching to cut

metal and build a prototype. Butler Hine led NASA's robotic lunar exploration office for the year it resided at Ames. When it moved to Marshall, Worden funded this group with his discretionary funds to continue working on the most interesting project—an inexpensive lunar lander. They started by designing a lunar orbiter and lander separately. As Worden pushed them to make the designs more modular, with components that could be easily swapped out for different science needs, the team realized that many of the modules could be used for either a lander or orbiter. Soon they had a set of modules that could be linked to satisfy a variety of missions: lunar lander, lunar orbit, libration points, and asteroid rendezvous. “We would drive up opportunity by driving down cost,” noted Hine.⁵² NASA contractors had a long history of promoting common buses, a history littered with failure. Hine's group studied them all: the THEMIS satellites designed by Swales Aerospace, the CubeSats devised largely by graduate students, and sensors and avionics components developed for the U.S. Air Force. “Why did we think we could succeed?” reflected Hine. “Because we inverted the design from a requirements-driven bus to a capabilities-driven bus.” They used available parts, like a crash sensor from an automobile manufacturer as a motion sensor. They designed it to launch as a secondary payload to a larger mission, or to launch on a small rocket like the commercial Falcon 1 under development. They developed software to manage the thermal environment while the spacecraft was operational. Reusable spacecraft often faltered in thermal design, which typically had to be tailored to the payload and the flight location of the spacecraft.⁵³ They tested early and often, using cold compressed air so that they could perform an indoor hover test every hour. By the time they were ready to test with conventional rocket engines, the flight control software worked well. In less than fifteen months, and with a budget under \$4 million, a group of fourteen researchers at Ames demonstrated that a bus could be built for a tenth of the cost of a conventional robotic mission.

To validate the concept in space flight, NASA asked Ames to use the common modular bus as the foundation of the LADEE mission to study the tenuous lunar atmosphere. The entire design,

and testing apparatus, was also shipped to Marshall Space Flight Center for possible use in the international lunar network. With the announcement of the Google Lunar X Prize in September 2007, many teams approached NASA Ames requesting access to this bus technology for their own transportation systems to the Moon.⁵⁴

To get right at problems encountered in Ames' growing portfolio of projects, Worden put in place a series of meetings. Worden reduced the meetings of key staff to three short "tag-ups:" a project tag, an institutional tag, and a strategic planning tag. General updates were relegated to an internal blog, and the tags were meant to focus on what changed and what problems senior management still expected to work through.

After Worden retired from the Air Force, its effort in responsive space suffered a bit, politically.⁵⁵ But by 2008, at congressional insistence, the Air Force re-emphasized the effort by creating an operationally responsive space office at Kirtland Air Force Base in New Mexico. This ORSO quickly forged a partnership with NASA Ames. In 2009 Ames was named the contracting agent for the ORSO rapid response space works, dubbed the Chileworks, which did basic research on open architectures, modular payloads, standard interfaces, and common ground infrastructure. NASA was one of the few agencies of the federal government that had the capability to build spacecraft itself, and supporting the Defense Department was part of its charter.

Worden was more vocal about calling itself a "partner," and being proud of its supporting contributions to projects led by other Centers—especially with Goddard and Northrop Grumman. He was the first senior NASA official to visit Korea, and the result was an agreement for more collaboration between NASA and Korea. Worden and Gary Martin brought onto the Ames campus, for the first time at a NASA facility, the summer session of International Space University which further expanded the prospects of NASA Ames partnering with nations that did not already have space programs.

In addition, Ames accelerated its efforts to build partnerships with its Silicon Valley neighbors, create educational alliances, and develop the NASA Research Park. Worden now managed

1,800 acres of Silicon Valley real estate, making Ames the largest landholder in the region after Stanford University. The growth of the NRP expanded in 2008, when Ames signed two key enhanced use lease agreements. University Associates, a consortium of local universities led by UC Santa Cruz, would develop seventy acres of the NASA Research Park for a campus supporting careers and research in science and engineering.

NASA Ames expanded its ongoing partnership with its Silicon Valley neighbor, Google. The agreement with Google first focused on making NASA images and planetary data more accessible to the public. Ames worked with Google to develop Google Moon so that anyone could take a virtual trip to the Moon. Planetary Ventures, a subsidiary of Google, drafted plans to develop unused land in the northwest corner of the Ames campus for expansion of the Google Mountain View campus.

NASA Ames and Airship Ventures LLC together celebrated the 75th anniversary of the commissioning of Moffett Field. Airship Ventures, a partner of the NASA Research Park, began operations of a dirigible at Moffett Field out of Hangar Two. The dirigible was available for NASA's remote sensing and atmospheric research and, by providing sight-seeing flights over the Bay Area, it gave insight into cleaner and more efficient vehicles for air tourism. Three of only twelve remaining airship hangars in the U.S. remained at Moffett Field.

Worden also focused Ames on its entrepreneurial space initiatives. Congress designated the International Space Station as a National Laboratory in 2005, and NASA Ames hosted a conference on its role in the commercial development of space. Biotechnology firms were especially keen on access to low Earth orbit. On Center, Ames forged a partnership with Life Source Biomedical, LLC and a plan to rejuvenate its animal care facility for life sciences research.

As acting director, Christensen had signed an agreement to create a Space Portal in partnership with the Alliance for Commercial Enterprises in Space, a trade group supporting space entrepreneurs. Led by Dan Rasky, it served as a friendly front door into NASA research for the entrepreneurial space industry. In December 2007 NASA Headquarters asked Worden to downsize the Space Portal,

perhaps concerned that privately built launch vehicles would compete for attention with NASA's Ares 1 and Ares 5 rockets. Though reduced in size and scope, the Space Portal remained at the center of discussion on how NASA people might support the commercial space industry.

Ames also served as NASA's lead for its SBIR/STTR program (for Small Business Innovation Research and Small Business Technology Transfer Programs). It managed \$125 million per year in funding for small business to participate in government research projects. The NRP division now hosted more than forty industry partners, including some high profile firms like Bloom Energy, and more than fourteen academic partners. NRP tenants were forging major new initiatives in green technology, disaster response, and science education. The NRP was beginning to demonstrate in very clear terms the value of collaboration—as opposed to funding procurements or research grants—with commercial firms.

Since arriving in 2006, Worden had encouraged Ames people to move in many different directions, but to move forcefully. Many of these initiatives quickly showed great promise.

THE IMPORTANCE OF DIRECTORS

It is entirely possible to envision the history of NASA Ames as revolving around the directors who have guided the Center—the expertise they brought to the position, how they organized their team, the challenges they faced. Through their tenures, we can chart the ebb and flow of budget and staffing, the facilities built, key partnerships, major administrative efforts on quality and safety, and relations between Ames and NASA headquarters and other NASA Centers. Where the directors have had the greatest impact, though, is in repackaging—re-organizing and re-branding—Ames' extant research efforts to fit NASA's changing strategic visions.

For example, Smith DeFrance, Ames' founding director, remained Center director from 1958 through 1965 as the NACA was absorbed into NASA. DeFrance was often described as conservative, but in fact, he positioned Ames well—culturally and organizationally—to perpetually develop new fields as NASA shifted its strategy.

DeFrance started Ames on the path toward becoming NASA's lead center for developing new space-related disciplines as with biology, space science, and information technology. Ames developed new disciplines even while the Center remained an engineering operation supporting the human space efforts of the 1960s. Hans Mark brought a new perspective to the Center—of more open collaboration with other agencies—and defined more focused research efforts in rotorcraft and computational fluid dynamics. Into the 1990s, Harry McDonald repackaged Ames work into several areas which resonated with headquarters and positioned Ames as the agency's think tank, integrated into the intellectual life of Silicon Valley which surrounds it.

"The director can shape the Center in some profound ways," noted Worden. First, they shape the Center in hiring senior staff, and encouraging those senior people to take a chance on younger people. "Directors can make it known that people should expect to be fired. Program managers who make mistakes should be assigned to staff, and maybe later reassigned to other projects." Second, they shape the Center in providing a vision and words that inspire people. The director takes the gambles for the Center; he decides which investments the Center should make. Third, in setting a tone of diligence in working through problems: "Show up, pay attention, and don't panic. I may be upset if there's a problem, but I'll be real upset if there's a problem and I wasn't told about it earlier."⁵⁶ This held true for all directors, starting with DeFrance.

Still, most Ames people are ambivalent about the importance of their directors, even those they liked. Other than DeFrance, who served as director for 25 years, the longest tenure of any director belonged to Hans Mark at seven years. While Ames accomplished many great things quickly, seven years is not much time to shift an institution like Ames, which is both governmental in its processes and academic in its inclination. Indeed, no director has had more influence on the Center than the cumulative impact of the many other people who dedicated their careers to it.

There is no self-evident way to organize a history of NASA Ames since 1958. There is no clear single technological trajectory to follow, as KSC has with launch operations or Marshall with engine design.

At Ames, what is so fascinating about its technological trajectories is how they branch off and intertwine into new disciplines and programs, and how the Center perpetually reinvents itself. To organize Ames history chronologically, or according to the tenures of directors, would give too much weight to NASA-wide politics in setting the agenda for work at Ames. Thus, this history will organize the Ames story according to broad and long-standing research areas at Ames: space projects, planetary science, life sciences, information technology, and aeronautics.

Space Projects

Project engineering at NASA Ames had a pre-history with the NACA, in that the wind tunnels Ames people built were among the most sophisticated scientific instruments ever built, with precision measurements emerging flawlessly inside massive hulls, generating streams of data that needed to be managed, while customers waited turns to use the facility. With the managerial oversight of Jack Parsons, Ames people built more than twenty wind tunnels during its years with the NACA, and proved very adept at building these quickly and to demanding specifications. The people who formed the early Ames cadre of space projects engineers—Charlie Hall, Al Seiff, Al Eggers—honed their skills as members of Harvey Allen’s high speed research division, which built among the most sophisticated wind tunnels, arc jets and ballistic ranges.

This chapter follows the trajectory of Ames’ growing competence in building small, effective robotic spacecraft, and the instruments flown on them. The Pioneer spacecraft figure prominently, as does the entry probes that mapped the atmospheres of Venus, Mars and Jupiter. It concludes with discussions of Lunar Prospector, SOFIA, Stardust, Kepler, and the many small spacecraft currently being designed at NASA Ames. Other chapters will address related topics: experiment packages for space life sciences, engineering work to support human spaceflight, and the evolution of the planetary sciences at Ames.

NASA Ames’ success in space exploration was built on a triad of people, thoughts and things. NASA Ames has not only built spacecraft, it has built the careers of scientists and engineers who build the spacecraft. Some of the research staff at Ames thrived in a matrixed environment. Scientists work in their fields, publishing papers, studying the state of the art in their disciplines, and advancing new theories. Some persistently involve themselves in project planning, hoping to build an instrument that will find its way onto a funded spacecraft. The proposal writing process is part of the

intellectual capital of the Center. If an instrument is not selected for a funded spacecraft, the proposer goes back to her disciplinary work, and the proposal lingers until another group decides to put together a new plan for a future spacecraft. Thus, in understanding the history of Ames, it is important to understand not only how spacecraft are built, but also how proposals become finished spacecraft and how the people who build spacecraft build their own careers.

SPACECRAFT PROGRAM MANAGEMENT

Smith DeFrance and Harvey Allen both preferred that Ames stick to research—either basic or applied to support those designing spacecraft—and stay out of what NASA called spacecraft project management. Russ Robinson agreed, as did Ira Abbott at NASA headquarters. Jack Parsons, though, encouraged the young Ames researchers who hoped to try their hand at building spacecraft, as did Harry Goett. Early in 1958, Goett and his colleague Robert Crane prepared specifications for an attitude stabilization system needed for the OAO (the orbiting astronomical observatory), as well as the Nimbus meteorological satellite. Encouraged by how well NASA headquarters received their idea, Goett persuaded DeFrance to submit a proposal for Ames to assume total technical responsibility for the OAO project. Abbott at headquarters, though, told Ames to stick to its research. Soon after Goett left Ames to become the first director of the Goddard Space Flight Center in Maryland, where these meteorological satellites were being built.

Al Eggers, backed by the expertise pulled together in his new vehicle environment division, was the next to try to get Ames involved in spacecraft project management. Eggers' assistant division chief, Charles Hall, wanted to build a solar probe to measure the sun from outside the Earth's magnetosphere. By late 1961, Hall had succeeded in getting audiences with headquarters staff, who discouraged him by suggesting he redesign it as an interplanetary probe. Space Technology Laboratories heard of Ames' interest, and Hall was able to raise enough money to hire STL for a feasibility study of an interplanetary probe. Armed with the study, DeFrance and Parsons both went to headquarters and, in November 1963, won the right for

Ames to manage the PIQSY probe (for Pioneer International Quiet Sun Year), a name soon shortened to simply Pioneers 6 to 9. DeFrance thought a Pioneer-based space flight program might suit Ames: the spacecraft concept was understood, the Delta launch vehicle to be used was proven, and tracking and data acquisition services could be obtained either through the deep space network at JPL or from the Goddard satellite network.

It was DeFrance's reputation that ultimately earned Ames the opportunity to lead the Pioneer program. The Pioneers would not be expensive—in fact they were the progenitors of the faster, better, cheaper style of program management—but they were important. The first set of Pioneers were solar sentinels, orbiting the sun and relaying information about solar flares so the Apollo astronauts could seek shelter from the radiation. Two later Pioneers would be the first to Jupiter and Saturn, and thus show that the way through the asteroid belt was safe for the more expensive Voyager mission to follow. NASA headquarters wanted assurance that Ames could follow through on its commitment to get the Pioneers into space.

In his history of the Pioneer probes Mark Wolverton recounts an interview with Charlie Hall, the Pioneer program manager. Hall had traveled back to headquarters to make a final presentation at the highest levels of headquarters staff. Everyone noticed that DeFrance, who would not fly because of promise to his wife after a very early airplane accident, had taken the train from California to support him:

Almost 40 years later, Hall still vividly remembered what happened next.

“[NASA deputy administrator Robert] Seamans turned to Smitty [Smith DeFrance] and said, ‘Smitty, what do you think of this?’ And my heart just dropped. I thought, God, he could kill it right now, do anything he wanted with it.” Even Hall, at that point, wasn’t fully certain of DeFrance’s unequivocal support. Would DeFrance, the old NACA engineer famous for his traditional ways, put his beloved Ames at risk? He did: “He said, ‘Ames is 100 percent behind it,’” Hall recalled. “And I knew we were going to get the program because DeFrance was

extremely admired at headquarters. They knew he would be backing me in any way, shape, and form and wouldn't let the thing fail."⁵⁷

Indeed, by backing Hall, and by encouraging the transfer of Charles Sonett from NASA headquarters to Ames, DeFrance had belatedly but firmly positioned Ames as a leader in planetary sciences. A position in planetary science was likely most important for DeFrance. Given DeFrance's belief in management by peer review, as was the NACA culture, when NASA gave him a choice of expansion through a university model or the program management method used by business, DeFrance thought the university model gave taxpayers the most value. The Ames space sciences and life science programs of the 1960s showed that.

DeFrance also reluctantly supported the Biosatellite program. Biosatellite started when headquarters asked Ames what science might come from sending monkeys into space in leftover Mercury capsules. When Carlton Bioletti submitted Ames' proposal to headquarters early in 1962, a jurisdictional dispute erupted with the Air Force over which agency should control research in aerospace human factors. Because the United States was already well behind the Soviet Union in space life sciences, NASA won the right to bolster its life sciences work. NASA headquarters decided Ames would do basic research, using animal models, while the Air Force and later the Johnson Space Center would do research applied to human exploration. In the meantime, university biologists started submitting unsolicited proposals to Ames. Bioletti's group visited each of these biologists to learn more about what specifications might look like for a series of biological satellites. Impressed with these efforts, in October 1962 NASA headquarters tasked Ames to manage Project Biosatellite.

By 1963, DeFrance recognized that without some specialized experience in managing projects, Ames would be left behind NASA's growth curve. In the NACA years, most engineers needing a new research facility actually designed and built it themselves. Harvey Allen, for a time, jokingly answered his phone "theoretical concrete

and reinforced aerodynamics section.” Ames had a tradition of successfully hacking together proof-of-concept tunnels from borrowed parts, using very little formal management process. Even for the larger wind tunnels an engineer only needed the help of Jack Parsons to marshal the necessary construction resources within the laboratory.

When projects were launched into space, however, executing them got more complex. First, most of the support came from outside the Center—from aerospace contractors or from the NASA Centers that built launch vehicles, spacecraft, or data acquisition networks. Second, nothing could go wrong when the spacecraft or experimental payload was so distant in space. Technical integration and reliability had to be well conceived and executed. Finally, the larger costs evoked greater concerns from headquarters, and thus warranted more reporting on how things might go right. Into the 1960s, program management was a skill taught in universities, something any engineers could do but not something all wished to do. Spacecraft engineers were increasingly willing to have a project management specialist handle these more burdensome tasks in network scheduling and systems engineering.

Ames management began to cultivate program managers. Bob Crane was named to the new position of assistant director for development and he, in turn, named John V. Foster to head his systems engineering division. The sought project managers attuned to the scientists that they served, and who would not put the machine above the results it produced. Charlie Hall, who had built wind tunnels as part of Harvey Allen’s group, managed the Pioneer project and Charlie Wilson managed Biosatellite. Both Hall and Wilson worked with lean staffs, who oversaw more extensive contracting with outside firms than was usual at Ames. Significantly, both reported to headquarters through the Office of Space Science and Applications (OSSA) whereas the Center as a whole reported to the Office of Advanced Research and Technology (OART). Project management at Ames remained segregated from the laboratory culture of the Center even as it, gradually, absorbed that culture.

EARLY SPACE FLIGHT EXPERIMENTS

Meanwhile Ames staff developed expertise in building experiment packages, the smaller black boxes integrated onto a spacecraft and able to deliver discrete and usable data to a single principal investigator. An instrument to measure solar particle flux was the first spaceborne experiment package led by an Ames principal investigator, Michel Bader. Bader's first job at Ames was building a land-based research facility—an ion accelerator that shot particles against a metal sheet so he could estimate the impact of solar wind on spacecraft. Bader built two plasma probes mounted on identical early Pioneer satellites (P-30 and P-31). While the satellites orbited the Moon, the plasma probes would measure energy and momentum distribution of protons above a few kilovolts to study the radiation affects of solar flares. Both experiments were built by late 1960; neither spacecraft launched successfully.

Pessimism was the rule in early spaceborne experimentation throughout NASA. Ames learned to build redundantly, in series, expecting failure of the spacecraft or of an experiment from many possible sources. During the 1960s, Ames built 35 separate instruments for scientific spacecraft, a good number given Ames' size relative to other NASA Centers. Virtually all of these were designed, built and tested by technicians on Center. The failure rate, either because of the instrument or its spacecraft, was discouraging but consistent with the failure rate throughout the early space age. John Mihalov, for example, built five spectrometers for various uses, including one to study the biological effects of space radiation. Only one reached orbit.

Carr Neel, notably, enjoyed greater success. Neel started at Ames working with Lew Rodert on thermal deicing systems and later joined the gasdynamics branch to study reflective surface coatings—paint—to keep spacecraft cool from ultraviolet radiation. He devised a simple experiment to study the temperature rise under various coatings. The OSO-1 (for orbiting solar observatory) launched in March 1962 and the OSO-2 launched in February 1965 carried experiments that returned conclusive results. On OSO-3, Neel adapted the laboratory apparatus he had used to calibrate the

previous experiments to measure total radiation reflected from Earth, called its albedo. His second experiment on OSO-3 was a directional radiometer to measure the spectral distribution of sunlight reflected from the Earth to better understand its impact on satellites orbiting near the Earth.

The theoretical foundations for Michel Bader's next experiment had been laid by John Spreiter and John Wolfe of the Ames theoretical studies branch, who tried to define the limits of the Earth's magnetosphere—where exactly the Earth's magnetic field interacted with the flow of charge particles from the Sun. Most space scientists thought that boundary would be at ten Earth radii, limited measurements showed it at fourteen Earth radii, and Spreiter's calculations put it at eight Earth radii.⁵⁸ Furthermore, he expected a that tenuous shock wave—not unlike that formed by a blunt body travelling at hypersonic speeds—might form at some distance ahead of the Earth's magnetosphere, with weak interactions between the fields.

Bader, working with Tom Fryer of the instrument research branch and Fred Witteborn of the physics branch, built an instrument that could measure the energy and density of ion trajectories. Their electrostatic analyzer was built with a quadrispherical curved plate, and with an electrometer as a detector. It was remarkably compact for the time. It used 145 milliwatts of solar cell power, weighed 1.1 pounds, with a volume less than 2 by 3 by 4 inches.⁵⁹ The instrument was one of six carried aloft by the Explorer 12 in August 1961. Preliminary results showed no ions were detected, so Bader concluded there was no defined proton ring, but rather a broad boundary between the solar wind and the geomagnetic field.⁶⁰ However, Bader soon realized his results were bad. Because of poor communication with the project team at Goddard, the instrument never looked directly at the Sun.

NASA Ames got a second chance to measure the solar wind with Explorer 14, launched in October 1962, this time with John Wolfe as principal investigator on the electrostatic analyzer. Charles Sonett had just arrived at Ames, and Wolfe was one of the first to join his space sciences division. (Bader led a science team aboard a DC-8

during a 1963 solar eclipse, and soon left spaceborne experimentation to devote his career to airborne astronomy.) While structurally the same as that on Explorer 12, this detector was more sensitive and better positioned on the spacecraft. However, the instrument was blinded by solar ultraviolet radiation whenever it looked within three degrees of the sun. Wolfe had made the error of not using a vacuum chamber while testing his instrument for ultraviolet response.⁶¹ The only useful data were obtained during a geomagnetic disturbance on October 7, 1962.⁶² Measuring the solar wind generally had proven very difficult. Of the ten efforts successfully launched up to then, only one instrument, built by JPL and launched aboard Mariner 2, returned any useful data that even confirmed the presence of a solar wind.

Wolfe flew three more electrostatic analyzers, each with fourteen energy channels, aboard three largely identical Explorers 18, 21 and 28 (also known as IMP-1, 2 and 3 for interplanetary monitoring system) launched in November 1963, October 1964 and May 1965. The instrument on Explorer 18 worked well for five months, then the spacecraft started to degrade. With Explorer 21, the spacecraft never achieved its planned apogee, limiting the utility of the data. With Explorer 28, the instrument failed at launch, even though the spacecraft operated for two years. At the same time he was working on the IMPs, Wolf built three electrostatic analyzers for OGO-1 and OGO-3 (for orbiting geophysical observatory), then the largest scientific spacecraft ever built. While the instruments worked, an unintended spin of the spacecraft limited the utility of the data. Within four years Wolfe launched six instruments with limited success. Still, Ames earned enough data to characterize the solar wind, to confirm the importance of continuing with measurements, and Wolfe refined his electrostatic analyzer for future flights. NASA Ames' experience with space experiments, especially in the measurement of the solar wind, took a major leap with the early Pioneer series of spacecraft.

PIONEERS 6 TO 9

The Pioneers span two decades in the recent history of Ames, transcending efforts to periodize them neatly. The first Pioneers—

the 6 to 9 solar observatories—were conceived under DeFrance and executed under Allen. Allen asked the same group to plan Pioneers 10 and 11, and Hans Mark, Allen's successor as director, presided over the execution of the Pioneers as simple, elegant, science-focused, and pathbreaking projects. Mark initiated a Pioneer Venus project, though Bill Ballhaus spoke at the press conference. Every subsequent Ames director—upon the occasion of data returned from some encounter on the trip of Pioneer 10 or 11 out of our solar system—has had occasion to reflect upon the meaning and value of these sturdy little spacecraft. Even in the 1960s, the Ames space projects division devised the Pioneer program as a shot across the bow of the NASA way of building spacecraft.

In 1963, largely at the urging of Charles Sonett, who had participated in earlier Pioneer flights, Ames was given a block of four Pioneer flights, and a small budget of \$40 million total. The bulk of this funding went to contractors—to Douglas and Aerojet-General to build the Thor-Delta rockets and to Space Technology Laboratories to build the spacecraft. NASA headquarters expected the program to leverage Ames' scientific expertise in measuring the sun, and let the Center try its hand at managing a simple spacecraft program. Charlie Hall was selected Pioneer project manager and worked to a very short timeline. Each of the four Pioneers was largely identical, though each carried a different set of ten of seventeen experiment packages. To keep the spacecraft simple, it was kept small (about 150 pounds and three feet in diameter), powered by batteries and solar cells wrapped around the body, and spin stabilized at sixty rotations per minute. The Pioneers, in fact, demonstrated the value of spin stabilization—as opposed to three axis stabilization—to very simply control spacecraft orientation.

Within two years of project funding, in December 1965, Pioneer 6 achieved its orbit around the sun just inside the orbit of Earth. It immediately began sending back data on magnetic fields, cosmic rays, high-energy particles, electron density, electric fields, and cosmic dust. Pioneer 7 followed six months later, Pioneer 8 six months after that, Pioneer 9 launched in November 1968, and the final spacecraft was destroyed in a launch failure.

These four Pioneers sat in widely separated orbits ringing the sun, but outside the influence of Earth, and returned data on the solar environment. Until 1972, they were NASA's primary sentinels to warn of the solar storms that disrupted radio communications and electricity distribution on Earth. When positioned behind the sun the Pioneers collected data to predict solar storms, since they could track changes on the solar surface two weeks before they were seen on Earth. During the Apollo lunar landings, the Pioneers returned data hourly to mission control, to warn of the intense showers of solar protons that could be dangerous to astronauts on the surface of the Moon.

In addition to building spacecraft and sensors to collect the data, Ames also designed the telemetry to gather the data and the computers to process it. Pioneer 6 first gave accurate measurements of the Sun's corona where the solar winds boil off into space. Pioneer 7 measured the Earth's magnetic tail as three times longer than previously measured, and the plasma wave experiment on Pioneer 8 provided a full picture of Earth's magnetic tail. For the Pioneer 9 spacecraft, Ames demonstrated the convolution coders later used for navigation on most deep space planetary missions. Since the sun is typical of many stars, Ames astrophysicists learned much about stellar evolution. Before the Pioneers, the solar wind was thought to be a steady, gentle flow of ionized gases. Instead, the Pioneers found an interplanetary region of great turbulence, with twisted magnetic streams bursting among other solar streams.

An adjunct to this program was the solar pointing attitude rocket control system (SPARCS) introduced in 1965. SPARCS guided Aerobee sounding rockets that carried reusable instrumentation for solar observations into low Earth orbit. By 1983 more than a hundred Aerobee rockets used the SPARC system to collect data on solar activity, and to demonstrate the value of solar experiments that would be launched into space.

As the group that designed and built the early Pioneers then turned their attention to the next space horizon, these simple satellites continued to send back data. Pioneer 9 expired in May 1983, well beyond its design lifetime of six months. It had enjoyed

its days in the sun, circling the sun 22 times in a 297-day orbit. The others remained alive, but their science instruments were turned on less often, and they were tracked less frequently as newer missions required time on the antennas of NASA's Deep Space Network. Pioneer 6 was contacted in 2000, and in 2007 was the oldest operating space probe.

MAGNETOMETERS

Ames space scientists also devised the magnetometers used to study the Moon's composition and structure. These magnetometers were designed by Charles Sonett, refined by John Wolfe and Palmer Dyal, and built at Ames around an advanced ring core fluxgate sensor. Four Apollo missions—12, 14, 15, and 16—flew Ames magnetometers to different sites on the surface of the Moon. Two portable magnetometers carried aboard the Apollo 15 and 16 lunar rovers measured magnetic fields while in motion. These were the first Ames instruments that functioned as landers. Paced by a stored program, the magnetometers measured the small permanent magnetic field generated by fossil magnetic minerals. They then measured the electrical conductivity and temperature profile of the lunar interior, from which scientists deduced the Moon's magnetic permeability and its iron content. And they measured the interactions of the lunar fields with the solar wind.

This data revealed much about the Moon's geophysics and geological history. The magnetometer left on the Moon by Apollo 12 showed that the Moon did not have two-pole magnetism as does Earth, but did have a stronger field than expected.⁶³ It also suggested that the Moon was a solid, cold mass, without a hot core like that of Earth. But it also unveiled a magnetic anomaly a hundred times stronger than the average magnetic field on the Moon. The whole series of magnetometers showed that the Moon's transient magnetic fields were induced by the solar wind and that they varied from place to place on the surface. Based on this magnetometer data, NASA developed an orbiting satellite to map the permanent lunar magnetic fields, as well as equipment to measure magnetism in other bodies throughout our solar system.

PIONEERS 10 AND 11

During the 1960s, astronomers grew excited about the prospects of a grand tour—of sending a space probe to survey the outer planets of the solar system when they would align, during the late 1970s, as they did only once every 175 years. The known hazards to a grand tour—the asteroid belt and the radiation around Jupiter—were extreme. The hazards yet unknown could be worse. So Ames drafted a plan to build NASA a spacecraft to pioneer this trail through our solar system.

In 1968, the Space Science Board of the National Academy of Sciences endorsed the plan. NASA headquarters funded the project in February 1969, following intensive lobbying by Ames' incoming director, Hans Mark, and Ames' director of development John V. Foster. Charlie Hall, manager of the Pioneer solar sentinels, led this project, Joseph Lepetich managed the experiment packages and Ralph Holtzclaw designed the spacecraft. Pioneer chief scientist John Wolfe also served as a principal investigator, with an experiment to do gamma ray spectroscopy and measure the interplanetary solar wind. Upon launch the spacecraft were named Pioneers 10 and 11.

Spacecraft able to explore the outer giants of our solar system—Jupiter and Saturn—had to differ from the many spacecraft that had already explored Mars and Venus. Jupiter is 400 million miles away at its closest approach to Earth, whereas Mars is only 50 million miles away. Since solar panels could not produce enough energy so far from the sun, the spacecraft needed an internal power supply. The greater distance demanded a larger, dish-shaped high gain antenna. In addition to changes demanded by distance, the instruments needed radiation shielding to travel near Jupiter—though no one knew how much shielding. At least twin spacecraft were needed, to optimize the data returned from two trajectories. And because of the greater costs in launching a spacecraft so far, NASA would only launch two, meaning they had to be tested for greater reliability.

Added to these more natural design constraints were two early engineering decisions Hall made to keep the project within budget. Both derived from Ames' experience with the earlier Pioneer plasma probes. First, rather than being stabilized on three axes by hydrazine

rockets, Pioneers 10 and 11 were spin-stabilized by rotating about their axes. The spin axis was in the plane of the ecliptic so that the data antenna, nine feet in diameter, always pointed toward Earth. Inertia came from the four heavy nuclear power units—RTGs or radioisotope thermoelectric generators—mounted fifteen feet from the axis on two long beams. Spin stabilization was cheap and reliable, but ruled out high resolution photography. The experiments on these flights would emphasize scientific data over visual images.

The second engineering decision Hall made was to send all data back to Earth in real time at a relatively slow stream of one kilobit per second. Storing data on board was expensive and heavy. This again lowered the resolution of the photographs and the precision of some measurements. It also meant that Pioneer would have to be flown from the ground. On-board memory could store only five commands, of 22 bits each, needed for very precise maneuvers such as those to move the photopolarimeter telescope (that served as the camera) quickly during a planetary encounter. Each navigation command had to be carefully planned, since signals from Earth took 46 minutes to reach the spacecraft at Jupiter. Hall convinced the scientists designing Pioneer experiments to accept these limits. They had much to gain, Hall argued, by getting their payloads on a reliable platform and getting out there first.

Eleven experiment packages were hung on the Pioneers, which measured magnetic fields, solar wind, high-energy cosmic rays, cosmic and asteroidal dust, and ultraviolet and infrared radiation. (The two spacecraft were identical except that Pioneer 11 also carried a fluxgate magnetometer like the one carried on Apollo 11.) Each spacecraft weighed just 570 pounds, and the entire spacecraft consumed less power than a 100 watt light bulb. One of the most significant engineering achievements was in electromagnetic control—the spacecraft was made entirely free of magnetic fields to allow greater sensitivity in planetary measurements. To test their electromagnetic controls, Ames designed a unique laboratory that was completely isolated from Earth's magnetic field.

Ames indeed kept the Pioneers within a very tight budget and schedule. The entire program for the two Pioneer 10 and 11

spacecraft, excluding launch vehicles, cost no more than \$100 million in 1970 dollars. (That compares with \$1 billion for the Viking at about the same time.) To build the spacecraft, Ames hired TRW Systems Group of Redondo Beach, California, the company that built the earlier Pioneers. Hall devised a clear set of management guidelines. First, mission objectives would be clear, simple, scientific, and unchangeable. The Pioneers would explore the hazards of the asteroid belt and the environment of Jupiter, and no other plans could interfere with those goals. Second, existing technology would be used as much as possible. Third, the prime contractor was delegated broad technical authority. Fourth, the management team at Ames could comprise no more than twenty people. Fifth, their job was to prevent escalation of requirements and keep the focus on fast and simple construction.

One other decision ensured that the Pioneers would have an extraordinary scientific impact. In the 1960s, NASA scientists had begun to explore ways of flying spacecraft through gravitational fields to alter their trajectories or give them a boost in speed. Gravitational boost was demonstrated on the Mariner 10, which flew around Venus on its way to Mercury. The Pioneers were the second spacecraft to try such bold maneuvers. Pioneer 10 would fly by Jupiter so it was accelerated on its way out of the solar system, to reconnoiter as far as possible into deep space. Pioneer 11 would fly by Jupiter to alter its trajectory toward an encounter with Saturn five years later. Without diminishing their encounter with Jupiter, the Pioneers could return better scientific data, for the small cost of keeping open the mission room, and would get there years earlier than would Voyager.

The Pioneers, though, were in some ways meant to be disposable. The true Grand Tour would be flown by two Voyager spacecraft, managed by JPL and designed as sophisticated platforms with three axis-stabilization and higher data transmission rates. The Voyagers weighed about four times more than the Pioneers, and cost more than two times more to build and nine times more to operate. The Voyagers flew much better cameras. The Pioneers encountered the asteroid belt and Jupiter about five years before the Voyagers. The data the Pioneers returned on the dangers of those encounters was

used to refine the trajectory and hardening of the Voyagers, in which NASA had a much greater investment.

Three months before spacecraft launch, Mark got a call from Carl Sagan, an astronomer at Cornell University, a friend of Mark's from time spent at the University of California at Berkeley, and a close follower of efforts at Ames to discover other life in the universe. Sagan called to make sure that Mark appreciated "the cosmic significance of sending the first human-made object out of our solar system."⁶⁴ Sagan wanted the Pioneer spacecraft to carry a message—in case they were ever found—that described who built the Pioneers and where they were from. So Sagan and his wife, Linda, designed a gold-anodized aluminum plate on which was inscribed an interstellar cave painting with graphic depictions of a man, a woman, and the location of Earth in our solar system. It was a simple and elegant map, and earned almost as much press as the spacecraft itself.

Thirty months after project approval, in March 1972, NASA launched Pioneer 10 toward the outer planets. Since the spacecraft needed the highest velocity ever given to a human-made object—32,000 miles per hour—a solid-propellant third stage was added atop the Atlas Centaur rocket. Pioneer 10 passed the orbit of the Moon eleven hours after liftoff; it took the Apollo spacecraft three days to travel that distance. A small group of five specialists staffed the Ames Pioneer mission operations center around the clock, monitoring activity reported back through the huge and highly sensitive antennas of NASA's Deep Space Network.

Very quickly, Pioneer 10 returned significant data, starting with images of the zodiacal light. On 15 July 1972, Pioneer 10 first encountered the asteroid belt. Perhaps the scattered debris of a planet that once sat in that orbit between Mars and Jupiter, the asteroid belt contains hundreds of thousands of rocky fragments ranging in size from a few miles in diameter to microscopic size. From Earth, it was impossible to know how dense this belt would be. But the Pioneers made it through the belt unharmed, and an asteroid and meteoroid detector showed that the debris was less dangerous than feared. Next, in August 1972, a series of huge solar flares gave Ames scientists the opportunity to calibrate data from both Pioneer 10, now deep in the

asteroid belt, and the earlier Pioneers in orbit around the sun. The results helped explain the complex interactions between the solar winds and interplanetary magnetic fields. Ames prepared Pioneer 11 for launch in April 1973, when Earth and Jupiter were again in the best relative positions.

Pioneer 10 flew by Jupiter nineteen months after launch, in December 1973. More than 16,000 commands were meticulously executed on a tight encounter schedule. The most intriguing results concerned the nature of the strong magnetic field around Jupiter, which traps charged particles and thus creates intense radiation fields. Pioneer 10 created a thermal map of Jupiter, and probed the chemical composition of Jupiter's outer atmosphere. Its trajectory flew it behind the satellite Io and, by observing changes in the telemetry signal carrier wave, Pioneer 10 provided direct evidence of the tenuous atmosphere around Io. Signals from the imaging photopolarimeter were converted into video images in real time, winning the Pioneer project an Emmy award for contributions to television. Most important, Pioneer 10 proved that a spacecraft could fly close enough to Jupiter to get a slingshot trajectory, without being damaged.

Pioneer 11 flew by Jupiter a year after Pioneer 10. In November 1974, its encounter brought it three times closer to the giant gas ball than Pioneer 10. Ames mission directors successfully attempted a somewhat riskier approach, a clockwise trajectory by the south pole and then straight back up through the intense inner radiation belt by the equator and back out over Jupiter's north pole. Thus, Pioneer 11 sent back the first polar images of the planet, as well as dramatic images of the Great Red Spot. Pioneer 11 reached its closest point with Jupiter on December 3, coming within 26,000 miles of the surface. This mission gathered even better data on the planet's magnetic field, measured distributions of high-energy electrons and protons in the radiation belts, measured its geophysics, and studied the Jovian gravity and atmosphere. Pioneer 11 then continued onto its encounter with Saturn in September 1979. There it discovered a new ring and new satellite, took spectacular pictures of the rings around Saturn, and returned plenty of data about Saturn's mass and geological structure.

Pioneer 10, meanwhile, continued on its journey out of the solar system. In June 1983 it passed the orbit of Neptune, which at that point was further than the orbit of Pluto. The Pioneer project team, now led by Jack Dyer and Richard Fimmel upon Charlie Halls' retirement, eagerly looked for any motion in its spin-stabilized platform that would indicate the gravitational pull of a tenth planet, but found none. Last contact with Pioneer 11 was in November 1995. On its 25th anniversary in 1997, Pioneer 10 was six billion miles from Earth, still the most distant of human-made objects, and still returning good scientific data. Pioneer was so far from Earth that its eight-watt radio signal, equivalent to the power of a night-light, took nine hours to reach Earth. Last contact was made in 2003, when it still had not detected the plasma discontinuity that defines the edge of the heliopause, where the solar winds stop and our sun no longer exerts any force.

The engineering backup of the Pioneers hangs in the Milestones of Flight gallery at the National Air and Space Museum since the actual Pioneers were, by some definitions, the first human-made objects to leave our solar system. They were honored as the spacecraft that demonstrated how we could explore deep space. The Voyager missions also succeeded, returned stunning photographs and deeper data sets, and were widely recognized as one of NASA's grandest achievements. Ames people will always remember the Pioneers, by contrast, as spacecraft that flew much the same mission, but faster, better, and cheaper. These spacecraft—simple in concept, elegant in design, competently executed, and able to return so much for so little—served as models for the engineering approach Ames would infuse into all of its work.

PIONEER VENUS

The Pioneer Venus program was run in the same spirit as the earlier Pioneer spacecraft—as a quick and simple way of generating data about the atmosphere of Venus. It was managed by many of the same team, on the same management principles, with the same thirty month schedule, a conservative approach to engineering, and a simple set of rules of the road for Pioneer Venus investigators that

kept the science paramount and focused. An orbiter mission around Venus was already under development when Ames added to it a planetary probe to explore the Venusian atmosphere, making it truly a pioneering spacecraft.

Given their work in analyzing the atmosphere of Earth at its extremes, Ames people had an abiding interest in the atmospheres of other planets. In 1960, Jack Boyd, Pat Peterson and Willard Smith filled the Ames supersonic free-flight ballistic range with a gaseous mixture of what was then thought to be the composition of the atmospheres of Venus (heavy in carbon dioxide) and Mars (heavier in nitrogen). They shot a blunt body through it and measured its stability and radiative heating.⁶⁵ This launched more than a decade of sporadic work on how to design flight and reentry vehicles for non-Earth atmospheres.

In the mid-1960s, Alvin Seiff and David Reese began to explore the idea that a probe dropped into the atmosphere of a planet can determine its structure—density, pressure, and temperature. Data on atmospheric structures was needed then, as the Ames' vehicle environments division began studying how to land a human mission on Mars through its still unknown atmosphere. Since Seiff's probe would enter at very high speed, and perhaps burn up, it could carry no sensors that took direct measurements like you would find on a weather station on Earth. Accelerometers, instead, would measure changes in air speeds which aerodynamicists used to compute changes in density and atmospheric pressure. Temperature during the entry burn yielded data on the molecular weight of the atmosphere, so long as the aerodynamics of the probe were calibrated in the Ames tunnels over a variety of Mach and Reynolds numbers and in a variety of pure gases. Aerodynamicists at Ames were accustomed to starting with the defined atmosphere of Earth then designing an aircraft configuration to produce the desired aerodynamic performance. Seiff turned the problem on its head—defining the configuration and performance of a probe in order to understand an atmosphere. Work began immediately in the Ames hypersonic free flight facility, and with probe models dropped from aircraft.

The precursor to all of Ames' work in planetary probes was the June 1971 planetary atmosphere experiments test (PAET). Designed and managed by Al Seiff, the PAET inverted all that Ames had learned about reentry and hypersonics to push the frontiers of planetary science. PAET was a complete prototype of the many planetary probes to follow. It carried accelerometers, pressure and temperature sensors, two instruments to measure the composition of Earth's atmosphere, a mass spectrometer and a shock layer radiometer. A Scout rocket launched from Wallops Station boosted the PAET out of Earth's atmosphere. A third stage rotated it back toward Earth, and a fourth rocket stage shot it into the atmosphere at 15,000 miles per hour. The data the PAET instruments returned perfectly matched what NASA already knew through conventional meteorological data on Earth's atmosphere. Quickly and cheaply, the PAET demonstrated the concept of the entry probe and provided the confidence to build probes to survey the structure and composition of atmospheres of other planets. Rather than adapting the chemistry and aerodynamics of a heatshield to the Earth's atmosphere, Seiff would take a heatshield of known chemistry and aerodynamics and use it to analyze an unknown atmosphere.

Following the spectacular results of PAET, in January 1972 NASA headquarters cancelled the Planetary Explorer program at Goddard which had been pursuing a series of probes and orbiters to study Venus. In its place NASA headquarters opened a Pioneer Venus group at Ames, two months before the Pioneer 10 launch. Unlike the previous Pioneer missions, based on a series of low-cost spacecraft, the Pioneer Venus mission emerged as a composite single spacecraft. Pioneer Venus, at \$444 million, was slightly more expensive to build than Pioneer 10 and 11 but only cost \$35 million to operate. Charles Hall again led the group as Pioneer project manager, and Hughes Aircraft built the spacecraft. Among the seven experiments selected to be carried on the large probe were four devised by Ames researchers: Alvin Seiff on atmosphere structure, Vance Oyama on atmosphere composition, Boris Ragent on cloud detection and Robert Boese on radiative deposition.

The Pioneer Venus spacecraft had two parts. An orbiter (Pioneer 12) carried seventeen instruments, solar cells around its cylinder and, like all the Pioneers, was spin stabilized. A multiprobe bus (Pioneer 13) carried one large probe and three identical smaller probes which it dropped into the atmosphere. The orbiter was launched in May 1978; the multiprobe that August. By December the two were inserted into orbit and, five days later, the probes were dropped. The large probe was most heavily instrumented; one small probe entered at sixty degrees north latitude, one entered at the day side, the third at the night side. All survived through the dense and acid-laden Venusian atmosphere. Even without a parachute, the day probe survived for an hour on the surface. Together, they returned the most thorough survey of another planet ever made.

Ames built each probe to known aerodynamic parameters so that its motion in flight, at an initial speed of 26,100 miles per hour, indicated the density of the atmosphere through which it travelled. As the probes heated up and interacted chemically with the atmosphere, they relayed data back to Earth on the chemical composition of the Venusian atmosphere. The Pioneer Venus science team found, for example, that there were remarkably small temperature differences below the clouds compared with the differences above, that the solar wind shapes Venus' ionosphere, and that the wavelike patterns visible from Earth are in fact strong wind patterns. They quantified the runaway greenhouse effect that makes the planet surface very hot. They identified widely varying wind speeds in the three major layers of clouds and a layer of smog, nine miles thick, atop the clouds. Using technology developed for the Viking gas exchange experiment, the Pioneer Venus orbiter first discovered the caustic nature of the Venusian atmosphere. They found that the surface was incredibly dry, and described the chemical process by which Venus' hydrogen blew off and its oxygen absorbed into surface rocks. They also measured its electrical activity, looking for evidence of lightning. Using these data and data returned from the Soviet Venera spacecraft, Ames scientists—James Pollack, James Kasting, and Tom Ackerman—proposed new theories of the origins of Venus' extreme atmosphere, which lent insight into the greenhouse effect on Earth.

The orbiter, and its seventeen instruments, continued with its mission. With the orbiter's precision radar, the Pioneer Venus team drew the first topographic maps of the cloud-enshrouded Venusian surface. They discovered that Venus had no magnetic field, from which they deduced that Venus had no solidifying core. They further discovered that Venus lacked the horizontal plate tectonics that dominated Earth's surface geology.

Early in 1986, Ames mission controllers reoriented Pioneer Venus, still in orbit around Venus, to observe Comet Halley. It was the only spacecraft in position to observe the comet at its most spectacular—at perihelion, where it comes closest to the sun and is most active. With Pioneer's ultraviolet spectrometer pointed at Halley, Ames scientists gathered data on the comet's gas composition, water vaporization rate, and gas-to-dust ratio. Five more times, mission controllers at Ames reoriented the Pioneer Orbiter to observe passing comets.

The Pioneer Venus orbiter continued to circle the planet, working perfectly, for fourteen years—over one full cycle of solar activity. Its mission ended in October 1992 when, short on fuel, controllers directed it into ever-closer orbits until it finally burned up. In doing so, it returned the best data yet supporting the theory that Venus was once very wet. For a cost averaging \$5 million per year over its fourteen year mission, Pioneer Venus generated a wealth of good science. By 1994, more than a thousand scientific papers had been written from Pioneer Venus data, authored by scientists from 34 universities, fourteen federal laboratories, and fifteen industrial laboratories. While planetary scientists continued mining Pioneer Venus data, Ames atmosphere scientists turned their expertise to exploring the atmospheres of Mars and Jupiter.

The two Viking landers that settled down on the surface of Mars in September 1976 carried an atmosphere structure experiment designed by Al Seiff. He had hoped to send a dedicated entry probe to Mars, since all that was unknown about atmospheric pressures on Mars made planning for future missions difficult. Instead, Seiff was asked to build a small set of instruments keyed to the entry heatshield of the Viking lander. During high-speed entry, his atmosphere structure experiment measured the profile of temperature, pressure

and density from an altitude of 100 kilometers to touchdown. Below twenty kilometers it took direct measurements of temperatures and pressures; higher than that the data were induced through deceleration profiles. Winds were derived from Doppler velocities and from gyroscope records of changes in the vehicle attitude. After it landed, the instruments continued to take readings which were matched with data from the meteorology experiments. It returned the first sounding of the structure of the Martian atmosphere, and provided data that remained useful to NASA's Mars missions of the late 1990s.

GALILEO JUPITER PROBE

Jupiter's atmosphere posed a far bigger challenge for Ames planetary probe builders. Jupiter's huge gravity accelerates a probe more than five times faster than the gravitational pull of the inner planets. Jupiter's thermal and radiation energy and violent cloud layers are ominous spacecraft hazards. Jupiter has no recognizable surface; its deep atmosphere just gets denser and hotter until the edge blurs between atmosphere and any solid interior. Ames scientists expected any Jupiter probe to encounter a hundred times the heat of an Apollo reentry capsule—something like a small nuclear explosion. Of course, these challenges portended enormous scientific possibility.

NASA Ames managed the Galileo probe, and again Hughes Aircraft of El Segundo built it. General Electric Re-Entry Systems Division built the heatshield, following the design for the Pioneer Venus probe. The Galileo orbiter was massive, and designed by JPL. A number of NASA Ames scientists served as principal investigators: Robert Boese developed a net flux radiometer, Boris Ragent developed a nephelometer to measure the scatterings of cloud particles, James Pollack and David Atkinson devised a doppler winds experiment, and Al Seiff again led the probe atmosphere structure experiment—measuring pressure, temperature and density. Ames built a unique outer planets arc jet, led by Howard Stine and James Jedlicka, to simulate the most caustic and stressful atmosphere a man-made material would ever encounter. After computing and testing various

exotic materials for their ability to withstand the heat, shocks, and erosion from the Jovian atmosphere, Ames chose carbon phenolic from which to build the heatshield needed to protect the probe as it entered the Jupiter's atmosphere.

Hughes delivered the probe on schedule in February 1984, expecting an encounter in May 1988. Then it sat in storage for eight years. Galileo was designed to be launched from the bay of the Space Shuttle orbiter, but the Challenger accident threw that launch schedule into turmoil. Furthermore, NASA would no longer allow the liquid-fueled Centaur booster to launch it from the orbiter in low Earth orbit. In January 1988 NASA sent Galileo, now eight years old, back to Hughes for refurbishment and performance checks. Galileo was finally launched in October 1989, with a less powerful upper stage rocket and a more convoluted flight plan—one taking it by Venus and Earth to pick up speed on its journey toward Jupiter. Between design and launch, Benny Chin had taken over as probe project manager from Joel Sperans, Richard Young had taken over as project scientist from Larry Colin, and John Givens arrived as probe development manager.

After travelling six years and 2.5 billion miles to Jupiter with the Galileo orbiter, the probe separated and continued on a five month coast—spin stabilized—to Jupiter. It entered Jupiter's atmosphere on 7 December 1995. The probe slammed into the atmosphere without braking, travelling 115,000 miles per hour, with deceleration forces 350 times Earth gravity. The incandescent gas cap ahead of the heatshield reached 28,000 degrees Fahrenheit, meaning to an observer on Jupiter it glowed as bright as the sun. Almost half of the probe mass was heatshield, most of which ablated away as the probe slowed to subsonic speed within two minutes.

The remainder of the heatshield fell away as the parachute deployed to slow its descent to relatively placid speeds. Then the instruments were activated. Seven instruments sent data back to the Galileo Orbiter where it was stored for relay to the mission operations center. But soon after the encounter, the Galileo orbiter went over the horizon, then followed Jupiter behind the sun, clouding the radio signal with noise. Scientists had to wait three long months

for the complete return of data. Data received the following spring confirmed that in the hour before it went dead under the pressure of the atmosphere, the Galileo probe returned the first direct measurements of the chemical composition and physical structure of Jupiter's clouds. The probe survived to a depth of 22 atmospheres and 153 degrees C, transmitting for an hour, sending data on atmospheric conditions and dynamics the whole way in. The probe had unexpectedly entered a hotspot—a gap in the clouds where the atmosphere was dry and deficient in ammonia and hydrogen sulfide—but still the data was a good representation of the whole atmosphere.

Al Seiff and Ames also assisted in one more major probe project—the Huygens Titan probe built by the European Space Agency as part of the Cassini mission to Saturn. The Huygens probe entered the atmosphere of Saturn's moon Titan in January 2005, descended for two and a half hours, and landed on solid ground. Probes continue to be of great use to planetary scientists, as an efficient way of gathering data about atmospheres. All trace their heritage back to Seiff and the PAET. Processing data from the planetary probes made Ames a leading center in research on atmospheres—both of Earth and other planets. But increasingly, Ames managed spacecraft projects derived from other questions. Astrobiology, and its focus on water in the universe, for example, drove the Lunar Prospector mission.

LUNAR PROSPECTOR

The origins of NASA Discovery program dated back to 1989, when NASA's solar system exploration division, led by Wesley Huntress, initiated a series of workshops to define a new strategy for space exploration, highlighting the use of small spacecraft. The space sciences had dwindled as NASA funded Shuttle projects. To launch the program, NASA's 1992 appropriations bill directed NASA to prepare "a plan to stimulate and develop small planetary or other space science projects, emphasizing those which could be accomplished by the academic or research communities."⁶⁶ Dan Goldin used the program to fund focused missions with lower costs, shorter timelines, and less risk, by giving the science investigation

teams a great deal of freedom. The cost for an entire mission would be less than \$425 million, time from start to launch could be less than 36 months, and NASA planned to have a missions flying every one or two years. The Discovery program encouraged focused, scientific studies of our solar system by sending robotic explorers to the planets, their moons, and small bodies such as comets and asteroids. The first two missions in the Discovery program launched in 1996: JPL's MESUR-Pathfinder, for sending a small lander and robotic rover to Mars, and the near Earth asteroid rendezvous (NEAR). In February 1995, NASA selected the Lunar Prospector as the third Discovery mission.

In the 25 years since Apollo, only a few spacecraft have flown by the Moon, and only one had a lengthy encounter. The Clementine spacecraft, built by the U.S. Air Force (with scientific input from NASA) orbited the Moon for two months in 1994 in an elliptical orbit no closer than 250 miles to the surface of the Moon. Clementine bounced radar signals off the Moon's surface to develop a map, and returned radar signatures that might be consistent with ice crystals at the lunar south pole. Since Apollo era samples showed the lunar regolith to be bone dry, scientists thought that water was transported to the Moon on comets and asteroids, which created deep craters with permanent shadows that shielded the ice from the sun's heat.

Spurred by these results, Ames developed plans for a spacecraft to lead NASA's rediscovery of the Moon. Called the Lunar Prospector, it would orbit the Moon for a year, in circular orbit at an altitude of about sixty miles. The idea for Lunar Prospector initiated at the Lockheed Martin Missiles & Space Company located adjacent to Ames in Sunnyvale. Former Ames deputy director Gus Guastaferro, then an executive with Lockheed, guided the project planning. Ames managed the Prospector contract, and G. Scott Hubbard of Ames' space projects division led all Prospector efforts as the NASA mission manager. The principal investigator was Alan Binder at Lockheed, and Tom Duggerty led the team at Lockheed that designed and built the Prospector. William Feldman of the Los Alamos National Laboratory led the design of three key instruments and the Hewlett-Packard Company built a custom test system using off-the-shelf

components. By contracting for parts and services from 25 other Silicon Valley firms, and by designing Prospector as a simple spin-stabilized cylinder just 4.6 feet in diameter and 4.1 feet in length, Lockheed took the spacecraft from go-ahead to final test in only 22 months. In addition, Lockheed Martin, at its facility in Colorado, built the Athena launch vehicle that was used for its first time to send Prospector skyward. It was the first commercially-developed rocket ever to launch a lunar mission. The total cost to NASA for the mission, including launch, was \$63 million. "Prospector has served as a model for new ways of doing business," said Hubbard. "This mission has made history in terms of management style, technical approach, cost management and focused science."⁶⁷

In 1997, Ames built a Prospector mission control room from the operation center that had so long served the Pioneer spacecraft. Mission controllers inserted the Prospector into lunar orbit in January 1998 carrying five science instruments. A gamma ray spectrometer remotely mapped the chemical composition of the lunar surface, measuring concentrations of such elements as uranium, titanium, potassium, iron, and oxygen. An alpha particle spectrometer looked for outgassing events that suggested tectonic or volcanic activity. A magnetometer and electron reflectometer probed the lunar magnetic fields for clues about the Moon's core. The doppler gravity experiment returned the first lunar gravity map with operational specificity. And a neutron spectrometer, the first used in planetary exploration, detected energy flux emanating from the lunar regolith. Hydrogen has a unique neutron signature that is indicative of water ice at higher concentrations. Prospector returned the first direct measurement of high hydrogen levels at the lunar poles, which Ames scientists claimed could only be explained as the presence of water ice.

Ames held a press conference in March 1998 to announce the first science results from Lunar Prospector, only seven weeks after it entered lunar orbit. The indication of water ice embedded in the permanently shadowed craters at the lunar poles made headlines around the world. Future lunar explorers could extract this water for life support or as a source of oxygen and hydrogen fuel. Rough

estimates showed up to six metric tons of water mixed in fairly low concentrations.

After its first year in orbit at sixty miles altitude, Prospector was instructed to swoop down as low as 25 miles to map the Moon in even greater detail. Ames scientists then refined their scientific data and their estimates of water volumes. Mission controllers instructed the Prospector—its fuel now exhausted, its design life far exceeded, and after its 6,800 lunar orbits had compiled a complete set of data—to crash into a crater at the lunar South pole in July 1999. The impact kicked up no debris visible by ground-based telescopes, and NASA scientists using space-based telescopes saw no real signs of vapor that they could analyze for further evidence of water ice. Ames would later launch a spacecraft, dubbed LCROSS, optimized for this impact mission.

STARDUST

Stardust, the fourth NASA Discovery mission, launched in February 1999 to return interstellar and cometary particles. In praise of the proposal, Wesley Huntress, as NASA associate administrator for space science, noted that “Stardust was rated highest in terms of scientific content and, when combined with its low cost and high probability of success, this translates into the best return on investment for the nation.”⁶⁸ Stardust’s mission cost to NASA totaled \$199.6 million.⁶⁹ After passing through the trail of comet Wild-2, Stardust stowed its precious cargo of captured particles in a sample return capsule (SRC) for the journey home. Reentry through the Earth’s atmosphere at 12.9 kilometers per second—the fastest reentry ever—demanded a leap in heatshield technology.

Ames researchers played three key roles in this mission. They developed the PICA heatshield used on the Stardust heatshield (PICA stands for phenolic impregnated carbon ablator), analyzed the captured organic compounds (including analysis of which organic compounds were contaminants), and did spectrographic observation of the Stardust capsule as it entered the atmosphere like a meteor.

The standard approach to high-speed reentry, from Mercury through Apollo, involved filling a polymer substrate with various chopped fibers, glass microspheres and even cork. Phenolic honeycomb cells provided structural integrity for AVCOAT, the heatshield Martin Marietta manufactured for the Apollo missions. Martin Marietta continued ablator development into the 1970s and produced the super lightweight ablator (SLA), which served as the heatshield material for the Viking probe as well as the more recent Mars missions Pathfinder, Spirit and Opportunity.⁷⁰ Ablator development largely stagnated, though, as the Shuttle demanded reusable heatshields.

When Daniel Rasky joined Ames in 1989 as a materials researcher, he found ablative reentry methods out of fashion. Going against the conventional wisdom, as Ames people like to do, he initiated development of a new class of materials called LCAs (lightweight ceramic ablaters) which included silicone impregnated reusable ceramic ablator (SIRCA) and PICA.⁷¹ PICA employed a fibrous ceramic substrate coated with an organic resin film. Because fabrication started with a ceramic substrate, the resulting ablator could easily accommodate different mission configurations.

Upon hearing of Ames' developments on PICA, in January 1995 Lockheed asked Ames for help applying PICA to the Stardust aeroshell. The Stardust sample return container weighed about a hundred pounds and encapsulated 132 blocks of aerogel to hold the particles. Though not large, Ames researchers had produced only small amounts of PICA. Project engineers Huy Tran and Christine Szalai traveled to Lockheed Martin in Denver and, in a short time, produced a full-sized heatshield mock-up in time for the Phase B presentation of the spacecraft.⁷² Fabricating this heatshield for the actual spacecraft required a source for preformed ceramic fibers. Fiber Materials Incorporated became the small business team member to join Stardust's Discovery-class assemblage of university, industry, government laboratory and small business partners. With funding from a SBIR grant, Fiber Materials produced a single-piece PICA heatshield for the Stardust capsule.

Two years prior, the failed reentry of another Discovery-class mission, *Genesis*, prompted concerns about *Stardust*'s reentry technology. Investigators found that technicians had installed the accelerometers designed to trip *Genesis*' parachute upside-down.⁷³ Still, the *Stardust* reentry technology was continually reviewed. Ablation and thermal performance testing occurred at the Ames 60 megawatt interaction heating arc jet facility, using 24 models and four test conditions. During the flight of *Stardust*, concerns arose regarding uncertainties in the initial arc jet heating rate calibrations. Ames aerothermodynamicists Jim Arnold, Howard Goldstein and Ethiraj Venkatapathy formed an internal review team. They found that PICA would "probably" perform well, but to ensure that there was no remaining doubt a secondary group at Ames, led by Al Covington, conducted new testing on *Stardust*'s forebody heatshield.⁷⁴ This group, independent from *Stardust* and the associated Discovery budget, found that the heatshield design was "conservative."⁷⁵ A flawless reentry in January 2006, confirmed these convictions.

Another uncertainty resolved at NASA Ames related to contamination of the comet particles stored in the aerogel by particles burned off the ablating heatshield. Not hermetically sealed, the sample return container would draw in particles as pressure equalized during reentry. These particles could include everything from heatshield ablation products to the mud at the Utah landing site. Anticipating such contamination, *Stardust* team members installed an air filter between the vents of the aeroshell and the canister interior. *Stardust* co-investigator and Ames astrochemist Scott Sandford tested the filter with mixtures of the nastiest possible chemicals thought to possibly bombard the craft, and the filter tested well.⁷⁶ Upon opening the capsule in the clean room at Johnson Space Center after its delivery in January 2006, the aerogel tiles were indeed pristine and in place.⁷⁷

NASA Ames researchers also contributed by developing aerogel for spaceflight. Aerogel was a lightweight and strong foam of silicon bubbles manufactured in carbon dioxide, and worked well for trapping dust grains travelling very fast. Other aerogel uses included Cerenkov radiation detectors in some nuclear reactors and as thermal

insulators on the Mars rovers Sojourner, Spirit, and Opportunity.⁷⁸ For the application of aerogel to the Stardust mission, Scott Sanford and Max Bernstein of the NASA Ames astrochemistry laboratory devised ways to make aerogel cleaner, largely by burning off organic contaminants introduced during manufacture.

The particles returned from Wild-2 offered insights into the materials that coalesced to form our solar system. Long period comets originating in the Kuiper Belt, where Wild-2 was believed to have originated, remain in relatively pristine condition out on the edge of our solar system. Astronomers suspect that comets may be the source of organics and water on Earth during its formation. After the Stardust encounter, material from Wild-2 now sits embedded in small aerogel tiles awaiting continuing extraction and analysis. Some of the early results of the organic analysis were far from ambiguous. The high concentrations of oxygen and nitrogen in labile organics looked nothing like organic contamination. Also, the presence of deuterium and nitrogen-15 suggested a protostellar heritage for some organics.⁷⁹ Determining the origins of these particles shapes our picture of the nebula from which our solar system formed. The presence of a range of organics in the Stardust samples supported the possibility that the delivery of cometary materials to early Earth played a role in the origin of life. Of particular interest was the amino acid glycine in the samples.⁸⁰ Stardust provoked interest in more sample return missions. A smattering of particles could not reproduce a model of the entire comet.

Peter Jenniskens of Ames led the observations of the Stardust capsule upon reentry. Flying with the Ames video team aboard a specially outfitted NASA DC-8, they recorded spectrographic data of the light produced as the PICA heatshield interacted with the atmosphere. Jenniskens previously had observed meteor showers, which required focusing on one part of the sky, whereas Stardust had a well defined trajectory across the sky to follow.⁸¹ Because the heatshield material contained carbon, its reaction with the shockwave upon reentry was similar to that of meteoroids. The fireballs produced upon entry by asteroids with diameters on the order of a meter (similar in size to the Stardust) deposited most their

mass in the atmosphere through ablation, spallation, fragmentation, and shock layer chemistry. The organic matter strewn throughout the atmosphere reacts chemically with the atmosphere in the shock layer to produce, perhaps, organic compounds different from those found in meteorites.⁸² While the composition of PICA and meteoroids differ significantly, the lack of metal line emissions from PICA made possible the study of the much weaker shock emissions from reacting organics.

In addition, the Stardust reentry provided flight-tested proof of the PICA heatshield's ability to protect a capsule at high reentry speed. During the time Stardust flew on its mission, NASA began the Constellation program to return humans to the Moon. PICA would be a possible new ablative material for the heatshield to cover the Orion crew exploration vehicle.⁸³

SOFIA

The Stratospheric Observatory for Infrared Astronomy (SOFIA) is an airborne observatory, built around a Boeing 747, which will study the universe in the infrared spectrum. SOFIA was two decades in the making, with more than a billion dollars being spent on that one aircraft. In May 2010 SOFIA achieved first light, when the instruments were first operational. When in full use, SOFIA will stand at the core of the discipline of infrared astronomy. Young scientists and educators will train there, and new observational techniques and instrumentation will be advanced. Teams of astronomers will observe the radiant heat patterns of space from the cold dark fringes of Earth's atmosphere. At its cruising altitude of 41,000 feet, SOFIA will fly above 99 percent of Earth's obscuring water vapor, allowing observations impossible for even the largest and highest ground-based telescopes. SOFIA will help answer questions about the birth of stars, the formation of solar systems, the origin of complex molecules in space, the evolution of comets, and the nature of black holes.

SOFIA succeeds the Kuiper Airborne Observatory, a C-141A aircraft carrying a 36-inch infrared telescope that was operated by Ames from 1974 through 1995. Named after famed University of Arizona astronomer Gerard Kuiper, the Kuiper observatory was used

to sight the rings of Uranus, the atmosphere on Pluto, and the disks around stars. Astronomers used it to track the formation of heavy elements in massive supernovas, and the distribution of water and organic molecules in regions of star formation. The first discussion of what sort of infrared telescope could fit inside a Boeing 747 began in 1984, when the Kuiper was the world's only airborne observatory.⁸⁴ Ames people—Edwin Erickson on the science side and Gary Thorley on the program side—spent five years on feasibility studies for the aircraft and telescope before serious planning began in 1990.⁸⁵ A 747, they calculated, could hold a telescope 2.5 times stronger than that on the Kuiper.

In the mid-1980s Ames researchers used their expertise in airborne observatories for the design of spaceborne observatories. An international team built the IRAS (for infrared astronomical satellite). Ames designed the IRAS telescope, which had a sixty centimeter mirror and an array of detectors cooled to near absolute zero by superfluid helium. IRAS launched in January 1983 and, during its one year in orbit, conducted the first whole-sky survey in the infrared region. In mapping the entire celestial sphere in four infrared bands from 8 to 120 micrometers, IRAS astronomers found 250,000 new infrared sources, almost doubling the catalog of infrared sources. They found suggestions of asteroidal collisions in the zodiacal cloud, particle rings around some stars, the core of our Milky Way galaxy, and the wispy filaments of the infrared cirrus covering much of the sky. And IRAS offered valuable experience useful in building the next generations of airborne telescopes.

James Murphy and Fred Witteborn conceived a liquid helium-cooled spaceborne infrared telescope they dubbed SIRTf. The acronym initially stood for Shuttle infrared test facility, though, once the contamination surrounding the Shuttle orbiter (dust, heat and vapors) was confirmed in flight they decided it must be detached from the orbiter. SIRTf was redesigned as a free-flying spacecraft. Eventually launched as the Spitzer Space Telescope in 2003, SIRTf became the instrument in NASA's great spaceborne observatories program that covered the infrared portion of the spectrum. A unique technology group sprang up at Ames, led by

Craig McCreight and Peter Kittel, to develop low noise detectors for SIRTF.⁸⁶ This was an exciting era in infrared telescropy, with instruments being designed for the ESA infrared space observatory, the second generation Hubble infrared spectrometer, SIRTF, SOFIA and a variety of ground-based infrared telescopes. When NASA headquarters moved SIRTF program management to JPL in 1991, despite Dale Compton's strenuous objections, McCreight and Kittel continued their work. Ames revised plans so that SOFIA capabilities specifically complemented SIRTF capabilities.

As with the Kuiper, SOFIA would have an open-air port for the telescope, and Ames aerodynamicists began exploring how to safely put so large a hole in the top of the aircraft. During a major upgrade of the information systems for the Kuiper, completed in December 1991, Ames refined the computing and data collection equipment that they would include on the SOFIA. Ames opened discussions with German astronomers, who agreed to raise funds to build the core of the telescope there. Throughout the early 1990s, Ames struggled to get funding approved by headquarters and Congress as they reshaped the institutional structure to support SOFIA. Soon after Harry McDonald arrived at Ames, NASA headquarters approved the program.

In December 1996, David Morrison, Ames' director of space, announced that Ames had awarded the \$480 million SOFIA prime contract to USRA (Universities Space Research Association), a private non-profit corporation with eighty universities as institutional members. USRA was formed in 1970 under the auspices of the National Academy of Sciences to provide a means for university and government collaboration in space exploration. USRA led overall project management, and would later lead scientific operations. The SOFIA contract was a new type of contract—performance based and with full-cost accounting. Other contracts specified the resources and personnel a contractor would devote to a project; Ames' contract for the SOFIA specified only the scientific work USRA must accomplish. "The SOFIA program is a stellar example of NASA's new way of doing business," exclaimed Dan Goldin. "We have taken the parts of a space science program that the private sector can do better

and more cost effectively, and had a competitive selection for the privilege of performing those duties.”⁸⁷

Also unique was the cooperation with the Germans. German astronomers were involved in the SOFIA from the beginning. NASA funded eighty percent of SOFIA costs, and the German government funded the other twenty percent. The infrared telescope, 2.5 meters in diameter, was designed and built by a consortium of German aerospace companies and managed by DLR, the German Aerospace Center. This partnership gave the program impressive momentum.

In April 1997 the 747SP that would be transformed into SOFIA was procured from United Airlines, and dedicated in a ceremony at NASA Ames. Modifications to the 747 began in 1998 at Raytheon E-Systems of Waco, Texas (which was soon after acquired by L3 Communications Integrated Systems). The telescope was heavy at 45,000 pounds. A sixteen foot diameter aperture was cut into the aft fuselage, which was covered by a sliding door that opened at high altitude. The aerodynamics of this weight and this hole were so complex, and unique, that existing CFD codes only clarified the concerns. Ames aerodynamicists fabricated a model and put it through a hundred hours of tests in the 14 foot wind tunnel, which was brought out of mothballs for them. They devised an aft ramp and a wind scoop at the back of the aperture. With the aft ramp, airflow was smoother over the aperture opening so that turbulent air did not drop into the opening, causing vibrations and pressure distortions which diminished image quality.

However, SOFIA soon ran into troubles, and Ames’ solution was to bring the work in-house. In April 2001, Ames completed conversion of hangar N211—built in 1946 and home to almost all aircraft stationed at Ames—into a SOFIA science and mission operations center. There, the scientific teams had their offices, and instruments would be installed into the aircraft and maintained. An alignment simulator could test all their instruments with the aircraft on the ground. A data archive would allow for rapid diffusion of results. But soon the hangar became the site of engineering work.

In April 2003, NASA Ames crews led by Dave Ackard and Bill Caldwell completed design and assembly of the lower flexible door

assembly. They needed to design special assembly tools so the door would meet the precision requirements demanded of the general airworthiness standards of the FAA. Soon after, in June 2003, the Ames aeronautics and space flight hardware division was selected to assemble the upper rigid door. Because of the bankruptcy of the project contractor, Aircraft Engineering Corp., the door assembly tools Ames received were only 75 percent complete. The door was massive, measuring 16 by 14 feet, with 4,500 parts. By August 2004 Ames technical staff had assembled the telescope cavity door, a major milestone, and it received FAA certification as flight-worthy.

Yet by 2005 the accumulated technical challenges took a toll on the program. The date of first light had slipped from summer 2001 to 2006, and the cost had ballooned from \$185 million to \$330 million, and soon to \$500 million. In April 2006, as Ames was struggling with budget cuts and had no permanent director, NASA headquarters sent to Congress a budget that had reduced SOFIA funding by thirty percent in 2006 and eliminated it in 2007. The Germans objected loudly to NASA's abrogation of its responsibilities to its partners. NASA headquarters launched an independent review, and Joel Kearns and Carol Carroll, SOFIA program manager, led Ames' response. The review concluded that, although Ames had done a poor job managing its prime contractor, there were no insurmountable technical hurdles to the successful completion of the observatory. The report went to the NASA program management council, which concurred.

In August 2006, NASA headquarters announced a major change in the SOFIA program. SOFIA would now be based out of a hangar in Palmdale, California and Dryden Flight Research Center became responsible for SOFIA flight testing and operations. Science operations were still based at NASA Ames, and managed by USRA. USRA still planned for the SOFIA to make about 120 flights per year of about nine hours each. Though the change had been in the works for months, and was driven largely by the perception that it was cheaper to operate aircraft out of Dryden, for Ames to lose program responsibility for SOFIA so soon after Pete Worden arrived as director was not seen around Center as a good omen. Still, Ames

people knew that the aircraft modifications had gone awry, and were glad to keep control of the more important science program.

SOFIA completed its first checkout flight in April 2007 in the skies over Waco, Texas. Soon after it was ferried to Dryden, where it underwent more complete flight testing. It made a visit to NASA Ames in January 2008, where 3,500 people lined up to look inside. In December 2009, for the first time its door was opened in flight and the aircraft flew well. The science program also hit its milestones. In July 2008, on their first try, the Ames science team successfully coated the mirror. After several decades of planning, it took only twenty seconds to apply the shiny aluminum layer on the highly polished piece of glass.⁸⁸ Ames had opened, in June 2001, a specially-built vacuum chamber in the N211 hangar to coat the mirror which, like many mirrors, needed to be recoated often. The challenge was to design a mirror support structure, out of carbon-reinforced plastic, that did not have to be dismantled before undergoing the vacuum needed for coating. The aluminum layer itself was only five one-millionths of an inch thick, which weighed only one-seventh as much as an aluminum can. The mirror was installed on the telescope and the telescope then installed on the aircraft. Soon after that the first three members of the science team were selected.

SOFIA's six hour "first light" flight, in May 2010, was staffed by an international group of astronomers from NASA, USRA, the German SOFIA Institute, and Cornell University—who built the camera mounted on the telescope. The stability of the aircraft and the pointing precision of the telescope were all they had hoped for. They recorded images of Jupiter unobtainable in any other way, which showed heat pouring out of Jupiter's interior through holes in its clouds.

KEPLER

The Kepler exoplanet observatory was a mission driven by astrobiology, matched with Ames' expertise in scientific instrumentation. Launched in March 2009, Kepler was NASA's first mission capable of finding Earth-sized planets in habitable orbits around other stars. While 347 exoplanets had been discovered prior

to the launch of Kepler, almost all of these were gas giants with no solid surface capable of supporting life. Others were ice giants or small planets in super-hot orbits like that of Mercury. Orbit in the habitable zone means the planet is just distant enough from its star that water can exist in liquid form.

With Kepler NASA may discover hundreds of planets similar to Earth; or it may discover none. We may learn that Earth is unique, or that our galaxy has the potential to teem with life. Within its first year of operation, Kepler had peered at 156,000 stars, and identified 706 that hosted some sort of planet—most much smaller than Jupiter—including five stars that likely hosted multiple planets. Regardless of whether we find a planet like Earth, Kepler will teach us much about the structure and diversity of planetary systems in our galaxy.

The heart of the mission is William J. Borucki, Kepler principal investigator and chief of its science operations. Borucki joined Ames in 1962 fresh from a masters degree in physics from the University of Wisconsin. He started in the hypervelocity free flight tunnel, doing spectroscopic analysis of the radiation environment of the Apollo heatshields. In 1972 he joined the theoretical studies branch and developed photochemical models of the Earth's stratosphere, specifically to study ozone depletion. Next he characterized lightning in the atmospheres of Earth, Venus, Jupiter and Titan. He did laboratory work on the optical efficiency of lightning in various planetary atmospheres, coupled with spacecraft observations, which he used to deduce the production rates of prebiotic molecules. He built instruments to measure the fraction of optical energy of laser-induced plasmas. His work on lightning led him to understand the potential of photometers, the instrument at the core of the Kepler mission. And fascination with big issues in space exploration led him to keep attune to the burgeoning work at NASA Ames in the early 1980s around the search for extraterrestrial intelligence.

In 1984 Borucki first proposed the photometric transit method for detecting other planets.⁸⁹ His proposal met much skepticism, not from doubts about the value of the science, but from whether photometry could ever be rendered precise enough. Borucki and David G. Koch of the NASA Ames astrophysics branch continued to

champion the mission, some say to the point of obsession, over many decades, all the while focusing on the engineering of the photometer. Ames director Bill Ballhaus funded their early efforts through his discretionary funds, as he would over the next few years. Borucki convened workshops in 1984 and 1987 to review the state of the art in spaceborne photometers. He worked with the National Bureau of Standards to determine that discrete silicon dioxide detectors might offer precision in tracking individual stars—one photon into the detector meant one electron out. In the late 1980s though, Borucki shifted his platform toward CCDs—charged coupled devices like those found in digital cameras.⁹⁰ Borucki preferred silicon dioxide, but CCDs were improving dramatically and were familiar to space scientists. The advantage they offered, other than easing acceptance of the mission, was that CCDs could monitor a whole field of stars. Eventually, the Kepler would use 42 CCDs, compared with four on the Hubble Space Telescope.

In 1992, Borucki and Koch first proposed a specific spacecraft mission, called FRESIP for frequency of Earth-sized inner planets, as part of the new NASA Discovery program. It was rejected because no suitable detectors were thought to exist. At the same time, David Black, John Dyer and Charlie Sobeck at Ames had been working on a proposal for an exoplanet mission based on astrometrics. The astrometric telescope facility (ATF) would be mounted to an arm on the International Space Station and be able to take precise position measurements of two hundred nearby stars to determine if any harbored exoplanets.⁹¹ Design work on the ATF continued from 1986 until 1993, when it was cancelled because of delays in the ISS.

Meanwhile, Borucki honed his detector technology. In November 1993, Ames sponsored another conference on the astrophysics—apart from exoplanet detection—that could be accomplished by FRESIP.⁹² The consensus was that FRESIP data would give significant insight into our own sun. By collecting data on star spots, FRESIP could clarify the composition and behavior of a normal star, and thus help us anticipate the sun's behavior. The conference cleared up another issue impeding approval of the mission. If the light emitted by stars naturally fluctuated over the course of a day, then it might

be impossible to detect the slight drop in light caused by the transit of a planet. However, data returned from NASA's Solar Maximum Mission showed that the variability of light from our sun was less than ten parts per million—smaller than the twenty parts generated by a transit. Another technical uncertainty was resolved.

Dale Compton, now Ames Center director, continued to fund development of the proposal. Larry Webster, a veteran spacecraft engineer, was named project manager and tasked with refining the engineering. Ames was aware that JPL was investing heavily in a space-based interferometer, and thought the FRESIP proposal was a good alternative—an elegantly simple spacecraft, inexpensive, driven by one highly refined instrument, that could provide high impact science. It nicely fit with the new “faster, better, cheaper” mantra of Dan Goldin. Still, the Discovery program reviewers with NASA headquarters again rejected the FRESIP proposal in 1994, on grounds that it would certainly cost more than the proposal estimated. The next proposal opportunity would open in two years.

In 1995, scientists using ground-based equipment at the Geneva Observatory announced discovery of the first exoplanet, a gas giant in a close orbit to its star in the constellation Pegasus.⁹³ Their method focused on doppler velocity measurements to find a periodic wobble in a star, and any planet able to cause such a wobble would have to be big. Other discoveries from astrometry followed in 1997, though all were gas giants in very tight orbits to their stars—so-called Vulcans. The French national space agency, CNES, funded a transit photometry mission named COROT (for CONvection, ROTation and planetary Transits). Though one-third the size of Borucki's proposed spacecraft, and only capable of detecting planets greater than ten times the size of Earth, it lent urgency to the American effort. (It would not launch, though, until December 2006.) Carl Sagan and Jill Tarter of the SETI Institute more vocally championed Borucki's spacecraft, and suggested renaming the mission to honor Johannes Kepler as the founder of celestial mechanics. To address concerns about cost, the Ames team simplified the mission, by moving it from a Lagrange point into an Earth-following orbit. Furthermore, Borucki's team had developed the algorithms that would allow them to make

sense of the CCD data. Despite this excitement, and refinements, the proposal was rejected again in 1996 because automated photometry of thousands of stars remained unproven.

So in December 1997 the Ames team installed a testbed, called the Vulcan camera, at the Lick Observatory near San Jose. The SETI Institute, increasingly intrigued by what the Kepler might find, helped organize volunteers to staff the small telescope during the night hours. Soon the Vulcan proved capable of continuous, automatic monitoring of 100,000 stars. Though Earth-based photometers were unlikely to detect transits, the Vulcan found one and discovered many eclipsing binary stars. (In 2003, this group placed a Vulcan South photometer at a research station in Antarctica, where it continued to serve as a testbed for Kepler technologies.)

Still Borucki's proposal was rejected again in 1998 because the ability to handle on-orbit noise remained unproven. This time, though NASA put in enough money (a million dollars, half from headquarters and half from Ames) for the Kepler team to provide an end-to-end demonstration of their technology. Within 88 days Borucki's team developed a laboratory-based photometer, a ten-foot tall rack of equipment surrounding a single CCD, installed in the basement of the Ames space sciences building. In tests conducted between April 1999 and July 2000, against a simulated 1600 star sky, it operated with precision and noise control at the twenty parts in a million required for the mission.⁹⁴ By the December 2001 proposal review the reviewers ran out of objections to the technology, and Kepler was selected as the tenth Discovery mission. Borucki finally saw some light at the end of the tunnel.

Borucki's patience continued to be tried, however. Weeks after the proposal was funded, NASA headquarters told the Kepler team that a drop in funding—because of overruns in other Discovery missions—would push the launch date back to 2007. Also, JPL would be tasked to provide program management through the launch of the spacecraft. NASA Ames led photometer design, spacecraft operations and data management, and the overall Kepler science program. Ball Aerospace of Boulder, Colorado designed and built the spacecraft, derived from the Deep Impact spacecraft. The

spacecraft itself was simple, little more than a platform to keep the photometer steady and to stream data back to Earth for analysis. Still, Ball Aerospace struggled with the work at the same time all of NASA was hit with full cost recovery. Kodak had started fabricating the lens and mirror, but in 2004 Ball Aerospace awarded the work to L-3 Brashear of Pittsburgh. Soon after, a crack in the mirror further delayed manufacturing. The project started to creep over budget, but the financial system set up at Ames in 2001 allowed them to control the overrun. The life-cycle cost of Kepler, including three planned years of operation, would rise to \$600 million. Tens of millions of Kepler's budget went towards building the science operations center on the third floor of the Ames space projects facility. NASA Ames had built mission control rooms for the Pioneers and for the Shuttle biological payloads, but the multimission operations center was designed with the flexibility to support any future Ames missions. It served as a data reduction and processing hub for Kepler scientists.

Borucki called Kepler "the most boring NASA mission ever."⁹⁵ The Kepler photometer, essentially a digital camera with a 37-inch diameter lens, stared unblinkingly at one small section of the Milky Way galaxy, about ten degrees square, in the constellation Cygnus. It measured minute changes—about 0.01 percent—in the light levels of the 156,000 stars the science team decided to track. A small change in the brightness of a star, once all the noise was removed from the signal, indicated that a planet was transiting in front of it. The frequency of the blip indicated the period of the planet's orbit, and thus its distance from that star, and thus its likely temperature. Kepler was funded to isolate such periodic blips for 3.5 years, even though it had enough fuel on board to power the mission for a decade.

The Kepler mission included a guest observer program for science beyond its hunt for exoplanets. Only data from the stars selected by the science team was routinely transmitted to Earth. There was bandwidth to track additional targets—3,000 at thirty-minute intervals and 25 at one-minute intervals. The Kepler science team would review proposals for research related to intrinsically variable stars that pulsate, rotate, erupt or explode. Kepler also provided data

on astroseismology, the study of fluctuations in the brightness of stars. Most often fluctuations arise from sun spots, and the only data we had on sun spots came from our sun. Astroseismology explores the internal structure of stars and helps determine the mass and radii of the stars that Kepler observed.

First science results were returned in June 2009. The data was calibrated at Ames, then archived at the Space Telescope Science Institute. Astronomers can then turn their telescopes toward these candidates to better characterize them. NASA also planned to use other telescopes—notably the forthcoming James Webb Space Telescope and the Space Interferometry Mission—to try to detect oxygen in the atmosphere of this planet.

NASA was studying a follow-on mission to Kepler, the Terrestrial Planet Finder, using a space-based stellar coronagraph. David Des Marais, of the Ames astrobiology branch, played a key role in describing how to look for features in the atmosphere of nearby exoplanets that might indicate the presence of life.⁹⁶ Knowing what to look for in other atmospheres derives from our understanding of how our own atmosphere developed. In 2001, two teams of Ames scientists each published a paper that proposed a new explanation for the rise of oxygen in Earth's early atmosphere. The first team—of David Catling, Kevin Zahnle, and Christopher McKay—developed a theoretical model in which the methane of the early atmosphere underwent photolysis and liberated hydrogen. This led to oxidation of the atmosphere as hydrogen from the methane escaped because Earth's gravity could not retain it.⁹⁷ The second team employed measurements of microbial mats. Lead authors Tori Hoehler and Brad Bebout, working with Des Marais, reported their measurements of the cyanobacteria-dominated mats at Guerrero Negro. They found that the mats produced lots of hydrogen and carbon monoxide as well as a flux of methane.⁹⁸ Given the contribution of oxygen from photosynthetic mats, which were far more numerous in the early Earth, the experimental findings of Hoehler, Bebout, and Des Marais supported the premise of Catling's team. Once Kepler identifies exoplanets, Ames will have instruments ready for characterizing its atmosphere.

LCROSS

The Lunar CRater Observation and Sensing Satellite (LCROSS) launched in June 2009 on a voyage to a permanently shadowed crater near the south pole of the Moon. In October 2009 it impacted a crater named Cabeus, kicking up dust and vapor that was recorded by a shepherding spacecraft that flew through the plume with cameras and spectrometers. NASA funded LCROSS to discern the concentration of water ice on the Moon—the water to dust ratio—and confirm data from the Clementine and Lunar Prospector missions a decade earlier. Water ice would enable settlement on the Moon, and LCROSS found plenty of it.

Principal investigator on LCROSS was Anthony Colaprete, and reviewing his path to the Moon illuminates how the careers of planetary scientists evolve at Ames. While earning his doctorate degree Colaprete worked with the NASA-funded Colorado Space Grant Consortium on many projects ranging from space shuttle payloads to small satellites. It proved to be a great environment to learn how a mission progresses from proposal to hardware to papers, how to work well with project engineers from aerospace industry, how to accomplish good science with a small payload, and how the heart of any mission lay in its instrumentation. Brian Toon recruited Colaprete to NASA Ames. Toon worked at Ames from 1984 through 1997, as a senior scientist in theoretical atmospheric sciences. In 1997 Toon joined the University of Colorado as founding chair in their department of atmospheric and oceanic sciences. With Toon's guidance, Colaprete focused his doctorate on the formation and climate effects of water and carbon dioxide clouds on Mars. At the same time, Colaprete collaborated with Julio A. Magalhães of the Ames space sciences division on a model of cloud formation on Mars using data from Pathfinder.⁹⁹ When Colaprete graduated he earned a NRC post-doctoral fellowship that brought him to Ames, to work with Robert Haberle on a climate model.

As a post-doc, his work remained theoretical. Colaprete took advantage of the increasing focus on Mars (during the Pathfinder and Global Surveyor missions) and developed a number of

microphysical models for characterizing the Martian atmosphere.¹⁰⁰ Colaprete, together with Toon and Ames astrobiologist Kevin Zahnle, compared the ages of craters and river features on Mars and proposed that heavy bombardment from comets and asteroids in the early solar system produced a cycle of rain and flooding across the planet.¹⁰¹ In August 2003, Ames hired Colaprete as a civil servant in the planetary systems branch. Colaprete worked on transitioning the Mars general circulation model onto a computer code that allowed smoother fields higher into the atmosphere and included a built-in transport scheme.¹⁰² Shortly thereafter, in 2005, Colaprete and fellow researchers discovered that Mars' southern polar cap was offset from its geographical south pole because of two different polar climates.¹⁰³

In joining Ames Colaprete expected to spend half his time on space projects, so with Kim Ennico he helped form an instrumentation working group. Until the early 1970s Ames had a world-renowned instrumentation group, who accounted for most of the patents issued to the Center. These instrumentation engineers refined precise measurement in the wind tunnels when Ames was part of the NACA, they transitioned into biomedical instrumentation to support human space flight, then began work on spaceborne instruments like those that flew on the Pioneers. Hans Mark disbanded the group in 1972 and dispersed its expertise throughout the Center. Colaprete's instrumentation working group was a grassroot effort to identify the pockets of instrumentation expertise around. They focused on engineering instruments that could be used on multiple spacecraft, and thus foster new business for Ames. Rather than recreate a central instrumentation shop, they fostered collaboration across many research groups at Ames.

In September 2005, the Ames instrumentation group put out a call for proposals hoping to match ideas for instruments with those who needed them. One proposal came from Philip Russell's atmospheric chemistry branch to develop the next generation of solar photometers, one for a nephelometer to measure saltation of grains across a surface, another for a wire impedance monitor to check for shorts in wiring harnesses. Other proposals came from the

planetary sciences and nanotechnology. The Center made investment funding available for promising proposals, and full-cost accounting forced the working group to evaluate the proposals according to the funding it would return. Without funding of its own, after a few years this instrumentation group disbanded. Still promising instruments emerged, and Ames people realized that sophisticated instrumentation mounted on simple spacecraft could indeed be a source of new business. It also demonstrated that Ames did host the facilities and expertise to design, build and test such instruments. LCROSS was an example of an instrument-driven mission.

NASA funded LCROSS in April 2006, as a secondary payload to the Lunar Reconnaissance Orbiter (LRO), a complex spacecraft designed to map the Moon in advance of the crewed mission promised in Bush's vision for space exploration. NASA moved LRO to a larger launch vehicle and thus opened up an extra thousand kilograms of throw-weight to the Moon. The Ames RLEP office, which had oversight of LRO, got nineteen proposals for spacecraft that could fit in that space and be ready to launch in 26 months. Ames' LCROSS proposal was already fairly mature, since it followed the science of Lunar Prospector, and won that competition. NASA called it a Class D risk-tolerant mission, meaning that the cost was small and the timeline so compressed that failure was not unacceptable.

Daniel Andrew served as LCROSS project manager, leading a tight team. Tony Colaprete served as principal investigator, and had already studied the suite of nine LCROSS instruments—visible light and infrared cameras and spectrometers—needed to analyze the plume. The LCROSS science payload was built inside the high bay of Ames' Center for Engineering and Innovation managed by Jim Connolly. As payload scientist and co-investigator, Kim Ennico traveled to Northrop-Grumman in Redondo Beach to check the integration of the instruments with the spacecraft. The backbone of LCROSS was the secondary payload adapter ring used to attach the LRO to the Centaur. Northrop usually built the ring to carry six small satellites, but for LCROSS it was modified to hold modular components for communication and navigation. By using flight-

tested parts, and working fast, Andrews and his team built the spacecraft for \$79 million.

LCROSS had two major parts. The Centaur upper stage of the Atlas V rocket remained attached to the LCROSS during the ride to the Moon then separated from it about ten hours before it was to impact the crater. The Centaur had the mass of a large automobile, and would hit the moon with two hundred times the energy that Lunar Prospector did. Peter Schultz ran simulations in the Ames vertical gun range to demonstrate how the resulting plume could be seen as it spread above the crater. The second part of LCROSS was the shepherding spacecraft equipped to maintain the proper trajectory and to relay data back to Ames. It held a suite of instruments to generate multiple complementary views of the plume: two near-infrared spectrometers, a visible light spectrometer, two mid-infrared cameras, a visible camera and a visible radiometer. When the plume vaporized in sunlight any water, hydrocarbons or organics broke into their basic elements, which could be monitored by the visible and infrared spectrometers. The near- and mid-infrared cameras tracked the total amount of water in the plume. All of these instruments had been built before, were understood by space scientists, and the companies supplying them were willing to work with firm fixed-price contracts.

After launch LCROSS orbited the moon for four months. This gave the Centaur tank time to vent extra fuel so it did not carry liquid hydrogen into the impact. It gave the shepherding spacecraft time to make simple observations of the chemistry of the lunar atmosphere (and it found much sodium). And it gave the LCROSS team time to review LRO mapping. Two weeks before impact they selected Cabeus as the best mix of topography and hydrogen signature. Ten hours before impact the upper stage separated from the shepherding spacecraft on a route to the most vertical possible impact. Ken Galal had mapped a trajectory that put the impact within 83 meters of their target. The plume kicked up about fifteen kilometers. The shepherding spacecraft followed about ten minutes behind the impactor and flew through the plume as it rose into sunlight. From the plume, Colaprete and his team distinguished between the

water vapor, water ice, and hydrated minerals like salts or clays that contained molecularly-bound water. Jennifer Heldmann coordinated an observation campaign with ground-based astronomers. The plume was not easily visible from Earth, but the limited data they gathered confirmed that collected by the shepherding spacecraft. It took many months for Colaprete and his team to analyze the data, and puzzle through why all the spectral lines appeared where and when they did in the very brief sequence of the impact. Four percent of the ejecta mass was water, they discovered, and it held many other interesting chemicals.

Since the Apollo days, the Moon was considered bone dry and with no atmosphere. Following the LCROSS impact, a fast-track inexpensive mission, the Moon was seen as vibrant and changing, and likely able to support human life.

CONTINUING MISSIONS

In addition to the science and mission operations center used to track Kepler and LCROSS and analyze their science data, Ames created a mission design division to more routinely develop future missions like them. The first technology Ames fed into that design center was the common modular bus, a new spacecraft architecture invented at Ames by a group led by Butler Hine. The first mission to emerge from the design center was built upon that bus. Called LADEE, the lunar atmosphere and dust environment explorer, it will orbit the Moon, starting 2012, to characterize its tenuous atmosphere before the scale-up in any human activity and to study electrostatically lofted lunar dust.

When the NASA robotic lunar exploration program left Ames to reside at Marshall, Worden had asked the Ames RLEP group to continue work on the modular bus. They had flown the bus for Alan Stern, then NASA's associate administrator for science, who was impressed. With the behemoth Mars Science Laboratory draining NASA's science budget, Stern saw the bus as a platform for inexpensive missions. He reviewed the priorities for research on the Moon, from a report by the National Research Council, and defined a scientific mission for the bus that became the LADEE mission.¹⁰⁴

Pete Worden recruited Rick Elphic to serve as LADEE project scientist and, as his deputy, Greg Delory from the space sciences laboratory at the University of California at Berkeley.

Hine's core team, which included Mark Turner, moved into a LADEE project office. Ames built the LADEE spacecraft in a clean room on Center, without relying on a prime contractor. The Ames chief engineer, Tina Panontin, issued a procedural requirement 8070.2 for "Class D Spacecraft Design and Environmental Test" that outlined the technical authority for the LADEE team to build the spacecraft. Stern specified certain measurements—species of dust, grain density and variability—and the LADEE team surveyed the industry to discern which instruments could capture that data. The neutral mass spectrometer was derived from a design for the Mars Science Laboratory. The ultraviolet spectrometer, proposed by Anthony Colaprete of Ames, had flown on LCROSS. The lunar dust experiment had a heritage dating back to the Galileo, Ulysses and Cassini missions. In some extra payload space, LADEE would also include a package to validate a laser communication technology.

Other missions for small spacecraft followed. In June 2009, NASA announced that two other Ames projects would be funded through the Small Explorer, or SMEX program. SMEX missions were capped at \$105 million, excluding launch costs. The IRIS mission, for interface region imaging spectrograph, will explore the sun's chromosphere using a solar telescope and spectrograph. The chromosphere is a thin, hot layer on the sun's surface that drives the transport of energy from the sun to the Earth through the solar wind. Recent studies showed the chromosphere to be more dynamic and structured than thought, and IRIS will generate data on the physical processes behind the temperature rise above the stellar photosphere. Data from IRIS will be processed on the ground by a new generation of fast scanning imagers, and Ames supercomputers will develop models of the transition between chromosphere and corona. With its launch in 2012, IRIS will join with a series of other NASA heliophysics missions, including SOHO (the solar and heliophysics observatory), SDO (solar dynamics observatory), and STEREO (solar terrestrial relations observatory). Alan Title of the

Lockheed Martin solar astrophysics laboratory in Palo Alto is the IRIS principal investigator, and John Marmie, formerly LCROSS deputy project manager, and Julie Mikula are managing the program at NASA Ames.

The other funded proposal was called GEMS, for gravity and extreme magnetism SMEX. Built around a new type of X-ray telescope it will measure the polarization of X-rays, then build up that data into coherent images. Thousands of X-rays sources in the universe have been observed with older X-ray satellites but only one object, the Crab Nebulae, has been measured in polarized X-rays. GEMS is a hundred times more sensitive in detecting polarized X-rays than any previous observatory. It will be focused on some of the most energetic and enigmatic objects in the cosmos, like ultra-dense neutron stars and stellar-mass black holes which have gravity fields trillions of times stronger than Earth's. GEMS will probe the bending of space and the curving of light near extreme gravity. Allison Zuniga and Jeffrey Scargle of Ames will manage the spacecraft program, further evidence that Ames' leadership intends to further build upon its legacy of success in creating small science-rich spacecraft.

Engineering Human Spacecraft

The NACA heritage of Ames is perhaps most evident in how it has supported NASA engineering of crewed spacecraft. Other Centers and aerospace firms led the design of the many generations of NASA rockets and capsules, while Ames people did the early research on materials, hypersonics aerodynamics and human factors that enabled those more applied engineering efforts to succeed. Indeed, many of the technologies developed during Ames' NACA years to study reentry systems—the hypersonic wind tunnels, ballistic ranges and arc jets—remained vital to the work Ames did to support the succeeding generations of crewed spacecraft that NASA produced, starting with Mercury, Apollo, Space Shuttle and continuing through the Constellation program.

“...RETURNING HIM SAFELY TO EARTH”

By far the biggest contribution Ames made to NASA's human missions was solving the problem of getting astronauts safely back to Earth. Ames started working on safe reentry in 1951, when Harvey Allen had his eureka moment known as the blunt body concept. In the early 1950s, while most aerospace engineers focused on rockets to launch an object out of our atmosphere—an object like a nuclear-tipped ballistic missile—a few started thinking about the far more difficult problem of getting it back into our atmosphere. Every known material would melt in the intense heat generated when the speeding warhead returned through ever-denser air. Most meteors burned up as they entered our atmosphere; how could humans design anything sturdier than those? Some of the NACA's best aerodynamicists focused on aircraft to break the sound barrier; others focused instead on the thermal barrier.

Harvey Allen and Al Eggers—working with Dean Chapman and the staff of Ames' fastest wind tunnels—pioneered the field of hypersonic aerodynamics. Though there is no clean dividing line

between supersonics and hypersonics, most people put it between Mach 3 and 7 where heat issues (thermodynamics) become more important than airflow issues (aerodynamics). Allen and Eggers brought discipline to hypersonic reentry by simplifying the equations of motion to make possible parametric studies; by systematically varying vehicle mass, size, entry velocity, and entry angle; and by coupling the motion equations to aerodynamic heating predictions. Allen appreciated that the key parameter to safe reentry was the shape of the reentry body.

A long, pointed cone made of heat-hardened metal was the shape most scientists then thought would slip most easily back through the atmosphere. Less boundary layer friction meant less heat. But this pointy shape also focused the heat on the tip of the cone. As the tip melted, the aerodynamics skewed and the cone tumbled. Allen looked at the boundary layer and shock wave in a completely different way. What if he devised a shape so that the bow shock wave passed heat into the atmospheric air at some distance from the reentry body? Could that same design also generate a boundary layer to carry friction heat around the body and leave it behind in a hot wake? Allen first showed theoretically that, in almost all cases, the bow shock of a blunt body generated far less convective and friction heating than the pointy cone.

Allen had already designed a wind tunnel to prove his theory. In 1949, he had opened the first supersonic free-flight facility—which fired a test model upstream into a rush of supersonic air—to test design concepts for guided missiles, ballistic missiles, and reentry vehicles. To provide ever better proof of his blunt body concept, Allen later presided over efforts by Ames researchers to develop light gas guns that would launch test models ever faster into atmospheres of different densities and chemical compositions.

Allen also showed that blunt reentry bodies—as they melted or sloughed off particles—had an important chemical interaction with their atmosphere. To explore the relation between the chemical structure and aerodynamic performance of blunt bodies, Ames hired experts in material science. By the late 1950s, Ames researchers—

led by Morris Rubesin, Constantine Pappas, and John Howe—had pioneered theories on passive surface transpiration cooling (usually called ablation) that moved blunt bodies from the theoretical to the practical. For example, Ames material scientists showed that by building blunt bodies from materials that gave off light gases under the heat of reentry, they could reduce both skin friction and aerodynamic heating.

Ames applied its work on thermal structures, heating, and hypersonic aerodynamics to the X-15 experimental aircraft, which first flew faster than Mach 5 in June 1961 over Rogers Dry Lake. Data returned from the X-15 flight tests then supported modifications to theories about flight in near-space. As America hurried its first plans to send humans into space and return them safely to Earth, NASA instructed Ames to make sure that every facet of this theory was right for the exact configuration of the space capsules. So in the early 1960s Ames opened several new facilities to test all facets—thermal and aerodynamic—of Allen's blunt body theory.

REENTRY TEST FACILITIES

The hypervelocity research laboratory became the home of Ames' physics branch and was the site of most research into ion beams and high temperature gases. Its 3.5 foot hypersonic wind tunnel used interchangeable nozzles for operations at Mach 5, 7, 10, or 14. It included a pebble-bed heater which preheated the air to 3000 degrees Fahrenheit to prevent liquefaction in the test section at high Mach numbers. Ames added a 14 inch helium tunnel (hacked together at a very small cost) to the 3.5 foot tunnel building, which already had helium storage, and opened a separate 20 by 20 inch helium tunnel. These provided an easy way of running preliminary hypervelocity tests from Mach 10 to Mach 25. Compared with air, helium allowed higher Mach numbers with the same linear velocities (feet per second). A one foot diameter hypervelocity shock tunnel, a remnant of the parabolic entry simulator, was built into an old Quonset hut. The shock tube could be filled with air of varying chemical composition, or any mixture of gases to simulate

the atmosphere of Venus or Mars. It produced flows up to Mach 14, lasting as long as 100 milliseconds, with enthalpies up to 4000 Btu (British thermal units) per pound. Enthalpy indicated how much heat was transferred from the tunnel air to the tunnel model, and was thus a key measure in hypersonic research.

The hypervelocity free-flight facility (HFF), which grew out of this hypervelocity laboratory, marked a major advance in Ames' ability to simulate the reentry of a body into an atmosphere. The idea of building a shock tunnel in counterflow with a light gas gun had been proven in 1958 with a small pilot HFF built by Thomas Canning and Alvin Seiff with spare parts. With a full-scale HFF budgeted at \$5 million, Ames management wanted a bit more proof before investing so much in one facility. So in 1961, Canning and Seiff opened a 200 foot-long prototype HFF. Its two-stage shock compression gun hurled a projectile more than 20,000 feet per second into a shock tunnel that produced an air pulse travelling more than 15,000 feet per second. Ames had thus created a relative airspeed of 40,000 feet per second—the equivalent of reentry speed. Using this facility, Canning showed that the best shape for a space capsule—to retain a laminar boundary flow with low heat transfer—was a nearly flat face. Seiff also used it to test the flight stability of proposed capsule designs. Ames next increased the airspeed by rebuilding the piston driver with a deformable plastic that boosted the compression ratio. By July 1965, when the HFF officially opened, Ames could test models at relative velocities of 50,000 feet per second. To vary the Reynolds numbers of a test, Ames built a pressurized ballistic range capable of pressures from 0.1 to 10 atmospheres. Every vehicle in America's human space program was tested there.

While the HFF generated an enthalpy (a total heat content) of 30,000 Btu per pound, the peak heating lasted mere milliseconds. These tunnels worked well for studying reentry aerodynamics, but the heating time was of little use for testing ablative materials. Ablative materials include ceramics, quartz, teflon, or graphite composites that slowly melted and vaporized to move heat into the atmosphere rather than into the metal structure of the capsule. To test ablative materials—both how well they vaporized and how the

melting affected their aerodynamics—Ames began developing the technology of arc jets. This work actually began in 1956, when Ames surveyed the state of commercial arc jets. Under pressure from NASA to mature this technology, in the early 1960s Ames designed its own. As the Apollo era dawned, Ames had a superb set of arc jets to complement its hypervelocity test facility.

These arc jets started with a supersonic blow-down tunnel, which channeled air from a pressurized vessel into a vacuum vessel. On its way through the supersonic throat the air was heated with a powerful electric arc—essentially, lightning controlled as it passed between two electrodes. The idea was simple but many problems had to be solved: air tends to avoid the electrical field of the arc so heating is not uniform; the intense heat melted nozzles and parts of the tunnel; and vaporized electrode materials contaminated the air.

So Ames devised electrodes of hollow, water-filled concentric rings, using a magnetic field to even out the arc. At low pressures, one of these concentric ring arc jets added to the airstream as much as 9000 Btu per pound of air for an extended period of time. Though significant, this heating still did not represent spacecraft reentry conditions. Ames people looked for a better way of mixing the air with the arc. They devised a constricted arc that put one electrode upstream of the constricted tunnel and the other electrode downstream so that the arc passed through the narrow constriction along with the air. This produced enthalpies up to 12,000 Btu at seven atmospheres of pressure. By using the same constricted arc principle, but building a longer throat out of water-cooled washers of boron nitride, in late 1962 Ames achieved a supersonic arc plasma jet with enthalpies over 30,000 Btu per pound and heating that lasted several seconds. Expanding upon Ames' technical success in building arc jets, Glen Goodwin and Dean Chapman proposed a gasdynamics laboratory to explore in a systematic way how arc jets work. Opened in 1962, the \$4 million facility accelerated theoretical and empirical study into ablation.

By 1965, Ames had built a dozen arc jets to generate ever more sustained heat flows. An arc jet in the Mach 50 facility could operate with any mixture of gas, and achieved enthalpies up to 200,000 Btu

per pound. As industrial firms designed ablative materials for the Apollo heatshield, Ames researchers could test them thoroughly and select the best. Nearby an electric arc shock tube was built to study the effects of radiation and ionization during planetary entry. The individual arc jets were essentially highly engineered tubes, on average twelve feet long and two feet in diameter, heavily instrumented, which sat in one of seven available test bays in the arc jet complex. What made the complex unique was its infrastructure to support the various arc jets. After many upgrades, the DC power supply could provide 75 megawatts for thirty minutes or 150 megawatts for fifteen seconds. A high volume steam ejector vacuum pump enabled the arc jets to match high altitude atmospheric flight conditions. With this infrastructure in place, the Ames thermophysics facilities branch could repeatedly try out new arc jet designs.

THE APOLLO PROGRAM

As with robotic spacecraft, in the late 1950s Ames moved tentatively into designing spacecraft for human space flight. Harry Goett had served on the NACA and NASA committees that defined the structure of a space capsule, and Harvey Allen had served on the committee that defined technical approaches to reentry and to navigating in space. In the NACA spirit, both committees focused on identifying big questions in human spaceflight and the best approaches to resolving them. The engineering work they did focused on component technologies rather than the complete spacecraft. Well beyond the 1960s Ames would continue to manage the engineering of vehicles for atmospheric flight—rotorcraft, airborne science platforms, experimental aircraft to validate specific technologies—but not vehicles for human spaceflight. Newer NASA Centers would do that work.

Ames' work in lifting bodies took it, briefly, into project management and systems engineering for crewed spacecraft. Alfred Eggers, backed by the expertise in his vehicle environment division, took Ames the furthest into vehicle design. Eggers and his group in the 10 by 14 inch tunnel in 1957 had conceived of a spacecraft that could safely reenter the Earth's atmosphere, gain aerodynamic control

and land like an airplane. They called these lifting bodies because the lift came from the fuselage rather than from wings, which if too large were vulnerable to melting during reentry. Using every tunnel available to them, Ames aerodynamicists formalized the lifting body design, tunnel tested it, and procured a flying prototype called the M2-F2 from Northrop for flight tests at NASA's High Speed Flight Station in 1965. These tests, in conjunction with flight tests of the SV-5D and HL-10 lifting bodies, gave NASA the confidence it needed to later choose a lifting body design for the Space Shuttle. While Egger's work laid a foundation for a future spacecraft, most of NASA work in the 1960s on crewed vehicles was driven by the need to get the Apollo astronauts to the Moon.

Apollo was a technological accomplishment as well as a managerial accomplishment. The seven years between Kennedy's speech in 1962 and the first landing in 1969, was a time of sweeping cultural change for NASA and the American aerospace industry. James Webb was a masterful NASA administrator. Not only did he marshal the necessary resources for Apollo, but he assured that the Apollo program focused on what it was intended to do: land a human on the Moon and return him safely to Earth.

Harvey Allen, completely imbued with the NACA spirit of relevant but free research, served as Ames Center director in the years leading to the Apollo landing. Ames contributed much to NASA's Apollo mission—in terms of science, technology and engineering culture—though Ames people largely envisioned the economy of knowledge during Apollo as they would have during the NACA years. During the Apollo years, competition between Centers was vigorous and heartfelt. The pie of funding was growing, regardless of how it was apportioned. Every member of the new NASA felt free to contribute ideas and effort to the mission. The culture was competitive largely because the intra-agency peer review culture, which NASA inherited from the NACA, went into overdrive. NASA people also felt free to criticize—constructively, and in scientific reports or around meeting rooms—any offered idea. And there was enough money available that the thrust-and parry of new ideas encountering peer critique could end by cutting metal and strapping sensors to it in order to prove the

point. Ames representatives to NASA committees especially earned a reputation for their show-me attitude.

Research done at Ames largely determined the shape of the Apollo reentry capsule. As early as the mid-1950s, Ames used its practical expertise in wind tunnels and its theoretical expertise in hypersonics and built free-flight tunnels to determine which precise capsule shapes would work best during reentry. They discovered that the weight of a reentry body, like its expected trajectory, affected its shape. The free flight ballistic range that Ames opened in 1961 created a relative airspeed equivalent to the reentry speed expect for an Apollo capsule. Using this facility, Ames showed that the best shape for a space capsule—for both aerodynamic performance and heat flows—was a nearly flat face. They also checked these shapes for lift, drag and stability—so that a capsule pushing air in front of itself would not start to tumble as it flew through the increasing density of Earth's atmosphere.

Once Ames demonstrated which blunt-body shape worked best, work began the best materials for the heatshield to protect it. Since no known materials could insulate against that kind of heat, NASA researchers at Ames developed an ablative heatshield. Ablation meant that the heatshield material slowly pyrolyzed and burned, and as it did it transferred a thin layer of material into the atmosphere and away from the underlying metal frame of the spacecraft. (Pyrolyzation means the chemical decomposition of a material through heating in the absence of oxygen.) Aerospace firms then designed ablative heatshields for the Apollo capsules, and these were tested again at Ames. The combined radiative-convective heating simulator at NASA Ames provided the most realistic test environment of Apollo reentry speeds. Convective heating (from air friction) was important for simple satellites, though radiative heating (from the glow of superhot air) grew more serious at higher speeds. In this simulator, intense radiation was generated by an electrical arc while an air stream charged with energy from a separate electric arc was driven over the test article. They could vary each type of heating independently. The result was superb thermal performance from all Apollo spacecraft during reentry into their home atmosphere.

In its lower speed wind tunnels, starting in May 1962, Ames did many of the tests on the launch aerodynamics of the Apollo command capsule coupled with the Saturn V rocket, especially on various proposed launch escape systems. North American Aviation in Downey, which designed the Apollo capsule, came to rely upon the Ames wind tunnels. Using a 0.105 scale model of the FS-2 capsule designed by NAA, Ames ran tests in the Unitary Plan Wind Tunnel at speeds ranging from Mach 0.7 to 2.4 Mach. Additional pressure distribution tests of the launch escape system were run in the 2 by 2 foot transonic tunnel, and tumbling tests were run in the 12 foot pressurized tunnel. The escape system design was validated with further tests in April 1965, at speeds up to Mach 3.4. NASA Ames also tested the forebody of the Apollo command module in various launch configurations to assure airflows over it remained smooth during launch. And Ames people used their ballistic ranges to study what damage might be done to the capsule from meteorite impacts on its trip to the Moon.

In the very early stages of Apollo development, in 1961 to 1963, before the decision had been made between touchdown on water or land, NASA Ames studied alternative landing and recovery systems for the Apollo capsule. This included design and tunnel tests of a paraglider, an inflatable afterbody to create a lifting body configuration, and a lifting rotor. Perhaps the most photogenic study was of a steerable parachute, tested in the 40 by 80 foot wind tunnel. These tests validated the utility of a three-parachute system, though in the end Apollo sported a simpler parachute design.

NASA Ames also served as the primary internal critic and peer reviewer for the Apollo guidance computer. In 1959, when NASA first tasked its Centers to explore the problems of navigating to the Moon, Stanley Schmidt recognized the potential for extensions to the Kalman linear filter—a statistical technique for correcting trajectories. The result was a state-estimation algorithm later called the Kalman-Schmidt filter used to calculate midcourse corrections. By early 1961, Schmidt and Gerald Smith had shown that a computer built with this filter, combined with optical measurements of the stars and data about the motion of the spacecraft, could provide the

accuracy needed for a successful insertion of the capsule into orbit around the Moon. They recommended mid-course corrections as early as possible in the flight, and built a navigation simulator to demonstrate how those corrections might be done. The Kalman-Schmidt filter was embedded in the Apollo navigation computer and ultimately into all air navigation systems, and laid the foundation for Ames' future leadership in flight and air traffic management.

NASA Ames also used its expertise in aircraft piloting, human factors research and flight simulators to develop backup methods for the Apollo astronauts to fly the capsule should the automatic systems fail. In doing so, NASA Ames supplied objective advice to the Apollo engineers at MIT developing the navigation computer. Ames used its Apollo navigation simulator to demonstrate how an astronaut in a pressure suit could use a sextant to navigate by the stars if needed. Gerald Smith, of the Ames theoretical guidance and control branch, demonstrated the value of manual ground-based guidance as a backup to on-board guidance. Studies done of piloting options at launch and reentry revolved around how the astronaut could move a stick under intense G forces and vibration, and how they could discern enough data from existing spacecraft displays under those conditions. Brent Creer and Gordon Hardy simulated a method of manually inserting the Saturn rocket into orbit following first stage burnout. At the tail end of the mission, Rodney Wingrove—using a spacecraft-like cockpit in the Ames centrifuges and the five-degrees of freedom flight simulator—demonstrated how an Apollo astronaut could manually navigate a safe reentry into Earth's atmosphere.

NASA Ames also applied its expertise in human factors to improve the environment inside the space capsule, again working closely with North American Aviation. Ames built a capsule mockup, and locked test pilots in it for a week to study work-rest periods and cockpit performance. This test showed calcium loss to be a concern, but also showed that a tiny sixty cubic feet per person was ample for an extended mission. The Ames human factors group studied new ways of designing a spacesuit. Apollo astronauts would be subject to far greater G forces—at both launch and reentry—than any previous astronauts. So that the forces were evenly distributed on the body,

Hubert C. Vykukal at Ames devised a simple system, a restraint suit that enveloped the astronaut's body and attached to the seat. After thorough testing in the 20G centrifuge, his restraint suit ideas were included in the ultimate space suit design.

Recognizing that interiors of all capsules were exposed to dangerous heat during reentry, and motivated by the Apollo 1 tragedy, in 1967 NASA Ames began a research program on fire suppressive materials. It had two quick successes: a char-forming low-density polyurethane foam, and an intumescent paint which reacted to fire by forming a polymeric coating. While neither materials were used in the Apollo program, both were widely used in subsequent aerospace projects.

SPACE SHUTTLE TECHNOLOGY

In 1971, while Apollo capsules were landing on the Moon, and NASA people were thinking about what would come next, Ames established a small space shuttle development office to coordinate all the people at the Center who had begun working on technologies needed for the envisioned space transportation system. Using the NFAC, the Unitary, and 3.5 foot hypervelocity tunnels, Ames did half of all wind-tunnel tests during the crucial phase B of the Shuttle design. Ames people used the expertise earned in lifting body studies to refine the Shuttle configuration, and expertise earned in digital fly-by-wire to design controls for the Shuttle.

In 1965 Harvey Allen opened a new structural dynamics laboratory at Ames featuring a hundred-foot-tall tower with equipment to simulate all the forces a missile would encounter during lift-off. In a massive pentagonal test chamber, it offered moderate vacuum, infrared heating, vibration with variable-frequency shakers, and noise as produced by a rocket motor. Allen was especially concerned with buffeting in new ballistic missiles with a hammerhead configuration, and optimized the building for those tests.¹⁰⁵ Albert Erickson and Henry Cole, who ran the laboratory and had earlier done studies of wing flutter, also did tests there on launch vehicle instability and fuel sloshing. The new space shuttle office used it to gather data useful in narrowing the choices on the structural strength needed in the

composite shuttle vehicle. It also proved useful in designing shuttle and spacecraft landing gear to withstand landing impact. By 1972, however, as structural dynamics research increased at other NASA Centers, Hans Mark closed the vehicle environment division and the structural dynamics laboratory was put to other uses.

Ames human factors experts were actively involved in design of the shuttle cockpit. Shuttle commander trainees each spent about fifty weeks in the Ames vertical motion simulator studying handling qualities during landing. Furthermore, Ames people were responsible for preparing NASA's Dryden facility to serve as the primary test facility and landing site for all early Shuttle flights. Despite the magnitude of these efforts, Ames worked on Shuttle technologies, as it had on Apollo technologies, without having the program dominate the mission of the Center. And as with Apollo, Ames' primary contribution was solving the problems of hypersonics and materials that got the Shuttle astronauts home.

When the Space Shuttle orbiter Columbia first touched down at Ames-Dryden in April 1981, shuttle commander John Young exited the orbiter, walked underneath, looked around, gave a thumbs up, then jumped with joy. The thermal protection system was the key to making the Space Shuttle the world's first reusable reentry vehicle. Heatshields used earlier on Apollo and other single-use capsules had been rigid, with ablative materials designed to burn up while entering the atmosphere only once. The airframe of the Shuttle orbiter, however, would be flexible like an aircraft, with complex curves, and had to be built from a system of materials that rejected heat without ablating. Once NASA had decided, in the mid-1960s, on reusable insulation for the Shuttle orbiter, the airframe firms that hoped to build it started showing up at Ames for advice and tests.

Howard Larson took over Ames' thermal protection branch in 1968. Larson had spent most of the 1960s studying how ablation changed the shape of bodies that entered Earth's atmosphere—like meteors, ballistic missiles, and capsules—and thus affected their aerodynamic stability. Nonablative thermal protection, however, required an entirely new class of heatshield materials. To help evaluate

these, in 1970 Larson hired Howard Goldstein, a thermodynamicist and material scientist then running arc jet tests at Ames for a NASA contractor. As the pace of materials testing accelerated Shuttle contractors increasingly bumped up against the size and run-time limitations of Ames' 20 megawatt arc jet. But Ames still had the largest direct-current power source in NASA, as well an enormous infrastructure for compressing gasses.

In 1971 Dean Chapman, who as director of astronautics oversaw Larson's work, secured funds to build a 60 megawatt arc jet. Materials science quickly took on new prominence at Ames. Larson's group directed its efforts to help Johnson Space Center evaluate a new class of reusable surface insulation for the Shuttle. Lockheed Missiles & Space in Sunnyvale had developed tiles based on low-density rigid silica fiber—called the LI-900 tile system—that was selected in 1973 to cover two-thirds of the Shuttle's surface. Goldstein led Ames' effort to apply the database built during arc jet tests of this and other candidate materials to develop improved heatshields. An early Ames product was a black borosilicate coating, called reaction-cured glass (RCG), that provided a lightweight and easily manufactured surface for the underlying silica tiles. In 1975 RCG was adopted for use over 75 percent of the orbiter surface. Ames also developed the LI-2200 tile (at a higher density than the LI-900) that was stronger and more refractory. This new tile, adopted in 1976, replaced ten percent of the tiles on the orbiter Columbia.

When the 60 megawatt arc jet came on line, in March 1975, Ames could test full-scale tile panels in flows running thirty minutes, which was twice as long as Shuttle reentry. Ames ran most of the arc jet tests to certify the Shuttle thermal protection system, often running two shifts to fully simulate the Shuttle's hundred flight lifetime. From this, Ames scientists gained new insight into the aerodynamic heating from plasma flowing over complex heatshields. When Shuttle designers grew concerned about hot gas flows between tiles, the Ames thermal protection branch devised a gap filler—a ceramic cloth impregnated with a silicone polymer. Once adopted in 1981, few Ames gap fillers have ever had to be replaced on operating orbiters.

NASA also hoped to replace the white tiles on the top surface of the Shuttle orbiters (called LRSI for low-temperature reusable surface insulation) with a material that was cheaper, lighter, less fragile, and easier to maintain. So Ames worked with Johns Manville to devise a flexible silica blanket insulation (called AFRSI for advanced, flexible, reusable, surface insulation). Ames later devised a new family of materials, which led to an even stronger and lower-weight tile system called FRCI-12 (for fibrous refractory composite insulation) which was adopted in 1981 to replace ten percent of the tile system. Into the 1990s, guided by James Arnold, Ames continued to develop new thermal protection systems. David Stewart led Ames' basic research in catalysis—the study of how nitrogen and oxygen decomposed in a shock then reform on a heatshield with lots of energy release—and made catalytic efficiency the basic measure for evaluating new insulators. An April 1994 mission with the shuttle Endeavor allowed the Ames thermal protection materials branch to test out a new material called TUF1 (for toughened uni-piece fibrous insulation) which was more resistant to impact damage from the dirt kicked up as the shuttle landed. Another new tile, called AETB for alumina enhanced thermal barrier, was adopted to replace tiles as the Shuttle further extended its operational life into the new century. The insulation for the orbiters has turned out to be lighter and easier to refurbish than expected, and provided an excellent technical base on which to build the heatshields for all future hypersonic vehicles. The new class of hypersonic vehicles and reusable launch vehicles under development in the late 1990s—such as the X-33, the X-34, the X-38 and the Kistler K-1—all depended upon Ames' work in thermal protection to extend the life of the Shuttle.

RETURN TO FLIGHT

On the first Saturday morning in February 2003, Jim Arnold was taking a shower when Ames deputy director Bill Berry called to tell him that the space shuttle Columbia had broken up over Texas. Immediately, Arnold knew that somehow the TPS would be involved. On Monday morning, Jack Boyd called to tell Arnold that he needed to be in Houston on Tuesday. Arnold joined the Engineering Group

of the accident investigation board, whose job was to figure out physically exactly what had happened.

Scott Hubbard, likewise, got a call. The director of Ames was predetermined to be a member of any spacecraft accident investigation board, likely because of Ames' distance from any specific engineering decisions made on the spacecraft, as well as Ames' history of fundamental and collaborative research across many disciplines. The Columbia Accident Investigation Board (CAIB), to track the massive amounts of data they generated, used the investigation organizer tool developed at Ames. Tina Panontin, who had earlier worked on the Shuttle Independent Assessment team, advocated the usefulness of this tool to derive the actual cause of the accident.

Arnold assembled a team of experts on tiles and carbon-carbon technology. For tiles, Howard Goldstein, then retired chief scientist of the Ames space technology division and retired chief of the thermal protection systems branch, provided his expertise and D.J. Rigali, the retired director of the aerospace systems center for Sandia National Laboratory brought his knowledge of carbon-carbon systems to the group. They worked with Don Curry, the reinforced carbon-carbon (RCC) lead engineer at Johnson Space Center.

Once the shuttle data recorder was recovered, it confirmed that a temperature increase propagated through the left wing—consistent with exposure to a superheated airflow entering through a fissure in the thermal protection system. Arc jet testing at JSC a few years before the accident supported this conclusion. Reconstruction of the debris revealed such damage in the RCC around panel eight of the wing. Independently, a Boeing team converged on the same answer. The testing conducted at the Southwest Research Institute (led by Hubbard) demonstrated that a roughly briefcase-sized piece of insulating foam striking the wing during launch would cause a fissure able to produce the sequence deduced by Arnold's team. Once all these pieces were in place, the reconstruction of the tragedy unfolded self-evidently.¹⁰⁶

In the months after the accident, NASA Ames set up a Shuttle liaison office much as it had done in the early 1970s, this time led by

John Allmen. Allmen helped JSC or the CAIB find Ames researchers to solve the puzzles identified by the investigation, and also helped Ames see the whole picture in the technical puzzles. Indeed, this response by Ames was a cultural remnant of its NACA origins—an appreciation for critical peer review, for basic research in supporting technical decisions, for the art of problem definition, and innovation in experimental validation.

The CAIB Report made two observations that shaped how NASA Ames would participate in the return to flight efforts leading to the launch of STS-114. First, the CAIB noted that the Shuttle operation centers had lost touch with the research work done at the Centers, and specifically noted that the Shuttle team should have involved Ames experts in thermal protection systems before clearing the Columbia for reentry. Second, that while NASA knew a fair amount about the thermal properties of the shuttle tiles, other than the effect of rocks kicked up during landing, it knew little about the mechanical properties of the tiles.

Building upon Ames' capabilities in computational fluid dynamics, Ames teams developed a model of the aerodynamics around the full ascent stack. This was used to understand and then modify parts of the external tank. Using a combination of CFD and wind tunnel tests, Ames quickly generated loads data on the protuberance air loads ramp prior to its removal. Stuart Rogers lead a team that developed debris transport analysis software and models. Rogers started with an overflow code developed at Ames and applied it to the entire flow field. With this model they showed that any shed foam would trim to a high drag configuration, then ran ballistic range tests to prove the point. With Ames' supercomputers on standby following the launch of the Shuttle, this software allowed Shuttle engineers to model what sort of impact damage might have been done to the orbiter from debris shed during launch.

One contribution driven by Ames was an effort to correlate arc jet data using CFD and calorimetry. JSC operated their own arc jet, which they used to certify TPS materials for use on the Shuttle. The JSC and Ames arc jets environments differed, as did their testing methods, and both differed from the heat environment of actual

reentry. So that both arc jets could be used complementarily to improve TPS materials, or to test scenarios quickly during a Shuttle flight, an Ames team led by David Driver developed codes through which arc jet data could be correlated. Ames also developed an optical technique, called laser-induced fluorescence, to correlate enthalpies in the arc jets.

As JSC declared interest in new ideas on how to repair the shuttle thermal protection systems in-space, Ames researchers offered many ideas. James Reuther led Ames' efforts to create an in-flight repair capability. Ames helped develop an orbiter boom sensor to do a final check of the leading edge after separation from the Space Station but before orbiter reentry to Earth. Ames also developed inspection tools for Shuttle processing on the ground. In August 2007, Ames introduced a high-speed 3D scanner to detect cracks in the 24,000 tiles that covered the Space Shuttle Endeavour. Previously, workers had inspected each tile manually, measuring all cracks and dings with scales. The wireless handheld scanner checked a tile in three minutes and archived a tile image that so engineers—visually or with computer analysis—could track any expansion in the flaws.

In addition to solving the problems identified by the CAIB, Allmen's group also created the ability to solve unforeseen problems in real time. Ames' problem solving capabilities were all at work with the second Shuttle mission (STS-121) following the return to flight. The Ames damage assessment team ran and resolved their debris impact models, documented the thermal analysis code and monitored the leading-edge check before orbiter reentry. Even while solving the problems specific to keeping NASA's shuttle fleet operating, NASA Ames continued to do fundamental research in thermal protections systems. One such research effort put NASA Ames, for a time, on the leading edge of the emerging field of nanotechnology.

NANOTECHNOLOGY

For roughly a decade, from 1996 to 2006, NASA Ames was at the center of nanotechnology research. Nanotechnology at Ames focused on devising new materials, sensors, and devices from the bottom up, taking advantage of the unique properties of matter

at the molecular scale. The Ames effort started in computational nanotechnology, moved to carbon nanotube manufacture, then applications of nanotubes, and the convergence of nanotechnology and biotechnology. Like astrobiology and other discipline-building efforts at NASA Ames, nanotechnology served an integrative mission. NASA called upon Ames management primarily to coordinate efforts at defining the state-of-the-art in nanotechnology, before pushing it forward.

The rise of Ames as a powerhouse in nanotechnology began with the arrival of Meyya Meyyappan in 1996. Within two years, the NASA Ames Center for Nanotechnology—with 55 permanent research staff, not counting the many postdoctoral and graduate students clamoring to work in their facilities—had emerged as the federal facility with the largest research effort in nanoscale science and engineering. Rather than simply adding staff, which would have been difficult to fund, Meyyappan leveraged the resources extant at Ames. Earlier in the 1990s, most of those researchers had simply been working on the nanoscale—in chemistry, biology, computing, or electronics. With the Center’s help, they repackaged their work to fit the emergent understanding of nanotechnology. Ames was not unique in that regard. Such repackaging was the case with almost every research effort in nanotechnology.

Meyyappan had been a colleague of Harry McDonald’s for twelve years at Scientific Research Associates in Connecticut. While at SRA, Meyyappan focused on computational modeling of microelectronic devices and material processes, primarily on Defense Department research contracts, and held various senior management positions. McDonald foresaw the importance of nanotechnology to NASA. As McDonald considered new areas in which Ames could distinguish itself, he suggested to Jack Boyd and Jim Arnold that Ames’ computational powers be turned toward new technologies, such as electronic devices. They agreed, and in 1996 McDonald tapped Meyyappan to build the NASA Ames Center for Nanotechnology (NACNT). This was one of the first research centers focused on nanotechnology.

Meyyappan first worked on building facilities capable of research

at the nanoscale. Jim Arnold, from the start, was the facilitator and godfather to Meyyappan's group. Arnold put Meyyappan in touch with Ames computational chemists such as Deepak Srivastava, Charlie Bauschlicher, Al Globus and Richard Jaffe. They were already highly regarded among nanotechnologists, having won the 1997 Feynman Prize for Nanotechnology (Theory) from the Foresight Institute for their paper on novel traits of carbon nanotubes. Stephen Walch of the Ames thermoscience institute won the 1998 Feynman Prize for his work with Ralph Merkle of Xerox PARC on computational methods of placing atoms on diamond surfaces.¹⁰⁷ Srivastava's work initially focused on comparing mechanical properties at the nanoscale with those at the macroscale—like elasticity, stress, and conductivity. He focused his computational work on strain, developed models to simulate the chemical effects of mechanical strain, and showed that multi-walled carbon nanotubes were especially resilient to deformation. Computer models had, by 2000, done far more to validate the properties of nanotubes than actual physical work. Nanoscale simulations were becoming predictive. Using their SGI supercomputer, the Ames computational chemistry branch had generated some well-regarded models of nanoscale gears and switches.

Together, they started thinking about how to apply existing tools to future electronic devices and space exploration.¹⁰⁸ Meyyappan used his limited hiring power to fill out a computational nanotechnology group, which he considered the foundation for any meaningful experimental work. While chemists had developed software able to depict complex molecules on the atomic scale, it required supercomputing to depict the structures that nanoscientists hoped to build. Not only did computational nanotechnology allow investigations of structures on the molecular level, it also allowed scientists to envision what such structures might look like.

About a half a year later, in spring 1997, Meyyappan received a call from Mihail Roco of the National Science Foundation. Roco wanted to pitch a program to the federal government on data devices built on a nanoscale. Roco had already included a representative of the Air Force Office of Scientific Research and of the Naval Research

Laboratory. Roco wanted a fourth representative from NASA, as well as a computational perspective. Meyyappan obliged. The four called themselves the interagency working group on nanotechnology (IWGN) and shared a small planning budget. Early on, the research they discussed was abstract, so other agencies were slow to join. Still, the funds enabled researchers to travel and network across the world with nanotechnologists. As the IWGN expanded to include Nobel laureates, eminent professors and chief technology officers in industry, the NSF held workshops devoted to the use of nanotechnology in materials, electronics, and military and space needs.¹⁰⁹ Some of the most concrete work was already taking place at NASA Ames.

Meyyappan's early work at the Ames NACNT came to the attention of Dan Goldin. Meyyappan recalled sitting beside Goldin at a dinner, when Goldin told him that if his work focused on short-term applications he would cut his funding. Goldin wanted Meyyappan to look at technology decades away; technology that companies did not have the resources to develop.¹¹⁰ Meyyappan's approach had to be big, bold, and futuristic. First, though, Meyyappan knew he needed some nanotechnology in hand.

A defining moment for Meyyappan came in a 1997 Rice University workshop led by Nobel laureate Richard Smalley. There, Meyyappan began to see where the NACNT could differentiate itself from nanotechnology work at the universities. Meyyappan realized Ames was uniquely positioned to advance carbon nanotube (CNT) production. Nanotubes, related to "buckyballs," were the first structures understood on the molecular level. When carbon atoms were rolled into tubes ten atoms across, they acquired extraordinary traits. Carbon nanotubes had a hundred times the tensile strength of steel with one-sixth the weight, were forty times stronger than graphite fibers, were excellent conductors of heat and electricity, and could be either conductors or semiconductors. Theoretically carbon nanotubes could be used in space exploration as a tether for a space elevator, as wires for nanoscale electronics, and rods and gears for nanoscale machines. Making enough tubes

to use, however, proved problematic.

At that time, most nanotube production used arc synthesis, which passed a large current through a graphite block. A hydrocarbon catalyst was mixed with the graphite, which meant nanotubes were produced among many other amorphous carbon materials.¹¹¹ Smalley had recently developed laser ablation; a much cleaner mode of production in which a laser beam struck a graphite block mixed with a catalyst such as nickel or iron. The resulting plume contained the nanotubes. There was (and had been) another method.¹¹²

Chemical vapor deposition (CVD) was a cornerstone of Silicon Valley production for silicon wafer computer chips. While CVD had already been used to grow other carbon structures, like diamonds, nanotubes needed much smaller catalysts to grow thinner tubes. However, there was no known way to remove the resulting amorphous carbon byproducts, such as methane and acetane, and still produce the nanotubes. From when he first arrived at Ames Meyyappan, working with Helen Hwang, pursued a solution based on plasma enhanced CVD (PECVD).¹¹³ With PECVD electrons supplied the energy rather than heated hydrocarbon gas. Meyyappan used CFD techniques to model and refine the plasma deposition process for all materials, and with T.R. Govindan, he authored a CFD code called SAMPR, for simple analysis of materials process reactors. Only after this work in reactors did he turn his attention to carbon nanotubes in 1998, working with John Finn and K.R. Sridhar. This pioneering work turned Ames into one of the world's preeminent nanotechnology centers. From 1999 onward, most of the researchers Meyyappan hired focused on either the production of carbon nanotubes or their application.

Meyyappan also started configuring new laboratory space for this new work. He struck a partnership with Dave Blake, chief of the Ames exobiology branch, who had great laboratory space but then lacked funding to pay for maintenance. Meyyappan agreed to pay the maintenance bills in return for access to an electron microscope. A new scanning electron microscope would have cost about a million dollars. Through thoughtful networking, Meyyappan

got access to the electron microscope he needed for roughly \$25,000 a year. In addition, the Ames advanced thermal protection branch, Arnold's group, had some high temperature growth reactors used for thermal protection systems. He made these available to Meyyappan, who tailored them as growth reactors to nanotube manufacture. Meyyappan then hired Alan Cassell from the University of South Carolina whose research required such a growth reactor. Cassell spent two years testing the various catalysts used to grow both single-wall and multi-wall nanotubes.¹¹⁴ Optimizing this manufacturing process presented problems because of the complexity of the reacting particles. Sometimes those tubes grew like spaghetti and other times like a tower. Plasma-enhanced CVD produced an electric field that caused the nanotubes to grow individually and free-standing—like an array of pickets.¹¹⁵ Carbon nanotube pillars were localized, vertically aligned, and well-ordered groups of multi-walled nanotubes. They were useful. With nanotube manufacture now predictable, NACNT researchers turned their attention to how best to use them to advance space exploration.

In 2000, nanotechnology became a boom science. President Bill Clinton authorized \$500 million in 2001 for a National Nanotechnology Initiative, with funding set to grow through 2006. Most state and local governments, allied with university and corporate partners, launched a variety of similar nano-initiatives to define their capabilities, forge potential collaboration, and capture this NNI money. Venture funds focused specifically on nanotechnology—but were hard pressed to find viable business plans. Other nations launched their own nano-initiatives. Nanotechnology became a familiar way of framing research and stitching together scientific communities.

NASA Ames became a policy leader in the promotion of nanotechnology around the Bay area. Scott Hubbard made a commitment to nanotechnology and to “bio-info-nano” convergence as the centerpiece of Ames’ connection with Silicon Valley. Hubbard served as chair of a blue ribbon task force on nanotechnology, convened in December 2004 to assess the state of nanotechnology in California. NASA Ames organized general conferences

on nanotechnology, including the *Nano2005* and *Nano2006* industry conferences. Ames also hosted meetings of the Bay Area Nanotechnology Forum, and partnered with the Northern California Nanotechnology Initiative. Meyyappan started spending more of his time clicking through PowerPoint presentations, explaining what nanotechnology was and could be.

Two Ames scientists easily migrated their work from astrobiology and information technology into nanotechnology, becoming symbols of the power of this convergence. Jonathan Trent was an ocean biologist who spent his career working on extremophiles—bacteria that lived in very hot or acidic areas, analogous to those that might live under the surface of Mars. He arrived at Ames in 1998 to work in its astrobiology group. From one of those extremophiles—archaea living in a near-boiling sulphuric acid hot spring—he isolated HSP60 (heat shock protein 60). He induced HSP60 to self assemble into double ring structures called chaperonin, which then formed filaments with nanometer accuracy. Because they were stable at temperatures up to a hundred degrees Centigrade, the filaments served as a support structure for gold and for semiconductor particles, advancing the goal of molecular manufacturing.¹¹⁶

Charles Bauschlicher was a computational nanotechnologist, and the binding properties of carbon was a constant theme in his work. He began his career in computational chemistry, modeling the efficiency of thermal protection materials for spacecraft. In the 1990s he applied his computational skills to astrobiology, by computing the possibilities of life in the universe based upon the chemical composition of interstellar matter. After that, he turned his attention to the binding properties of carbon nanotubes, and specifically how carbon nanotubes might bond with other surfaces. The images generated by him and other Ames computational nanotechnologists gave the public the first glimpse of the structures at the heart of nanotechnology.

In August 2004 Meyyappan convened a workshop on nanotechnology in space exploration.¹¹⁷ The topics covered an enormous range of shorter-term possibilities, in nanomaterials, instrumentation, microrobotics, and astronaut health monitoring.

Many of these had already been developed through work done at Ames. The NACNT built a sensor platform based on carbon nanotubes, which was among the most promising early applications of nanotechnology. Nanotubes have a large area of surface to their volume, and the binding of a target molecule to a nanowire made a clear change in its electrical conductance. Being able to detect fuel leaks prior to launch would greatly improve the reliability of rockets. NASA Ames collaborated with KSC to build a nanosensor unit, a five inch square box, which was flown in 2006 aboard an Atlas V rocket launched by the U.S. Navy. The sensor looked for nitrogen dioxide, a signature of common rocket fuel, while in microgravity. KSC continued developing the sensors to detect hydrazine leaks aboard the Space Shuttle.

Chemical nanosensors also could provide a sensitive and energy efficient means to monitor air quality in the Shuttle cabin, and detect harmful chemical gas on manned spacecraft. Carbon nanotube sensors could be used in a life support system for monitoring water quality and detecting bacteria. Carbon nanotubes then could be used to remove those impurities and filter the air and water aboard a spacecraft. Four grams of carbon nanotubes have the same surface area as a football field. On rovers and probes, the sensors could detect water vapor on Mars as well as greenhouse gases in the Earth's atmosphere. This sensor platform was also being developed into a "lab-on-a-chip" to monitor the health of the astronaut crew. It required innovations in microfluidics to handle liquid samples of body fluids in the small, precise amounts required. This biosensor platform was initially developed for cancer diagnostics with funding from the National Institute of Cancer.

And the NACNT also made some headway on its initial goal of applying nanotechnology to improve electronic devices. Nanowire arrays on infrared detectors and spectrometers might allow them to operate at room temperature, significantly reducing the weight of cooled detectors.¹¹⁸ For existing infrared detectors, such as those on the Hubble space telescope, Ames developed a nanotube thermal interface to improve cooling. Though it was never used for that purpose, NACNT adapted the same vertically-aligned nanotubes to

conduct heat away from microprocessors in a computer. In 2004, NANCT licensed its patents in this cooling application to a local start-up named Nanoconduction Inc. NACNT developed a process to generate a large flux of high energy electrons. Using this process Oxford Instruments, an Ames small business collaborator, developed an X-ray tube that fit in the palm of a hand. David Blake of NASA Ames led the effort to include this instrument on the Mars Science Laboratory as *CheMin*, an X-ray diffraction and X-ray fluorescence instrument for definitive mineralogical analysis.

NASA Ames also began developing a three-in-one system for manned spacecraft for protection against heating during atmospheric reentry, radiation from solar flares, and micrometeor and debris impact. Traditionally, spacecraft have used three shielding systems for these threats. Jim Arnold worked with Mark Loomis on a material that could resist meteoroid impact, and Huy Tran began work on a self-healing ablative material that foamed on impact and thus sealed any holes prior to reentry. Arnold and Meyyappan investigated using carbon nanotubes inside a heatshield, to about one percent total weight, to improve its mechanical strength.¹¹⁹ Radiation shielding was more problematic, in that radiation can hit a spacecraft in any orientation. The current solution, in case of a solar flare, called for astronauts to pull Teflon blankets over themselves. For a true three-in-one solution, building on the PICA material invented at Ames for heatshields, Ames added hydrogen-rich polyethylene for radiation protection, and sheets of Nextel and Kevlar for impact protection.¹²⁰ Heatshield materials were becoming more precisely engineered.

In 2002, the NACNT suffered a blow to its rapid progress. Since 1996 its staffing levels were fairly constant, peaking at 65 from 2001 to 2003. However, Sean O'Keefe, interested in more immediate engineering results, shifted NACNT funding to NASA's exploration directorate. NACNT no longer had a mandate to explore technologies decades in the future, as Goldin asked. Furthermore, competition for nanotechnology funding grew intense. Funding for the National Nanotechnology Initiative went from virtually nothing to \$464 million in 2001, and had more than doubled to \$1.1 billion in 2005. Other NASA Centers wanted to expand their efforts

in nanotechnology, and now people from NASA headquarters represented the agency at policy planning meetings. The Bush administration decided to fund basic research in nanotechnology through the National Science Foundation, and NASA employees could not get NSF grants. Meyyappan began cutting computational chemistry staff, which was a natural step since the NACNT had moved into exploring production and application. Eventually, funding for that research was threatened too.

Hubbard made an effort to promote funding for nanotechnology within the Constellation program, but with few results. From 2003 to 2006, funding for NACNT dropped from \$8 million to \$1.5 million. The University of California at Santa Cruz, the principal academic partner of NASA Ames, stepped up its efforts in nanotechnology—in part to fill the void left by the decline in NASA funding, in part to take advantage of nanotechnology money flowing into academia. UCSC chancellor Denise Denton promoted a vision for a Bio-Info-Nano Research and Development Institute (abbreviated BIN-RDI and pronounced Been-Ready). Its goal was to fund research in those three fields, looking for convergences, and develop a laboratory at the NASA Research Park. The goal was to get nanotechnologies across the so-called funding valley of death, the five years between when a technology is new enough to qualify for basic research funding, and widely used enough to attract funds from venture capitalists.

But without core funding from NASA, and competition from industry, it proved difficult to retain staff. By 2005 the NACNT became a more modest operation, with about a dozen civil servants and an equal amount of students. Meyyappan spent more time writing grants, and got funding from outside sources such as DARPA, the National Institutes of Health, the National Cancer Institute and companies through Space Act agreements. Some of his staff went on to found companies. Deepak Srivastava helped Nanostellar use CFD models of deposition to coat platinum on catalytic convertors to reduce automobile emissions. Jie Han formed Integrated Nanosystems Inc. to manufacture nanosensors. Early Warning Inc. developed water quality sensors under a NASA license to commercialize a NACNT nanotechnology-based biosensor developed for space applications.

When Worden was appointed director of NASA Ames in

2006 Mike Griffin asked him why Ames should continue to fund nanotechnology research in the face of more urgent engineering needs. Meyyappan's service as director of NACNT ended in 2006, and he transitioned into a senior scientist role. Nanotechnology work at Ames moved into a new organization without nanotechnology in its title, the NASA Ames Center for Advanced Aerospace Materials & Devices, led by Harry Partridge and then Minoru Freund. Green technology initiatives offered some interesting applications for Ames' nanotechnology expertise, in building better substrates for solar cells, lightweight materials for wind turbines, and new ways to store energy. Research was still being done on materials at the nano-level. But this work had been repackaged at Ames into nanotechnology a decade before, and no longer was that packaging viable.

Just as quickly as it had emerged as a powerhouse within Ames, nanotechnology declined. Nanotechnology remained a tools-driven discipline rather than a question-driven discipline, as astrobiology had been. As such, researchers could work actively in both fields. Even from the beginning of the NACNT, NASA Ames approached nanotechnology as if its life cycle would look more like such tools-based disciplines as computational fluid dynamics or gravitational biology, where the prospects for theoretical insights will diminish as the tools mature, become more pervasive, and are commercialized.

CONSTELLATION

In the months following the announcement of the vision for space exploration in January 2004, NASA refined plans for its Constellation program—a comprehensive system of launch vehicles and spacecraft that would allow humans to return to the Moon as a stepping stone to Mars. NASA Ames supported Constellation as it had the Apollo and Shuttle programs before it. There were wind tunnel tests, CFD modelling, and structural dynamics issues to address. Ames also worked on several key safety issues. In February 2006, Ames ran tests on 0.5 percent scale models of the Orion crew exploration vehicle in the 11 foot wind tunnel. But most of Ames' work on Constellation, as with earlier vehicles, involved reentry systems, information technology, and human factors.

Pete Worden grew fond of saying: "It doesn't matter how you get

into space; if you want to come back you have to come talk to us.” Ames remained one of the few institutions able to engineer radical new reentry vehicles, which would be a big part of Constellation. There were other arc jets around the United States, but only the arc jets housed at Ames could test in the most realistic circumstances. Led by Charles Smith, in 2008 NASA Ames upgraded all of its arc jets with new electrical and cooling systems to be ready for this new work.

Relying on these arc jets was an agency-wide group of about a hundred researchers, led by James Reuther, funded with \$150 million and charged with developing the heatshield for the Orion crew exploration vehicle. In some ways, the Orion heatshield was simpler than that for the Shuttle since it would not be reusable. But because Orion would return directly from the Moon, it would experience heating five times greater than the Shuttle orbiter returning from the Space Station. Furthermore, ablative material had not been manufactured for many years.

As the primary heatshield material for Orion, the Constellation program office selected the new PICA material developed at Ames.¹²¹ PICA was used on the Stardust return capsule, which successfully entered the Earth’s atmosphere in January 2006 at the fastest reentry speed ever by a human-made object. The Stardust heatshield was only three feet in diameter, however, and made from a single block of PICA. The Orion heatshield would be more than sixteen feet in diameter, so Reuther commissioned a unit to prototype methods of manufacturing and handling it. But as the Orion design overall grew overweight, NASA challenged Reuther’s group to make the heatshield lighter. They studied eight ablative materials made by five commercial vendors, and in the end revived the Apollo-era Avcoat heatshield material. However, the research done on PICA proved immediately useful in a redesign of the heatshield for the Mars Science Laboratory, which had suffered a catastrophic failure during arc jet tests. PICA was later adopted as the ablative material for the Dragon capsule built by commercial rocket firm SpaceX.

A key factor in a human-rating a rocket is that failures can be anticipated with enough time to resolve them or escape. The Ames intelligent systems division, led by Robert Mah, was tasked by the

Constellation program office to work on integrated vehicle health monitoring systems (IVHMS)—algorithms that diagnosed glitches in the electro-mechanical subsystems of aircraft and spacecraft. The IVHMS group at Ames developed vehicle monitoring software named Livingstone, which was successfully tested on the Deep Space 2 spacecraft in May 1999.¹²² Ames project manager Sandra Hayden successfully uploaded the next iteration, Livingstone2, to the spacecraft Earth Observation-1. After EO-1 ended its mission in 2002, it was recast as a testbed for evaluating autonomous procedures. A reasoner function drove Livingstone. Contradictions between predicted and actual performance, based on readings from sensors throughout the spacecraft, identified root causes of the problems. Ames expected Livingstone to be most useful in rendering distant spacecraft autonomous, though they also discovered uses in most complex systems. Ames released Livingstone as open source software and launched DASHLink, among the first social networking sites in the federal government, to build a community of researchers applying IVHMS to a variety of industries.

Specifically for Constellation, Mark Schwabacher developed a ground diagnostic system to monitor the thrust vector controls of the Ares 1-X flight test.¹²³ The Ares 1-X system incorporated three software tools, one developed at Ames by David Iverson, one developed using Ames SBIR funding, and one developed at JPL. The Ames human computer interaction group, led by Alonso Vera, developed a suite of four quality assurance programs used for Constellation. The Ames team leveraged the open-source community, partnerships with Silicon Valley companies, and in-house expertise to develop a single code base to support a suite of system analysis and quality assurance software. Regardless of the future of Constellation, like CFD, the IVHMS movement looks to become a major feature of all aerospace engineering.

Of course, there was more to Constellation than the launch vehicle, like an ultimate goal of a human presence on the Moon and Mars. In June 2009 Michael Wright was named principal investigator of entry, descent and landing technology development to support human exploration of Mars. Wright had been at Ames since 1998, working on computational aerothermodynamics and

margin definition for thermal protection systems. He was a primary developer of DPLR, an aerothermodynamics code named the 2007 NASA Software of the Year. He marshalled Ames expertise to the problem of landing humans on the surface of Mars.

The Ames “green” building—officially known as N238 and unofficially called Sustainability Base—reflects a return to the ways NASA Ames traditionally supported human spaceflight. The building models a lunar outpost on Earth and will be the most environmentally efficient building in the federal government. It started out though, as a rather usual building. The Ames facilities group had won a competition for NASA funds intended for replacing old buildings. While the 14 foot transonic wind tunnel was being torn down, Ames prepared plans for a new office building on the site. Steve Zornetzer, Ames associate director, attended an early design review, after six months of time and money had been spent on it. “I was underwhelmed,” he reflected. “It was a very conventional building; not what you should expect of NASA Ames.”¹²⁴ Soon after, he happened to attend a talk by renowned green architect William McDonough, and his ideas crystallized. Zornetzer started with a blank sheet of paper, and took ownership of the project. Headquarters had given Ames a strict budget and schedule, and the green building design team came in under budget and ahead of schedule when ground was broken in July 2009.

The building will be a platform for testing new life support technologies. One key technology is an intelligent control built by Ames computer scientists atop a commercial environmental control system. Sensors are distributed throughout the building, will measure load factors in every room, and conditions outside the building. Every occupant will know how his or her behavior affects resource use in the building, be it energy or water. The building’s environmental controls will learn how to operate with utmost efficiency, a tool that will prove useful in any habitat whether on Earth, on another planet or on a spaceship heading that way.

Planetary Sciences and Astrobiology

Planetary sciences underwent a major shift in the mid-1960s as robotic spacecraft began to return new types of data from our solar system. Because of their relationship with the instruments and spacecraft that returned this data, NASA Ames quickly emerged as a leading research center in the planetary sciences, and has remained so. The planetary sciences at Ames has also remained small, but with great impact on the discipline. Three Ames scientists have been awarded the Gerald P. Kuiper Prize of the American Astronomical Society, for career achievements that most advanced our understanding of the planetary system—James Pollack (1989), Dale Cruikshank (2006) and Jeff Cuzzi (2010). The work of these planetary scientists, like that of the many other scientists at Ames who have won awards from their professional societies, reflects an enormous range of personal ability: an overlapping combination of theory, laboratory experimentation, spaceborne instrumentation, as well as a record of publication and a dedication to training future generations of planetary scientists.

There are many useful approaches to the history of the planetary sciences at Ames. Biography, even of select individuals, shows how theory, experiment and publication overlapped. The development of new tools, like airborne science platforms, showed how Ames scientists established their place in the ecology of scientific knowledge. But perhaps the most fruitful approach is in looking at topics of interdisciplinary inquiry, most importantly exobiology and astrobiology—the study of life beyond Earth and in the universe.

IMPACT PHYSICS AND TEKTITES

Among the earliest topics in planetary science studied at Ames were those related to aerodynamics. For example, for clues on reentry aerodynamics, Harvey Allen suggested that his colleagues at Ames study meteorites, nature's reentry bodies. Using their high-speed guns and ballistic ranges, Ames engineers explored the theory

of meteor impacts by hurling spheres of various densities at flat targets. Ames built a vertical gun range optimized for impact studies with a test section on the horizontal plane. At the highest impact speeds, both the sphere and target would melt and splash, forming a crater coated with the sphere material—much like lunar craters. Ames then turned its attention to lunar craters with radial rays of ejected materials by shooting meteor-like stones at sand targets like those on the Moon. This was all useful to lunar scientists debating whether lunar craters were caused by meteors or volcanoes. Also, by showing how much material was ejected from the Moon with every meteor impact, they paved the way for lunar landings by suggesting the surface of the Moon was mostly settled dust.

One stunning example of what results when Ames' raw scientific genius is unleashed was the work of Dean Chapman on tektites—naturally occurring glass that had entered Earth's atmosphere. In early 1959, Chapman used the 1 by 3 foot blowdown tunnel (as it was about to be dismantled) to melt frozen glycerin in a Mach 3 airstream. In the frozen glycerin he first photographed the flattening of a sphere into a shape similar to Allen's blunt body. The ball quickly softened, its surface melted into a viscous fluid, and a system of surface waves appeared that were concentric around the aerodynamic stagnation point. On his way to England for a year of research, Chapman visited a geologist at the American Museum of Natural History, who saw some similarity in the wave patterns on the glycerin balls and the wave patterns on glassy pellets of black glass called tektites. Tektites had been uncovered for centuries, mostly around Australia, though geologists still vigorously debated their origin. When geologists asked the Australian aborigines where the tektites came from, they pointed vaguely up to the sky.

Chapman applied the skills he had—in aerodynamics and ablation—and learned what chemistry he needed to. He cut open some tektites and found flow lines that suggested they had been melted into button shapes, after having been previously melted into spheres. From the flow lines he also calculated the speed and angle at which they entered Earth's atmosphere. He then melted tektite-type

material under those reentry conditions, in Ames' arc jet tunnels. By making artificial tektites, he established that they got their shape from entering Earth's atmosphere just as a space capsule would.

Chapman next offered a theory of where the tektites came from. By eliminating every other possibility, he suggested that they came from the Moon. Ejected fast enough following a meteor impact, he suggested these molten spheres escaped the Moon's gravitation field, hardened in space, then were sucked in by Earth's gravitation. Harvey Allen walked into Chapman's office one day and egged him on: "If you're any good as a scientist you could tell me exactly which crater they came from." So Chapman accepted the challenge, calculated the relative positions of Earth and Moon, and postulated that they most likely came from the Rosse Ray of the crater Tycho. In October 1963, Chapman won NASA's medal for exceptional scientific achievement.

But only a single sample returned from the Moon, during Apollo 12, bore any chemical resemblance to the tektites. The community of terrestrial geologists turned against Chapman's theory of lunar origin. While geologists accepted that tektites had entered Earth's atmosphere at melting speeds, most think they are terrestrial in origin—ejected by volcanoes or by a meteor crash near Antarctica. But before Apollo astronauts returned samples from the Moon, Chapman's scientific sleuthing had accelerated curiosity about the composition of the Moon and the forces that shaped it, and in the process validated some theories about ablation and aerodynamic stability in entry shapes.

PLANETARY ATMOSPHERES AND AIRBORNE SCIENCE

The study of planetary atmospheres fit the skill set of Ames since it merged work in the life sciences, atmospheric entry, aerodynamics and instrumentation. By the mid-1970s, a space science renaissance was born of the incredible diversity of data being returned from the planets of our solar system—from the Pioneers to Jupiter and Saturn, the Pioneer Venus atmospheric probes, and the Viking lander. Meanwhile, Ames scientists turned their gaze to Earth with a fresh set of questions and instruments.

Ames rebuilt its on-Center fleet of aircraft, and outfitted them as flying laboratories used to conduct research in airborne science and Earth observation. Ames' medium-altitude aircraft included a Learjet, a Convair 990 named Galileo II, and a Lockheed C-130. The Learjet, though most often used for infrared astronomy, proved useful in atmospheric studies of low-altitude wind shear in the 1970s. The Lockheed C-130 most often looked downward on Earth resources—in support of agriculture, meteorology, and geology—and carried sophisticated equipment for mapping cropland, soils, and nonrenewable resources. The C-130, equipped with a thermal infrared mapping sensor, was often called into service throughout the western United States to locate hot spots obscured by the dense smoke over forest fires. George Alger of Ames' medium altitude missions branch led the C-130 crew through a variety of meteorology missions looking, for example, at biogeochemical cycling—how land interacted with the atmosphere.

Galileo II was the fastest aircraft in the fleet, and accommodated teams of up to 35 researchers from around the world. This made it especially valuable for atmospheric research. Observers aboard Galileo II explored the origins of monsoons in India, interactions between ice, ocean and atmosphere off the northern coast of Greenland, and global atmospheric effects from the eruption of the Mexican volcano *el Chicon*. In 1990, Galileo II flew a research team led by Charles Duller that verified the discovery of a crater rim along the Yucatan peninsula. This provided evidence for a cometary or asteroid impact on Earth that might have led to the extinction of the dinosaurs.

Ames' first high-altitude aircraft, capable of flying to 70,000 feet, were two Lockheed U-2Cs that arrived in June 1971. As with many research tools acquired during Hans Mark's tenure as director, the U-2s were grabbed as surplus from another agency. The U.S. Air Force had announced that it would make the U-2s available for basic research. NASA was then in final preparations for the Earth resources technology satellite (ERTS), managed by Goddard, and scientists were concerned that infrared and spectral-band photographs obtained on ERTS might be distorted because they would be taken through the entirety of Earth's atmosphere. The Air Force tasked

Martin Knutson, one of the first U-2 pilots, to evaluate Ames' ability to fly and maintain the U-2s, which were notoriously slender and sensitive aircraft. Knutson then retired from the Air Force to lead Ames' airborne sciences office in simulating the data collection process from the ERTS satellite. When delays meant the ERTS would miss its opportunity to survey chlorophyll levels in American crops during the summer 1972 growing season, Ames leapt to a plan and with three months of flights completed the entire benchmark survey with the U-2s. From there, research uses for the U-2s branched in many directions. In 1972, NASA headquarters designated Ames its lead center in Earth-observation aircraft and as a liaison to the scientific community. In response, Ames established an atmospheric experiments branch.

In June 1981, the U-2s were joined by a Lockheed ER-2 (for Earth resources), a civilian version of the U-2. In May 1988 Ames acquired a second ER-2, and retired its thirty year old U-2C. (Before being retired to static display at an Air Force base, this U-2C shattered sixteen world aviation records at Dryden for time-to-climb and altitude in horizontal flight, to 73,700 feet. These records were the first official acknowledgment of the U-2's previously classified altitude capability.) NASA and Lockheed Martin would later share a Collier trophy for development of the ER-2. Compared with the U-2, the ER-2 was thirty percent larger, carried twice the payload, had a range of 3,000 miles, had a flight duration of eight hours, and had four pressurized modular experiment compartments. In addition, Ames modified a DC-8 airliner into a flying laboratory for Earth and atmospheric sensing and for other key roles in NASA's mission to planet Earth. Ames often teamed the DC-8 and ER-2s on specific missions to study the planetary atmosphere of Earth.

Ames scheduled the ER-2s flexibly enough, and built basing alliances with 42 airports around the world, so that Ames pilots could use them for quick-response storm observation, atmospheric sampling, and disaster assessment. Instruments aboard the Ames U-2 measured how the ash cloud dispersed following the May 1980 eruption of Mount Saint Helens in Washington state. Life scientists at Ames and the University of California at Davis used

remote-sensing data on vegetation growth, collected between 1984 and 1988, to devise a model that actually predicted the spread of mosquitoes that carried malaria. Similar remote spectral scanners were used in April 1993 for Project GRAPES, an effort to plot the spread of phylloxera infestation through California vineyards. The ER-2s proved especially useful in calibrating new remote-sensing equipment flown aboard LANDSAT Earth-observation satellites and the Space Shuttle. In 1989 and 1990, the DC-8 flew the global backscatter experiment (GLOBE) to survey airborne aerosols in the Pacific basin and test out new experiment packages designed for the Earth Observing System satellite. In February 1993, Rudolf Pueschel and Francisco Valero of the Ames atmospheric physics branch led the DC-8 and an ER-2 to Australia to map the interior of a tropical cyclone and explore the coupling of the atmosphere and a warm ocean.

Perhaps the most significant research done by Ames' airborne scientists was the many-year exploration of Earth's ozone layer. In August and September 1987, operating from Punta Arenas at the southern tip of Chile, Ames scientists used the ER-2 and the DC-8 to make the first measurements that implicated human-made aerosols in the destruction of stratospheric ozone over Antarctica. During the winter of 1989, the ER-2 and DC-8 team, led by Estelle Condon and Brian Toon and based in Norway, completed an airborne campaign to study ozone chemistry and distribution over the Arctic. The ER-2 and DC-8 returned to the Arctic in 1992 to map changes in stratospheric ozone, and their work laid the foundation for the Montreal Accord on limiting chemicals that deplete the ozone.

NASA's most recent airborne science platforms were a series of UAVs—uncrewed aerial vehicles—built by General Atomics near San Diego, and developed for NASA's ERAST program (for environmental research aircraft and sensor technology). The UAVs envisioned for the ERAST program, started in 1994, would fly at high altitudes carrying instruments to measure aerosols and trace gases in the stratosphere. As UAV design progressed, the Earth sciences branch at Ames used a Piper Navajo aircraft as a platform to validate the technologies of the sensors and of an over-the-horizon

telemetering system that would enable extended voyages. The first operational UAV, acquired in 1996, was an Altus UAV notably used in a study of the interactions between clouds and radiation. A unique solar-powered UAV, the AeroVironment Pathfinder, was used in a high-resolution imaging mission over coffee fields in Kauai to help guide the harvest.¹²⁵

In September 2001, an Altus II UAV carried sensors designed by Vincent Ambrosia, Steve Wegener, and James Brass in the FiRE experiment (for first response) to support wildfire fighting. FiRE first demonstrated the calibrated use of multi-spectral thermal imaging, a high-speed satellite data link, image processing computers, mapping software, and distribution of data over the internet to involved disaster response agencies.¹²⁶ They also integrated video cameras into the UAV so it would be more useful in responding to disasters like floods and earthquakes, and used global positioning system data to track firefighting units as they moved around the fire field.

The Ikhana, acquired in November 2006, was a civilian version of a military MQ-9 Reaper UAV with advanced avionics so it could fly in domestic airspace. Ikhana is the Choctaw word for intelligence or aware. It flew at high altitude, above 40,000 feet, carried 400 pounds of instrumentation in internal bays, and 2,000 pounds in external pods. Its control station fit in a trailer, so it could be deployed around the globe. Most important, it flew missions that could not easily be flown by pilots, more than thirty hours long, over complete day-night cycles, and over remote areas like oceans and ice caps.

The Ikhana quickly proved its worth when NASA helped firefighters battle some of the worst wildfires in California's history.¹²⁷ In September 2007 NASA pilots flew Ikhana over the Lick wildfire near Gilroy. NASA Ames, through its partnership with UC Santa Cruz, developed the autonomous modular sensor-wildfire instrument, a thermal infrared camera that could see through thick smoke to locate hot spots. In less than five minutes, that data was relayed to NASA Dryden by satellite data link then sent to NASA Ames and overlaid on Google Earth maps made available via internet to fire commanders to assist them in allocating firefighters and equipment. Several times, this data allowed firefighters on the

ground to be warned before their positions were engulfed in flames. In October 2007, NASA pilots again flew Ikhana over wildfires raging in southern California. California Governor Arnold Schwarzenegger visited to thank Ames for their work in stemming the blaze. Ames scientists, meanwhile, used this experience to improve their methods of tracking changes to the Earth as a planet.

INFRARED ASTRONOMY

The other airborne platforms in Ames' fleet looked skywards, mostly to support the discipline of infrared astronomy. The SOFIA was the latest in a line of airborne observatories built and managed by Ames. Until the 1960s, the main reason telescopes were mounted on airplanes was to follow solar eclipses. The invention, in 1961, of a germanium bolometer able to detect infrared radiation up to 1,000 microns in wavelength opened a new age of infrared astronomy.

The ancients gazed into the night sky and saw a majestic canopy of points of light. Optical telescopes and spectrographs of great power further unveiled the immensity and complexity of the universe but within a small window—wavelengths that were both visible and made their way through Earth's atmosphere. Balloons, then aircraft and spacecraft, let astronomers place instruments far above the obscuring water vapor of the atmosphere where they could see all the messages that the universe was sending us—all the radiation, from all the sources, at all the wavelengths. Infrared (or heat) radiation conveys information about the composition and structure of Earth-bound solids and gases. It also penetrates the dense clouds of dust that obscure regions where stars and planets are forming. Infrared observation became our best source of information about the chemical composition of remote planets, stars, and nebulae.

Ames started its work in infrared astronomy in 1964, soon after Michel Bader, chief of the Ames physics branch, returned from a successful airborne expedition to observe a solar eclipse. Ames purchased an old Convair 990 aircraft, named it Galileo and began converting it into an airborne science platform. Along the upper left side of the fuselage, Ames mechanics installed thirteen 12 inch

apertures for optical-quality glass in time for the solar eclipse of May 1965. From the beginning, Ames made its airborne science expeditions open to scientists from around the world. The Soviet Union participated in observations over the Bering Strait. Aboard Galileo astronomers observed three solar eclipses, the comet Ikeya-Seki, Mars during opposition, and the Giacobinidi meteor shower. Using a telescope with a gyrostabilized heliostat for precise pointing, one team of scientists obtained a remarkable set of near-infrared spectra for Venus, showing that the Venusian clouds were not made of water as suspected. Later flights showed that they were made of sulphuric acid droplets. In April 1973, the Galileo, returning from a short flight to test instruments for an oceanography observation, due to a fault of the air traffic controller, collided in mid-air with a Navy P-3 on approach to Moffett Field. All eleven passengers on board died. It was replaced by another Convair, named Galileo II, though it was used primarily for Earth science.

In October 1968 Ames' Learjet observatory made its first flights. Its apertures were larger than those on the Galileo and opened to the sky without an infrared-blocking quartz cover. Flying above 50,000 feet, teams of two observers aboard the Learjet discovered a host of bright infrared sources. They measured the internal energies of Jupiter and Saturn, made far-infrared observations of the Orion nebula, studied star formation regions, measured water in the Martian atmosphere, and generally pioneered astronomy in the wavelength range of 30 to 300 microns. Ames also used the Learjet to observe events around Earth, like eclipses and occultations.

Encouraged by the success of the Learjet, Ames built the much larger Kuiper airborne observatory (KAO). The KAO platform was a military jet transport (a Lockheed C-141A Starlifter) housing a 36-inch reflecting telescope in an open port. Soon after its first observations in January 1974, it was renamed in honor of Gerald P. Kuiper, director of the Lunar and Planetary Laboratory at the University of Arizona and a leading light in infrared astronomy. The KAO flew only as high as 45,000 feet, yet was a big advance over the Learjet. It accommodated up to twenty scientists, flew missions

more than seven hours long, and averaged seventy missions per year. Carlton Gillespie, mission director for the KAO, always put the interests of the science team foremost and young astronomers around the world finished their dissertations through his encouragement. The KAO telescope balanced on a 16-inch diameter spherical air bearing (the largest ever constructed) and was completely gyrostabilized so it would not bounce around from air turbulence. Light from the telescope passed through the air bearing and into the many instruments attended by scientists in the pressurized cabin.

Observers on the KAO made many significant discoveries: they found the rings around Uranus; mapped a heat source within Neptune; discovered Pluto's atmosphere; detected water vapor in comets; explored the structure and chemical composition of Supernova 1987a; mapped the luminosity, dust, and gas distributions at the Milky Way's galactic center; and described the structure of star-forming clouds. Jesse Bregman developed a spectrograph used with the KAO telescope that in June 1993 detected water molecules on the surface of Jupiter's moon Io. (Laboratory work in 1988 on planetary ices by Farid Salama first suggested the presence of water on Io.) They also discovered 63 spectral features—atomic, molecular, solid-state—of interstellar materials. Before the KAO, astronomers had identified only five molecular species; KAO observers identified 35 others in the galaxy. As important as all these scientific breakthroughs, a generation of infrared astronomers trained on the KAO and expected to improve upon it.

Ames researchers applied their expertise in airborne observatories to the design of spaceborne observatories, including the IRAS and the Spitzer space telescopes. With its infrared astronomy and planetary probes, Ames scientists had gathered huge data sets on the molecular dynamics and chemical composition of the universe. With the airborne science experiments, Ames calibrated that universal data with all we knew about Earth. Ames people wanted to make sure that those hard-won data were well used and, in sorting through every nuance, they advanced both planetary science and our understanding of life in the universe.

EXO BIOLOGY AND ASTROCHEMISTRY

In the mid-1960s exobiology emerged as the most visible planetary science program at Ames. Exobiology then pondered what life might look like if it appeared beyond Earth. Exobiology research focused on the chemical origins of life, based on what was known about the composition of the universe and the formation of our early solar system. Ames biologists, led by Chuck Klein, did important laboratory work on primordial life on Earth, planning for eventual robotic experiments on other planets. An important engineering adjunct to exobiology was planetary protection, or sterilizing spacecraft so that microbes from Earth would not harm other planets before we knew if they harbored life.

Cyril Ponnampерuma arrived at Ames in the summer of 1961 in the first class of postdoctoral fellows under a joint program between NASA and the National Research Council. The excitement over planetary science he saw at Ames led him to join the permanent staff, and for the next decade he infused Ames' exobiology efforts with a fresh outlook to the question of how life began at all. Geologists had learned much about primordial Earth, and planetary scientists had used chromatographs and spectroscopes to detect minute amounts of organic compounds in extraterrestrial bodies, like meteorites. From this, Ponnampерuma's colleagues in Ames' chemical evolution branch elucidated a theory about the inanimate building blocks and natural origins of life. Like many biochemists, they suspected that life was a property of matter in a certain state of organization, and that if they could duplicate that organization in a test tube then they could make life appear. If they did, they would learn more about how to look for life elsewhere in the universe. By the end of 1965, in apparatus to simulate primitive Earth, Ponnampерuma and his group succeeded in synthesizing some of the components of the genetic chain—bases (adenine and guanine), sugars (ribose and deoxyribose), sugar-based combinations (adenosine and deoxyadenosine), nucleotides (like adenosine triphosphate), and some of the amino acids.

A breakthrough in exobiology came when the Murchison carbonaceous meteorite fell on Australia in September 1969. In the Murchison meteorite, Ames exobiologists unambiguously detected

complex organic molecules—amino acids—which suggested prebiotic chemical evolution. These amino acids were achiral (lacking handedness) thus unlike the chiral amino acids (with left handedness) produced by any living system. The carbon in these organic compounds had an isotope ratio that fell far outside the range of organic matter on Earth. The organic compounds in the Murchison meteorite arose in the parent body of the meteorite, which was subject to volcanic outgassing, weathering, and clay production as occurred prebiotic Earth.

Because of the expertise Ames people had developed in the chemical composition of nonterrestrial environments and in the life sciences, NASA headquarters asked Ames to build one of two lunar sample receiving facilities. Apollo astronauts spent a total of 340 hours on the lunar surface and carried back to Earth more than 840 pounds of lunar rock. To prevent any contamination of the samples, this facility had to be very clean, even beyond the best of the Silicon Valley clean rooms. The lunar receiving facility at NASA's Manned Spacecraft Center looked the lunar samples to characterize its geology and to identify any potential hazards to the Apollo astronauts. Ames scientists—led by Ponnampersuma, Vance Oyama and William Quaide—studied the overall composition of the lunar regolith (the term for its rocky soil). They closely examined the carbon chemistry of the regolith and concluded that it contained no signs of life. But this conclusion opened new questions. Why was there no life? What kind of carbon chemistry occurred in the absence of life? Continuing their efforts, Ames researchers discovered that the lunar regolith was constantly bombarded by micrometeorites and the solar wind, and that interaction with the cosmic debris and solar atomic particles defined the chemical evolution of the surface of the Moon.

The Viking landers, which alighted on Mars in July 1976, carried Ames' first exobiology experiment to another planet. After Earth, Mars was thought to be the most likely planet in our solar system to support life. The Viking mission, like JPL's Voyager mission to the outer planets, was complex. NASA's strategy in the 1960s of launching many smaller spacecraft expecting failure let them refine their

engineering practice so that by the early 1970s they felt confident in building single spacecraft with many components. Viking cost more than \$3.2 billion and included twin spacecraft, each with an orbiter holding four instruments and a lander with thirteen. Most of the instruments on the lander dealt with geological, meteorological and imaging data, but four comprised a biological experiment. Chuck Klein, head of the Ames life sciences division, led that team. That too, in retrospect, was complex in that rather than searching for water or carbon they searched for the metabolic activity then so central to exobiologists.

To search for the biosignatures of life, Vance Oyama built a gas-exchange laboratory. An arm extended to collect soil, dropped it in a sealed metal receptacle, the Martian atmosphere was replaced with inert helium, the soil mixed with nutrients, then with water, a gas chromatograph measured concentration of emitted gases, and the data was relayed back to Earth. Oyama thought any metabolizing organisms would consume or release one of six gases measured. The gas-exchange experiment worked flawlessly, but measured no metabolic gases. The other three experiments also worked, but all together returned inconclusive results. In a labeled release experiment, seven nutrients tagged with radioactive elements were dropped into Martian soil. The first nutrient elicited a steady stream of radioactive gas, but other nutrients did not. A similar pyrolytic release experiment looked for evidence of photosynthesis and biomass. A very sensitive gas chromatograph and mass spectrometer measured no organic molecules in the Martian soil, which contained even less carbon than the lifeless regolith returned from the Moon. That came as the biggest surprise, given the presence of carbon throughout the solar system. Plus, the null result from the gas chromatograph voided any prospects for life indicated by the other experiments. In the decades that followed, most scientists interpreted the data as evidence of the highly reactive chemical structure of the Martian soil. A few interpreted it as the presence of life. Questions about what the lander found motivated planetary scientists for years.

Exobiology continued as a major focus at Ames, tied more closely to planetary science and developing into what became known as

astrobiology. Donald DeVincenzi, the exobiology program manager at NASA headquarters, asked Ames to host workshops and write papers that redefined the scientific core of the discipline. Sherwood Chang led the planetary biology branch and, along with Ted Bunch, did pathbreaking work on organic material and water in meteorites. Christopher McKay studied the intricate lives of some of Earth's most primitive microorganisms, while Jack Farmer, David Blake, and Linda Jahnke studied fossil markers for extinct microbial life. This led to bold explorations to find organisms in extreme environments—hot springs, Antarctic deserts, and frozen lakes. Finding organisms in those places was good practice, they thought, for finding life on Mars. Exobiology started as the science without a subject matter, though Ames exobiologists found good proxies. Extremophiles on Earth showed the chemical and physical limits of life, and that life is less limited than once thought.

THEORETICAL SPACE SCIENCE

James B. Pollack, a radiative transfer theorist in the planetary systems branch of the Ames' space sciences division, arrived at Ames in 1970. He was hired by Ray Reynolds who, as early as 1964, had done theoretical work at Ames on the formation of planets and built a world-class theoretical studies branch to complement Ames' work in spaceborne instrumentation. In the 24 years Pollack worked at Ames before his death, he earned a solid reputation as a theoretician and wrote nearly 300 articles on all facets of planetary science. Postdoctoral fellowships offered by the National Research Council fed much of the scientific vigor at Ames, especially in the planetary sciences. The best young scientists came to Ames for two-year projects, often to work with Pollack, and the best of those hired on. A great many others came to hang experiments on NASA spacecraft or to mine NASA data.

Pollack's drive to understand the origins of planets and the evolution of their atmospheres—especially for the habitable planets like Earth, Mars and early Venus—led him to use any variety of numerical, observational, or experimental tool. Pollack worked with Richard Young and Robert Haberle to develop an entire suite of

numerical models of the climate and meteorology of Mars. These models comprised a unique resource—used to plan Mars missions, analyze the data they returned, and advance theories on how the climate of Mars changed over eons as the sun warmed up and Mars' atmosphere escaped. The Ames team devised similar numerical models to explain the greenhouse-gas climate of Venus, its high surface heat, its current lack of water, and its acidic atmosphere.

Pollack inevitably teamed with other environmentally concerned researchers exploring the atmosphere of Earth. With James Kasting and Thomas Ackerman he initiated some of the first studies of atmospheric aerosols in the evolution of Earth's climate. Brian Toon contributed his expertise on the microphysics of clouds on Earth, thus bridging efforts in the planetary sciences and Ames' Earth-observation aircraft. Pollack and these colleagues led the team that later wrote the famous paper on "nuclear winter," suggesting that dust and soot kicked into the atmosphere by a nuclear war would degrade the habitability of Earth as much as the comet impacts that reshaped the climates of other planets and that might have led to the demise of the dinosaurs.¹²⁸

Voyager's grand tour of the outer solar system, coupled with data returned from the Pioneers and observatories, drove a revolution in planetary science focused on the evolution of Jupiter, Saturn, and their moons. Pollack, Reynolds and their collaborators wrote stellar evolution codes to explain the residual internal heat of these gas giants, their growth by accumulation of planetesimals, and the subsequent capture of hydrogen envelopes. Jeff Cuzzi and Jack Lissauer unraveled puzzles in the rings of Saturn and the other gas giants, including spiral waves, and their rapid evolution under meteoroid bombardment. Dale Cruikshank was among the first to identify frozen sulfur dioxide on the surface of Io, the only body in the solar system other than Earth to have intense volcanic activity. Saturn's large moon, Titan, with its smoggy haze and possible ethane oceans, was studied in detail as a fossil of the primordial soup which led the Ames group to suggest the Titan probe that later flew as the Cassini mission.

Pollack also fueled interest in the origin of other planetary systems. David Black, who first discovered signs of interstellar

material in a meteorite, came to Ames and, along with Patrick Cassen, built a Center for Star Formation Studies. The center was a consortium of Ames and two University of California astronomy departments (at Berkeley and Santa Cruz) and greatly advanced the astrophysical theory of protostellar collapse. The center used supercomputers well: they modeled systems ruled by self-gravitation, like galaxies, protostellar clouds, and solar nebula; ran three-dimensional, n -body calculations that followed the motions of billions of stars in their own gravitational fields; calculated the collapse of rotating interstellar clouds to ten orders of magnitude in density; demonstrated that the true shape of elliptical galaxies was prolate rather than oblate; and showed how galaxies collided. Black led the early studies of how to find planets around other stars, which presaged NASA planetary detection efforts like Kepler. In addition, Ames planetary scientists did early studies of the gravitational and fluid dynamics of protoplanetary disks.

Life is made from organic material. Into the early 1990s a unifying theme in Ames planetary science was to chart the path of organic material from its origin in the interstellar medium (where infrared astronomy revealed it was formed), through primitive meteorites (available for chemical analysis), and into Earth's biosphere. David Hollenbach and Xander Tielens studied the physical evolution of grains in space. Lou Allamandola picked up the critical question of the chemical evolution of organic materials. It took him many years to piece together laboratory equipment to mimic the space environment and show how organic material could be produced from hydrogen, oxygen, carbon, and nitrogen formed first in the big bang and then subsequently in stars. Allamandola's group showed how polycyclic aromatic hydrocarbons evolved from elementary carbon, and dominated infrared emissions from the Milky Way.

The unique atmosphere at Ames allowed all this work to cross-pollinate—in planetary formation, the evolution of planetary atmospheres, and the chemical, thermal, and gravitational evolution of the solar system. It also coupled Ames' early pioneering work in exobiology and the chemical origins of life with the broader discipline later called astrobiology.

SEARCH FOR EXTRATERRESTRIAL INTELLIGENCE

In the late 1960s, John Billingham of Ames' biotechnology branch began to move Ames into SETI, or the search for extraterrestrial intelligence. SETI was a natural area of interest for Ames. It combined the exobiology quest for life beyond Earth, with the insights of planetary theory on where to look for it, and radio astronomy and computation as the means to search for it. In 1971 Billingham teamed with Bernard Oliver, a former vice president for research at the Hewlett Packard Company and a technical expert in microwave signal processing. They proposed Project Cyclops—\$10 billion for a circular array of a thousand telescope dishes, 100 meters in diameter, to do a full-sky survey of coherent microwave signals. NASA headquarters would not endorse so expensive an effort in such uncertain science.

Billingham then sketched more modest steps that NASA could take to help the many university astronomers engaged in SETI. Collectively, they decided to start searching for nonrandom radio waves in the microwave portion of the spectrum (microwaves travelled well in space and earthlings were already propagating them around the universe). They also decided to search between the natural spectral emission of hydrogen and the hydroxyl radical (OH)—dubbed the water hole—since water is essential for life.

Hans Mark appreciated the value of a comprehensive SETI program, not only for what it might discover, but also for what it could teach us about pulses in the universe and as a way to excite children about science. In July 1975, Mark asked NASA headquarters to fund a second international SETI meeting. Fletcher instead obliged Mark to find money from the National Academy of Sciences, but to hold the meeting at Ames. Fletcher did not want NASA to fund SETI prior to a formal commitment authorized by Congress. Over the next five years, and with Sy Syvertson's encouragement, Ames and JPL (which ran NASA's Deep Space Network) contributed a total of \$1.5 million to design signal processing hardware and algorithms and to hold a series of workshops to map out the best scientific strategy for SETI. Billingham organized the series of multidisciplinary workshops

that brought together a range of scholars—from astronomy, electronics, biology, psychology, and philosophy—to debate the once taboo subject of contacting life beyond our solar system. Two regular attendees were Frank Drake and Philip Morrison, the first astronomers to lend credence to the subject by calculating the probabilities of extraterrestrial intelligence.

NASA began to fund SETI more seriously in 1981—at an average of \$1.9 million per year over the next decade—but its value was constantly challenged. Senator William Proxmire had bestowed a Golden Fleece on the SETI program in 1978, and in 1981 Proxmire passed an amendment deleting SETI's fiscal 1982 funding. Carl Sagan met with Proxmire to argue the merits of the science, and Proxmire agreed to no longer oppose the program. SETI backers became more politically active. They founded the nonprofit SETI Institute near Moffett Field, encouraged university astronomers to turn their ears skyward for focused searches, and got Soviet scientists to release data on their efforts. The FAA showed an interest in using frequency analyzers developed for SETI, and the National Security Agency learned about code breaking. SETI was small, well-managed, on budget, and returning interesting science—if not yet evidence of intelligent life, at least far better knowledge about the energy patterns in the universe.

On the 500th anniversary of Columbus' discovery of America, NASA formally launched a SETI program. Renamed the high resolution microwave survey, it was funded out of the NASA headquarters exobiology program, located at Ames and managed by project scientist Jill C. Tarter of the SETI Institute. It received \$12 million in fiscal 1992 against a \$100 million budget over ten years. After two decades of arguing over the mathematical probabilities of other intelligent life, Ames researchers finally got a chance to actually look for it in a systematic way. While scientists at JPL geared up for a lower-resolution sky survey of the full celestial sphere, Ames developed the equipment and algorithms for a targeted search of solar-type stars. Devices built at Ames would resolve 10 megahertz of spectrum into 10 million channels, simultaneously and in real time. The resulting coverage would have 100,000 times more bandwidth

than devices used in previous searches, and was a billion times more comprehensive.

Yet less than a year later, Congress killed NASA's high resolution microwave survey. It died from fervor over the federal deficit and a history of unfounded associations with UFOs. The scientific community did not lobby consistently for it—SETI was an exobiology effort that used the tools of radio astronomy. To make it politically palatable, NASA had moved SETI from its life sciences to its space sciences directorate, which gave it low priority. SETI was small enough to sacrifice, and headquarters already felt bloodied from its 1992 budget encounter with Congress. The SETI Institute continues its work in radio astronomy with private funding. It collaborates closely with NASA Ames, and with NASA funding on a great many research topics in astrobiology.

NEAR-EARTH OBJECTS

NASA Ames researchers, from a wide range of perspectives, had long done important work in near Earth objects (NEOs), which include asteroids and some comets. Harvey Allen had studied meteors for insights into how they enter the Earth's atmosphere, as had Dean Chapman with tektites. Ames opened its vertical gun range in 1960s to study asteroid impacts on the Moon, and also meteoroid impacts on spacecraft. Ames exobiologist Ted Bunch spent his career focused on comets and asteroids, first in using impact history to understand the geological history of planets and later on their composition. In the late 1960s Cyril Ponnamperna and Sherwood Chang studied the role of comets in seeding Earth with the precursors of life. In the late 1980s, Kevin Zahnle began to include impacts in his models of the evolution of planetary atmospheres. None of these efforts, though, considered NEOS as a threat.

In 1980 physicist Luis Alvarez published geochemical evidence that the extinction of the dinosaurs coincided with a major asteroid impact—known as the K-T impact or Cretaceous extinction event. “This was very cool,” noted Ames astronomer David Morrison. “It marked a revolution in our understanding of the relationship between Earth and the cosmos.”¹²⁹ The TTAPS paper on nuclear

winter, published in 1983, drawing on the work of Jim Pollack and Brian Toon, deliberately compared the global devastation of a nuclear attack with an asteroid impact—noting that soot from fires would block far more sunlight from Earth’s atmosphere than dust.¹³⁰ Then in 1991, Charles Duller of NASA Ames, using the remote sensing equipment on an ER-2, mapped a series of sinkholes in the northern Yucatan peninsula that clearly defined an impact crater at the same time of the dinosaur extinction.¹³¹ Asteroids had entered the field of human concern, and thus perhaps the field of action as well as study.

David Morrison, though, is the Ames person most identified with work on NEOs. While still at the University of Hawaii and working at the Keck Observatory, Morrison helped develop a technique of using thermal infrared imaging to detect the sizes of main belt asteroids. He was part of a team that discovered the fundamental difference between the evolved, high albedo (reflective) asteroids of the main belt and the low albedo, dark asteroids of more primitive material on the further edges of the solar system. Asteroids had different histories and to make sense of them Morrison published on the taxonomy of the asteroids. In 1978 he edited a volume on what was known about the structural and chemical composition of asteroids that would be useful in planning a mission.¹³²

Concerned with how little public policy addressed the threat of asteroid impact—a low probability event but with grave consequences—in 1989, with Clark Chapman, Morrison published a well-received popular book on asteroid impacts, *Cosmic Catastrophes*.¹³³ Later that year, NASA announced that asteroid Asclepius came within 700,000 kilometers of Earth, that it had passed through exact position where the Earth was six hours earlier, and it was only discovered nine days after it had passed that spot.

In 1990 Congress instructed NASA to take the NEO threat seriously, starting with planning workshops. Morrison, who had arrived at Ames in 1988, chaired the workshop on detection. Brian Toon calculated how big an impact would cause an “impact winter” that plunged Earth into starvation. Using what was known about the composition of asteroids, Morrison then calculated that asteroids larger than one kilometer carried enough energy to do

global damage. His group proposed a Spaceguard survey, a catalog of every Earth-crossing NEO larger than one kilometer, using a network of six new ground-based telescopes, costing about \$8 million each, competitively funded by NASA and managed by university observatories.¹³⁴ NASA refused to fund this survey. Using existing telescopes, with modern detectors and database technology, astronomers nonetheless started surveying. They soon discovered that there was a third fewer one-kilometer class NEOs than they estimated in 1992. With total funding of less than \$1 million per year, the survey still made good progress.

The prospect of an asteroid hitting Earth was the subject of two Hollywood films released in 1998, *Armageddon* and *Deep Impact*. Morrison and Zahnle both consulted for the films. In May 1998 Congress again asked Morrison to testify on NEOs. “The first week’s gross from *Deep Impact*,” (of \$41.0 million) lamented Morrison, “would be enough to implement the Spaceguard Survey.”¹³⁵ Perhaps because of the heightened political presence of NEOs, in June 1998 Carl Pilcher of the NASA science mission directorate stood before Congress and committed NASA to open an NEO program at JPL, with funding of about \$3 million per year. This office coordinated data detected by two Air Force telescopes, called NEAT and LINEAR, and used it to characterize the orbits of discovered NEOs.

Morrison also continued his research on the structure and chemical composition of asteroids. Once the Spaceguard Survey discovered new asteroids, astronomers working in more traditional radar and optical telescopes characterized their composition and orbits. Astronomers also began to learn a great deal more about the structure and composition of asteroids through a series of small but effective spacecraft. Galileo had flown by two asteroids—951 Gaspra in October 1991 and 243 Ida in August 1993—on its way to Jupiter. Deep Space 1 was a flyby mission to the asteroid 9969 Braille in July 1999. NEAR, NASA’s near-Earth asteroid rendezvous, orbited asteroid 433 Eros for almost a year in 2000, before touching down in February 2001. Stardust, which returned samples from a flyby of the comet Coma, also flew by the asteroid AnneFrank in 2002. Hayabusa was a Japanese mission which imaged asteroid 25143

Itokawa in September 2005, and collected a sample to return. Rosetta was an ESA comet mission, which also flew past the asteroids 2867 Steins and 21 Lutetia in September 2008, enroute to a landing on a comet. Dawn launched in 2007 to flyby the asteroids Ceres and Vesta beginning in 2011. These missions, done at small cost, taught scientists a great deal about the composition of asteroids—some were piles of rocks, some were half void—and thus clarified what sort of force could be used to divert them. Nuclear weapons could do nothing, for example, if the asteroid collapsed on explosion.

Pete Worden's appointment as director further raised the salience of NEOs at Ames.¹³⁶ As Worden worked on the ballistic missile defense effort he advocated a program on planetary protection (meaning from asteroid impact, not from microbial cross-contamination as exobiologists thought of planetary protection). He considered the Air Force responsible for protecting America from any spaceborne threat, natural or human made. Furthermore, the technology used to detect satellites and to shoot down ballistic missiles could also be used to detect NEOs and divert the dangerous ones. Worden worked to make Defense Department assets available for science. He declassified military satellite data relevant to the NEO threat. Worden championed the use of the Air Force GEODSS (ground-based electro-optical deep space surveillance) network and the LINEAR (the Lincoln near-Earth asteroid research) telescopes to catalog asteroids, and indeed these military programs have had by far the best success in identifying NEOs. Worden also championed exploitation of microsatellite technologies to identify smaller NEOs.¹³⁷ In 1993, while at the Ballistic Missile Defense Office, Worden co-organized a workshop on NEOs as part of the Erice seminars on nuclear war and planetary emergencies and invited Morrison to speak.¹³⁸ Of course, the proposed use of nuclear weapons angered civilian scientists in NASA dedicated to the non-militarization of space. To bridge the deflection dilemma gap between the civilian scientists and the defense community, Morrison and Edward Teller co-authored a paper on asteroid hazards.¹³⁹

Worden used the NEO threat to justify his small satellite efforts. The Clementine I spacecraft, in 1994, after successfully surveying

the Moon and finding a chemical signature for water, was targeted at the asteroid 1620 Geographos. However, a thruster malfunction rendered Clementine crippled before it encountered the asteroid. As deputy director of requirements for the U.S. Space Command, Worden then championed the Clementine II microsatellite. It would launch in late 1999 and fire autonomous camera-tipped impactors at asteroids. Clementine II was an unclassified mission, designed to clarify the structure and composition of asteroids and demonstrate what sort of force might deflect them. In October 1997 President Clinton did one of his first line-item vetoes on the \$30 million project, perhaps thinking that Clementine II was not appropriate for the Defense Department. NASA's Deep Impact mission, started in 1999, did an impact experiment with an autonomous satellite, firing a 500 kilogram projectile at the Comet Tempel 1 in July 2005.

Worden continued to work on planetary protection. In February 2000, Worden issued a personal opinion that the Defense Department should also take international responsibility for tracking the Tunguska class asteroids (100-meter class). Such an asteroid breaking apart in the upper atmosphere, as the Tunguska one did, would look enough like the explosion of a nuclear weapon that it might provoke a misguided military response. Worden recommended a series of microsatellites to probe each recognized asteroid and populate a database on asteroid structure. Perhaps because Worden tried so hard to move NEO research into the Defense Department, in 2002 Congress clarified that NASA should have NEO responsibility.

By 2003, Spaceguard had found 800 NEOs, three-quarters of the estimated total. A NASA study team outlined the next step, \$25 million to fund a deep sky survey using Earth-based and space-based telescopes optimized to identify smaller and fainter NEOs—the 100-meter class, below the threshold for global catastrophe but still damaging to a region.¹⁴⁰ Congress required NASA to respond to the report, but NASA administrator Mike Griffin refused to, perhaps concerned about the cost. Morrison began to spend more time abroad, trying to convince other governments to fund the survey since they would be affected as much as the United States—the only nation to have invested any meaningful work in NEOs. This survey

would be done with telescopes similar to the Large Synoptic Survey Telescope, optimized for detecting small NEOs. Another reason NASA underfunded work on NEOs was that it fell into no clear budget: the science mission directorate hesitated to fund research with defense applications and the operations mission directorate, which tracked orbital debris, hesitated to fund science missions.

Working with Morrison and Jill Bauman, Worden tried to make NASA Ames a program office in NEOs, with funding authority to develop spacecraft missions. Morrison developed a proposal for the MAAT spacecraft, using the common modular bus technology developed for the LADEE spacecraft, to rendezvous with asteroid Apophis and fly with it while NASA honed its orbit measurements. Apophis was discovered in June 2004, and was once thought to be a threat. In October 2007, Worden asked Morrison and Ames chief scientist Stephanie Langhoff to convene a workshop on low-cost missions to explore NEOs.¹⁴¹ They recognized that, given the potentially large number of NEOs worth exploring, that more but cheaper missions could boost the science return. They also recognized that the desire to explore asteroids would only increase—not only in the interest of planetary protection, but also to study what asteroids could teach us about the far reaches of our solar system.

NASA ASTROBIOLOGY INSTITUTE

During the tenures of Dan Goldin and Harry McDonald, in addition to leadership in information technology and air traffic control, Ames accepted the lead center role in astrobiology. Astrobiology is the multidisciplinary study of life in the universe. It incorporated issues earlier explored as exobiology—the origin of life within evolving planetary systems, and how life and biospheres would look different on other planets. Whereas exobiology focused on the origin of life, astrobiology also looked at the evolution, distribution and future of life in the universe. A key difference between exobiology and astrobiology was that exobiology was largely laboratory based and hypothetical in that objects had not yet been found to study. Astrobiologists made a paradigm shift in claiming they had objects to study, starting with life on Earth. Astrobiology addressed how life

shaped Earth as they co-evolved, how life thrived in Earth's harshest environments, and how life ends as it did in at times in Earth's history and as it may have on Mars or Venus. It addressed the destiny of life, how life might adapt to environments beyond Earth, and thus overlapped with topics in fundamental gravitational and radiation biology. Astrobiology was also massively interdisciplinary in that it encompassed any scientific approach to these issues—observational, experimental, and theoretical.

The term “astrobiology,” as well as revolutionary plans to pursue it, were sparked to life in the intense pressure and complex chemistry of the primordial zero base review in the early 1990s. The future of space science at Ames looked bleak. NASA headquarters had decided to support only two Centers pursuing space exploration—and that Goddard was best established in Earth orbit missions and JPL in planetary missions. NASA chief scientist France Cordova chaired discussions on the role of science within NASA, which were very sensitive to the excellent work done at Ames. She suggested—given the chronically, and now acutely, threatened status of the space, Earth, and life sciences at Ames—those scientists be privatized outside of Ames in association with a local university.

The idea of a privatized institute, however, hit roadblocks. David Morrison contributed to an agency-wide review, led by Al Diaz, of possible forms for such an institute. Each encountered problems over how to move civil servants into a private institute. Congress balked at passing legislation that eased post-employment restrictions for NASA employees or allowed them to transfer their pensions. Without it, universities balked at the task of integrating an entire research directorate with 600 civil servants and 1,000 support contractors. More important, the institute plan lacked a coherent vision. It would be called, simply, the Institute for Space Life Sciences.

In meetings to define a forward-looking agenda for this institute, NASA associate administrator for space science, Wesley Huntress, suggested the term astrobiology. “Astrobiology” appeared in the NASA 1996 Strategic Plan, defined as “the study of the living universe,” and this was the enabling document that gave Ames the astrobiology mission.¹⁴² Exciting scientific announcements in 1996

cemented interest in astrobiology—the discovery of new planets around other stars and hints of microbial fossils in a meteorite from Mars. In August, data from the Ames-managed Galileo probe returned data on Jupiter’s climate drivers. The Galileo orbiter returned photos that showed Jupiter’s moon Europa may harbor warm ice or even liquid water—both key elements in sustaining life. Goldin considered biology a science with a future, named Ames as NASA’s lead center in astrobiology, and tasked it to promote collaboration through an institute.

Astrobiology stands as a prime example of how NASA managers at Ames re-integrated NASA strategic enterprises around a bold new mission. The NASA Astrobiology Institute (NAI) was in essence creating a new discipline. Ames people had created the discipline of computational fluid dynamics in the 1970s, driven to theorize the experimental work they had begun. Based on that experience, they took a more deliberate approach to creating astrobiology. A series of astrobiology roadmap conferences identified the holes in the discipline they would need to fill, and established an inclusive, virtual institute that linked universities and research organizations across the United States.

Scott Hubbard was named acting director of the NAI, and David Morrison as senior scientist. In June 1998, the brick-and-mortar institute opened at Ames, though it was a small office with superb teleconferencing and a good digital archive. One of their first tasks was to pick science teams. From among 57 applicants, they selected eleven teams to build astrobiology research and training programs. One of those teams was at Ames, led by David Des Marais as principal investigator and Lou Allamandola as lead co-investigator. This extended Ames’ tradition of research into organic astrochemistry, planetary habitability, and early microbial evolution. To recognize the integrative role of astrobiology on Center, in August 1999 Harry McDonald renamed the Ames directorate overseeing all space, Earth and life sciences to the astrobiology and space program directorate, led by Hubbard.

McDonald decided that the NAI should be led by a scientist with a global reputation as sterling as what the institute intended

to accomplish. In May 1999 he announced that its new director would be Baruch S. Blumberg, who shared the 1976 Nobel prize in physiology and medicine for his work on the origins of infectious diseases that led to the discovery of the hepatitis B vaccine. Blumberg would be the first Nobel laureate employed by NASA. Goldin turned Blumberg's appointment into an opportunity to make a major address on NASA's vision of exploration, and capped the day by signing an agreement between NASA and SGI, Inc. on a plan to develop new supercomputers. Goldin exclaimed, "It doesn't get much better than this."¹⁴³

Along with roadmap documents defining the essence of astrobiology, given its interdisciplinary nature conferences were as important. NAI organized annual general meetings where all team members could meet, summer schools offered specialized training to graduate students, and a biennial AbSciCon or astrobiology science conference attracted thousands of scientists. At the earliest conferences the papers presented focused on techniques, hoping to draw researchers from disparate fields into the discipline of astrobiology. Soon papers coalesced around topics that defined the core of astrobiology. Blumberg decided that the classification scheme for their papers should map to the astrobiology roadmap, to better show how well the NAI was pursuing its plan. In 2003 a competition for a new cohort of NAI teams attracted even more proposals, reflecting the continued growth of the discipline.

Astrobiology, like all science in NASA, was affected by the shift in NASA funds toward Constellation. Paleontologist Bruce Runnegar from the University of California at Los Angeles, who had succeeded Blumberg as NAI director when he retired, struggled to engender cooperation among the teams after they had competed so hard to be selected. In 2006, NAI was asked to cut its budget in half and so eliminated many of its fellowship programs and meetings. Carl Pilcher, science program director for solar system exploration at NASA headquarters, was named NAI director in September 2006 and stabilized funding. In 2007 NASA allowed a competition that brought the number of science teams up to sixteen, comprising more than 700 researchers at universities and research organizations

around the world. More than twenty NAI members were members of the National Academy of Sciences.

Significantly, NAI stands for NASA's astrobiology institute and not a national or international institute. NAI's work explicitly helps NASA better plan its missions and many of NASA's recent missions are driven by an astrobiological agenda. Members of the NAI are frequently included on science teams for mission proposals, or asked to build instruments for planetary missions. NAI members collaborate to design drilling tools for astrobiology missions. Ames astrobiologists Nathalie Cabrol and David Des Marais provided the crucial insights that guided the MERs' (Mars exploration rovers) traverse across Mars in search of water. With Lunar Prospector and LCROSS, Ames generated data to find water on our Moon. Infrared astronomy, as done with the Spitzer space telescope and SOFIA, provides data on the chemical composition of the universe and the origins of our solar system.

The Kepler mission—with its science program managed at Ames—is explicitly astrobiological, in that it is looking for planets in our galaxy that might harbor life. The first Pale Blue Dot Workshop held at Ames in June 1996 focused specifically on spectroscopic means of detecting life on the growing numbers of extrasolar planets. The second workshop in May 1999, organized by Larry Caroff and David Des Marais, reflected the impact of the NAI in broadening astrobiology. NASA astronomers could now study extrasolar planets with insights from atmospheric chemistry, gaseous biosignatures, and the early habitability of Earth.¹⁴⁴ By the third Pale Blue Dot meeting in 2006 at the Adler Planetarium in Chicago, the MER rovers had followed the trail of water on Mars and more than 200 extrasolar planets had been cataloged. The meeting emphasized science communications, helping both scientists and journalists explain these advances in astrobiology.

The NAI was widely considered a success. The numbers of scientists working in astrobiology, or at least those calling their work that, had exploded over the decade. By leveraging information technology, all the infrastructure of a scientific discipline—meetings, seminars,

journals, peer-review, fellowships, education and training—were in place and for relatively little cost. The organizational form of the NAI, the virtual institute, was ready for application elsewhere.

LUNAR SCIENCE

At a conference in October 2007, Alan Stern, who led the science mission directorate at NASA headquarters, announced the creation of a NASA Lunar Science Institute (NLSI). Its goal was to re-invigorate the lunar sciences in preparation for NASA's return to the Moon. It would be modeled on the NAI and be based at NASA Ames. The announcement surprised everyone at Ames, and Stern gave almost no guidance on what he expected.

Kristina Wilmoth, who led outreach at the NAI, led a group to structure the institute, and Pete Worden named as interim director David Morrison, whose eminence in planetary science spanned many fields and who had been involved with NAI since its start. Joining his NLSI staff were others who had worked with NAI—like deputy director Greg Schmidt, and Estelle Dodson and Joe Minafra who had built the tools for videoconferencing and web collaboration. While Morrison reported to Worden as Ames director, he held weekly teleconferences with the program office at headquarters. Stern resigned from NASA in March 2008, and headquarters oversight of the NLSI moved to Jim Green, director of the planetary sciences division, who remained supportive of NLSI at Ames.

Morrison moved quickly. NLSI opened its website first, updated it to be a center of all information related to science “of the Moon, on the Moon, from the Moon.”¹⁴⁵ The small institute office opened its doors in April 2008, in renovated space in the old Admiral's office on historic Shenandoah Plaza of Moffett Field. Drawing on the NAI model, they formulated a five-year budget and drafted a cooperative agreement notice, or CAN, to shape the competition for potential teams. The first NASA Lunar Science conference—held in July 2008 and organized by Chris McKay—drew more than 500 participants, far more than expected, many looking to build or promote their teams. The conference proved that the Moon was still active terrain for scientific exploration.

In response to its CAN, the NLSI received 33 applications. Each team addressed some element on the National Academy of Sciences' report on *The Scientific Context for the Exploration of the Moon*, which served as a roadmap for the NLSI.¹⁴⁶ After intense peer review, in March 2009 they selected seven multidisciplinary teams of scientists distributed at universities and think tanks throughout the country. Each team was funded at about \$2 million for four years. None were based at Ames, a situation Worden expected to resolve by the time of the next competition. Education was an important part of each proposal, in that each team had to involve graduate students and allocate five percent of its budget to education. NLSI also created a program for international partners, and the first selected was the University of Western Ontario. Their team got no funding from NLSI, but got access to its collaboration tools in return for funding a lunar science effort.

The second Lunar Science forum, in June 2009, was even better attended than the first. This time, there were results to announce: from the Lunar Reconnaissance Orbiter, Chandrayan, Selena, and Chang'e orbiters. Other nations clearly had active lunar exploration programs; this marked the first time the leaders of the Chinese mission to the Moon presented results in the West. The NLSI hosted Moonfest 2009, a public event to celebrate the 40th anniversary of the Apollo 11 landing on the Moon. More than 11,400 local residents showed up—making it the largest public event since the 1997 open house.

Fresh data from the Moon continued to make it a more interesting place. Carle Pieters at Brown University, a principal investigator with both the NLSI and the Chandrayan orbiter mission to the Moon, announced that water pervaded the surface of the Moon as the hydroxyl molecule. NLSI principal investigator Bill Bottke revisited the bombardment history of the Moon and proposed a model of our early solar system with a huge debris disk, like astronomers were beginning to discover in the solar systems of other stars.

A sense of history was also important, in that all the teams in some way revisited data from the Apollo missions. In November 2008, the NLSI unveiled a remastered iconic image of Earth taken

in 1966 by the Lunar Orbiter 1. The Lunar Orbiter image recovery project, located at Ames and managed by Dennis Wingo and Keith Cowing, restored the image using lovingly refurbished tape drives and modern digital technology. These images had twice the resolution and four times the dynamic range of the original Lunar Orbiter images. It showed objects as small as a meter, comparable to the data being returned in 2008, thus generating insights into how the lunar surface has changed over the past four decades. Specifically, it will help measure the rate of impacts on the Moon so NASA can plan for the proper amount of shielding on future colonies.¹⁴⁷

The NLSI, while built upon new technologies for collaboration and the organizational form of the virtual institute, reflected how Ames in the past opened fertile new fields in the planetary sciences. Over the past fifty years, Ames scientists established positions in studies of astrobiology, NEOs, planetary atmospheres, SETI, and infrared astronomy. Each new field of expertise reflected the ability of Ames scientists to combine theory, laboratory experimentation, spaceborne instrumentation, a record of publication, a willingness to partner, and a desire to train future generations in space science.

Space Life Sciences

Perhaps the first wholly new activity at Ames following its transition into NASA was the fundamental space life sciences, meaning research into extending life beyond the environment of Earth. NASA quickly set about studying how humans would adapt to spaceflight, and tasked Ames to develop animal models and laboratory experiments to answer specific questions. As the Manned Spacecraft Center near Houston formalized its responsibility for the astronaut corps into the 1960s, NASA moved there the more applied, risk-reduction work on human space medicine and capsule environments. Over the ensuing decades Ames continued to pursue its more fundamental and future-focused work in space biology.

By the late 1990s, more doctorate-level biologists worked at NASA Ames than at any other NASA Center (though their numbers dwindled drastically in the decade that followed). Biology at NASA Ames was dispersed and integrated into most every research program at the Center, including information technology and aeronautics. The two most prominent areas were astrobiology and gravitational biology, which often overlapped. Many scientists worked in both areas and the two were often conjoined organizationally. Astrobiology at Ames, though, shared an intellectual framework with the planetary sciences while gravitational and the space life sciences traced a lineage to Ames' work in human factors dating to the NACA. Furthermore, experimental practices differed. Life scientists enjoyed reasonably good access to low Earth orbit—from Biosatellite to Cosmos/Bion, and the Space Shuttle program—meaning their work revolved around building flight-qualified experiment packages for living things. Astrobiologists worked with more restricted data sets.

Over the years biology at Ames has been fundamental, integrative and collaborative. Biology at Ames mixed the entire range of work in the discipline: the concurrent development of theory, veterinary care, bioinstrumentation, fieldwork, comprehensive spacecraft missions, unique spaceborne experiment packages, data analysis

and education. At Ames, biologists enjoyed the freedom to define for themselves new research agendas, so the engineering impact of their work was profound.

The work Ames did in the 1950s in aircraft handling qualities and pilot workload led to the design of research-oriented flight simulators, on which they validated new ways to test the interaction of human with machine. With the launch of America's human space program, Ames did early work in capsule design, crew life support, and the manual control of spacecraft. As NASA shifted to the Space Shuttle in the 1970s, Ames continued to find new ways to optimize crew performance—with studies in cockpit design, visual perception, and crew life support for longer missions. The Ames instrumentation group invented biomedical sensors, its aviation systems group pioneered methods of safety reporting, and its information technology group tested tools to make astronauts more intelligent and capable. Biofeedback to reduce space sickness was one example of how Ames improved the performance of astronauts in space. The space life sciences at Ames enjoyed a broad scope.

START OF LIFE SCIENCES RESEARCH

In November 1961, soon after the arrival of James Webb as NASA administrator, several new research responsibilities were assigned to Ames, most notably the life sciences. Of all the former NACA laboratories, Ames' leadership in simulator design and cockpit usability studies earned it the largest contingent of researchers working with human subjects. NASA first imposed on Ames the life sciences program—reporting to headquarters but housed in DeFrance's shop. The first life science chief at NASA Ames was Webb Haymaker, an eminent neurophysiologist who had done some important experiments on radiation effects on the brain using high altitude balloons. Haymaker recruited a world-class team of biologists—mostly working on radiation and microgravity effects—but he was no manager. Furthermore, Haymaker did not really fit the culture of the Center in fashioning fundamental research derived from engineering needs.

One of his early hires was Harold P. “Chuck” Klein. Klein’s initial interest in exobiology was sparked as a professor at the University of California at Berkeley, when one of his graduate students regaled him with glowing reports on a series of lectures by astronomer Carl Sagan on the prospects for extraterrestrial life. As the task was first given to Ames, exobiology focused more narrowly on how to identify any life encountered beyond Earth and how to sterilize early spacecraft to protect Earth and other planets from unknown biocontaminants.

After moving to Brandeis University, Klein researched the possible biochemical processes which might be displayed by non-terrestrial life. Informed by a colleague that Ames was looking for someone to head its new exobiology division, Klein took the post. He arrived at Ames in 1963 to head the exobiology branch and guided construction of Ames’ superb collection of gas chromatographs, mass spectrometers, and quarantine facilities. He continued with his own research, while also supporting the seminal work of other Ames exobiologists such as Cyril Ponnampertuma, who synthesized organic molecules under conditions simulating primitive Earth. A year after he arrived on Center, DeFrance asked Klein, who had experience as chairman of the Brandeis biology department, to become director of Ames’ life sciences directorate which would encompass both exobiology and human spaceflight research. Klein brought intellectual coherence to Ames’ efforts, fought for both support and distance from Washington, and did a superb job recruiting scientists from academia. Klein led Ames’ life science work for more than two decades, building a world-class research group in gravitational biology and astrobiology.

One key to DeFrance’s trust in Klein was their agreement on peer review. The NACA aeronautics publications system transitioned easily into a NASA publication system for space and materials scientists, and maintained its high level of quality through internal peer review, tiered publication and public distribution. However, NASA publications did not naturally reach the community of biologists. Klein insisted he could not recruit good biologists unless they could publish their NASA work in outside, proprietary and academic journals. Furthermore, many of the principal investigators

on the experiments were university employees, and expected to publish in ways appreciated by tenure review boards. DeFrance appreciated that Klein needed good feedback because he was setting the research agenda for this new field, and was performing experiments in new environments and with new types of controls. So that DeFrance could best represent his agenda at headquarters, Klein kept DeFrance abreast of how the results of his division were received by professional biologists.

In the early 1960s, as in the early 1940s, Ames was a construction zone. Not only were new arc jet and hypervelocity tunnels being built at top speed, but the life sciences division had to build numerous facilities from scratch. The first life scientists to move out of their temporary trailers and off-site space, in 1964, moved into the new biosciences laboratory. There they worked on instrumentation and enclosures for spaceflight experiments. This laboratory included an animal shelter, where Ames housed a colony of pig-tail macaques from southeastern Asia for ground-based control experiments prior to the Biosatellite missions. In December 1965, Ames dedicated its life sciences research laboratory primarily for exobiology research. It was architecturally significant, within the Ames compound of square, two story, concrete-faced buildings, because it stood three stories tall and had a concrete surfacing dimple like the Moon. On each floor were wet laboratories, surrounded by offices along the windows. It cost more than \$4 million to build and equip its state-of-the-art exobiology and enzyme laboratories.

These new facilities were designed to help Ames biologists understand the physiological stress that space flight and microgravity imposed on humans. The Manned Spacecraft Center screened individual astronauts for adaptability and trained them, and Ames developed the fundamental science underlying this tactical work. Mark Patton in the Ames biotechnology division studied the performance of humans under physiological and psychological stress to measure, for example, their ability to see and process visual signals. Other studies addressed how well humans adapted to long-term confinement, what bed-rest studies showed about muscle atrophy, and what sort of atmosphere was best for astronauts to

breathe. Ames' growing collection of flight simulators was used to study human adaptability to the gravitational stress of liftoff, microgravity in space flight, and the vibration and noise of reentry. All this data was used to define the shape and function of the Gemini and Apollo capsule interiors.

Ames' environmental biology division studied the effect of spaceflight on specific organs, mostly through animal models. Vance Oyama pioneered the use of centrifuges to alter the gravitational environment of rats, plants, bacteria, and other living organisms, and thus pioneered the field of gravitational biology. In conjunction with the University of California Radiation Laboratory, Ames used animal models to determine if the brain would be damaged by exposure to high-energy solar rays that are usually filtered out by Earth's atmosphere. To support all this life sciences research, Ames asked its instrumentation group to use the expertise it had earned in building sensors for aircraft to build bioinstrumentation. Under the guidance of John Dimeff, the Ames instrumentation branch built sophisticated sensors and clever telemetry devices to measure and record physiological data with minimal impact on the subjects.

BIOSATELLITES

One constant to all life as we know it is gravity, and biologists at Ames developed many of the tools central to understanding how gravity affects life. Ames managed the Biosatellite program in the late 1960s, the first coordinated effort to use living organisms in experiments on gravitational biology. NASA launched three Biosatellites between December 1966 and June 1969, each built from repurposed Mercury capsules. The first two Biosatellites carried thirteen experiments using fruit flies, frog eggs, bacteria or wheat seedlings. The first Biosatellite was never recovered because its retrorocket failed to ignite, but information gleaned from orbit showed it was working well. The second was scheduled to orbit for 72 hours, but was recovered after 45 hours due to an impending storm in the recovery area. Still, it accomplished its primary objective of determining if organisms were more sensitive to ionizing radiation in microgravity than on Earth. NASA headquarters cancelled the

Biosatellite program, which would have included six spacecraft, in 1969 just before the third spacecraft was launched. Since the Biosatellites offered the only expected opportunity for flying experiments, the headquarters offices for basic bioscience and for astronaut-focused research fought bitterly over the program's research goals. Added to that was opposition from the Air Force, concerns in Congress about raising costs, and a feeling at Ames that they could not properly control design of the spacecraft.

The third Biosatellite, in addition to the previously flown experiment packages, carried a small pig-tail monkey to study the effect of spaceflight on performance, cardiovascular health, hydration and metabolic state. This experiment was led by a principal investigator from the University of California at Los Angeles and Charlie Wilson, the Biosatellite project manager at Ames, did not properly limit his scientific ambitions. This Biosatellite was scheduled to orbit for thirty days, but was deorbited in nine days because the health of the monkey rapidly declined. It died soon after landing, from a heart attack caused by dehydration.

The Biosatellites, compared with the Pioneers, were considered a learning experience. Most of the experiments worked well, returned valuable data, and gave Ames biologists the confidence to build autonomous biological experiment packages. The few experiments that did not work showed the need for more advanced testing and more focused objectives. Regardless of what they learned, Ames life scientists faced the prospect that they would have no future opportunities to experiment in space. Biosatellite was cancelled, power failures crippled Skylab in 1973 making it unable to host experiment packages, and the Shuttle would not open its manifest to experiments until the early 1980s. The Soviets came to the rescue.

A good example of Ames' ability to do pioneering science quietly and on a small budget was the Cosmos/Bion missions. Every two to four years, between 1975 and 1997, the Soviet Union shot a Cosmos biosatellite into space carrying an array of life science experiments, many built at Ames, to study how plants and animals adapted to microgravity. The Cosmos/Bion program quickly became the single best source of data on the effects of weightlessness on earthly life.

A unique spirit of cooperation underlay the success of *Cosmos/Bion*. Even in the darkest days of the Cold War—following the Soviet invasion of Afghanistan and the Reagan presidency—life scientists from Ames, western and eastern Europe, and the Institute for Biomedical Problems in Moscow collaborated on basic research.

The Soviets, like NASA, had prepared for their early human space flights by flying animals in space. They continued their life sciences flights into the 1960s and had already flown two *Cosmos* biosatellites before inviting NASA to join the third, to be launched in November 1975. Delbert Philpott, who had long done research on the effect of radiation on eyesight, launched an experiment on a high-altitude balloon that drifted into Soviet airspace. This started a conversation that led to the *Cosmos/Bion* invitation. Ames scientists jumped at the chance. While Ames had a superb set of ground-based centrifuges for use in studying the biological effects of hypergravity, the only way to study microgravity was in space. In addition, the Soviets offered to pay the entire cost of the spacecraft and launch; NASA need only pay for design and construction of experiment payloads to fly on board. During the 1970s, this never cost NASA more than \$1 million per launch. For this relatively small cost, Ames produced some superb data.

The first launch, *Cosmos 782*, landed nineteen days later in central Asia. For security reasons, Soviet scientists recovered the experiments and returned the samples to Moscow. Eighteen institutions from five countries did studies on every major physiological system in the rat. Many of these experiments were designed by people at Ames: Delbert Philpott of the Ames electron microscope laboratory studied radiation bombardment to the retina; Emily Holton measured bone density and renewal; Joan Vernikos studied gastric ulceration; Adrian Mandel evaluated immunity levels; Henry Leon measured degradation of red blood cells; and Stanley Ellis and Richard Grindeland charted hormonal levels. As experimental controls, the Soviets built a biosatellite mockup that stayed on the ground simulating every flight condition but weightlessness, as well as a small centrifuge for the biosatellite that kept a small control colony at 1G of artificial gravity. Ames scientists concluded that the stress on the rats came from weightlessness rather than from other flight

conditions, that space flights up to three weeks generally were safe, but that specific results needed to be verified.

After the second flight, *Cosmos 936* in August 1977, the results were clearer. Basic physiological systems showed no catastrophic damage, but there was measurable bone loss and muscle atrophy from exposure to microgravity, as well as retinal damage from radiation bombardment. Indeed, the regularity of the *Cosmos/Bion* flights let Ames biologists constantly improve their protocols and confirm their data. Ames scientists were initially unaccustomed to sending up experiment packages every two years, but they eagerly adapted to the quickened pace of data analysis, publication, experiment proposal, and payload design. New collaborators were added constantly, using new types of organisms—plants, tissue culture, fruit flies, and fish. Every flight used a mass-produced spherical *Vostok* spacecraft—eight feet in diameter, a volume of 140 cubic feet, with active environmental control, and a payload of 2,000 pounds. Ames project engineer Robert Mah built the cages and bioinstrumentation to fit the space allocated by the Soviets. Kenneth Souza at Ames and Lawrence Chambers at NASA headquarters oversaw the entire program in one capacity or another, and the Soviets appreciated this continuity of leadership that was so rare within NASA. Eugene Ilyin led all efforts in Moscow, and Galina Tverskaya of Ames served as ambassador on program and technical matters.

During the 1980s, the cost to NASA rose to an average of \$2 million for each *Cosmos/Bion* mission, primarily because the mission group added a pair of rhesus monkeys as subjects. The Soviets had never flown monkeys in space, and NASA had limited success. So the *Cosmos 1514* mission in December 1983 lasted only five days, largely to test life support systems. Not until *Cosmos 2044* in September 1989 would the monkeys fly a full two-week mission. These flights displayed the progress Ames had made in bioinstrumentation over the previous two decades. Specimens in the first *Cosmos/Bion* missions flew undisturbed, and descriptive data were collected post-flight. For the later flights, the animal and plant specimens were fully instrumented and data was collected continuously during flight. James Connolly became project manager

in 1985 and focused the Cosmos experiments to complement those now flown aboard the Shuttle.

The final Cosmos/Bion mission included a rhesus monkey experiment devised by American and French scientists. It was originally designed to fly aboard the Shuttle, but was cancelled because of cost and sensitivity concerns. Ames had developed a well-established protocol for the low-cost development of biological experimentation, and quickly modified the rhesus project to fly on Bion 11 for \$15 million, a fraction of the original cost. It launched in December 1996 and landed fourteen days later with the monkeys in good health. However, a day later, during a biopsy requiring anesthesia, one of the monkeys died. A panel of experts convened by NASA headquarters confirmed the validity and safety of the rhesus research. But animal rights activists vilified this death, and Congress questioned why NASA was spending money to help the Russians send monkeys into space. Indeed, with the dissolution of the Soviet Union, the Russians had begun asking NASA to fund a greater portion of the flights. Early in 1997 Congress refused to appropriate \$15 million for the Cosmos/Bion mission planned for the summer of 1998. Few at Ames participated full-time in Cosmos/Bion, since the efforts of the life sciences division focused on the space station biological research project, so its cancellation had little impact on staffing levels. The cancellation, however, immediately degraded Ames efforts to pursue a systematic research program.

GRAVITATIONAL BIOLOGY

The Cosmos/Bion program was the free-flier portion of a broader research effort at Ames on the prospects of earthly life living in space—a program that also included Shuttle-flown and Earth-based experiments. This research work was also pursued on Earth, where Ames people devised ingenious ways to explore how humans responded to weightlessness even while bathed in gravity. Dolores “Dee” O’Hara managed Ames’ human research facility where, since the early 1960s, Ames life scientists had refined bed rest into a superb tool for understanding specific responses to weightlessness. Bed rest with a head-down tilt of six degrees, for example, simulated the

decreased blood volume incurred during space travel. Joan Vernikos, chief of Ames' life sciences division, used the bed-rest facility to determine which methods of plasma expansion made fainting less likely upon return to Earth. She also studied how much gravity was required to remain healthy, supporting NASA's decision to provide intermittent gravity with an on-board centrifuge rather than rotating an entire space station. David Tomko directed the Ames vestibular research facility made available to many Ames life scientists studying the body's system of balance and spatial orientation.

Emily Holton's research results on how bones and muscles atrophy in microgravity are among the most cited in NASA history. Her hind limb suspension model, a method of studying bone loss in laboratory rats on Earth, was validated on more than fifteen spaceflight experiments. It became a compelling example of how basic research in space life sciences proves useful in medical research, on bone loss in the elderly, on Earth.

Likewise, researchers interested in hypergravity had access to the 20G centrifuge. The 20G centrifuge, built simply under the test section of the 40 by 80 foot wind tunnel, was an example of how Ames built prototype facilities before committing to construction of much larger facilities. The 20G was designed in-house, by the research facilities engineering division, led by Robert Eglington. John Salas, an expert on electrical feedback controls, designed the electrical controls system that rendered the centrifuge controllable, and thus man-ratable. It was one of the first centrifuges designed with an open truss arm, which meant the test chamber could be mounted anywhere along the arm, thus changing the G force. It was initially called the planar motion generator, a generic platform for human factor studies. Construction was funded through the Biosatellite program, to test how well packages flown in Biosatellite would survive the hypergravity of take-off and landing. It was human-rated in 1964, and remained one of the few human-rated centrifuges in operation. It was used almost entirely for human factors research rather than astronaut training—which was done at the Naval Air Development Center in Pennsylvania or a centrifuge

built at the Manned Spaceflight Center. This design worked so well that it formed the basis for the 50G centrifuge.

Design of the 50G started a year after the 20G opened, and the 50G started its shake-out testing in 1967. Formally called the man-carrying rotation device and centrifuge, it was designed to simulate every sensation, other than weightlessness, of a trip to the Moon or Mars. In addition to the forces of lift-off and landing, it provided angular and vertical motion. The test cabin had a complete set of motion controls, computer-driven visual cues, and an environment that simulated the temperature, radiation, and vibration environment of a space capsule. At the end of a 50 foot arm, driven by a motor rated at 18,600 horsepower, the three-person cabin could be accelerated to 20G at rates up to 7.5G per second. A smaller cabin could be accelerated up to 50G or, if carrying a person, up to the level of human tolerance. However, the 50G never performed to expectations, and was shut down in the late 1970s.

By the early 1990s, the 20G was one of six hypervelocity facilities at Ames, but the only human-rated centrifuge within NASA. "It's a simple facility," noted centrifuge director Jerry Mulenburg, "but it's very flexible for our purposes."¹⁴⁸ Ames upgraded its controls and data collection system, completed in March 1994, and built a new treadmill cab to fit on the end of its 58 foot diameter arm for exercise tests in it up to 12.5G. The 20G remained very active in human factors research.

Microgravity, by contrast, could only be sustained in space, where it is expensive to send any living thing. Gravitational biology grew management-intensive at every step: to select the experiments from hundreds of proposals; to oversee the precise construction of habitats and biosensors; to ensure that tissues were carefully prepared and distributed equitably around the world; to involve every interested biologist in reviewing the data; and to make sure the results were repeatable from flight to flight with very small numbers of subjects. In the mid 1980s, when the Space Shuttle allowed easier access to two-week long periods of microgravity and room for a wider array of plant and animal habitats, Ames developed experiment packages that allowed biologists to ask more complex questions.

Spacelab, a reusable pressurized module flown aboard the shuttle orbiter, provided an opportunity to study the effects of weightlessness in an integrated fashion. The Ames space life sciences payloads office provided half of the experiments flown aboard the Spacelab life sciences-1 (SLS-1) mission in June 1991. The crew hooked on biomedical sensors, many developed at Ames, to study the effects of weightlessness, and ran experiments on animals and plants. Bonnie Dalton was project manager and oversaw training of the mission specialist crew, coordination of the experiments, and development of new biosensors. The Ames payload included two comprehensive laboratories. The research animal holding facility (RAHF) provided life support to 24 rats, while isolating them from the human crew. The general purpose work station was a glove box to contain liquids while the crew processed experiments in orbit.

The SLS-2 (Spacelab life sciences-2) mission flew aboard the shuttle orbiter in October 1993 as a continuation and extension of the experiments flown aboard SLS-1. Few scientists had an opportunity to repeat their studies so completely so soon after first collecting data. It marked the first time ever that astronauts collected tissues in space. Before then, all tissues were collected by the principal investigators after the flight landed, making it impossible to separate the physiological effects of microgravity from the hypergravity of lift-off and landing. Furthermore, the shuttle payload specialists first collected tissues on the second day in space—by sacrificing five rats, doing rough dissections, and preserving the tissues—allowing life scientists back at Ames to do the fine dissections and to note how quickly the organisms adapted to space. Tissues were collected again on day fourteen, the day before reentry, so that life scientists could study how quickly the organisms readapted to the Earth's gravitation. The speeds of adaptation and readaptation were especially notable in experiments on bone density and neurological development. Martin Fettman, a veterinarian, flew as the payload specialist responsible for the rats, and Tad Savage and John Hines of Ames managed the payload of nine experiments.

Ames life scientists continued to build smaller payloads as space opened up aboard individual shuttle flights. For example, in

September 1992, Ames investigators flew an experiment aboard the STS-47 Spacelab-J mission. Kenneth Souza designed a frog embryo experiment, Greg Schmidt served as payload manager, and James Connolly designed the frog box. Not only was this the first time live frogs flew in space, but they would also shed eggs that would be fertilized and incubated in microgravity. The experiment showed that reproduction and maturation could occur normally in space—at least with amphibian eggs. Biologists had studied amphibian eggs for more than a century because of the unique way they orient themselves to gravity once fertilized.

And as small spaces arose in spacecraft manifests, Ames continued to fly biological experiments in collaboration with international partners. In the mid-1990s, Ames' work in gravitational biology shifted to the Shuttle/Mir program which continued the collaboration begun with the Cosmos/Bion missions and paved the way for life science research on the international space station. From June 1995 to January 1998, Ames managed several experiments transferred during the eleven dockings between the Shuttle and the Russian Mir space station. For the first time, a complete life cycle (seed-to-seed) of plants was lived in space. Desert beetles, previously flown on Cosmos/Bion flights, demonstrated the effects of extended space travel on a circadian rhythm. Ames researchers swapped tissue cultures with their Russian counterparts, gave the Russians a strain of wheat to grow aboard Mir, and supplied cardiac monitors and bone measuring devices for Mir cosmonauts. Meanwhile, Ames flew a number of experiments collaboratively with the European Space Agency using its Biorack hardware.

The STS-90 mission, called Neurolab and launched in April 1998, was perhaps the most complex mission flown by NASA bioscientists. The laboratory contained a variety of organisms—crickets, fish, mice and rats, as well as monitors for the Shuttle astronauts—all designed to help explore the impact of gravity on cognition and neural development. Neurolab began in 1991 as NASA's contribution to the government's effort to make the 1990s the decade of the brain. The Neurolab announcement of opportunity in 1993 drew 172 proposals from around the world. JSC managed the eleven experiments selected

that dealt with the Shuttle crew. All the non-human experiments—fifteen of the 26 total experiments—were managed by Ames. Chris Maese of the Ames life science division served as Neurolab project manager, supervising the design and verification of the experiment packages. Muriel Ross designed one of the key experiments—her third experiment on a Spacelab mission—that led to exciting new reinterpretations of neural plasticity in space.

Neurolab was like a flying, highly sanitary zoo. To accommodate the litters of rats, Ames provided the research animal holding facilities previously flown on SLS-1 and SLS-2. Mice were housed in animal enclosure modules. The Japanese space agency contributed the vestibular function experiment unit, which had flown as a freshwater habitat on SL-J and IML-2 and which on Neurolab would support a saltwater fish, the oyster toadfish. The German Space Agency provided an incubator to house the crickets, as well as the closed equilibrated biological aquatic system that would incubate fresh water plants and animals. Ames also provided its general purpose work station, a laminar flow hood developed for in-flight experiments, including the first in-flight surgery. The mission made for an exciting sixteen days. Some of the Ames payload crew began ground control studies and prepared for landing activities. Some sat at consoles to answer questions from the Shuttle crew, track hardware performance, and record data. Things progressed as planned, until the start of the second week. First, the Shuttle system that removed excess carbon dioxide from the air appeared to be failing. While the Neurolab team began reprioritizing experiments anticipating a failure, the Shuttle crew was able to solve the problems by swapping out an air filter. A second problem, with the youngest group of neonate rats onboard, persisted. The rats were essential to a study on whether the nervous system needs gravity to develop. Payload commander and in-flight attending veterinarian, Richard Linnehan, kept the mortality numbers to a minimum and principal investigators earned enough data to achieve their research objectives. Soon after the Shuttle landed at KSC, it was clear the rest of the experiments had gone well. They were able to examine their crickets, count how

many snails were born, perform behavioral testing, and examine tissues collected during the flight.¹⁴⁹

Neurolab was the last Shuttle mission to fly the Spacelab module, and the last comprehensive life sciences mission NASA planned to launch. Shuttle flights thereafter would focus on construction of the space station until the opening of the space station itself. When the space station was completed, it would present new questions life scientists would need to answer and new opportunities to experiment. In the meantime, life scientists at NASA Ames looked to do more focused studies in small satellites and on Earth.

AUTOGENIC FEEDBACK TRAINING

One series of experiments—present on many of the life sciences-dedicated Shuttle flights, and intended to help astronauts aboard the space station—helped researchers to develop autogenic feedback training. Human potential has always fascinated Patricia Cowings—both how she could realize her own potential and how she could help astronauts realize theirs. While in the graduate program in psychology at the University of California at Davis she met Hans Mark, who encouraged her to join the Center through the graduate research science program. She picked a topic that has guide her career, how to train humans to overcome space adaptation syndrome (similar to motion sickness) through autogenic feedback (meaning training and exercises rather than drugs).¹⁵⁰ At Ames she crunched the data needed for her dissertation, using the Ames computers in the odd hours they were available, thinking all the time about how to design a laboratory specifically suited to biofeedback work.

She entered the civil service in 1978 and started that work. Cowings married William Toscano, who had joined her as a research associate from the Langley Porter Institute of UC San Francisco and they collaborated happily ever after.¹⁵¹ Melvin Sadoff, assistant chief in the biomedical research division, proved an adept mentor as did psychophysiological Joseph Sharp, assistant director of life sciences. Sharp named her the principal investigator for the Ames psychophysiology laboratory and outfitted it with a Barany chair,

named for the physician who studied the role of the vestibular system in balance. It was like a barber's chair, except that it cost \$16,000, the experimenter controlled its rate of rotation on several axes, and data from the subject travelled through wires for computer analysis. Cowings studied 24 male subjects who experienced motion sickness from Coriolis acceleration in the rotating chair, trained them to recognize changes to their vital signs, then to use mental exercises to control the motion.¹⁵² "What were previously considered involuntary, or autonomic, responses are in fact voluntary if you are taught properly," said Cowings. This proved a breakthrough in the control of motion sickness. Motion sickness would be especially problematic when astronauts were able to move about their spacecraft, and for two weeks, as they would in the larger shuttle orbiter. In 1979 NASA selected Cowings' experiment—known as AFT for autogenic feedback training experiment—to be carried into space with the shuttle.

To support her AFT experiment, Cowings became the first woman scientist trained as an astronaut. In contemplating crews for the new Space Shuttle, NASA considered training women as payload specialists—scientist-astronauts focused on running experiments in space. Furthermore, Ames and JSC collaborated on a particular experiment, Spacelab mission demonstration III (SMD3) that simulated a Shuttle mission dedicated to studying the biological toll on humans. Bill Williams of the Ames biosystems division trained as the payload specialist with Richard Grindeland and Cowings as backups. The press made light of Cowing's training, especially NASA's lack of space suits that could be worn by women. All recognized that Cowing could conceivably become the first woman in space.¹⁵³ The payload specialist would be in charge of about fifty experiments—half of them designed at Ames. The candidates trained at Ames, first on surgical techniques for research animals, and then on the experimental apparatus integrated into the rack configurations. The crew back at JSC served as test subjects and practiced the experiments inside the Earth-bound Spacelab simulator.

Meanwhile at Ames, a group led by Hal Sandler and David Winter was leading a group of women—twelve Air Force flight

nurses—through bed rest exercises to better understand the effect of microgravity on women's bodies. The human body was designed to distribute blood despite the pull of gravity. Extended bed rest, like microgravity, caused the body to lose a lot of fluid and redistribute what remained. In this test, Ames scientists were tracking the effect of simulated microgravity on biorythms, muscle atrophy, bone density and hormones, comparing the women with tests done on men in 1972.¹⁵⁴ Cowings would have some data to anticipate the affect that microgravity might have on her.

At the end of Cowings' two years training for SMD-3, her colleagues at Ames threw her a splash-down party. The Shuttle program was delayed, and meanwhile NASA instead decided to train women as mission specialists (pilots who would fly several missions) rather than train scientists as one-flight payload specialists.¹⁵⁵ Cowings' AFT experiment eventually flew in 1985 on STS 51-C and STS 51-B with her on the ground.

Following SMD3, Cowings continued her work in the gravitational research branch.¹⁵⁶ She upgraded her system to the autogenic feedback system-2 (AFS-2), which was ambulatory. The garment, similar to a camisole, included all the necessary transducers and signal processors, a feedback display worn on the wrist, and a cassette tape recorder. Cowings' AFTE experiment would fly one last time on Spacelab-J. Two astronauts on that flight, Mae Jemison, the first African-American women in space, and Mamoru Mohri, the first Japanese astronaut, received autogenic feedback training at Ames with Cowing and were monitored in space.

Cowings also began to look for applications of autogenic feedback beyond NASA. During the 1990s NASA increasingly collaborated with the Russians and Cowings' Russian collaborator invited Cowings and Toscano to Star City in September 1996 to train cosmonauts in AFTE in preparation for MIR 23 and 25. The next year, in 1997, NASA patented AFTE.¹⁵⁷ The patent covered the six-hour training program, the AFS-2 equipment, and the software to process the data. BioSentient Corp., a company founded by Mae Jemison in 1999, gained an exclusive license to commercialize the technology for nausea, anxiety, diabetic autonomous neuropathy, and other

stress-related disorders. Ames work on autogenic feedback shifted to military users, who trained a great many more sufferers of motion sickness than did NASA. To improve upon a Navy air-sickness desensitization program, Cowings began work in 2002 under an interagency agreement with Navy researchers in Pensacola, Florida. Most human factors scientists change the machine to fit the human. Like many of her colleagues in the Ames human systems integration division, Cowings studied human potential to modify the human to fit the machine.

SPACE HABITABILITY

By engineering these many life science payloads, Ames researchers had learned much about how organisms adapted to microgravity and how to sustain life economically in space. Ames people authored many of the earliest studies of what long-term settlement of space—both in orbit and on other planets—might look like. More importantly, Ames did actual experimental and bioengineering work that provided the scientific basis for space settlement concepts—generating data on exposure and countermeasures to radiation, on useable *in situ* resources, and on life-support in regenerative environments.

In the mid-1960s, Ames also participated in the design of suits for astronauts to wear for extravehicular activity. Vic Vyukal led Ames' space human factors staff in designing the AX-1 and AX-2 suits for extended lunar operations, and in validating the concepts of the single-axis waist and rotary bearing joints. Though none of these concepts were included in Apollo spacesuits, many were incorporated in the next-generation of suits designed for Space Shuttle astronauts. The AX-3 spacesuit was the first high-pressure suit—able to operate at normal Earth atmospheric pressures—and demonstrated a low-leakage, low-torque bearing. The AX-5 suit, designed for the space station, was built entirely of aluminum with only fifteen major parts. It had stainless steel rotary bearings and no fabric or soft parts. The size of the AX-5 could be quickly changed, it was easy to maintain, and it offered excellent protection against meteorites and other hazards. Ames also developed a liquid-cooled

garment, a network of fine tubes worn against the skin to maintain the astronaut's temperature. To expedite Ames' efforts in spacesuit design, in September 1987 Ames would open a neutral buoyancy test facility, only the third human-rated underwater test facility in the country. In building these suits, Ames relied upon experts in human physiology, like John Billingham, joining the Center's burgeoning work in the life sciences. Bruce Webbon continued Ames' work on spacesuits and developed technologies suited for extravehicular activity. Well-designed spacesuits also gathered data on the health of the astronaut wearing it. Ames consolidated its work in biotelemetry into a sensor engineering program, led by John Hines and later renamed the Sensor 2000! program.

Ames work in the engineering of regenerative life support systems began in 1979 with a series of workshops, and was followed by a series of grants to university researchers. The primary research goal was defining a mix of plants that satisfied the human diet and improving the energy efficiency of photosynthesis. By 1984 they had achieved energy conversion efficiencies of nine percent with higher plants and eighteen percent with algae. To apply this knowledge to future NASA human spaceflight missions, in March 1990 Ames created an advanced life support division. Initially led by William Berry and deputy Lynn Harper, the division developed bioregenerative and closed loop life support systems that would allow astronauts to colonize the Moon or travel for long periods to distant planets. In 1993 Ames built a ground-based, functional mockup of a self-contained life support system. Called the controlled ecological life support system, or CELSS, it was a twelve square meter greenhouse, that required only fifteen kilowatts of energy, and by using higher plants provided the nutritional needs of one person, while recycling their waste into mineral nutrients and drinkable water and scrubbing the air of carbon dioxide.¹⁵⁸ The Ames group estimated that, compared with resupply from Earth, a CELSS at a lunar station would reach a break-even point within five years.

They also continued working on smaller systems that could be useful in the international space station. Some systems had simple goals—like a self-contained salad machine designed by Robert

MacElroy and Mark Kliss, to grow fresh vegetables aboard the space station. Some improved ways of scrubbing waste products and gases from a spacecraft atmosphere. Some were more complex, like chemical and biological technologies to close the life support loop and enable nearly self-sufficient human habitats in space or on other planets. All of this work made Ames a leading center in the design of biologically sustainable habitats, work that would increasingly become useful in designing habitats for Earth.

SPACE STATION BIOLOGICAL RESEARCH PROJECT (SSBRP)

For more than a decade, Ames led engineering on the space station biological research project (SSBRP)—meant to be a complete and long duration laboratory for biological research in microgravity. The SSBRP would support habitats for a variety of life forms, and all the research efforts would focus on the adaptation of Earthly life to long-term presence in space. The SSBRP would allow NASA to realize some return in scientific research on its massive investment in building the station.

The first report on priorities for life sciences aboard a space station appeared in 1982, and Ames life scientists John Billingham and Kenneth Souza participated in the many committees over the succeeding two decades that honed these research priorities. Ames created a centrifuge project office in 1984, led by Roger Arno, which authored requirements for a centrifuge, drew together a scientific working group, and did hardware feasibility studies on the centrifuge, a glovebox, and primate, rodent and plant habitats. The centrifuge would provide artificial gravity to specimens while in orbit, and thus would be important as an experimental control. In 1992, a separate effort to define a gravitational biology facility was established at NASA Ames to focus on cell and developmental biology. Both facilities were designed as part of an American laboratory, a node, aboard the station.

The SSBRP module was redesigned as often as the space station itself. NASA initially intended for the station to primarily support scientific research, but during the mid-1990s more than \$1 billion was moved from the science facilities to pay for basic construction

of the station itself. In 1994, the two Ames groups were merged in the SSBRP, led by John Givens as program manager and Orlando Santos as chief scientist. NASA tasked them to reduce its cost and complexity—or “descope” the project.¹⁵⁹ The various parts under design would be housed in a single centrifuge accommodation module. In 1995, NASA assigned construction of the centrifuge and glovebox to the Japanese space agency to offset the payment NASA would receive for later launching other Japanese laboratory modules to the station. For the American-built portions of the SSBRP, rather than relying on a single aerospace firm to do systems engineering, Ames integrated the parts from various manufacturers.

Despite the descoping, the SSBRP remained a very complex system. Whereas experiment packages on the shuttle mostly used air from the main cabin, the station habitats were self-contained. This meant additional layers of redundancy and monitoring. The most important piece of equipment was the centrifuge, on which various habitats would house control groups under artificial gravity. The centrifuge initially measured 2.5 meters in diameter, could rotate at selectable rates from 0.01G to 2G, and would be human-rated so that the crew could experience 1G at times during their stay in space. It was also designed so a habitat could be removed without stopping the centrifuge. The human-rating and extraction capability were removed during the 1994 descoping exercise, but the large-scale and long-term exposure of rats to both microgravity and artificial gravity remained a key part of the SSBRP research program.

Three holding racks held microgravity habitats for a variety of life forms: rats and mice, insects, plants, small fresh water and marine organisms, avian eggs, and one-celled organisms. A glove box would allow two astronauts to perform dissections, transfer samples, and conduct photomicroscopy while keeping the biological samples isolated from the rest of the space station. Flash freezers would preserve samples for return to Earth. And a sophisticated data collection system would telemeter data back to scientists at Ames, who would then convey it to university biologists around the world. Ames began to solicit proposals for experiments from collaborating biologists, so that the experiments run on the SSBRP would study

the effects of microgravity on virtually every physiological system.¹⁶⁰

When John Givens retired in 2000, George Sarver became program manager and parts of the SSBRP began to fly. Three pieces of SSBRP equipment tested well on shuttle flights to the space station. Early in 2001, an autonomous radiation monitoring system flew to the station. Later in 2001, an avian development facility, basically a self-contained egg incubator, was flown to the station though it stayed aboard the shuttle. In April 2002 the biomass production system, a versatile plant habitat based on work done for the CELSS program, was controlled onboard the station from Ames. After the station crew successfully completed an experiment on photosynthesis—anticipating the day plants would be used to regenerate the station atmosphere—the habitat was returned to Ames for refinements.

By 2003 all the major technical concerns had been resolved—most importantly on how to isolate any vibrations from the centrifuge from ramifying through the station. The centrifuge had passed its critical design review, all the equipment had been fabricated and stored in a high bay clean room at Ames. Though it had been descoped several times in response to funding cuts, the project remained on budget. Unexpectedly, the SSBRP suffered an ugly death. When Sean O’Keefe saw that total station costs had risen \$4 billion over its planned costs, largely because of a Clinton administration commitment to the Russian part of the program, he decided to cancel the crew habitation module and the X-38 crew rescue vehicle. Station crew would be limited to three astronauts rather than six. Since it took the time of two astronauts just to maintain the station, that meant no time would be available to do research, and thus there was no need to complete the SSBRP. Plus, a human research facility, managed by the Johnson Space Center had mated to the station in March 2001, and was returning biomedical data on changes in humans during prolonged space flight. The station’s international partners objected to the downsizing, and NASA reinstated funding to build equipment that might someday support the larger crew. Still, in response to concerns about the smaller crew size, the Ames SSBRP group studied ways to automate the cell culture unit.

When Michael Griffin again descope plans for the space station to free up funds for the Constellation program, in 2004 he declared the SSBRP non-essential. Congress reinstated funding, which NASA refused. Griffin toured NASA Ames and saw all the equipment built to fly in the SSBRP but remained unmoved: “We just don’t need all this stuff,” program manager George Sarver remembers him remarking.¹⁶¹ In 2005 NASA zeroed out SSBRP funding from its budget, and succeeded in killing it. It also cancelled the work done by the Japanese, though NASA later stood by its commitment to launch the Japanese module. All the hardware constructed was scrapped, with a few parts sent to the station as spares, and three racks built by Boeing sent to Kennedy Space Center for possible future use. More than a hundred jobs were eliminated, mostly within Lockheed Martin Space Operations, the contractor that supported the SSBRP effort at Ames.

Most damagingly, the community of space biologists lost their already irregular access to space. Bion/Cosmos had not flown American experiments since 1997, and after the Columbia accident in 2002 shuttle flights focused on completing the station. In December 2006 Ames and university partners sent the tiny GeneSat into orbit and in May 2009 Ames sent PharmaSat, a small biological nanosatellite, into space. Both were dedicated to single experiments using microbes. Without access to microgravity, many space biologists abandoned their research efforts in gravitational biology. The space life sciences, an enormous part of the intellectual life of the Center since the 1960s, and despite the early success of the small biosatellites, by 2010 was much diminished.

Information Technology

Information technology (IT) at NASA Ames has always been both a research tool and a mission. NASA Ames scientists have often leveraged expertise in IT to bolster their research and collaboration. This chapter focuses instead on how Ames took the lead in developing new IT platforms for NASA. The development of IT platforms at Ames follows two trajectories. The first follows expanding hardware and infrastructure. At Ames, this revolved around the big leaps in technology needed for birthing supercomputers, starting with the Illiac in the early 1970s, extending through the Cray and SGI clusters in the 1980s and 1990s and the Columbia supercomputer in the 2000s. It included pioneering work in internetworking, notably Ames' early role in the development of routing and packet switching technology. Capabilities also include ways to gather and display data, as with Ames' work on pilot perception, cockpit design, telepresence, and new sensors. The display of data includes the development of graphics terminals and virtual reality. Ames' later basic research into robotics also falls into the category of IT-driven capabilities.

The second trajectory revolves around those writing code to solve NASA's problems. The best example of this is computational fluid dynamics, a set of software tools which spread throughout the aerospace industry to allow for modeling of complex airflows before metal was cut. Other examples include climate modeling, vehicle health monitoring, and computational chemistry, especially as it pertained to the birth of the universe and to nanotechnology.

Ames' location in Silicon Valley, the center of the global IT industry, plays an important role in its history in information technology. Did Ames become a center of excellence in IT because it was situated in Silicon Valley, or did it have a role in creating the IT industry that blossomed around it? The answer is that innovation flowed both ways. Much historical literature on the role of Stanford University in the growth of Silicon Valley focuses on spin-offs, of faculty and graduate students forming companies around engineering

ideas. NASA Ames' contributions to Silicon Valley are as important, but different. In Silicon Valley, innovation is driven in part by people moving easily between firms to cross-pollinate technological plans. But Ames people are sticky. Few leave to start firms; most that do leave join the engineering ranks of established firms. Silicon Valley leaders often lament not being able to hire away Ames talent more easily. Lots of NASA-developed technology is licensed out, and NASA documents spin-offs closely. But few NASA spin-offs have been breakthrough products.

Rather Ames' primary contribution to Silicon Valley has been as a good lead customer—in an engineering sense. NASA can let grants to develop interesting technologies before they are far enough along to be called products. Two types of integrated circuits, VLSI and MEMS chips, are good examples of products developed on NASA grants. Through Space Act agreements, NASA Ames can make government facilities available to any variety of corporate partners. The MAE-West router and SGI supercomputers are good examples of technologies developed through partnerships. NASA has a well-developed procurement hierarchy, which means companies get a thorough review of their products, and NASA engineers often understand how the equipment they buy will need to be broken in. Visualization systems are good examples of technologies that Ames people helped shepherd to usefulness. And while the types of information technologies pioneered at Ames has changed dramatically over the decades, one constant has been the value Ames has placed on serving as a partner-like customer.

SUPERCOMPUTING

Computational fluid dynamics (CFD)—using computers to depict air flows—was one of NASA's most important contributions to the American aerospace industry. CFD emerged as a scientific discipline largely because of work done at Ames. Two events mark its birth. Harvard Lomax, a theoretical aerodynamicist, in 1969 formed a computational fluid dynamics branch and recruited a world-class group of researchers to staff it. Second, in 1970, Ames negotiated the acquisition of the Illiac IV, the world's first massively parallel

computer. As with most things at Ames, though, these two birthing events merely accelerated established tradition.

Information technology had a pre-history with the NACA in that Ames in the 1950s actively bought and used digital and analog computers in reducing its data. Computers at Ames initially were women, hired to generate smooth curves from the raw data of tunnel and flight tests using electromechanical calculators and mathematics textbooks for reference. In 1947, Harry Goett bought Ames' first electronic computer, a Reeves Electronic Analog Computer (REAC) and used it to drive simulators to study aircraft stability and control. Under the leadership of Stanley Schmidt in the dynamics analysis branch, Ames procured about a dozen analog computers in the early 1950s, mostly single purpose machines. Ames was the first customer for an analog flight simulator built by GPS Inc., a firm spun off from the Lincoln Laboratory.¹⁶² Using these computers, Ames simulated the flying characteristics of several new aircraft, such as a study of roll induced instability in the F-100A.¹⁶³

Despite the usefulness of analog computing, Ames made an early move into multipurpose digital computing. The first digital computer, an IBM card program calculator, arrived at Ames in 1951. Ames' electrical staff lashed together three accounting machines from the IBM product line—a punch card reader, a printer, and an electronic calculator—and taught it to do mechanical reduction of wind tunnel data. To make better use of this machine, in 1952, DeFrance formed an electronic computing machines division, led by William Mersman, with help from Marcie Chartz. By 1955 Mersman's division had succeeded in connecting an Electrodata Datatron 205 computer directly to strain gauges in the 6 by 6 foot tunnel and the Unitary plan tunnels, making it one of the first computers to do real-time compilations of test results. Now, tunnel operators could see quickly if their setup generated errors that required rerunning a test. In 1955 Ames acquired an IBM 650 digital computer for theoretical work. In 1956, they added a second Datatron computer for wind tunnel reduction both off-line and in real time. Because this was a unique application of the equipment, Ames aerodynamicists also first learned to do their own programming.

For seventeen years, Harv Lomax shared a carpool with Marcie Chartz Smith, a woman computer who joined Mersman's division and who later became chief of the computer systems and research division. Lomax worked on simplified fluid flow equations, developing mathematical approximations of idealized airflows with no fluid friction, heating, compression or turbulence. One morning, Lomax complained about having to redo a hand calculation because he used the wrong integral. Once at work, Smith wrote a one-line equation, pulled priority on the IBM calculator, and Lomax had his answer by eight o'clock that morning. Lomax became an instant convert, though other Ames theoreticians remained unconvinced that computers were here to stay. That changed in 1958 when Ames acquired an IBM 704 digital computer capable of running the Fortran programming language, with which they could calculate area rules that reduced drag on wing-body configurations. Calculations were a batch operation, done in octal dumps, meaning they did not know until after the punch cards finished running if there was a programming fault. So Lomax hooked up a cathode ray tube so he could watch the transactions in process and could stop the run if he saw a fault. Lomax continued to use digital computers for theoretical work in aerodynamics, but largely to automate the mathematics.¹⁶⁴ There was little direct connection, throughout the 1960s, between theoretical computing in aerodynamics and aircraft design.

Ames opened its first dedicated, central computer facility (CCF) in 1961 adjacent to the circle ringing the headquarters building. At the heart of the CCF was a Honeywell 800 which replaced the Datatron and, until it was retired in 1977, collected data from all the wind tunnels for on-line data reduction. The CCF building also included an IBM 7094, used primarily for theoretical aerodynamics. Ames took its first step toward distributed computing in 1964 by adding an IBM 7040 to front-end the 7094 so that the time-consuming input-output efforts were not done directly on the 7094 computer processor. Ames acquired two smaller, short-lived mainframes—an IBM 360/50 in 1967 and an IBM 1800 in 1968. Mainframe computing took a giant leap forward in 1969, when Ames acquired an IBM duplex 360/67 as surplus from the Air Force Manned Orbiting Laboratory project in

Sunnyvale. Now on one time-shared computer, Ames did scientific computing, administrative data processing, and real time wind tunnel data reduction. By adding remote job entry stations around the Center, Ames cut its teeth on distributed interactive computing.

Lomax's principal contribution to CFD was using finite-difference techniques to calculate unsteady flows around aircraft as they reached the speed of sound. Using the IBM 7094, in 1964 he wrote a program to predict flows past blunt-nosed objects during reentry which was widely cited in studies of manned space capsules.¹⁶⁵ His signal contribution came as a mentor, in training students in a new field. More important, he taught them to trust themselves and each other. Too often, graduate students would write a code to solve a problem, publish the results, throw away the code, and then start on a wholly different code. Lomax convinced them to leave their code unmodified, on Ames memory, so that other researchers could refine and verify it. As they did, the codes became more useful to aircraft designers. And by coming to Ames to refine the codes, these researchers were exposed to the problems on NASA's agenda. Ames began to make some headway on computing separated flows, airfoil buffeting, aerodynamic noise, and boundary-layer transitions. The Baldwin-Lomax turbulence model, became the leading application for code validation, as Lomax put it, "in so far as its good points and its bad points are known for more types of flow applications in a wider variety of situation than any other."¹⁶⁶

While NASA Ames had built a solid collection of computers and staff with programming expertise, by the early 1970s its computing capability was hardly unique among federal research facilities. With the acquisition of the Illiac IV Ames leaped to the cutting edge of supercomputing. The Illiac started a new era in supercomputing, in which speed was sought from innovative architecture rather than faster components.

The Illiac IV originally had been built as a research tool in what was then called non-von Neumann computer architecture, and later called parallel processing. Burroughs Corporation built it, with funds from the Defense Advanced Research Projects Agency, based on a design by Daniel Slotnick of the University of Illinois,

for installation in the computer science department at the Urbana-Illinois campus. However, student unrest at campuses around the country, especially at the University of Illinois, made DARPA want to put the Illiac somewhere more secure. When Hans Mark heard through his old friend, Edward Teller, that the Illiac was in play, he asked Dean Chapman, his new chief of the thermo and gas-dynamics division, and Loren Bright, director of research support, to negotiate an agreement that got the Illiac sited at Ames. Chapman and Bright promised that Ames could get the Illiac to work and prove the concept of parallel processing. They also promised Ames would get a return on DARPA's \$31 million investment by generating applications in the emergent field of computational fluid dynamics—using computers to model airflows and thus do the parameter variation phases of aircraft design on computers rather than in wind tunnels.

The Illiac IV arrived at Ames in April 1972. It was the world's first massively parallel computer, with 64 central processing units, and was the first major application of semiconductor rather than transistor memory. For three years, the Illiac was little used as researchers tried to program the machine knowing the results would likely be erroneous. In June 1975, Ames made a concerted effort to shake-out the hardware—replace faulty printed circuit boards and connectors, repair logic design faults in signal propagation times, and improve power supply filtering to the disk controllers. Not until November 1975 was it declared operational, meaning the hardware worked as specified, but it remained very difficult to use. Designed for research in computer science, it lacked even the most primitive self-checking features. The programming language Burroughs wrote for it, called GLYPNIR, was general enough for computer science research but too bulky for computational fluid dynamics. Most CFDers at Ames found it easier to continue writing Fortran codes and running them on existing serial computers.

A few persisted, however. Robert Rogallo began looking at the architecture and the assembly language of the Illiac IV in 1971, even before it arrived. In 1973, he offered a code called CFD that looked like Fortran, and could be debugged on a Fortran computer, but that forced programmers to take full advantage of the parallel

hardware by writing vector rather than scalar instructions. Vector computing meant that programmers wrote algorithms that divided a problem into simultaneous discrete calculations, sent them out to the Illiac's 64 processors, then merged the results back into a single solution. Some problems in CFD were especially amenable to parallel processing. For example, air flow over a wing could be divided into cubic grids—containing air of specific temperatures and pressures—and the algorithms could compute how these temperatures and pressures change as the air moves into a new grid.

Ames acquired a CDC 7600 computer in 1975, built by Seymour Cray of the Control Data Corporation and also surplused from the U.S. Air Force. In translating Illiac-specific CFD language to run on the 7600, Alan Wray wrote VECTORAL, a more general programming language used in some form in all subsequent supercomputers at Ames. Hans Mark felt the younger researchers, who struggled to get the Illiac to work, never appreciated the risk he took in getting the Illiac to Ames. With just these early codes for CFD, Ames had proven the value of locating the Illiac at Ames.

By the late 1970s, Ames leadership began to look for a way to build a more coherent program. Mostly, they wanted a new Cray 1S supercomputer to replace the Illiac. They initially planned to buy one and rent time on it to interested researchers, but instead decided to work around all the problems posed by that plan. Such a large capital purchase would likely be precluded by the Carter administration. If it did get the money, Ames would need to compete the contract, which could take five years, and they would likely end up with a DEC computer which would satisfy the requirements but not do what they wanted. If they tried to sole source the procurement to Cray, there would be protests that would delay delivery of the computer for months.

So Ames leadership defined the NAS as a program. (Initially NAS stood for numerical aerodynamic simulation facility, later changed to the NASA advanced supercomputing facility.) Rather than the NAS being one computer, it was a program whereby one contractor supplied “computer cycles and systems engineering.” The contractor would then buy a series of computers, upgraded as technology

improved, eventually housed in one facility, and internetworked around the United States. This larger vision for the NAS was more palatable within the NASA budget, and the NAS was funded in 1983. As the contractor to support the NAS, in June 1983 James Arnold and Ken Stevens of Ames' astrophysics division encouraged formation of the Research Institute for Advanced Computer Science (RIACS), allied it with the Universities Space Research Association (USRA), and recruited Peter Denning as its director.

Arnold remembers that during a stint at NASA headquarters, he witnessed firsthand how the government works at the administrator's level. On one quiet night, the day before Thanksgiving, Arnold had to write a reclama for the OMB to explain why RIACS deserved funding. Hans Mark was the deputy administrator for NASA and the two had developed a good friendship. Arnold visited Mark on this evening and Mark showed Arnold a hand-written note that he had just composed for the OMB. Because of the note, the funding for RIACS survived. "That's what sold it," recalled Arnold, "I had nothing to do with that. It was all Hans."¹⁶⁷

Though Ames had signalled its commitment to the development of parallel supercomputing, its first hardware purchases signalled their larger vision for the NAS. With the encouragement of RIACS, NAS bought two fairly standard DEC VAX 11/750 computers and named them Wilbur and Orville (back then all computers were given names to facilitate networking). These VAXen were then linked together by ethernet and by hyperchannels, then a fast and expensive way to transfer data between machines. Ames continued to build a network-centric system of these VAXen by using UNIX as their operating system and networking via TCP/IP (for transmission control protocol/internetworking protocol, the communication method on which the internet was built). Wilbur and Orville functioned as a friendly front door to the Crays at the NAS, used for compiling code and data and facilitating internetworking.

Thereafter, supercomputers arrived at the NAS in a regular flow. Ames installed the Cray 1S in 1981, followed by the CDC Cyber 205 in 1984 (the largest ever constructed), the Cray X-MP/22 in

1984, and the Cray X-MP/48 in 1986. In addition, Ames was the launch customer for a variety of mini-supercomputers introduced in the early 1980s—like the Convex C-1, the Alliant FX/8, and the Thinking Machines Connection Machine. The Intel iPSC Hypercube and Sequent Computer supercomputers, installed in 1985, allowed expanded research in parallel algorithms.

Because of the rapid development of new chips useful in parallel computing, the NAS needed a measurable standard by which to assess new processors and their ability to work in the NAS. The result was the NAS parallel benchmarks, a standard released in 1982 to objectively study the performance of parallel supercomputers.¹⁶⁸ It included five kernels and three CFD applications, and was also useful in evaluating new architectural concepts. By the 1990s the NAS benchmark was widely used for evaluating the performance of parallel computers.

All these computing tools attracted computing talent. In keeping with the USRA charter of cross-organizational teamwork, RIACS was designed as a bridge between Ames, the Silicon Valley computer industry, and universities around the world. RIACS forged a match between the scientific problems of interest to NASA and the potential of new supercomputers, then created efficient new algorithms to solve problems in CFD and computational chemistry. Ames researchers focused on theory, while the visiting scholars at RIACS pioneered applications, either patented or open-source. These would come to include new processes for software testing, aerodynamic simulations, autonomous vehicles, and enterprise collaboration.¹⁶⁹

The NAS building opened in March 1987, and gave a physical center to Ames' established expertise in graphical supercomputing, parallel processing, and numerical aerodynamic simulation. At the heart of the NAS was one of the world's greatest central processors, the Cray-2 supercomputer. The Cray-2 had an enormous 256 million word internal memory—sixteen times larger than any previous supercomputer—because Ames CFDers had visited Seymour Cray to impress upon him the need for massive memory that was quickly

addressable. It was the first Cray to run the Unix operating system, the emerging open standard in scientific and university computing, which brought new blood into the field of CFD. It had cost \$30 million, computed a quarter of a billion calculations per second, and had to be cooled by liquid nitrogen rushing through clear plastic tubes. Ames acquired the Cray-2 in September 1985, and had already written the technical specification for the computer that would supersede it.

The Cray Y-MP arrived in August 1988, sporting eight central processors, 32 megawords of central memory, and a \$36.5 million price. The Y-MP performed so much better because its bipolar gates allowed faster access to memory than the Cray-2's metal oxide semiconductor memory. The NAS plan was to always have in operation two of the fastest supercomputers in the world—one fully operational and one going through its shake-out period. By May 1993 the NAS added to its stable of computers the Cray Y-MP C90, then the world's fastest, and six times faster than the Y-MP.

The NAS building itself was sophisticated, flexible, and capable of constant upgrades. As a home for the Cray, it was kept cool and clean by an air system thirty times more powerful than the systems serving any normal office building of 90,000 square feet. NASA expected to fund ongoing operations at the NAS with an annual appropriation of about \$100 million, so the NAS also housed one of the world's great computer staffs and a range of input and output devices. Support processors had friendly names, like Amelia, Prandtl, and Wilbur—the smaller processors named for aviators, the larger ones for mathematicians. The NAS acquired the earliest laser printers and graphical displays. F. Ron Bailey, NAS project manager, directed his staff to provide supercomputing tools for aerospace research which took them into the development of computing technology itself.

INTERNETWORKING

Though the NAS was a physical center for computing at Ames, its tentacles reached into much larger communities. First, around Ames, NAS staff worked directly with wind tunnel and flight researchers to make CFD an important adjunct to their work. Virtually every other research community at Ames—those working

in the life, planetary, astronomical, and materials sciences—found the staff of Ames’ computational branch ready to find new ways to apply supercomputing to research questions.

Plus, the NAS was born wired into the larger world of science. ARPA had decided that its Illiac should be accessible via the Arpanet—an early network of data cables that linked universities and national laboratories. Hans Mark agreed, based on his experience in using supercomputers in the nuclear laboratories following the end of above ground tests. Ames built an IMP, an interface message processor, now known as a router, to connect Illiac to the Arpanet. Notably, it used TCP/IP, a communications protocol that would drive the future growth of the internet. The Illiac became the fourteenth node on the Arpanet and the first supercomputer.

Editors, compilers, and other support software for the Illiac initially ran only on IBM, DEC, or Burroughs computers. Programmers submitted their code while remotely logged into the IBM 360, usually between the hours of midnight and eight o’clock in the morning, and results were returned back over the Arpanet. This made the scientific community more aware of bandwidth and reliability limitations of the network, and to solve those Ames continued to lay cables from the NAS leading to the Arpanet ring around the Bay Area.

A shift to the Unix operating system also spurred the growth of networking at Ames. Budget pressures in the mid-1970s forced Ames to do more with less. Jim Hart, on the technical staff of the computation division, convinced Ames leadership to buy VAX mainframe computers then rent time on them to research groups around the Center. Most VAXen then were operated as stand-alone machines with minimal memory. Hart instead acquired smaller, non-batch VAX computers, with mass storage and graphics capabilities, and linked them together. Beginning in 1978, Ames acquired several VAX computers and soon Ames had the largest DECnet in the world—outside of the Digital Equipment Corporation itself—and a reputation for aggressive development of distributed computing.

Notably, many of these DEC computers ran the Unix operating system. Bill Joy at UC Berkeley, and later a founder of Sun

Microsystems, had first ported Unix to a VAX. Unix was an open source operating system, and thus substantially cheaper than DEC's proprietary operating system. Programmers at Ames also considered Unix more flexible and stable, and VAXen running Unix achieved faster speeds than with the DEC operating system. Ames struggled to get a license for Unix because AT&T, the company that wrote the operating system, was not willing to indemnify Ames for any problems with it. The first Unix machines on Center were bought by RIACS for Dave Nagel in the Ames life sciences division. Nagel wanted to use the computers to expand collaborative work in human factors: including the work of Everett Palmer on cockpit displays, Steve Ellis on visual displays, and Andrew "Beau" Watson on a computational model of human visual motion perception. Ames had access to speech synthesis software that the human factors group made good use of. Soon after, Unix proliferated on the Ames VAXen.

However, VAX computers remained an expensive way to run Unix. In November 1982, Ames computer scientists Eugene Miya, Creon Levit and Thomas Lasinski circulated a message asking "What is a workstation?" specifically, how should a workstation divide with the network and the mainframe the many tasks of scientific computing. They compiled the comments into the specifications for the first graphic design workstations built by local firms with close ties to Ames—Sun Microsystems and Silicon Graphics, Inc. Unix would not have penetrated Ames had not a contracting officer, Rosemary Buchanan who reported to Ron Bailey in the NAS, been able to procure the machines from start-up vendors. With the rise of Unix workstations, most of which supported ethernet networks and TCP/IP, internetworking accelerated. The next piece of technology in the expansion of the internet was the router.

Eric Schmidt of Google and of the Carnegie Mellon University board of directors reflected at the dedication of the CMU class building in October 2003 at the NASA Research Park: "A decade ago one-fifth of all the world's internet traffic travelled through this place, through the MAE-West server at NASA Ames and the NASA Research and Education Network." Ames' place at the birth of the internet is usually attributed to Milo Medin. Medin arrived

at Ames in 1984, after having studied at UC Berkeley and spending a few years programming supercomputers at Lawrence Livermore National Laboratory. As a contractor at Ames through Informatics and Sterling Software, his immediate task was to network the NAS, and NAS leadership encouraged his enthusiasm for building an open network that could link many government research centers.

The dominant networking standards, both at Ames and around the world, were proprietary. Throughout most of NASA it was an IBM protocol, and around the scientific community it was Digital's DECnet. In 1984 Ames, primarily through RIACS, began development work on a local area network for the international space station, called LANES. They chose the dedicated computer-to-computer wiring of the DECnet. Jim Hart, as the civil servant in charge of internetworking at Ames, considered DECnet a good vehicle. Some networks at Ames and elsewhere were already using open-source packet switching TCP/IP internet protocols on local networks, but these networks weren't interconnected.

In 1987, NASA headquarters asked the Ames central computing facility to form a NASA Science Internet project office (NSI) which would merge NASA's DECnet-based network into a secure TCP/IP network. NASA had hoped to achieve operating efficiencies by consolidating networks. The larger the network, the cheaper each site was to support. Furthermore, in 1987 the NSF had started laying fast T1 internet cables around the nation, and within three years would begin laying even faster T3 cables. NASA wanted to be able to manage the increased data flow. Medin and Ames made a commitment to the networking technology that allowed closer collaboration with universities and industry: TCP/IP, servers running the UNIX operating system as refined by Silicon Valley firms like Sun Microsystems, and object-oriented client computers like the Apple Macintosh. The first NSI effort linked Ames with the Goddard, Marshall and JPL centers. It was funded by the NASA office of space science and applications to link project scientists working on Earth remote sensing data.

Through the NASA Science Internet, NASA also got added security. On the night of November 2, 1988 a computer virus, one of

the first, was released onto the network. Medin and John Lekashman of the NAS detected the virus, isolated the NAS from it, then sent notices to systems administrators around the country advising them how to control the virus. Peter Gross at Ames had put the Center on the USEnet communication network, which was how systems administrators then communicated. By the next morning, Ames was swamped with telephone calls from network managers seeking advice on how to apply a software patch and bring their networks back onto the national network. In this one episode, by providing leadership on network security, Ames had proven its value as a central node in the internet.¹⁷⁰

In 1989, Medin built the first interconnect facility at Ames that used TCP/IP to run wide-area networks. Rather than build one huge, expensive network, he built a network of backbone networks, called the federal internet exchange (FIX West) that was at the heart of the NASA Science Internet. Medin and Jeff Burgan also helped develop some of the first router protocols, including OSPF, for the open shortest-path first interior gateway protocol, which permitted routers to exchange information about the accessibility of other networks.¹⁷¹ In April 1990, Medin switched the entire NASA Science Internet to OSPF. By supporting the open standard, NASA Ames helped establish TCP/IP as the major protocol for the internet.

The NSI enabled exchange of data between several government networks (notably the National Science Foundation's NSFNET and its regional BARRnet, the Department of Energy's ESnet, the Department of Defense's MILNET, and DARPA's TWBNET). NSI also had international connections to Japan, Australia, New Zealand, Chile and several European countries. FIX West was the first switch to use a multicast protocol, all ethernet peered. The entire NSI was displayed on an electronic map in the network operations center on Center. By the time the Cray Y-MP was operational in 1989, more than 900 scientists from more than a hundred locations around the United States were wired into the NAS over the internet. By 1994 the NASA Science Internet linked researchers at 175 sites in sixteen countries and six continents (including Antarctica). The NSI was among the largest networks, and certainly the most diverse in the

type of connections. Almost all of Australia's access to the internet globally came through the NSI.

While the NSI was borne of a need to save money by consolidating operations, it expanded through service to specific NASA programs. With the discovery of polar ozone depletion in the late 1980s, NASA called for increased cooperation between science and meteorological organizations around the world, especially on the construction of models of global climate change.¹⁷² NSI built a network, at the request of NASA's Earth Observing System program, that transferred the data—from satellites, data archives, and climate models—needed for this global research program.

NASA Ames had hosted FIX West for five years when, in October 1994, it was asked to build MAE West, the first major interconnect point on the west coast, designed to support the nascent commercial internet. When the National Science Foundation divested itself of the ARPAnet in May 1993 it sold its four nodes to telecommunications firms. The fiber company MFS Inc. bought the network that served the Washington beltway and named it MAE East (for metropolitan area exchange). In October 1994, seeing the explosive growth of internet traffic on the west coast, the NSF asked Ames to extend its interconnection service to everyone. MFS also had an office in San Jose, and using a Space Act agreement to reimburse NASA for the use of federal facilities, connected the Ames FIX with what became the MAE West network. MAE West was many machines, a conglomeration of servers, routers and switches, where diverse networks traded information. MAE West was the first distributed network, in that its machines were located at both Ames and at an office on Market Street in San Jose.

MAE West was the fifth NAP (network access point), and in 1995 there were only five exchange points in the world. By 1995, at the birth of the commercial internet, MAE West handled every federal network, including everything for the White House, as well as the networks of 35 private internet service providers. No one kept accurate statistics on how much traffic went through each node, so as not to alert terrorists to which were the most heavily trafficked nodes. Still, there is likely much truth to the anecdotal estimate of one-fifth

of the world's internet traffic at the birth of the commercial internet travelling through Ames. Medin left NASA in 1995, becoming chief technology officer for @Home Network, the first major provider of household cable modems and cable internet access.

The commercial internet exploded in the mid-1990s, and thereafter NASA Ames came to rely on commercial products for the expansion of its internetworking. The default desktop computer for Ames employees was an Apple Macintosh, which facilitated the integration of desktops with high-end computing. The integration of data archives with high-performance computing underlay NREN, the NASA research and education network, which dramatically improved how researchers in other parts of NASA Ames did their work. Ames work in telepresence and air traffic control was largely driven by the ability to move great amounts of data over vast areas, and make sense of it. Visualization technology enabled computational chemistry to develop into a tool useful to many engineering efforts at Ames. And many of these technologies traced their origins to the maturation of computational fluid dynamics.

COMPUTATIONAL FLUID DYNAMICS

The technology of CFD is transferred via computer codes—generic programs into which aerospace designers enter a proposed design in order to model how air flows around it. The increasing sophistication of these codes—over the two decades that Ames committed itself to CFD—reflected not just the application of greater computing power. CFD was also built upon a concomitant flourishing in aerodynamic theory around the Navier-Stokes equations, and validation of those codes through wind tunnel tests and flight experience.

The Navier-Stokes equations were introduced in 1846, as a theoretical statement coupling various algebraic equations based on the rules of conservation of mass, momentum and energy. The Navier-Stokes equations are so complex that until the advent of CFD aerodynamic theorists avoided the full set of equations. Aerodynamicists won acclaim, instead, by reducing a flow calculation to its essence and then applying the appropriate partial differential equations—either elliptical, hyperbolic, or parabolic. The only flows

they could simulate were for slender aircraft, at small angles of attack, outside the transonic regime, flying in perfect gas with no viscosity and with no flow separation. Thus, even though the advent of Fortran-based computers in the 1960s made it possible to run these so-called inviscid linearized equations in three dimensions, the simplified aircraft configurations on which their calculations were based bore little resemblance to actual aircraft. Nevertheless, Harvard Lomax continued to refine his calculations of supersonic flows over blunt objects, and Robert MacCormack of the Ames vehicle environment division continued to refine his calculations of viscous flows.

In the early 1970s, CFD took a major leap forward with code that allowed the velocity, density, and pressure of air flowing over a realistic aircraft design to be calculated, ignoring only viscosity or flow separations. Ames CFDers wrote codes that generated results near Mach 1 and other speeds where tunnel data were unreliable—codes to model wing-body interactions in transonic flow, the blast wave over a hypersonic missile, blunt bodies, and supersonic aircraft configurations. The first experiment run on the Illiac IV was a model of how a sonic boom changed as it approached ground air. Thomas Pulliam wrote the ARC3D code, which superseded Harvard Lomax's ARC2D code. For the first time, the Illiac allowed three-dimensional portrayals of airflows.

By the late 1970s, with the Illiac IV in more routine operation, CFDers were modeling incompressible flows—flows in which the atmosphere expands or grows denser, adding kinetic energy to the flow and requiring equations that coupled velocity and pressure with temperature. This was the first step toward models of supersonic and hypersonic shock waves, as well as models of turbulent boundary layers. By the early 1980s, CFDers had essentially developed a complete set of Navier-Stokes solutions. They had computed time-dependent flows, which depicted how flows changed over time, rather than time-averaged flows, which showed their general tendencies. Furthermore, they had improved their models of turbulence, from simple eddy viscosity models to finite difference models of turbulence in separated flows. Some, like Helen Yee, worked on

using chaos theory to study turbulence numerically. Ames and Stanford University, in February 1987, formed a joint venture called the Center for Turbulence Research to develop turbulence models to inject into the Navier-Stokes equations. Once these individual calculations were proved theoretically, Ames CFDers coupled them together to push the Navier-Stokes equations to the limits of their approximation. They also packaged them into routine codes with real industrial significance.

At first, CFDers always used tunnel data to validate their computed results. If CFD replaced any types of wind tunnel testing, it was in the parameter variation stage early in the design process, when designers were deciding between gross variations in aircraft configurations. As airframe companies made more complex aircraft, the number of tunnel and flight tests required in the design of any new aircraft grew at an exponential rate in the 1960s and 1970s. Charles “Bill” Harper who led Ames’ full-scale and systems research division, made this argument in a major 1968 address. During F-111 design definition, in the mid-1960s, Ames did 30,000 hours of tunnel tests at a cost of \$30 million. For the Space Shuttle, Ames aerodynamicists planned even more tunnel time. CFD codes, they expected, could eventually eliminate half of this testing in the early design stage. Only in the 1990s did CFDers write code that complete enough to replace tunnel tests for simpler designs. Some especially complex CFD simulations, like airflow around rotors remained routinely verified in wind tunnel tests.

The first major research program at the NAS validated the design parameters for the National Aerospace Plane, a Reagan administration effort to build an aircraft that could take-off from a runway and reach low-Earth orbit. Using the Cray-2, Ames researchers evaluated airframe designs proposed by the three contractors, calculated thermal protection requirements, and suggested ways of integrating the unique scramjet engine into the shock waves around the airframe. Ames’ computational chemistry branch helped by calculating the energies released by air-hydrogen combustion and evaluating the promise of ceramic-ceramic composite heatshields. Of course, others at Ames then validated all these computational results with tests in the wind tunnels or in the arc jet complex.

Thus, in less than two decades, Ames had brought the field of CFD to maturity. Ames people helped design the supercomputers, visualization equipment, and internetworking that linked them. They rebuilt aerodynamic theory around the complete Navier-Stokes equations, wrote the codes for general approximations of airflow, rendered these codes routine design tools, then pioneered codes for more complex problems. Ames CFDers authored code for virtually every flow problem: external as well as internal flows in the subsonic, transonic, and hypersonic regimes. They coupled these codes to encompass more parts and, eventually, model entire aircraft and spacecraft. Ames CFDers then worked up tools of numerical optimization, so that designers could specify the performance of a new design and the code would suggest the best configuration for it. Wing designs, especially, could be optimized computationally so that wind tunnel tests were needed only to verify performance.

Ames CFDers wrote code used in the design of virtually every aircraft in the western world. The Cray version of ARC3D was reportedly used to hone the first Airbus, the A300. Ames developed the general aviation synthesis program (GASP) to do quick configuration studies of general-purpose aircraft. Industrial users included Beech Aircraft, Avco-Lycoming, and Williams International. The code was used to analyze configurations of subsonic transport aircraft with turbo-props, turboprops, prop-fans, or internal combustion engines. It predicted flight performance, weight, noise, and costs, and allowed easy trade-off studies. Ames CFD work helped Orbital Sciences, a start-up company trying to develop the first new American launch vehicle in decades. Under NASA's program for small expendable launch vehicles, Ames CFDers adapted code to hone the design of Orbital's air-launched Pegasus rocket and arranged for flight tests with the Pegasus hanging under the Ames-Dryden B-52 aircraft in November 1989. Boeing and McDonnell Douglas followed the state of the art in CFD to refine their commercial transports, but by far the biggest users of CFD were entrepreneurial firms or the airframe firms designing entirely new fighter aircraft.

Definition of the fundamental fluid mechanics problems of rotorcraft notably lagged behind those of fixed wing aircraft. Those

problems, including stall, transonic flow and acoustics, were first worked out in the 1960s and 1970s during the formative years of CFD. William MacCroskey studied the dynamic-stall problem and, by writing code and devising new ways of gathering flight data, validated rotorcraft designs based on fundamental aerodynamics. The Ames-Army CFD team developed path-breaking code on airfoil stall, acoustic wave propagation, tip vortex interaction and rotor-body flow interactions. CAMRAD was a comprehensive code capable of analyzing various rotor configurations—tandem, counterrotating, and tilt rotor—used to predict blade loads, aeroelastic stability, and general performance. ROT22 was a code for rotor field flows, applicable from hover to forward flight, and was three-dimensional, transonic, and quasi-steady. The Ames rotorcraft CFD team produced the first Navier Stokes simulations of a complete rotorcraft, the V-22 Osprey in helicopter mode in forward flight.

For designers of supersonic inlets, Leroy Presley of Ames devised the first three dimensional internal flow code. In 1988, Ames researcher Man Mohan Rai published a code to model the complex pressures, temperatures, and velocities within a jet turbine engine. Engine parts moved constantly relative to each other, clearances were tight, and pressure changes produced by entering air created unsteady states. Controlled experiments of engine prototypes were expensive. Rai's model not only solved unsteady three-dimensional Navier-Stokes equations but did so for complex geometries. It first needed 22 trillion computations, performed on the Cray-XMP at the NAS, before others at Ames set to work simplifying the code to make it a practical tool for industrial design. A highly accurate method for transferring calculated results between multiple grids was the key to Rai's model, and this method later found extensive applications to multiple rotor-stator aircraft.

Some NAS programmers applied their codes to the solution of peculiar problems which then shed light on more general solutions. To depict flows within the space shuttle engines, Ames CFDers Dochan Kwak, Stuart Rogers and Cetin Kiris created a program called INS3D (an incompressible Navier-Stokes solver in general three-dimensional coordinates). Because it was useful in modelling

low-speed, friction-dominated flows, in 1993 the group also applied the code to model air flow over transport aircraft at take-off and to improve a mechanical heart developed at Pennsylvania State University.

In 1996, Ames researchers began work on algorithms to simulate steady state flows in three dimensions using Cartesian grids. This was released as CART3D, an inviscid analysis package for preliminary aerodynamic design. CART3D was suitable for a wide range of vehicles, including aircraft, spacecraft, ships, submarines, race cars and trucks. CART3D automated grid generation, speeding up the modeling of complex geometries by a hundred times over previous methods. In 2002, CART3D won the NASA software of the year award. A month later a patent was awarded and CART3D was commercialized. CART3D helped resolve the physical cause of the Columbia disaster, by simulating the trajectory of tumbling debris.

Another project that displayed the utility of CFD was the discovery of vortex burst on the F-18 fighter aircraft. The leading-edge strakes on the F-18 generated strong vortices, and when the aircraft flew at high angles of attack these vortex bursts induced a rolling moment. Using CFD, David Kenwright at Ames demonstrated how these vortices turned turbulent.¹⁷³ In 1991, Ames researchers put a full scale F-18 into the NFAC and verified their models of the burst and some strakes to mitigate it. As part of a larger NASA research program on high alpha technology, the F-18 then moved to Ames-Dryden where it flew as a test bed for thrust vectoring research.¹⁷⁴

Not all of Ames supercomputing focused on modeling airflows. In fact, only twenty percent of the computing time on the Illiac IV was spent on aerodynamic flows, and only a slightly higher percentage on the Crays that followed it. Various users, overseen by Melvin Pirtle of RIACS, also spent computer time modeling climates, seismic plate slippage, radiation transport for fission reactors, and the thermal evolution of galaxies. When the NAS became available, Ames people wrote codes to extract aerodynamic stability derivatives from flight data. Airframe designers worldwide used this code to acquire aircraft parameters from flight data, and thus validate aerodynamic models, update simulators, design control

systems, and develop flying qualities criteria. Ames people wrote the hidden-line algorithms underlying most computer-aided design. This code depicted large, complex, engineering renderings faster than ever, and could be applied to aircraft design, architecture, and systems design. It became the best-selling software in NASA history. But the biggest use of Ames supercomputers, apart from CFD, was for computational chemistry.

COMPUTATIONAL CHEMISTRY

Aerothermodynamics and heatshield research brought computational chemistry to Ames. James Arnold had spent his entire career, starting in 1962, analyzing the chemical properties of shock-heated air and other planetary gases, and how these atmospheres interacted with ablating materials on heatshields. Ames had built shock tunnels and simulators used on Earth to experiment on atmospheric entry, though at great expense. With his colleague Ellis Whiting, Arnold saw ways to apply Ames' emergent infrastructure in supercomputing to solve problems in atmospheric entry physics. Ames' growing infrastructure in computational chemistry, though, would benefit many fields.

As a young man growing up in the Midwest, Jim Arnold might have pursued his early passion and become an automobile mechanic. Arnold was at a junior college in Kansas City, Missouri when Sputnik launched in October of 1957. He went to the University of Kansas where he completed a degree in engineering physics. With a dream common to many midwesterners, Arnold moved to California. He began his career at Ames in 1962 just as the Apollo program began in earnest. In his first week at Ames, Arnold turned around and there stood Harvey Allen, interested to hear about Arnold's work. Within two years, Arnold had his first publication, a NASA technical report co-authored with Bill Page, on shock layer radiation.¹⁷⁵ Arnold was amazed at how quickly he had gone from a farm in Kansas to the cutting edge of space travel.

Shock layer radiation defined much of Arnold's work over the next decade, as would his work with Alvin Seiff. Arnold always

left meetings with Seiff excited about his work, even though the meetings were sometimes scientifically daunting. Arnold and Whiting designed the multi-channel radiometer aboard the PAET, Seiff's landmark atmosphere probe launched in 1973. Arnold focused on radiation from the gas cap, the hot gases produced in the bow shock wave of the entry body which generated a unique spectral fingerprint from which he could deduce the chemical composition of the atmosphere.¹⁷⁶

With Ames' funding, Arnold continued his education. He earned his master's degree from Stanford University in aeronautics and astronautics and his doctorate in molecular physics from York University. Arnold's thesis was based in part on work he had done at Ames. The cyanide molecule was then of much interest, both in its bond association energy and transition moments.¹⁷⁷ Cyanide as a shock layer product might provide insight into the composition of the Martian atmosphere. His doctoral research and collaboration with Whiting drove Arnold's interest in theoretical chemistry and ultimately to the establishment of computational chemistry at Ames.

Arnold recalled his first encounter with Hans Mark in 1969:

"I got back from Toronto and thought I was hot stuff. My branch chief, Bill Page, asked me to give a talk on another person's work. As I was discussing his measurements of transition moments for the carbon monoxide molecule this tall guy I'd never seen before said, 'Why don't you compute those?' I got up there and I wrote out Schrödinger's equation and I said, 'There it is, but you can't solve it.' Fred Hanson backed me up. The tall guy was Hans Mark, and he had been doing calculations on transition moments on atoms while he was at Livermore."¹⁷⁸

Unabashed, Arnold and Whiting approached Mark and proposed to develop the field of computational chemistry, so they could compute gas properties rather than relying on measurement. Mark responded enthusiastically. While Mark was visiting NASA headquarters he

secured \$50,000 in research funding and computational chemistry at Ames was born. They were supported by Dean Chapman who had pioneered theories of aerothermodynamics and, as director of astrophysics, helped lead Ames into CFD.

At the time, researchers at Argonne National Laboratory had some success with diatomic fluorine predictions that showed the potential for reliable computations of the gas properties of small molecules. Whiting and Arnold visited and returned with computer code they adapted for the Illiac IV at Ames and a CDC 7600 at Livermore. Together with G.C. Lyle, they developed code to predict the spectra resulting from electronic transitions of diatomic molecules and atoms. These predictions were done faster and cheaper than measurements in a shock tube. With the success of this work, Arnold, now branch chief, hired young researchers like Richard Jaffe, Stephanie Langhoff and Charlie Bauschlicher. They were joined by David Cooper who also earned his doctorate from York University with a thesis on the carbon molecule.

Around 1980, Bill Ballhaus asked Arnold to spend a year at NASA headquarters, working with the associate administrator of OAST to sell the idea of the NAS. He proved remarkably effective and the NAS was funded for a 1984 start. After Arnold's promotion to chief of the thermal and gas dynamics division, Cooper served as the NAS supercomputer division chief and they spent years as peer division chiefs, able to support both the hardware and applications work for computational chemistry. Ames' computational chemistry branch developed, under Arnold's leadership, into a unique resource in NASA.

Academic chemists had computed results that were accurate only for single atoms. Fairly quickly, computational chemists at Ames—including Langhoff, Bauschlicher, and Jaffe—developed tools to predict rates of gas-solid chemical reactions involving thirty atoms, predicted forces in molecules and atomic clusters as large as 65 atoms, and simulated material properties involving up to 10,000 interacting atoms. Applying this work to problems of interest to NASA, they designed polymers that were resistant to degradation by atomic oxygen and improved noncatalytic thermal protection

systems. Computational chemists explored several species of ablative materials for the heatshield of the Galileo Probe—which had to be well matched to the atmosphere of Jupiter—and derived the radiative cross sections and absorption coefficients of these species to determine what data was required to design the heatshield.

With these tools in place, David Cooper led the Ames computational chemistry branch to apply its research to other problems. To develop better aircraft fuels, Ames explored the chemistry of transition metals used in catalysts. To understand gas properties in aircraft engine flows, Ames computed bond energies and gas transport properties more precisely than ever done experimentally. To develop smaller robotic vehicles, better computer memory devices, and other nanotechnologies, Ames calculated how to make materials bond at the molecular level. To understand the chemical evolution of the solar system, Ames calculated the composition of unidentified spectra observed from space telescopes. Within a decade, Ames had nurtured computational chemistry into a discipline of major importance to American industry and NASA.

Most important, virtually the entire first generation of CFDers and computational chemists had circulated through Ames in order to use the best machines, to try out new code, and to train with the best in the field. As Ames computational experts saw their fields mature, they reinvented themselves as pioneers in new areas of information technology like artificial intelligence, virtual reality, and distributed networking.

INTELLIGENT SYSTEMS AND TELEPRESENCE

In the early years of artificial intelligence (AI), symbols rather than numbers were used to represent information, and heuristic rules structured this information rather than the yes/no algorithms used in numerical computation. In 1980 Henry Lum acquired a computer that ran the LISP (for list processing) computing language, and used it to develop the symbolic language of artificial intelligence. By 1984, Lum had established an artificial intelligence plan for NASA Ames. Increasingly, Ames researchers focused specifically on communications protocols for integrating various artificial

intelligence agents, as needed to guide spacecraft or manage complex and changing projects. The goal was to construct rational agents that could acquire and represent abstract and physical knowledge and reason with it to achieve real-world goals.

Pentti Kanerva's work on sparse distributed memory made neural networks a standard approach in robotics and speech and vision recognition.¹⁷⁹ A sparse distributed memory system mimicked human long-term memory. It stored long patterns, up to thousands of bits of data, that represented encoded sensory data and retrieved patterns when presented with clues. Bayesian statistics was likewise an important approach in Ames work on intelligent systems. The AutoClass software suite, developed by Peter Cheeseman, found unexpected classifications, or groupings of like things, in large data sets.¹⁸⁰ AutoClass was the first AI software to make a published astronomical discovery. In July 1989 AutoClass detected statistical patterns indicating a new class of infrared stars in data from the IRAS low resolution spectral catalog.¹⁸¹ AutoClass was used for other astrophysical discoveries, as well as discovery of new classes of proteins and introns in DNA sequence data. AutoClass won a 1992 NASA space act award and was cited in numerous patents.

Ames formed an information sciences division in June 1987 to apply artificial intelligence to space missions. NASA had plans for an autonomous Mars rover and Ames hoped to provide the technology for many such intelligent agents. The enormity of NASA's just-announced space station, for example, required on-board automation for many of the housekeeping functions that would otherwise need to be done by astronauts. Ames' artificial intelligence branch looked at the scheduling of shuttle orbiter ground processing and developed software that, beginning in 1993, saved NASA \$4 million a year in shuttle maintenance. "Shuttle refurbishing is a difficult problem because you can only predict half of the work in advance," noted Monte Zweben. Zweben led a team of contractors at Ames and the Johnson Space Center, shared in the largest Space Act award ever granted by NASA, then left to start up a company to program scheduling software for industry.¹⁸² Peter Friedland led a group working with JSC to automate Shuttle mission control and

reduce human-intensive tasks by forty percent. Silvano Colombano worked with MIT researchers to develop the astronaut science advisor, a laptop computer running artificial intelligence software that helped astronauts perform spaceborne experiments as they unfolded. Astronauts referred to it as the “PI in a box”—like having the principal investigator on board. While the Ames information sciences division contributed to larger NASA missions, for missions not yet conceived they continued to refine the basic principles of artificial intelligence.

Artificial intelligence enabled humans and robots to work as an integrated team of rational agents when coupled with the technology of virtual reality and telepresence. In 1984, when Michael McGreevy, a researcher in spatial information transfer, learned that a head-mounted display developed for the Air Force would cost NASA a million dollars, he pulled together a team to build its own. The result was VIVED (for virtual visual environment display), the first low-cost head-tracked and head-mounted display, with stereo sound and a wide field of view. McGreevy soon built the first virtual environment workstation by integrating a number of components, including the VIVED helmet, a magnetic head and hand tracker, a custom-built image conversion system, an Evans & Sutherland vector graphics display, a DEC PDP-11/40 computer, and software he wrote that generated and displayed three-dimensional stereoscopic scenes of commercial air traffic in flight. It was the first major advance in wearable personal simulators since the laboratory systems built by Ivan Sutherland in the 1960s. By 1987 NASA boosted the budget thirtyfold for this work in virtual reality.

A whole industry was built around virtual environments, with many of the major innovations inspired or filtered through Ames. Start-up VPL Research of Redwood City commercialized the VIVED design and supplied low-cost virtual reality systems around the world. Scott Fisher, who joined Ames’ virtual reality team in 1985, worked with VPL to develop a data glove for computer input. Though the first systems at Ames used Evans & Sutherland vector graphics, Ames later used some of the first raster graphics systems.

Jim Clark credits the many image generation projects at Ames with helping his start-up company, Silicon Graphics, Inc. (SGI) of nearby Mountain View.¹⁸³ Beginning in the early 1980s, 3D imaging became commonplace in the entertainment industry—in films, television, cartoons and video games—as well as in engineering, manufacturing and medicine. In 1980, Jim Clark, then a computer scientist with Stanford University, introduced himself to Jim Hart of the Ames computer systems division. He heard that Hart, who managed all research on visualization for CFD, had purchased an Evans & Sutherland display. Hart created some research contracts for Clark to develop algorithms needed for visualizing the aerodynamic fluid flows around jet aircraft. CFDers at Ames were already modelling such flows on their Control Data and Illiac computers, generating massive amounts of data that proved difficult to understand when printed in two-dimensions on a page. Using the algorithm he devised at Ames, Clark built a sophisticated chip, a pioneering example of very large scale integration or VLSI, dubbed the Geometry Engine. This chip was transformed CFD data into visual portraits in three dimensions, portrayed on a computer screen. With subtle shading of different surfaces, these images were more intuitively understandable to the human eye. Furthermore, the images were conveyed in real time and allowed multiple views of the object under study.

SGI bundled these chips with video displays into its IRIS workstations and, with a \$2.9 million order placed in September 1984, Ames was its launch customer.¹⁸⁴ Marcie Smith and Ken Stevens were the computer scientists in the NAS who understood the promise of the SGI system. SGI headquarters were less than a mile from Ames as the crow flies (Google would occupy that building after 2003). One of the biggest selling points for the IRIS workstations in other industries was the depiction of fluid flows emanating from the NAS. Engineers could envision the complex airflows around an aircraft as it broke the sound barrier, then see what would happen as they tweaked the design. With useful CFD codes ready to run, aerospace firms adopted both supercomputers and SGI workstations. Because Ames had encouraged SGI to adopt the Unix operating system and

TCP/IP for the IRIS, engineers around the world could network into the Ames supercomputers via their SGI workstations. They could send their simulations to run on the remote supercomputers, then view their results the next morning on the SGI workstations in their offices.

SGI realized that to succeed they needed to make their workstations useful beyond CFD. SGI worked with Ames on 3D landscapes for flight simulators and on simulating the evolution of the universe following the Big Bang. SGI then worked on code for oil prospecting, weather forecasting, automobile design, parts manufacturing, and viewing scans for medical diagnoses. In the late 1980s, Industrial Light and Magic and Tippett Studio in Berkeley began to use the SGI workstations for film work, and the breakthrough for SGI computers came with *Terminator 2* and *Jurassic Park*. By 1997, after fifteen years in business, SGI's annual revenues topped \$3.6 billion.

Ames work in virtual reality also depended on new tools for real-time computing. Working with Sterling Software, an Ames support contractor, Ames people developed the mixture of peripherals and interfaces for data acquisition, telemetry, computer animation, and video image processing to compute and portray data points as they were collected. More immediate access to data made virtual reality of use in space exploration. Virtual reality put Ames at the forefront of human-centered computing. With human-centered computing, people would not consciously interact with the computer itself but rather interact directly and naturally with remote, computer-augmented or computer-generated environments. NASA saw the value it might have on the space station, by allowing astronauts to control robotic devices around the station. Ames used images generated by CFD to build a virtual wind tunnel—wherein the wearer could walk around a digitized aircraft and see the brightly colored lines depicting airflows. Elizabeth Wenzel of Ames' spatial auditory displays laboratory led a university and industry team developing virtual acoustics using headphones to present sounds in three-dimensions. Stephen Ellis and Mike Sims developed other key components of virtual reality.

Space scientists at Ames saw other uses for telepresence in

virtual planetary exploration. As NASA's planetary probes returned digital data on the planets—like Magellan's mapping of the surface of Venus—Ames used that data to project images through a personal simulator. It gave anyone—geologists, astronaut trainees, journalists or schoolchildren—the feeling of being there. They used the panoramic views returned from the Viking landers to plan the digitization technology for the Mars Pathfinder, then tested this technology on remotely operated rovers. Prototype rovers imaged the hostile terrain around Death Valley, Antarctica, the volcanoes of Alaska and Hawaii, and underwater in the Monterey Bay. The Marsokhod Rover, lent to Ames in 1993, was a superb platform on which to test the technology of telepresence.

Work in human-centered computing at Ames took a major leap forward in 1990 with the dedication of a new human performance research laboratory (HPRL). David Nagel had championed the laboratory to house Ames' aerospace human factors research division. After all, Ames' traditional work in flight simulators and fly-by-wire technology was a form of telepresence. In addition to supporting Ames' longstanding work in aviation flight training, cockpit resources, and pilot and controller performance, the HPRL brought together researchers working to solve the problems of extended human presence in space, like with Vic Vyukal's work in spacesuit design. In the HPRL Ames continued its work on how to make spacecraft more habitable by investigating microgravity restraints, visual orientations, and changes to circadian rhythms.

Built adjacent to the human factors laboratory was the automation sciences research facility (ASRF) so that experts in human factors and artificial intelligence could collaborate. The ASRF opened in January 1992, four months ahead of schedule and \$500,000 under its \$10 million budget. The ASRF provided office space for the growing number of artificial intelligence and robotics experts at Ames, led by information sciences division chief Henry Lum. It also provided eleven superb laboratories. In the high bay, Ames built a simulated lunar terrain and used it to test intelligent systems for a rover that would explore planetary surfaces. "We consider it our responsibility to not only promote the productivity of people housed in space,"

noted Ames environmental psychologist Yvonne Clearwater, “but to assure that once there, they will thrive, not merely survive.”¹⁸⁵

CENTER OF EXCELLENCE IN IT

“The future of NASA lies in information technology and information systems,” proclaimed administrator Dan Goldin in May 1996 in a ceremony designating Ames as the NASA center of excellence for information technology (COE-IT). The COE-IT developed rapidly, directed by Jack Hansen and then Kenneth Ford, with operations led by to Steven Zornetzer. Zornetzer was a neurobiologist who had studied how the brain processed information, hoping to mimic those processes in the design of artificial systems. He taught at the medical school of the University of California at Irvine, then directed the life sciences program at the Office of Naval Research. Ford introduced Zornetzer to Harry McDonald, who was looking for someone skilled at managing the intersection of Washington with cutting-edge research. Zornetzer appreciated that “Goldin asked NASA to be bold, take risks, hire the best people, then let them attack the biggest problems, like human-centered computing.”¹⁸⁶

Zornetzer was no computer scientist, but when he arrived in 1997 he managed a staff of 700 of them with authority to hire a hundred more. This was during the internet boom in Silicon Valley, and Zornetzer was able to hire well by offering computer scientists interesting problems and the freedom to attack them. For example, he hired Peter Norvig, a Silicon Valley millionaire, to turn the computational science directorate into an intelligent systems directorate and apply artificial intelligence to NASA’s exploration missions.

The COE-IT served as the center of a virtual corporation that linked NASA Centers, industry, and academia into tight-knit teams. These teams developed enabling technologies in modeling, database management, smart sensors, human-computer interaction, and high-performance computing and networking. These enabling technologies then supported NASA’s missions—like networking data for simulations, improving efficiency in aviation operations,

and developing autonomous probes to make space exploration more frequent, reliable, and scientifically intense. By the mid-1990s internetworking had become commercial and commodified, so Zornetzer convinced McDonald to move any continuing research on internetworking and the management of Ames' IT infrastructure into the center operations group so that he could focus on new application of IT. Furthermore, all of Ames' expertise in human factors then worked in aeronautics, so Zornetzer convinced McDonald to move half of them into his division where they could work on human centered computing. The COE-IT was more than a simple reorganization. It simplified the funding relationship with NASA headquarters, and allowed Ames to build out unique capabilities. Ames became NASA's lead for supercomputer consolidation. Consolidation began with an inventory of NASA's high-performance computers—including central computer facilities, the NAS facility, and the testbed supercomputers—and identified forty systems with a total purchase price of \$300 million. Consolidation continued with Ames matching the right computer to the right job within NASA.

One Ames effort integrated into the CoE-IT was the NASA Center for Bioinformatics, which had opened in August 1991 with a dazzling display in the Ames auditorium by Muriel Ross. A biologist specializing in the neural networks around the vestibular system, Ross joined Ames in 1986 for access to its supercomputing. She suspected, and later experiments confirmed, that exposure to microgravity caused the inner ear to add new nerve cells. She also suspected, rightly, that this rewiring could only be accurately depicted in three-dimensional models. Reconstructing the architecture and physiology of this expansive neural network was painstaking work. Ross worked with programmers in the NAS to devise a technology for reconstructing serial sections of a rat's vestibular system into a three-dimensional computer model. This combination of supercomputing, internetworking, and telepresence stood as a model of what the COE-IT might achieve.

Ross' efforts paved the wave for Ames' work in virtual surgery. Ames' artificial intelligence experts explored this model for clues about building neural networks with computers. Ames experts in

virtual reality bought a prototype virtual boom from Fakespace Corporation and linked it with Silicon Graphics workstations to project reconstructed images into the first immersive workbench. There, surgeons could rehearse difficult procedures before an operation.

The Center's next step was to build collaborative networks with other NASA centers using emergent Silicon Valley networking technology. Stanford University Medical Center was first, followed by the Cleveland Clinic Foundation, then the Salinas Medical Center, and the Navajo nation. With each new collaborating clinic—each more distant and less sophisticated in computing—Ames tested technologies for doing remote medicine, preparing for the day when astronauts many days distant on the space station might need to respond to medical emergencies. In the meantime, the Center became a national resource that allowed investigators to apply advanced computer technology to the study of biological systems. When challenged to apply its skills to a national initiative in women's health, the Ames Center for Bioinformatics developed the ROSS software (for reconstruction of serial sections) to provide very precise three-dimensional images of breast cancer tumors.

Ames made telepresence into a useful tool for planetary exploration. In the late 1980s, the Ames space instrumentation and studies branch, led by G. Scott Hubbard, developed mission plans for the Mars Environmental Survey (MESUR). The plan was to build a global network of sixteen landers around the Martian surface—each capable of atmospheric analysis on the way down and, once on the surface, of performing meteorology, seismology, surface imaging, and soil chemistry measurements. Because the network could grow over several years, the annual costs would be small and the landers could be improved to optimize the scientific return. With the data, NASA could pick the best spot to land a later human mission to Mars. However, in November 1991, NASA headquarters transferred MESUR to JPL, where it was trying to centralize work in planetary exploration. JPL transformed the idea of the MESUR lander in to the single Mars Pathfinder, which roved across the Martian landscape in July 1997. Pathfinder was an exciting early step in human telepresence

on Mars. Ames continued developing the technology to support telepresence missions to Mars. In January 1992, Geoffrey Briggs was appointed scientific director of Ames' new Center for Mars Exploration (CMEX). Since the Viking missions of the mid-1970s, Ames maintained a world-class group of scientists specializing in Martian studies across a broad spectrum. CMEX brought all of this expertise—especially in robotic spacecraft and data processing—to bear on questions on the geographical and atmospheric evolution of Mars.

“Antarctica is the most Mars-like environment on Earth,” said Carol Stoker of the Ames telepresence technology project. “We’re taking this technology to a hostile environment to conduct research that has direct application to NASA’s goal of exploring Mars.”¹⁸⁷ In December 1992, Stoker and Dale Andersen tested telepresence technology on mini-submarines exploring the sediments under the permanent ice covering Antarctic lakes. The next Antarctic summer they returned with a rover with stereoscopic vision, not only so they could generate a three-dimensional terrain model of McMurdo Sound but also so the teleoperator had depth perception to better collect samples with the rover’s robotic arm. Back at Ames, Butler Hine controlled it using a teleoperations headset developed by Ames’ intelligent mechanisms group. They were linked via a powerful satellite and internet connection put together by Mark Leon and the NASA science internet team. The COE-IT was making the tools of scientific telepresence more useful.

Remote Agent was the first artificial intelligence to control a spacecraft without human supervision. NASA’s Deep Space-1 spacecraft, launched in October 1998, was the first mission under NASA’s new Millennium program to test the innovative technologies for truly “smart” spacecraft. One new technology was Ames’ AutoNav remote agent that rendered the spacecraft capable of independent decision-making so that it relied less on tracking and remote control from the ground. In May 1999, for the first time, an artificial intelligence program was given primary control of a spacecraft. Then in July 1999, after getting a brief instruction to flyby the asteroid 9969 Braille, the DS-1 remote agent evaluated the state of the spacecraft,

planned the best path by which to get there, and executed a flyby no more than ten miles from the asteroid. The Remote Agent laid the foundation for autonomy in future robotic space flight. The Remote Agent team was honored with the NASA software of the year award, and was widely considered one of the top achievements in the history of artificial intelligence. It also validated much of the automated scheduling software used for the Mars Exploration Rovers. RIACS scientists based at NASA Ames developed MAPGEN, a ground-based human-in-the-loop control system used to generate plans for the twin Mars rovers. A few days after its landing in January 2004, command sequences created from MAPGEN activity planning software brought the MER Spirit to life. MAPGEN was used to plan activities for every day on the Martian surface, and the MER science team credited it with boosting scientific yield by thirty percent. The core of MAPGEN was the Europa artificial intelligence suite, which RIACS released as open-source software, and which subsequently found wide adaptation.

Zornetzer himself spearheaded a research effort in bioinspired engineering, which culminated in a prototype Mars airplane flight-tested in 2001. It was designed to be released into the Mars atmosphere from a high altitude, unfold, and with a solar-powered engine fly at low altitude over the Martian landscape taking high resolution images of geologically interesting locations below. The concept required thorough knowledge of the Martian atmosphere, as well as new methods of artificial intelligence for aircraft navigation. Using neural net algorithms, it flew autonomously around Moffett Field.

The Ames CoE-IT, managerially, was increasingly integrated into the Ames information science and technology division as applying this expertise became more routine. Ames assumed oversight of the NASA facility in Fairmount, West Virginia that independently tested and validated new software for space projects. Ames applied its skills to test Shuttle avionics software, to make commercial software compatible with proprietary software already used in the Shuttle, and to create an integrated vehicle health management to further expedite Shuttle maintenance. Ames also applied its expertise to help

NASA develop aerospace hardware quicker and cheaper, with less technical risk. Integrated design systems, for example, let engineers see and test a system before metal was ever cut. Ames information technologists had systems to translate, in real time, massive amounts of data into images, which proved useful in monitoring environmental changes—like fires, hurricanes, and ozone holes—from space. And Ames information technologists applied their expertise to solve the logistics and information problems of the airspace system.

Earth science was an especially intensive user of information technology. In 1996, Ames and SGI signed a cooperative research arrangement as part of the Ames COE-IT. SGI introduced its Onyx and Origin supercomputers, and the NAS again served as launch customer. Ames encouraged SGI to develop a shared memory architecture whereby many chips operating in parallel served as a single system that modified the same memory. Using those computers, NASA scientists built detailed models of ocean circulation and its impact on climate. Notably, they predicted and displayed the periodic warming of the Pacific Ocean during the El Nino years of the late 1990s. While Ames cooperated fruitfully with SGI over the coming decade, this marked the high point of SGI as a Silicon Valley powerhouse. Visualization programs migrated to cheaper servers, offered by companies like Sun Microsystems and Hewlett Packard, and SGI stuck to the high end of the workstation market. SGI bought Cray in 1996 to enter a higher end of the market, supercomputers, but divested itself of Cray within four years. In May 2006 SGI declared bankruptcy and, though it emerged from reorganization soon after, its position in the visualization market remained small.

Ames was also challenged financially. The concept of centers of excellence throughout NASA died in 2003 as Sean O’Keefe consolidated program responsibility in headquarters. IT funding was pulled from Ames, and many IT specialists finally left for the private firms swelling during some boom years in Silicon Valley. Ames remained the primary conduit for advanced information technology flowing into NASA, though it grew less revolutionary. What NASA called the “technology readiness level” of its research grew shorter,

and Ames worked on tools needed for missions launching sooner. A period of radical innovation in IT was drawing to a close.

REBIRTH OF SUPERCOMPUTING

Though IT in the service of space exploration had blossomed, comparatively supercomputing had stagnated. By the turn of the century the NAS was struggling to provide adequate computing power, as needed for global models of climate change. Walt Brooks, the NAS director, asked his staff to explore the potential of Intel Itanium processors in an SGI Altix system, and they mocked up a system using 512 Altix processors. They named it for Kalpana Chawla, the astronaut who perished aboard the Columbia and a former CFD researcher at Ames. This system proved such systems could produce great speeds, cheaply. Scott Hubbard issued a challenge. If Brooks could build a supercomputer in four months, Hubbard would find funds for it.

On 18 June 2004, Congress funded the project, named Columbia. Team engineers—from SGI, Intel and the NAS—designed a high speed internal network that efficiently linked the processors, upgraded an internal fiber network for system users, developed a robust computer security architecture, and modified facility power and cooling systems with under floor water piping. The first two SGI Altix 512-processors systems were installed on June 28, ten days after start, and quickly networked. By the end of the first week, one system was running operational codes for work on the Shuttle return to flight. One month later, it produced its first results. By 2 August, more processor nodes arrived, along with six new power distribution units, and the Kalpana system was merged into Columbia. The NAS itself was replumbed and rewired to accept the new system, work completed by September. Twelve more SGI Altix systems were installed in September, bringing Columbia to ninety percent completion, and NASA staff began to test integration approaches with a Linpack benchmark.

By September, the Columbia visualization team developed a way to view simulations of Hurricane Frances. Using the line integral convolution technique developed by the NAS, the team deployed

the new method on the finite volume global circulation model (fvGCM). They corrected some hardware errors in October, and the Columbia achieved a Linpack benchmark speed of 42.7 teraflops, well exceeding the speed of the then top system, the Earth Simulator in Japan. On October 25, four months and a week from start, all twenty nodes—more than 10,000 Intel processors accessing twenty terabytes of memory—ran for the entire nine hours needed for the Linpack run. The numbers were reported to the Linpack organization, to be publicly released at the supercomputing conference SC2004 in November. Then Columbia immediately went to work. Eight nodes were dedicated to return to flight simulations, six nodes for science applications, two to refine the efficiency of the system, and four nodes were used by SGI to test their Altix 3700-Bx2 technology.

The Linpack numbers showed that Columbia ran at 51.9 teraflops, making it the second faster computer in the world (an IBM machine had topped it the week before). With this one machine, NASA computing power increased ten-fold. Columbia remained NASA's most powerful computer until 2008. The Columbia first ran simulations of debris flow patterns to support the return of the Space Shuttle to flight. Within a year, the Columbia allowed a complete CFD simulation of the Shuttle's ascent from launch to orbit. The Columbia was also used to model the interaction of climate and sea ice, study the evolution of the dark matter halo that envelops the Milky Way galaxy, and help scientists understand the evolutionary history of our galaxy.

The success of the Columbia led to a renaissance of supercomputing at Ames. For example, in November 2007 the Army opened a new high performance computing research center at Ames, and installed a Cray X1E and Cray XT3 at the NAS. This center forged collaboration between the NAS, Stanford University, and other university partners to solve the challenges of Army aviation, notably in the design of rotorcraft.

Ames continued its prowess in building supercomputers with the Pleiades. It debuted at the SC08 conference in November 2008 as number three among the world's fastest computers, and as the fastest of all non-defense computers. Managed by William

Thigpen, the Pleiades was designed as an SGI Altix ICE system with 12,8000 Intel Xeon quad core processors running at 487 trillion teraflops. It featured the world's largest InfiniBand network which connected the processors with memory and allowed sophisticated visualization and data analysis. It also ranked as one of the most energy efficient supercomputers in the world. Pleiades was a general purpose computer, like Columbia, and easy to use for a variety of applications. It ran NASA codes with minimal modification, and was compatible with standard desktop workstations. With the surge in supercomputing, as usual, came a need to depict the massive amounts of data.

NAS staff developed its hyperwall, a set of integrated screens that debuted in November 2002 as the largest display in the world based on the number of pixels. Rather than pushing the size limits of a single screen, NAS staff took a low cost approach. They mounted smaller screens into an immersive display, and developed software to project the data seamlessly. NAS engineers presented the idea to Ames management in February 2002, and challenged the team to complete it by SC02. NAS staff scrounged up four screens, which they integrated into an array. Soon after, an order of fifty eighteen inch LCD screens arrived, and these were integrated into ever larger arrays. A specially designed rack held the seven by seven array of screens in a dish shape for a more immersive viewing experience, and each screen was driven by a its own computer with a graphics card. In eight months they had it ready for SC02.¹⁸⁸

The NAS hyperwall presented 64 million pixels, distributed over 55 square feet of viewing area. It was put to use in all research areas at Ames—aerodynamics, protein docking, galaxy formation, Earth climate data, multispectral imaging of Mars—where large, multidimensional data sets needed to be understood. A single large image, perhaps of clouds moving across the Earth, could be presented as a mosaic across all of the screens, similar to the powerwall displays then in use. What made hyperwall an advance over powerwalls was software developed by Chris Henze, which let the hyperwall control many independent but related images, so-called spreadsheet visualization. Data series could be displayed in sequence on

individual screens so viewers could better perceive trends in data. For example, users could see 49 unique steps in protein docking. Or, as an example of parameter variation, one hyperwall display could show surface pressures and streamlines from a computational model of airflow about a proposed reusable launch vehicle. All images in the same column represented simulation at the same Mach number (but increasing angles of attack), while all images in the same row showed simulations at the same angle of attack (but increasing Mach numbers). Parameter variation research was a legacy of Ames dating back to its NACA roots, and hyperwall kept such research eminently useful.

At SC08, NAS debuted its hyperwall-2, a 23 by 10 screen display developed in partnership with Colfax International of Sunnyvale. It had a hundred times more processing power than the hyperwall introduced in 2002. The hyperwall-2 was powered by 128 graphics processing units and 1,024 processor cores, with 74 teraflops of peak processing power and a data storage capacity of 475 terabytes. It was more explicitly designed to support the supercomputing being done in the NAS. “The hyperwall-2 offers an environment that is truly up to the task of visualization and exploration of the very large datasets routinely produced by NASA supercomputers and instruments,” said Bryan Biegel, NAS deputy chief. “The system also will be used to get detailed information on how NAS supercomputers are operating, enabling staff to quickly diagnose problems or inefficiencies with the supercomputers or the software running on them.”¹⁸⁹

World Wind represented another leap forward in imaging capability. World Wind was created by NASA's learning technologies project, led by Patrick Hogan, and was the most downloaded program on the internet when released in 2004. World Wind was a world viewer that used data from the Landsat satellites and shuttle radar topography elevation data to provide an interactive view of Earth. Starting with a global view of Earth, users could zoom into a regional three dimensional picture that portrayed climate, elevation, vegetation, population density or other data traits. In May 2008 NASA Ames released it as a Java program able to run on a wider variety of platforms, supported by World Wind servers which hosted

geospatial data. World Wind preceded Google Earth, a similar world viewer. But World Wind was entirely open-source, meaning users could constantly add new data and applications. World Wind won NASA's software of the year competition for 2009, and was widely adopted by other government agencies for their mapping projects.

CHAPTER 7

Aeronautical Technology and Flight Research

With the integration of the NACA into NASA, not every aerodynamicist at Ames shifted to work on the Apollo project. Throughout the 1960s, most Ames people continued working on high-speed aerodynamics, on such issues as boundary-layer transition, efficient supersonic inlets, dynamic loads on aircraft structures, and wing-tip vortices. Ames also continued its work on low-speed aerodynamics, notably on high-lift devices, improved landing technologies, and new approaches to vertical and short take-off and landing aircraft. Ames continued to use its wind tunnels to solve the seemingly intractable flight problems encountered by the military's supersonic and transport aircraft—problems often uncovered during action in Vietnam.

Still, Ames work in aeronautics underwent a profound shift in the 1960s and 1970s, not so much in the research topics addressed but rather in relationship between NASA and the aircraft manufacturers. Aircraft engineering had matured. The shape of transport aircraft went largely unchanged since the 1950s and, with the exception of a few radical departures like variable sweep wings, so had supersonic aircraft. The NACA had considered its function to be engineering research and testing, providing data and insights which all aircraft firms were free to use to improve their designs.¹⁹⁰ Most of these NACA innovations were on the component or operational level, leaving the manufactures in charge of system integration.

NASA, by contrast, especially at the new human spacecraft centers in Huntsville and Cape Canaveral, saw itself as builders of spacecraft. In its early years NASA did not jump into building aircraft as it had with spacecraft, though it did commission more of its X-plane series of experimental aircraft. Into the 1970s, NASA engineers more commonly devised the complete configurations of aircraft, as with the tilt rotor and the oblique wing aircraft. NASA shifted its efforts away from the component level and toward issues on the system level. Other examples of system-wide

issues NASA addressed included pilot workload and safety and air traffic management.

Perhaps the best example of NASA efforts to work on the system level was with commercial supersonic transport (SST), especially in the 1960s.¹⁹¹ NASA outlined the general configuration from which an aircraft firm would build the SST. Because of Ames' long interest in delta wings and canards—dating back to tests of the North American B-70 supersonic bomber—Victor Peterson and Loren Bright helped define the aerodynamics of a delta-canard configuration. The Ames vehicle aerodynamics branch also suggested a double-delta configuration that Lockheed used for its SST proposal. Then Ames used its wind tunnels to help the Federal Aviation Administration (FAA) evaluate the efficiency and environmental impact of the designs. And Ames used its flight simulators to coordinate handling qualities research by NASA, pilot groups, industrial engineers, and airworthiness authorities from the United States, the United Kingdom, and France. Ames thus led development of the criteria used to certify civil supersonic transports. The European-built Concorde was certified to these criteria in both Europe and the United States.

Into the 1980s and 1990s, though, as funding for aeronautics declined as a portion of NASA's budget, Ames researchers retreated from their work on high-concept experimental aircraft. Increasingly, they partnered with other government agencies—like the FAA for work in air traffic management and with the Army in rotorcraft. And they refocused on what they historically did best—provide research capability in such areas as flight simulation, wind tunnel testing, and component development to serve a variety of aircraft.

FLIGHT SIMULATION

Ames people constantly reinvent themselves to apply the skills they have to problems that they are just defining. One example of personal reinvention, in the 1960s, is reflected in Ames' emergence as a leader in flight simulators. Ames had begun building simulators in the early 1950s, when the Center acquired its first analog computers to solve dynamic equations, and as part of Ames' work in aircraft handling qualities. Harry Goett, leader of Ames' full-scale flight

research, had pushed his colleagues to move further into simulator design, and George Rathert had led this effort. George Cooper, the Ames chief test pilot and author of the Cooper-Harper handling qualities rating scale, also advocated greater use of simulators to study the how pilots worked with aircraft.

Ames' computing staff recognized that they could program analog computers with an aircraft's equations of motion, that a mockup of the pilot stick and pedals could provide computer inputs, and that computer output could drive mockups of aircraft instrumentation. Thus, the entire loop of flight control could be tested safely on the ground. Simulators for entry-level flight training were already widely used, but by building their system around a general, reprogrammable computer, Ames pioneered development of the flight simulator for research.

By the late 1950s, using parts scrounged from other efforts, Ames had constructed a crude roll-pitch chair. Goett championed construction of another simulator, proudly displayed at Ames 1958 annual inspection, to test design concepts for the X-15 hypersonic aircraft. Ames was ready to move when NASA asked for simulators to help plan spacecraft to be piloted in the unfamiliar terrain of microgravity. Fortunately, Ames had on staff a superb group of test pilots and mechanics who wanted to stay at Ames even after NASA headquarters, in the early 1960s, sent most of its aircraft south to Rogers Dry Lake. Led by John Dusterberry, this analog and flight simulator branch pioneered construction of sophisticated simulators to suit the research needs of other groups around NASA.

In 1959, Ames embarked on an ambitious effort to build a five-degree-of-freedom motion simulator. This was a simulated cockpit built on the end of a thirty-foot long centrifuge arm, which provided curvilinear and vertical motion, and also the G-forces pilots were encountering in supersonic aircraft. The cockpit had electrical motors to move it about pitch, roll, and yaw. It was a crude effort, built of borrowed parts by Ames' engineering services division. But the simulator proved the design principle, pilots thought it did a great job representing airplane flight, and it was put to immediate use to develop stability augmenters for supersonic transports.

In 1963, Ames opened a six-degree-of-freedom simulator for rotorcraft research, a moving cab simulator for transport aircraft, and a midcourse navigation simulator for use in training Apollo astronauts. Ames combined its various simulators into a space flight guidance research laboratory, opened in 1966 at a cost of \$13 million. One of the most important additions was a centrifuge space flight simulator at the end of a centrifuge arm capable of accelerating at a rate of 7.5 G-forces per second. Another was a satellite attitude control facility, built inside a 22 foot diameter sphere to teach ground controllers how to stabilize robotic spacecraft.

Ames had become the best in the world at adding motion generators to flight simulators, and connecting them with programmable analog computers to simulate aircraft not yet built. Into the 1970s, Ames researchers pioneered out-the-window scenes to make the simulation seem even more realistic for the pilot. These began with wooden models of airfields, over which a television camera would fly in response to how the pilot flew the simulator. They evolved into digital images generated by increasingly more powerful computer visualization methods.

Throughout this work, Ames also emphasized the modular design of simulator components, so that various computers, visual projectors, and motion generators could be interconnected to simulate some proposed aircraft or spacecraft design. All of this technology was available to aerospace firms, who by the 1980s had bought their own simulators for cockpit design. Likewise the NASA centers focused on human space flight had procured simulators for astronaut basic training (though the most challenging landing scenarios were still trained for at Ames). So Ames continued to build simulators with unique capabilities, and increasingly used them to attack problems of aircraft safety.

Ames opened its flight simulator for advanced aircraft (FSAA), in June 1969, initially to analyze concepts for wide-body aircraft and supersonic transports. It was followed by the vertical motion simulator (VMS) that, like the FSAA, was part of a comprehensive flight and guidance simulation laboratory (known as the SimLab) which officially opened in February 1980. The FSAA had superb

horizontal motion, so the VMS was optimized for studies of vertical motion. The VMS tower was 110 feet high and 73 feet long, and offered vertical displacement of thirty feet up or down, with maximum vertical velocity at twenty feet per second. All other degrees of freedom were built upon the vertical.¹⁹²

The VMS was initially used to study aircraft flair and touchdown, and a cab was soon added for studies of helicopter control. Ultimately five different cabs were built—to simulate helicopters, transport aircraft, the Shuttle orbiter, short take-off and vertical landing aircraft, and advanced cockpit designs. The VMS was where the control laws of V/STOL aircraft were worked out. The Shuttle orbiter cockpit was refined there, and every Shuttle commander used it to train for the very precise dead-stick landing as the orbiter returned to Earth.¹⁹³

Ames continued to study theories of cockpit automation to reduce pilot error in conventional airliners, and then built these ideas into the crew-vehicle systems research facility (CVSRF). Opened in 1984, the facility encompassed all facets of air traffic control from the pilot's perspective—air-to-ground communications, navigation, as well as a computer-generated view out of the simulated cockpit. It housed two simulators with six-degrees of freedom, one modeled after a Boeing 747-400 and one with greater flexibility to model advanced cockpit concepts. It also housed an air traffic control laboratory, a room where stand-in controllers could track data on their computer screens and talk with pilots about where they should pilot their simulators. It was located near the Ames research laboratories for aerospace human factors and information technology; the vertical motion simulator was located closer to the flight research groups. The CVSRF was used to test, cheaply and quickly, potential improvements to cockpits and air traffic control centers.

Harvey Allen had built at Ames a comprehensive and overlapping set of experimental facilities to study all aspects of reentry aerodynamics, and Ames aerodynamicists had built a comprehensive and interconnected set of computing machines to develop CFD. In that same spirit, Ames built the CVSRF and VMS as parts of a comprehensive set of Ames facilities to experiment

on improving pilot workload, aircraft automation, flight safety, airline efficiency and, later, air traffic control around airports. Ames researchers then broadened their use to encompass safety within the entire national airspace system. As it had with the Army to study the aerodynamics of rotorcraft, Ames built an alliance with the FAA, which had a research laboratory for its applied research but did little basic research. Ames brought into this flight safety partnership its full range of capabilities—in communications, simulation, materials science, and computing.

The FAA asked Ames, for example, to devise an aviation safety reporting system (ASRS) to collect data—supplied voluntarily by flight and ground personnel—on aircraft accidents or safety incidents in American aviation. The Ames human factors group, led by Charles Billings, brought every involved group into the planning, and ASRS director William Reynard implemented it with a reputation for fairness. The ASRS won the trust of pilots and air traffic controllers, who initially balked at reporting incidents because they almost always arose from simple human error. Ames did not collect the data anonymously, since they had to verify reports, but they removed identification before compiling data for the FAA. In its first fifteen years, ASRS received 180,000 safety reports, at a rate of 36,000 a year by 1991. From this massive database on human performance in aviation, Ames staff generated hundreds of research papers that led to incremental improvements in aviation safety. The ASRS also put out periodic alert messages about matters that required immediate attention and a monthly safety report. “There’s nothing worse than sending information to a government agency,” said Reynard, “and seeing nothing happen.”¹⁹⁴

Using these data to locate weak spots in the system, Ames used its simulators to minimize human errors. One protocol tested on the simulators became known as line-oriented flight training (LOFT) a method devised at Ames in the late 1970s for evaluating and training crews in all facets of flight management. Earlier methods of training flight crews focused on their reaction to emergencies. Because these reactions emphasized maneuvers, these training methods tended to instill rote and isolated responses. Line-oriented

flight training was done in a simulator, which recreated an entire flight from gate to gate, interjecting complications along the way to test the crew's anticipation of problems and coordination of decision-making. All major airlines adopted a version of it, as did the American military. During these full-flight simulations, Ames discovered that most accidents occurred not because pilots lacked technical skill, but because they failed to avail themselves of all the resources available in the cockpit. Paradoxically, most training focused on technical proficiency with individual parts of the cockpit. So the Ames aeronautical human factors branch developed methods for use in training pilots to manage all cockpit resources. Ames and the U.S. Air Force Military Airlift Command organized a conference attended by more than 200 aircraft safety experts from 14 countries, who established the importance of training pilots in cockpit resource management.

This work then led to better workload prediction models, which Ames used to devise simulations subjecting pilots to standardized workloads. From this the U.S. Air Force adopted a single code to promote its pilots, and NASA adopted a target-selection code to evaluate control devices for the Space Shuttle. What pilots call the "NASA nap" originated in a long running experiment by Curtis Graeber, begun in 1979, that proved short periods of rest dramatically improved pilot performance during long-haul flights. By 2000, NASA Ames consolidated its efforts in improving human performance into PDARS, the performance data analysis and reporting system, which moved safety beyond the cockpit and into the air traffic control tower. Six FAA centers prototyped the PDARS, which rapidly processed air traffic data and provided daily reports to facility managers on the operational health of their facilities. They could then model operational changes to boost the capacity their centers could safely handle.

Ames' aerospace human factors research division, in October 1993, installed a Boeing 747-400 simulator in its CVSRE. The cockpit simulator was identical to those used to train airline pilots, except that the new displays were reprogrammable and stocked with equipment for collecting computer, audio, and video data. "Our goal is to find

ways to improve human capabilities using automation,” said CVSRF manager Robert Shiner. Indeed, one of the first studies addressed replacing voice communication between pilot and controller with a digital datalink.¹⁹⁵ Ames was working on all the technological components to allow the airspace system to be managed as an integrated whole.

A major upgrade of the vertical motion simulator was completed in May 1997, adding a new interchangeable cockpit. Ames built this new T cab in-house to satisfy the needs of NASA’s tilt rotor and high-speed airliner programs. The new T cab had a side-by-side arrangement and an all-glass cockpit, so pilots could press easily altered touch-screens rather than actual instruments. The 270 degree view out the window was twice that of the other four cabs available to the simulator, which simulated helicopters, airplanes, and the Space Shuttle. Into the 2000s, the VMS and CVSRF remained fully booked. The VMS, for example, was used to study ways to pilot a new lunar lander being built for the Constellation program. The CVSRF was connected with FutureFlight Central, an air traffic control simulator that looked like an airport tower, which allowed realistic simulations of how air traffic controllers and flight crews would interact following any redesign of a major airport. Using these interconnected facilities, Ames simulated how civil tilt rotor aircraft might be handled around an airport. They allowed a crew and controller to simulate a flight between, say, the Dallas and Chicago airports using the data generated by next generation air traffic control technologies. Air traffic safety, from the human perspective, continued to be a key part of the NASA Ames research agenda.

INTEGRATIVE FLIGHT CONTROL

Leonard Roberts served as Ames director of aeronautics and flight systems from 1972 through 1984, when integrative projects dominated. He helped match all Ames facilities—the tunnels, computers, simulators, and the test grounds at Dryden—with new flight research programs in maneuverability, short takeoff and landing aircraft, and aircraft safety. Ames grew especially adept at building light, inexpensive, and well-focused flying laboratories to verify

component technology, to test seemingly bizarre new configurations, or to gather data that could not be gathered otherwise.

Exemplifying this integrative urge—especially between researchers at Ames and Dryden—was digital fly-by-wire technology (DFBW). Engineers at Ames had pioneered the concept of digital fly-by-wire in the 1960s, expecting it to replace the heavy and vulnerable hydraulic actuators still used in high-performance aircraft. Ames had already built many of the electronic controls for its ground-based flight simulators, which were made digital in order to run programs stored on their computers. Making these codes, controls and connectors reliable enough for a flying aircraft, though, required a magnitude greater of integration and reliability. So they acquired an F-8 Crusader fighter aircraft, removed all the mechanical controls, and installed their best DFBW technology. In 1972 in the air above Ames-Dryden, they first demonstrated the concept of DFBW.

Once Ames had demonstrated the feasibility of DFBW, they worked on hardware and code that the aerospace industry could use in any new aircraft. For example, any bug in a multiple channel digital system, like DFBW, could crash all redundant channels. To avoid the cost, complexity and weight of a backup system, Ames designed software that could survive any problem in the main program. They further designed this fault-tolerant software to check itself automatically during flight. Other Ames scientists working in computational fluid dynamics applied algorithms that incorporated nonlinear functions into the software, and thus allowed DFBW to expand the flight envelope to the extremes of turbulence and boundary layer separation. The success of fly-by-wire in the Ames-Dryden tests convinced NASA to use it as the basis of the Space Shuttle flight control system.

Ames next applied its skills to the equally complex, multichannel task of controlling jet engines. Ames designed a digital electronic engine control (DEEC) that could optimize the ten variables on the F100 engine that powered the F-15 and F-16 fighter aircraft. Electronic control improved engine performance, with higher thrust, faster throttle response, improved afterburner response, stall-free operation, and eight times better reliability and maintainability than

the mechanical controls it replaced. The Ames DEEC first flew on a NASA F-15 in 1982 and, revised by McDonnell Douglas to military specifications, entered production on U.S. Air Force models in 1985.

Ames continued integrating the components of its digital control technology. In the skies over Ames-Dryden, in June 1985, a group of engineers led by program manager Gary Trippensee witnessed the first flight of the NASA F-15 that had been modified as the HIDEDEC aircraft (for highly integrated digital electronics control). By integrating data on altitude, Mach number, angle of attack, and sideslip, HIDEDEC let the aircraft and engine operate very close to its stall boundary. Simply by improving these controls, and reducing the stall margin, thrust improved two to ten percent. The next phase of the Ames-Dryden HIDEDEC program included flight path management, by adding a digital flight controller built for the Air Force. This technology optimized trajectories to lower fuel consumption, suggest faster intercepts, and allow navigation in four dimensions. The FAA asked Ames to expand upon this flight path controller in order to improve capacity in the commercial airspace system. So Ames developed a set of algorithms to process data from aircraft sensors into cockpit instructions on how a pilot could fly more efficiently. The Ames algorithm found its way onto new Boeing 757 and 767 and Airbus A310 aircraft, and airlines estimated Ames' work saved them four percent on fuel costs. Ames-Dryden staff also used the F-15 flight research aircraft to develop self-repairing flight controls. In flight tests during May 1989, sensors and computers aboard the F-15 correctly identified a simulated failure in the flight controls. Diagnosing failures on the ground was always time consuming, and often fruitless since the failures could only be identified in specific flight conditions. Once the system identified the failure, it could reconfigure other parts of the aircraft to compensate.

Ames' powerful triad of facilities—tunnels, computers, and simulators—allowed it to create and prove the fundamental hardware and software that controlled that generation of aircraft. Ames people also created protocols useful in the integration of electronics and software in flight systems. And it validated the use

of airborne laboratories—like the F-8 and the F-15—to quickly and cheaply demonstrate new component technologies.

Ames also drove development of new experimental aircraft. In the early 1960s, for example, Ames aerodynamicist R.T. Jones worked out the theory behind the oblique wing. The oblique wing was perpendicular to the fuselage at take-off to provide maximum lift, then it swiveled in flight so that one half-span angled forward and the other angled backward to decrease drag. This shape could solve the transonic problems of all naval aircraft, which needed high lift to get off a carrier and a sleek profile to go supersonic. Swept wings, like those on the F-111, solved this problem by using a joint that was heavier and weaker than the swivel joint needed to support an oblique wing. Aerodynamically, though, the oblique wing was quite complex. First, the airfoil had to provide lift with air moving over it at a variety of angles. Second, flight controls had to be sophisticated enough to compensate for the asymmetry of the control surfaces. Ames' ongoing work in digital fly-by-wire made it easier to design the oblique wing, by enabling programmers to write code to control an inherently unstable aircraft.

Jones had already established his reputation in theoretical aerodynamics. He saw in the oblique wing not only a promising concept and an intellectual challenge, but also a program to validate Ames' integrative approach to flight research. Jones marshalled the scientific resources of Ames—especially its wind tunnels and computer modeling—to design the experimental aircraft called the AD-1 (for Ames-Dryden). Then, the AD-1 was fabricated quickly and cheaply, using sailplane technology and a low-speed jet engine. With this low cost approach, Jones quickly validated the concept and assessed flying qualities without the bureaucratic squabbles that usually accompany X-series aircraft.

Soon after the AD-1's first flight, in 1987, the U.S. Navy joined Ames to sponsor the Grumman X-29A. The X-29's bizarre aerodynamics had both wings swept forward and a canard for lateral axis control. Because it was inherently unstable, the X-29 made extensive use of the flight control software and digital fly-by-wire

technologies developed at Ames-Dryden. Also used to validate the concepts and technology behind the X-29A was another unique NASA Ames aircraft.

The HiMAT, which first flew in July 1979, was specifically designed for flights tests of high-maneuverability concepts. HiMAT (for highly maneuverable aircraft technology test bed) was a Dryden project until Ames was called in to help solve some aerodynamic problems. Bill Ballhaus wrote code to solve three-dimensional, transonic, small-perturbation equations—which marked the first time computational fluid dynamics had been used to design a wing. (Later this code was used to design the wing for the Sabreliner and for the B-2 stealth bomber, establishing Ballhaus' reputation in applied CFD.) Dryden and Ames staff built the HiMAT as a small-scale, remotely-piloted, and heavily-instrumented aircraft to test risky technology. At a fraction of the time and cost of a human-carrying vehicle, Ames tested the interactions between many new high-maneuverability devices on an aircraft in flight. HiMAT included digital fly-by-wire, relaxed static stability, close-coupled canards, and aeroelastic tailoring. Aeroelastic tailoring of composite materials allowed Ames to construct wings so that airflows twisted them to the optimum camber and angle, whether at cruise speeds or undergoing heavy loading during maneuvers. Tests of aeroelastic tailoring on the HiMAT provided valuable data on the use of composite materials in all modern aircraft.

Perhaps because Ames people directed work at the Dryden flight research facility, there was a flourish of research into improving the correspondence between tunnel tests and flight tests. For example, Ames designed a remotely augmented vehicle to expand its skills in flight test instrumentation. This vehicle collected data using the same sensors that collected data during flight tests, telemetered it to a computer on the ground, which transmitted back commands to the flight controls to augment the aircraft's performance. This ground-based computer was easy to maintain and upgrade, flexible enough to control several test aircraft, and powerful enough to run more sophisticated software than was possible on flight-approved computers. Ames used this technology to test artificial intelligence

algorithms before including them in flight controllers. And it proved a far more efficient way in which to take the next step forward in variable-stability flight-test aircraft.

Similarly, Ames' flight-test autopilot was a digital computer into which engineers programmed an exact flight-test maneuver. Since this test autopilot was patched directly into the on-board flight controls, there was no need for additional actuators. The pilot could, of course, override it at any time, but it proved especially valuable when a pilot had to simultaneously perform many maneuvers and control many flight variables, or when repeatability of a maneuver was important.

Ames-Dryden pilots also developed the technology of the transition cone. To scale results from wind tunnel models up to full-scale aircraft, aerodynamicists needed to understand where boundary layers made the transition from laminar to turbulent flow. Researchers at the USAF Arnold Engineering Development Center originated the transition cone concept, which pilots and flight test engineers at Ames-Dryden then tested at a variety of Mach numbers in wind tunnels and mounted to the nose cone of NASA's F-15. They obtained data that set standards, used worldwide, on the quality of airflows in wind tunnels.

NASA's high-alpha technology program was an effort to calibrate its many research tools while exploring an intriguing regime of aerodynamics. For twelve weeks beginning in June 1991, an Ames team led by Lewis Schiff tested a Navy F/A-18 in the 80 by 120 foot section of the NFAC, making it the first full-scale aircraft tested in the world's largest wind tunnel. The goal was to understand how a modern fighter aircraft performed at very high angles of attack (called high alpha) like those encountered in aerial combat. Wind tunnel data were matched against the data predicted by computational fluid dynamics, and both were compared with flight-test data collected on a highly instrumented F/A-18.

The NASA/Boeing X-36 tailless fighter agility research aircraft proved, with dramatic efficiency, the concept of the tailless fighter. It was conceived in 1989 by researchers at Ames' military technology branch and McDonnell Douglas' Phantom Works in St. Louis

(later part of Boeing). It embodied the results of a decade of Ames research into tailless fighters—using wind tunnels, simulators, supercomputers, and flight controls. The X-36 lacked vertical and horizontal tails. Instead, it got directional stability and flight control through a split aileron and engine thrust vectoring. This innovative design promised to reduce weight, drag, and radar signature and increase the range, maneuverability and survivability of future fighter aircraft.

Rather than build a full-scale prototype needing a pilot, the Ames/Boeing team built a 28 percent scale model that was remotely piloted. Two X-36 prototypes rolled out in May 1996, only 28 months after go-ahead, at a total project cost of \$21 million shared between Ames and Boeing. They were fully powered by turbofan engines providing 700 pounds of thrust, and flown by a pilot sitting in a ground-station cockpit, complete with a heads-up display. By keeping a pilot in the loop, Ames eliminated the expense of complex, autonomous flight controls. “When we saw this airplane lift off,” exclaimed Rod Bailey, the X-36 program manager, “we saw the shape of airplanes to come.”¹⁹⁶ Between May and November 1997, the X-36 prototypes flew 31 flights, for a total of 15 hours, in only 25 weeks. Four different versions of flight control software were tested. The X-36 reached an altitude of 20,200 feet, and a maximum angle of attack of forty degrees. The flight tests clearly demonstrated the feasibility of tailless fighters, and showed that they could possess agility far superior to that of today’s best fighters.

The X-36 was the last high-concept test aircraft to be managed at Ames, attesting to the decline in NASA funding for aeronautics research. At the turn of the century, funding for basic aeronautical research shifted to the defense department. The research that remained within NASA, on aircraft efficiency, played to the historic strengths of the Glenn Research Center in propulsion technology. Ames remained capable of reinvigorating its aeronautical research when Congress directed it to do so. At the request of the Army, Ames continued a comprehensive research program on rotorcraft and subsonic aircraft. Ames had improved its monitoring and control software, for spacecraft, and was looking for ways that

spacecraft technology could be used to improve aircraft. And Ames had upgraded its wind tunnels and other research facilities.

UPGRADING THE WIND TUNNELS

Even beyond the 1980s, Ames' wind tunnels tied together work in computational fluid dynamics at the start of aircraft design and automated flight testing at the end. The golden age of wind tunnel research had passed, though Ames researchers continued to invent new techniques to make more efficient use of its tunnels. With laser speckle velocimetry, for example, Ames solved the seemingly intractable problem of measuring unsteady fields in fluid flows. By seeding the air with microparticles, then illuminating it with a coherent light like that of a pulsed laser, they created speckled patterns which were superimposed on a photographic plate to create a specklegram. This specklegram recorded the entire two-dimensional velocity field with great spatial resolution. From this single measurement, aerodynamicists easily obtained the vorticity field generated by new aircraft designs. Similarly, Ames' fluid mechanics laboratory in 1987 started working closely with chemists at the University of Washington to develop pressure-sensitive paints that would turn luminescent depending on the amount of oxygen they absorbed. The paint was easily sprayed on an aircraft surface before tunnel or flight testing and returned good data on the distribution of air pressure over the aircraft surface.

Ames had built many special-purpose tunnels in the 1950s and 1960s, which were then dismantled. But many of the general-purpose tunnels built in the 1940s had started to degrade. In 1967 NASA participated in a nationwide review of American wind tunnels, and three at Ames were designated as key national resources—the 40 by 80 foot, the 12 foot pressure, and the Unitary. (This result was repeated in a 2004 study by the Rand Corporation, and the vertical motion simulator and the arc jet complex were designated national resources in their categories.) Ames planned a long-term effort to bring these tunnels up to the state of the art, and to keep all its tunnels operating safely.

Perhaps the most significant upgrade was the December 1987 rededication of the National Full-Scale Aerodynamics Complex (NFAC). The 40 by 80 foot wind tunnel, the largest in the western world since its opening in 1944, remained Ames' most unrivalled tunnel. It had been in almost constant use. Beginning in the late 1960s, and for more than a decade, Mark Kelly led groups from Ames to headquarters asking for funds to repower the 40 by 80 foot tunnel and add a new test section. With the support of the Army and Air Force, Congress relented.

In November 1978, Clarence Syvertson turned the first spade of dirt under the new 80 by 120 foot test section of the now renamed NFAC. (In addition to the one tunnel housing the two test sections, the complex also included Ames' outdoor aerodynamic research facility to test airflow beneath vertical take-off aircraft.) New drive motors rated at 135,000 horsepower—four times more powerful than the original motors—drove the need for new wood-composite fan blades and strengthening of the hull. The 40 by 80 foot section would continue to work as a closed-loop tunnel, with an air circuit a half-mile long. The 80 by 120 foot section would be open at both ends, rather than closed loop, which reduced the cost to \$85 million and construction time to an additional six months. It would gulp in air through a horn-shaped inlet as big as a football field. Kenneth Mort, lead aerodynamicist on the upgrade, built a 1/50th scale model of the tunnel itself to show that Bay Area winds would not unacceptably degrade the smooth ingest of test air. This bigger section would operate at an airspeed only one-third that of the 40 by 80 foot test section, but was big enough for ever-larger military and commercial aircraft. Furthermore, the higher speed and larger size of the modified facility made it ideal for Ames' growing body of work in VTOL aircraft, helicopters, and aeroacoustics. The larger test section minimized tunnel-wall interference, which worsened at low speeds or when air was deflected downward and outward by rotorcraft. Since sound waves took some distance to propagate, large test sections were also important in aircraft noise studies, an issue becoming more politically sensitive. To make the new tunnel better suited to aeroacoustic research, and reduce the noise made while

the tunnel was running, Ames engineers lined the test sections with sound-absorbing insulation. Cranes were added for moving around larger models. Better sensors, model mounts, wiring and computers improved data collection. Construction of the composite tunnel ended in June 1982.

Just before noon on 9 December 1982—with only two months of shakedown tests to go before it would be fully operational—the NFAC suffered a serious accident. While running at 93 knots in the 80 by 120 foot test section, close to its maximum speed, a slip joint holding the hinge mechanism on vane set number five slipped. The entire lattice work of vanes broke up and its debris blew into the drive fans. Vane set five stood 90 feet high, 130 feet wide, and weighed 77 tons. Located a hundred feet upwind of the fans, the nose sections of the vanes hinged to guide airflow around a 45 degree corner from the new 80 by 120 section into the old tunnel. All ninety fan blades, handcrafted of laminated wood, were destroyed. The institutional trauma of the accident announced itself with a terrifying thump heard around Center.

Ames had done a poor job supervising design and construction of the vane set. More stunning, Ames could no longer be proud of its safety record (though no one had been hurt in this accident). Syvertson had earlier nominated the Ames machine shop for a NASA group achievement award to recognize its year of no loss-time accidents. When NASA headquarters refused the nomination, on the grounds that NASA gave no awards for safety, Syvertson was so incensed that he refused the NASA Distinguished Service Medal that he was to be awarded.

Yet Ames wrested success from the tragedy. Ames tunnel managers shuffled the test schedule to make use of smaller tunnels, so that the accident added little to the two-year backlog of tests waiting for the tunnel to open. Ames estimated it would take one year and cost \$13 million to repair. However, a blue ribbon panel of aerospace experts convened by NASA and led by Robert Swain suggested this was an opportunity to make additional upgrades to boost NFAC reliability. This raised the total renovation cost to \$122 million, the amount Ames had originally requested. Better instrumentation,

stronger structural steel, and turning vanes with sophisticated airfoils and no movable parts all created a more capable tunnel. New wiring for 1,250 channels pushed data at rates up to two million bits per second into computers where they could be instantly compared with theoretical predictions. Although both tunnels could not be run at the same time, engineers could set up tests in one tunnel while the other one ran. In September 1986, the Ames project group led by Lee Stollar, started the first preliminary tests. Almost a year passed before the NFAC was declared fully operational.

Following the upgrade, airspeeds in the 40 by 80 foot test section could reach 345 miles per hour, the low cruise speed for many aircraft. The 80 by 120 foot tunnel, operating at 115 miles per hour, became the world's largest open-circuit tunnel. It proved especially useful in studies where low-speed handling was especially critical, like during landing and take-off. It has been used to test a variety of aircraft on a large scale—fighter jets, lifting-body configurations, Space Shuttle models, supersonic transports, parachutes, and even trucks and highway signs.

Once Ames got the tunnel renovation program back on track after the accident, it focused on the 12 foot pressure tunnel. The tunnel hull had, since its opening in 1946, undergone constant expansion and contraction as it was pressurized to achieve its extraordinarily smooth flows of air and then depressurized. Such extensive, unrepairable cracks in the welds were discovered during a detailed inspection in December 1986, that Ames decided to rebuild the hull completely. Models of virtually every American commercial airliner had been tested in the 12 foot pressure tunnel, and aircraft designers hoped to continue to rely upon it. Beginning in 1990, a project team led by Nancy Bingham stripped and rebuilt the closed-loop pressure vessel, and installed an innovative air-lock system around the test section. The new air-lock let engineers enter the test section without depressurizing the entire tunnel, boosting its productivity and reducing the pressure cycling that had earlier degraded the hull. Ames also integrated new test and measurement equipment, and upgraded the fan drive. The 12 foot pressure tunnel reopened in November 1994, creating a superb test facility at a renovation cost of

only \$115 million. Unfortunately, it was almost immediately placed on standby due to a lack of a testing backlog.

Since being placed in service in 1955, the Unitary Plan wind tunnel, like many Ames facilities, had been heavily used. Such constant operation was planned, since Ames had designed the tunnel with massive diversion valves that allowed a test to be run in one section while models were set up in the other two. The drive system had accumulated more than 70,000 hours of use, as the Unitary complex tested every military aircraft, every significant commercial transport, and every manned spacecraft since its inception. The 11 foot transonic tunnel still had a 2.5 year backlog of tests, and the cost had risen to \$300,000 for a one-week test. Ames shut down the Unitary in 1996 for an \$85 million renovation to make it operate more efficiently. Modernization would automate the control system and improve flow quality in the transonic section by adding honeycomb flow straighteners, turbulence reduction screens, and segmented flaps in the wide-angle diffuser to eliminate flow separation.

Other wind tunnels did not fair so well. One of the 7 by 10 foot tunnels, the first opened at Ames, remained in active use by Ames and Army researchers. The second tunnel, though, was largely scavenged for parts to keep the first one operating. The 14 foot transonic wind tunnel, largely unused since the 1980s, in 2009 was demolished. But with the modernization of the NFAC and Unitary, some of the most valuable facilities at Ames were available to continue moving aircraft concepts to flight tests—as with VTOL aircraft.

VERTICAL TAKE-OFF AND LANDING AIRCRAFT

The separation of lift from thrust (that is, using an airfoil and an engine instead of flapping wings) was the insight that made powered flight possible. Reuniting lift and thrust into propulsive lift, with the technology earned over a half century of flight, promised a revolution in the relationship between aircraft and the populations they serve. In a tilt rotor or VTOL aircraft (for vertical take-off and landing), wing-tip rotors lift the aircraft like a helicopter, then the rotors tilt forward like propellers and transfer the lift from the rotors to the airfoil until the aircraft flew like an airplane. Helicopters do not fly forward

efficiently. Fixed-wing aircraft find forward efficiency in higher wing loading, which requires longer runways, which then mandate bigger and more congested airports, farther from population centers. Tilt rotors can fly longer distances than helicopters, yet require little more space than a helipad to take-off and land.

The XV-3 tilt rotor that Bell Aircraft designed for the U.S. Army was a small aircraft. A single engine mounted in the center turned a gear box that powered large rotors at the wing tips. The XV-3 first flew in 1955, and every flight was nerve-racking. In a hover flight, in 1956, a rotor pylon coupling failed catastrophically and the pilot was severely injured. Bell strengthened the structure, then, in 1957, Ames engineers started working with Bell on the XV-3 with tests in the 40 by 80 foot wind tunnel. The XV-3 flew again in 1958, with NASA pilot Fred Drinkwater at the controls to define the flight envelope between vertical and horizontal flight. Full conversion from helicopter to forward flight was flown in August 1959, and the XV-3 test program proved a major advance in understanding the transition from ground to air. The XV-3 program ended in 1965 after a rotor pylon tore loose while the aircraft was inside the 40 by 80 foot tunnel. In 1966, Ames finally mothballed the XV-3.

In the 1960s, though, the excitement over propulsive lift swirled around vectored-thrust jet aircraft—that is, aircraft that could lift straight up when its jet exhaust is pointed to the ground. Ames began that flight research effort with another Bell VTOL aircraft, the X-14, a twin-engine deflected turboprop. It was dramatically underpowered, but did hover and allowed Ames pilots to discover ways of controlling VTOL flight.¹⁹⁷ NASA then contracted with British Aerospace to build the XV-6A Kestrel, which flew so well that it was quickly redesigned into the Harrier, known in the United States as the AV-8B. The jet exhaust nozzle of the Harrier was pointed downward to lift it off the ground, then rotated backward to provide forward thrust. The Harrier was inefficient when hovering but otherwise performed well in the marine attack role. Ames received early prototypes of the Harrier, which they tested in the 40 by 80 foot tunnel to better understand the complex airflows of vectored thrust.

Ames also used their flight tests with the AV-8B Harrier, as well as wind tunnel and simulator tests, to author handling qualities definitions for all future VTOL aircraft. VTOL aircraft feel different to any pilot, whether they train on helicopters or fixed-wing aircraft. First published as a NASA technical note, these handling quality definitions were applied to all VTOL aircraft in NATO and in the U.S. military through its VTOL flying qualities specification.

But ideas for higher-efficiency propeller-driven VTOL aircraft continued to percolate. NASA let contracts for a variety of approaches—like the Ryan XV-5A which used tip-turbine driven lift fans. For the U.S. Army, Vought built several XC-142 tilt-wing prototypes, which flew well but had problems in conversion. Bell invested its own money, with considerable help from Ames, in designing its Model 300. It had good hover and rotor efficiency and its pylons proved stable in wind tunnel tests. Ames had worked hard, since the demise of the XV-3, to solve the lingering problems of tilt rotor aerodynamics.

In 1970, NASA decided to fund another effort in tilt rotor design. Foreign competitors were especially strong in small aircraft and helicopters, and NASA headquarters wanted America to regain the lead through a technological leap. In the debate that ensued, Gene Love and his colleagues at Langley favored a tilt-wing approach. But Bill Harper, then director of aeronautics at NASA headquarters, sided with his former colleagues at Ames in favoring the tilt rotor approach. This resulted in the Bell XV-15, the first successful tilt rotor aircraft.

A key factor in Ames earning the XV-15 project was its relationship with the Army airmobility research and development laboratory, co-located at Ames since 1965. Richard Carlson became director of the Ames/Army effort in 1976, and infused it with a theoretical foundation for VTOL aerodynamics. Because of this alliance with the Army, Ames had funds to refurbish one of the 7 by 10 foot tunnels for small scale tests in advance of tests in the full-scale tunnel. The complex aerodynamics of helicopters and VTOL aircraft meant that they ultimately had to be tested in full-

scale tunnels. On VTOLs, effects could not be scaled, interference from downwash was extreme, and the hard work was in the details. The XV-15 was intended for medical evacuation and search and rescue missions like those the Army had flown during the war in Vietnam. The XV-15 had a gross weight of 15,000 pounds, a payload of 4,000 pounds, a cruising speed of 350 knots, and a range of 1,000 nautical miles—roughly twice that of the best helicopters. In 1970, management of the XV-15 went to a joint NASA-Army project office at Ames with David Few in charge. Half of the \$50 million required for the project came from Ames, half from the Army. Hans Mark gave it his full support, and considered it one of his most significant accomplishments while director of Ames. This was the first time Ames procured an aircraft meant to be a full-scale technology demonstrator—to show the military and airlines how easily they could build such an aircraft for regular service.

In September 1972, the NASA-Army project office gave both Bell and Boeing design contracts, and in April 1973 declared Bell the winner. Bell then apportioned the work for two XV-15 prototypes using standard components as much as possible. Rockwell fabricated the tail assemblies and fuselage, Avco-Lycoming modified a T-53 engine, Sperry Rand designed and built the avionics. Ames aerodynamicists started modeling wind flows around the aircraft, for example, formulating equations to predict whirl flutter caused by a rigid rotor spinning on a pylon. In exterior configuration, the XV-15 looked much like the XV-3. But as often happens in aircraft development, better propulsion made the whole system better. The Lycoming turbine engines had better power-to-weight ratios than those on the XV-3. Bell mounted one at each wing tip to turn the three-bladed proprotors, which were 25 feet in diameter. The only cross-shafting in the XV-15, that is, linkages between the wings, was designed to carry load only if one engine failed.

The XV-15 underwent a careful series of flight tests, spread over three years. The first prototype rolled out of the hangar in October 1976 for ground tests by Bell pilots. In May 1977 Bell chief project pilot Ron Erhart first flew the XV-15: “It flew just like the simulator,” wrote Erhart, “but with better visuals.”¹⁹⁸ A year later, the XV-15

arrived at Ames for more extensive flights. Ames pilots tested it in engine-out flight, and found the cross-shafting worked well in an emergency. In July 1979 it made the full conversion from vertical to forward flight. Ames uncovered some fascinating aerodynamic problems. When the proprotors were tilted at certain angles relative to the wings, a vortex over the wings caused buffeting in the tail. The only solution was to brace and stiffen the tail. Pilots found it took some time to get the feel of the conversion, and that it behaved oddly during taxiing and in light wind gusts.

In spring 1980 Ames opened its outdoor aerodynamic research facility (OARF), essentially a tilt rotor tie-down facility on a hydraulic lift. By raising the wheel height from two to fifty feet off the ground (to accommodate the large proprotors) they could evaluate the XV-15 flying through air in any flight configuration. Ames aerodynamicists could measure rotor torque, fuel consumption, aircraft attitude, pilot control positions and—at various hover altitudes—ground effects, downwash, handling qualities, exhaust gas ingestion, and noise levels.

The XV-15 program was scientifically interdisciplinary—human factors, computing and digital controls all contributed in the crucial area of pilot workload. Flight data were cross-checked with tunnel data, which were matched to early efforts in computational fluid dynamics. The XV-15 culminated in an intense research program at Ames to further develop the VTOL concept and to prove its commercial and military utility. Yet it took some big steps to move the tilt rotor to its next iterations.

In 1978 Ames, emboldened by Hans Mark's duty as secretary of the Air Force, directly, and without success, tried to get the Army or Air Force to buy an improved tilt rotor for search and rescue missions. Mark made a special, and again unsuccessful, pitch to Admiral Holloway, former chief of naval operations who led the investigation into the failed April 1980 effort to extract the American hostages from Iran. Resistance came because the U.S. Air Force had always fought its air wars from protected airfields, and thus saw no need for an airfield-independent aircraft. The Army already had expensive new helicopters entering service to fly those same missions.

Mark moved from the Pentagon to become deputy administrator of NASA early in 1981, and one of his first decisions was to take the XV-15 to the Paris Air Show. It was a hit. The new secretary of the Navy, John Lehmann, saw it and turned staunch advocate of the tilt rotor. In 1982, NASA departed from usual practice and let its experimental aircraft be used in operational tests. The Army flew the XV-15 to simulate electromagnetic warfare near Fort Huachuca, Arizona. The Navy evaluated it aboard the *U.S.S. Tripoli*. P.X. Kelley, commandant of the Marine Corps, also became a tilt rotor advocate, especially after the 1982 Argentine-British conflict over the Falkland Islands. Standoff distances between ships and a hostile shore had to be farther than the short operating ranges of ship-based helicopters allowed.

In 1983, the Marines issued the specification for what became the V-22 Osprey, a VTOL designed to replace the Boeing Vertol CH-46 and the Sikorsky CG-53 assault helicopters. Bell Helicopter Textron Inc. of Fort Worth teamed with Boeing Vertol of Philadelphia and won the contract in 1985. The V-22 was three times the size of the XV-15, with a total gross weight of 40,000 pounds, but otherwise similar. It would carry 24 heavily armed Marines from ship to shore in amphibious assaults. Marking an advance in airframe technology, most of the key structural members of the V-22 were made from fiber-reinforced graphite-epoxy laminate. The V-22 designers were comfortable using composites so extensively because of the VTOL technology database developed at Ames, and overseen by John Zuk, Ames' chief of civil technology programs.

The first V-22 flew in March 1989. However, it worked itself slowly into military service and dramatically exceeded its budget. The U.S. Marine Corps began crew training for the Osprey in 2000, and in 2007 deployed it for combat in Iraq and Afghanistan with good results. Though Ames went further into aircraft development with the tilt rotor than was typical, it reflected the sort of radical technology that can emerge with intense NASA research support on all the elements required to make it a success.

SHORT TAKE-OFF AND LANDING

Ask pilots, and they'll say that just as important as flying fast, is being able to fly slowly well. Slow-speed flight remained out of fashion as engineers built aircraft to go faster and farther, but Ames researchers always held a great deal of respect for complex airflows at slow speeds. So Ames developed expertise in the aerodynamics of slow-speed flight in order to help in the design of fixed-wing aircraft that handled better in the trickiest parts of any flight—takeoff and landing. Better performance at slow speeds also resulted in aircraft that could takeoff or land on much shorter runways—important for commuter airlines operating from smaller regional airports or for military pilots operating from unimproved foreign airfields.

Ames began its research on STOL aircraft (for short takeoff and landing) during the NACA years, in the wind tunnels. They saw that large lift gains came in immersing the wing in the propeller slipstream and using engine thrust to augment wing lift. However, this came at the cost of stability while landing. Ames moved to flight tests, in 1960 with a Stroukoff Corporation YC-134A and, in 1961, a Lockheed NC-130B. In 1965, NASA Ames evaluated a Boeing 367-80, paying attention to STOL capability to reduce noise during landing. Ames also matched these flight tests with simulator models of the landing approach to figure out the general handling rules.¹⁹⁹

Into the 1970s, in conjunction with researchers from the U.S. Army, Ames built a series of research platforms that they used to fine tune their theories and designs of STOL technology. These aircraft included the augmented-wing quiet short-haul research aircraft (QSRA), the rotor systems research aircraft (RSRA), and the E-7 short takeoff and vertical lander (STOVL) test model.

Ames first worked to develop specific components that airframe firms could apply to their STOL aircraft. A rotating cylinder flap, for example, improved lift by energizing boundary layers as it turned airflow downward over the trailing edge of the wing. Ames installed a rotating cylinder flap on an OV-10 Bronco and, even though radically modified, the OV-10 proved the point faster and cheaper than building a completely new demonstrator. Ames shortened the

wings, removed the flaps and pneumatic boundary-layer control, shortened the propellers, and cross-shafted the two engines for better performance at slow speeds. Before its first flight in August 1971, Ames completely tested the OV-10 in the 40 by 80 foot tunnel. The rotating cylinder used so little power that full horsepower was available for takeoff. Compared with the basic OV-10, it achieved 33 percent better lift.

In the 1970s, Ames and Canadian researchers joined to study jet-STOL with a complete flying test bed. They modified a surplus deHavilland C-8 Buffalo turboprop aircraft to show the technology of powered-lift ejector augmentation. The modified Buffalo first flew in May 1971 and remained at Ames in flight tests through 1976. Its thrust-augmentor wing achieved augmentor ratios of 1.2 with significant gains in lifting coefficients, so that it could fly as slow as fifty knots and approach the landing field at sixty knots. It routinely demonstrated takeoffs and landings in less than a thousand feet, with ground rolls less than 350 feet. After a full range of flight tests, Ames pilots flew the Buffalo in a series of joint flights—with the FAA and the Canadian department of transportation—to develop certification criteria for all future powered-lift aircraft.

Ames' next iteration of powered-lift aircraft was the QSRA (for quiet short haul research aircraft). Boeing built the QSRA from the Ames C-8 Buffalo and four spare Lycoming turbofan engines. They mounted the engines on top of the wing, so that exhaust air blew over the upper surface, creating more lift, while the wing shielded the ground below from noise. The QSRA wing was also new, emulating a supercritical airfoil capable of Mach 0.74 (though the QSRA never flew that fast). The result was a quiet, efficient aircraft, capable of short takeoffs and landings.

Boeing delivered the QSRA to Ames in August 1978, and it quickly validated the concept of upper-surface blowing. The QSRA could fly an approach at only sixty knots, at a steep, twenty-degree angle. "It feels as if it's coming down like an elevator," said Jim Martin, QSRA chief test pilot.²⁰⁰ During carrier trials in July 1980 aboard the USS Kitty Hawk, with wind over the deck at thirty knots, the QSRA took off in less than 300 feet and landed in less than 200. In zero-

wind conditions, during Air Force tests to simulate operations on bombed runways, the QSRA took off in less than 700 feet and landed in less than 800 without thrust reversers. The real military payoff, though, was that augmented lift boosted payload by 25 percent. In 1983, Martin and Robert Innis flew the QSRA to the Paris Air Show to encourage firms to use the technology in commuter aircraft. Short takeoffs and landings were important to operating bigger aircraft on smaller, local runways; more important, the QSRA surpassed federal requirements for noise abatement. It flew a demonstration landing into the Monterey, California, airport undetected by the airport monitoring microphones.

Over the fifteen years that Ames pilots flew the QSRA, they conducted 697 hours of flight tests which included more than 4,000 landings—averaging nearly six landings per flight hour. More than 200 research reports emerged from data collected on the QSRA. Once the aircraft itself was understood, the Ames QSRA team, led by John Cochran and then Dennis Riddle, used it more as a test bed for new technologies. Renamed the NASA powered-lift flight research facility in 1990, it was an ideal platform to test a jump-strut nose gear that kicked up an aircraft nose during takeoff. Ames retired the QSRA in March 1994.

Another unusual aircraft that bridged the worlds of vertical and fixed-wing flight was the rotor systems research aircraft (RSRA). Sikorsky built two RSRAs, originally for research at Langley, that arrived at Ames in September 1979. Ames and Army engineers designed them as flying wind tunnels—highly instrumented flying test beds for new rotor concepts. One was built in a helicopter configuration, powered by two T-58-GE-5 turboshaft engines. The second had a compound configuration, meaning it could fly with lift provided by two short wings as well as by the helicopter rotor. Two TF-34-GE-400A turbofans were added as auxiliary engines, and the aircraft was instrumented to measure main and tail rotor thrusts and wing lift. Warren Hall served as RSRA project pilot in exploring the differences between the two versions. The helicopter version of the RSRA was later modified to test an X-wing design proposed by the Defense Advance Research Projects Agency (DARPA). The X-wing

RSRA had a single four-blade rotor, built out of composite materials, that lifted the aircraft vertically like a helicopter. Air blown through a fore or aft strip along each rotor blade provided pitch and roll control. As its turbojet engines thrust it forward as fast as Mach 0.8, the rotor provided lift as a symmetrical airfoil with a four-blade X shape. The convertible engine divided its power as it shifted between rotor flight and jet exhaust. In aircraft mode, the air blown through the rotor blades provided lift and control. The RSRA flew only three times in the X-wing configuration, before being abandoned as too difficult to control.

ROTARY WING AIRCRAFT

Ames began working on rotorcraft in the mid 1960s as its research relationship with the Army aeroflightdynamics directorate expanded. Initially, studies focused on pilot control during terminal operations—getting aircraft on and off the ground, especially during bad weather—and Ames built a sophisticated series of flight simulators for helicopter pilots.

Ames' inventory of rotorcraft jumped after 1976, when five helicopters were transferred to Ames from Langley: the UH-1H and AH-1G for rotor experiments, and the SH-3 and CH-47 for operational studies. Ames established a new helicopter technology division to focus on these aircraft, to pursue research in rotor aerodynamics and rotor noise, and to develop new helicopter technologies. The Army, likewise, continued to beef up the technical expertise in its aeromechanics laboratory, led by Irving Statler. Ames and Army aerodynamicists developed a free-tip rotor, for example, with a tip that was free to pitch about its own axis, which was forward of the aerodynamic center. Ames built a model that showed that the free-tip rotor reduced power at cruise speed, minimized vibratory flight loads, and boosted lift by sixteen percent.

Another airborne research platform arrived at Ames in April 1977. Lockheed originally built the YO-3A as an ultra-quiet spy plane. The sailplane wings, muffled engine, and slow-turning, belt-driven propeller kept the YO-3A quiet enough that Ames and Army

researchers could add microphones to the wing-tips and tail-fin to accurately measure noise from nearby aircraft. Ames and Army researchers used the converted YO-3A primarily for studying helicopter noise. The test aircraft flew behind the YO-3A, while on-board aero-acoustic measurements were synchronized with data on flight and engine performance telemetered from the test aircraft. Again, based on this research, the FAA asked Ames to play a larger role in research on flight noise mitigation.

Ames flew the UH-1H to develop automatic controls for landing a helicopter, culminating in an automatic digital flight guidance system known as V/STOLAND. Principal engineers George Xenakis and John Foster first developed a database of navigation and control concepts for instrumented flight operations. Kalman filtering extracted helicopter position and speeds from ground-based and onboard sensors. To define the helicopter's approach profile and segregate it from other airport operations, the system investigated several descending flight paths. Lloyd Corliss then led a series of UH-1H test flights on flying qualities for nap of the Earth operations and Victor Lebacqz used it to devise certification criteria for civil helicopter operations. Later, project pilots Dan Dugan and Ron Gerdes flew the UH-1H in the first demonstration of automatic control laws based on the nonlinear inverse method of George Meyer.

When the Bell AH-1G White Cobra arrived it was highly instrumented for a tip aerodynamics and acoustics test. Ames got the highly instrumented rotor blades that the Army had used for its operational loads survey, and added additional absolute pressure instrumentation to the rotor tips. Thus, one rotor blade returned 188 pressure transducer measurements, with 126 more measurements added by the other blade and the rotor hub. Robert Merrill was chief pilot and Gerald Shockey led the project, which returned detailed measurements of aerodynamics, performance, and acoustics.

Ames modified the CH-47B Chinook to include two digital flight computers, a programmable force-feel system, and a color cathode-ray tube display. This system allowed wide variations in the helicopter's response to pilot controls, making it an ideal variable-

stability research helicopter. Ames used it in flight simulations to define new military handling qualities. In close cooperation with Stanford University researchers, Michelle Eshow and Jeffery Schroeder used the CH-47B to investigate control laws developed on Ames' vertical motion simulator. The Army let Ames use the CH-47B from 1986 until September 1989, just before they closed out the line that remanufactured them into a CH-47D suitable for Army duty.

To carry forward this variable-stability research, in 1989 Ames acquired a Sikorsky JUH-60A Black Hawk. Known as RASCAL (for rotorcraft aircrew systems concepts airborne laboratory), it carried extensive rotor instrumentation, a powerful 32-bit flight control computer, and image generators for the cockpit. "We're putting a research laboratory in a helicopter," said RASCAL program manager Edwin Aiken. "Now when we experiment with flight control software, advanced displays or navigation aids, we can get a realistic sense of how they work."²⁰¹ Ames and Army engineers used RASCAL to develop a range of new technologies—active sensors like millimeter wave radar, passive sensors using infrared, and symbologies for advanced displays. The goal was to make helicopters respond to pilot controls with more precision and agility, to provide better obstacle avoidance and automated maneuvering close to the terrain, and to improve vehicle stability when carrying loads or using weapons. For example, Ernest Moralez helped devise algorithms that would automatically protect a flight envelope in which pilots could then maneuver freely.

Another UH-60 Black Hawk also entered the Ames inventory in September 1988 as part of the modern rotor aerodynamic limits survey. Sikorsky Aircraft built two highly instrumented blades for the Ames/Army program. A pressure blade with 242 absolute pressure transducers measured airloads—the upward force produced as the blades turn. A blade with a suite of strain gauges and accelerometers measured the structural responses to air loads. The pressure blade alone returned a 7.5 megabit data stream, demanding a bandwidth well beyond the state of the art. An Ames group, led by Robert Krufeld and William Bousman, devised a transfer system that returned

thirty gigabytes of data during test flights in 1993 and 1994—data then archived for access by rotorcraft designers. The UH-60 studies ended a ten-year airloads program, launched in 1984 and completed for only \$6 million. Its legacy was an airloads database actively used to refine helicopter design and to better predict performance, efficiency, airflows, vibration, and noise.

When NASA headquarters transferred other Ames aircraft to Dryden, the Army aeroflightdynamics directorate insisted that its research helicopters stay at Ames. After several years of negotiation, in July 1997 NASA headquarters signed a directive that Ames would continue to support the Army's rotorcraft airworthiness research using three helicopters. One UH-60 Blackhawk configured as the RASCAL remained as the platform for advanced controls. The NASA/Army rotorcraft division, led by Edwin Aiken, used it to develop programmable, fly-by-wire controls for nap-of-the-Earth maneuvering. Another UH-60 was rigged for airloads tests, and an AH-1 Cobra was configured as the flying laboratory for integrated test and evaluation (FLITE). In addition, the rotorcraft division made good use of the upgraded wind tunnels. For example, Stephen Jacklin led load and efficiency tests in the 40 by 80 foot wind tunnel of an advanced rotor hub, without hinges and bearings, designed by McDonnell Douglas for its new generations of helicopters.

Even as NASA cut its budget for helicopter research in the 2000s, the Army remained a consistent source of funds. In 2006, Ames refocused its work to defining first principles in helicopter aeromechanics.²⁰² Ames research in helicopter flight proved to be just as valuable as its work in integrative flight control for fixed-wing aircraft. By taking novel technical approaches to first isolating and then solving seemingly intractable problems, and integrating their use of computation, tunnel, and flight testing, Ames bolstered the core technologies found in all helicopters.

AVIATION OPERATIONS

Research in air traffic management harkened back to Ames' legacy in the NACA. The NACA purview included any topic that affected American aviation. Thus, in the early 1920s, during the early

years of American airmail service, the NACA turned its attention to weather forecasting, airport design, and radio communication. The NACA continued to monitor problems in aircraft operations, as with flight near cold-weather airports in the 1940s. In the 1970s, NASA Ames first focused on automating the environment in which aircraft operated.

In April 1972 Heinz Erzberger published the fundamental papers on analyzing aircraft trajectories in four dimensions—the three spatial dimensions plus time. Erzberger had joined Ames in 1965 in applied mathematics as part of an environmentally-friendly effort to determine which flight paths generated the least noise. Soon after he was modelling the best way to get STOL aircraft, that others at Ames were designing, into and out of an airport. During the fuel crises of the 1970s he shifted his emphasis to study ways to optimize America's air traffic system. Over the ensuing three decades Erzberger served as principal architect of the Center-TRACON automation system (CTAS), a suite of software that generated new types of information to “advise” air traffic controllers. His work was not driven by supercomputing. He relied instead on Ames innovation in visualization and internetworking, and used fairly simple client-server computers. He brought scientific rigor to the air traffic management and, along with his colleague Dallas Denery, built a major research program that served the flying public by reducing delays and boosting safety.

Notably, he accomplished this in close collaboration with the FAA, the federal agency responsible for the national airspace system. NASA Ames had earlier done much of the human factors work that enabled automation of aircraft cockpits. “Flight management systems in today's aircraft help pilots do their job much better,” noted Erzberger. “The CTAS program is about providing the same benefits to air traffic controllers.”²⁰³ In 1991 the FAA asked Ames to begin programming specific tools to infuse the airspace system with greater safety, efficiency and timeliness. In November 1996, Victor Lebacqz, chief of the Ames flight management and human factors division, announced a joint NASA and FAA plan to focus the many facets of Ames' air traffic efforts. In June 1997, NASA announced a \$450

million aviation system capacity program, with Ames as lead Center.

The Center-TRACON system released in 1997 included three computer advisors to air traffic controllers. The traffic management advisor picked up aircraft when they were twenty minutes from landing, and figured out the best way for them all to land. The descent advisor graphically depicted incoming aircraft as they converged forty miles from the airport, to make their descent most like a fuel-efficient glide. The final approach spacing advisor let controllers quickly correct aircraft spacing as aircraft approached the runway.

CTAS quickly proved its value in both time and cost savings at some of America's busiest airports. As early as May 1992, Ames installed the simplest version of CTAS at the Stapleton international airport in Denver, then continued to refine the more complex parts. The software was integrated with the existing radar system at the Dallas/Fort Worth airport in 1994, and saved an average of two minutes per flight. With those results the FAA chose CTAS for implementation at all major airports. Resistance from airlines and local airport authorities delayed its use within the United States, though CTAS appeared in many other nations. Michelle Eshow, on behalf of a team of 37 contributors who wrote and implemented CTAS, in 1998 accepted NASA's software of the year award.

NASA Ames continued to augment its software advisors into a comprehensive suite of air traffic management tools. Once aircraft were on the ground, a different set of advisors chimed in. The surface movement advisor (SMA) provided data to the airlines, through the flight controllers, on when aircraft would land and arrive at the gate, thus improving gate scheduling and reducing radio traffic. Programming for surface movement was more complex than with air traffic, in that each airport had a unique layout and was controlled by an airport authority rather than the FAA. Still, from a go-ahead in March 1994, Ames got a prototype of the SMA working at the Atlanta airport in time for the 1996 Olympics. After eighteen months, taxi-time reductions averaged one minute per aircraft and Delta Airlines calculated that SMA saved them \$50,000 a day in fuel costs alone. NASA Ames and the FAA expanded SMA into the surface management system (SMS), verified it in the FutureFlight

Central simulator, and in September 2003 tested it successfully at the Memphis and Dallas airports.²⁰⁴ FedEx and UPS made it a key part of their operations. The FAA began exploring ways to install the SMA at all airports.

Another key software innovation was FACET software, for future ATM concepts evaluation tool, which won the NASA software of the year award in 2006. Drawing actual but delayed weather data from NOAA and air traffic data from the FAA, FACET rapidly projected thousands of aircraft trajectories through climb, cruise and descent. It was used to model new approaches to air traffic planning, including aircraft self-separation, integrated aircraft and space vehicle launching, and monitoring of rerouting. “FACET started as a simulation tool for NASA research,” noted Banavar Sridhar, FACET team leader, “and has evolved into an operations planning tool for the FAA and airlines.”²⁰⁵ NASA Ames researchers also integrated air-based and ground-based systems. Unrestricted flight routing, or free flight, for example, allowed more aircraft to share airspace under all weather conditions. Ames’ advanced air transportation technology branch developed a block-to-block planning service that allowed each aircraft to choose its own best flight path, potentially saving minutes of air time per trip.

Another example of using information technology to solve safety issues was FutureFlight Central (FFC), a simulator designed to prototype Ames’ surface movement advisor. “Surface movement around airports,” said Stanton Harke, who managed construction of FFC, “is really the bottleneck to making the air transportation system more safe and efficient.”²⁰⁶ The FFC looked like the interior of an air traffic control tower, with consoles that could be moved to fine-tune the layout. Harke’s staff used off-the-shelf video and SGI computers to generate a high resolution display with a 360 degree view out the window. For less than \$10 million the FFC became the world’s most sophisticated test facility for air and ground traffic simulation. The FFC was configured to simulate what controllers saw at the world’s major airports—both in the arrangements inside the tower and in the view out the window. (By projecting panoramic images of the Martian landscape out the windows, they also simulated the control

station of a Mars base.) By reprogramming the display, airport designers saw how well aircraft moved around a proposed airfield before concrete was poured. FFC was also used to test new airport designs so that aircraft would spend less time idling their engines as they waited for take-off or looking for a landing gate.

Ames also completed a system to automatically record and process huge amounts of real-time flight data from new aircraft. "We can detect accident precursors that we didn't know existed," said Richard Keller of his work on the FAA and NASA aviation safety reporting system. Alaska Airlines and United Airlines helped Ames demonstrate the recorder, beginning in 1998, and reported that the data returned could be used to not only improve safety, but also improve aircraft performance and maintenance scheduling.

In 2008 Ames researchers shared in the Collier Trophy, awarded to a public-private team working on the automatic dependent surveillance-broadcast, or ADS-B. Instead of relying on radar, ADS-B used global positioning system (GPS) satellite data to give pilots and controllers accurate traffic information in real time. The system also gave pilots access to weather services, terrain maps and flight schedules. The ADS-B had been certified by the FAA in 2000, and was widely, though not universally, deployed around the United States. By 2004, as part of the FAA Capstone program, it was installed on 300 aircraft that flew remote routes in Alaska, and reduced accidents by 47 percent. It was installed more widely outside the United States, and reduced air accidents more than any previous technology. United Parcel Service was early adopter, specifically to improve aircraft separation around its airport hubs, where its air fleet showed remarkable gains in efficiency. "ADS-B is a ground-breaking effort for next-generation airborne surveillance and cockpit avionics," noted the FAA press release. "Its implementation will have a broad impact on the safety, capacity and efficiency of the national airspace system."²⁰⁷

The next generation of air traffic control, in fact, would be built around this GPS technology rather than the radar technology in use since World War II. Ames researchers continued to contribute to the design of NextGen air traffic management using GPS technology

matched with more complex algorithms, not only to improve safety and the economics of air travel, but also to reduce its impact on the environment.

GREEN AVIATION

Into the 2000s, as the Constellation program diverted NASA funds from aeronautics research, Ames leadership began to question the role of aeronautics research in NASA. There likely would not be much new work on aircraft structures. The shape of jet airliners had changed little since the 1960s. The Boeing 777 was the first airliner designed, in the 1990s, entirely on computer, relying on codes brought to maturity at NASA Ames. Thomas Edwards, then deputy director of aeronautics at Ames, recalled that “all of those classical problems in structures, controls and aerodynamics are sufficiently well understood that the one company that’s left in the U.S. making airplanes can pretty much do it themselves.”²⁰⁸ In response to declining funding for more traditional aeronautics research, Ames reframed its aeronautics portfolio as “green aviation.” Under this umbrella fell all the various efforts aimed at reducing the significant environmental impact of air transport.²⁰⁹

Some of these innovations arose at the component level, under the purview of NASA’s subsonic fixed wing project. The most prominent of these innovations was the advance turboprop engine, which had won the Collier Trophy in 1987, and served as the basis for work on a geared turbofan by Pratt & Whitney and an open rotor propulsion system by General Electric.²¹⁰ Other more recent work focused on extensive use of lighter weight composite materials. Some work looked much like that done during the NACA days, as with laminar flow control or on the aerodynamics of the hybrid wing-body which was a variant of the flying wing. Other work proceeded into the development of low-carbon fuels to reduce emissions, and biofuels to achieve carbon-neutrality across the system. Jonathan Trent, for example, pursued a comprehensive research program into generating biofuels from tubes of plastic sheeting full of algae, floating in the ocean, and fed sewage.

Green aviation also encompassed work in radically new airframes. Airships, such as the dirigible based at Moffett Field since 2005, were a decidedly green alternative for air tourism, for carrying large payloads, or for hovering over a fixed spot for surveillance or environmental monitoring. Electric aircraft showed the most promise as short-range VTOL aircraft or as uncrewed aerial vehicles. VTOL aircraft also earned attention because of the maturity of the XV-15 Osprey in military service. Since the 1970s VTOLs have been studied as a way of locating air transport more closely to population centers, and thus reducing the overall environmental impact of getting to the airport.

Battery performance was the limiting factor in the development of electrical aircraft, as it was in other types of electric transport. One solution came in the development of a solid oxide fuel cell, a spin-off of technology developed to generate oxygen from the carbon-dioxide heavy atmosphere of Mars. KR Sridhar arrived at NASA Ames in 1996 as an NRC postdoctoral fellow from the University of Arizona, focused on solid oxide electrolysis for *in situ* resource utilization on other planets. He collaborated with John Finn, a young chemist working on carbon dioxide adsorption for air purification with Mark Kliss in Ames' regenerative life support branch. In 1997, an oxygen generating system proposed by Sridhar and Finn was selected to fly on the Mars 2001 Survey Lander. It would generate enough oxygen to, some day, propel a sample return capsule off the surface of Mars. In the wake of the Mars failures in 1999, though, this mission was cancelled. Harry McDonald encouraged Sridhar to continue working on other space applications of solid oxide technology, and Sridhar was successful in earning NASA grants. In April 2002 Sridhar and Finn founded a company—ION America, later renamed Bloom Energy—to reverse the electrolysis and produce electricity instead of oxygen. They leased space in the NASA Research Park as they refined their technology with venture funding.²¹¹ In February 2010 they unveiled their Bloom Box, which promised energy efficiencies twice that of the American electrical power grid. While the Bloom solid oxide fuel cells were too heavy to use in conventional transport

aircraft, Bloom hoped to refine it to be useful on solar-rechargeable, high-altitude rockets.

Aeronautics represented an ever-declining portion of NASA research portfolio, but Ames engineers continued to make major advances. As during the NACA days of fundamental research, some advances were on the component level, others came from re-envisioning the entire airspace system. As in the NACA days, this work was driven by attention to the long-term needs of the aeronautics industry. The NACA model, which revolved around support of commercial firms in developing aeronautics, would eventually return to favor within NASA.

Conclusion

In January 2010, a year into the administration of Barack Obama, NASA administrator Charles Bolden announced that NASA aspired to a new approach to American space exploration. NASA's budget, as proposed, would increase \$6 billion. NASA would cancel the Constellation program and reshape its human space flight efforts. NASA abandoned the ESAS architecture with the Moon as its destination. NASA instead opted for a flexible technological path leading toward destinations later determined opportunistically. The Space Shuttle would still be retired in 2011, as decided during the Bush administration, and NASA committed to the International Space Station through 2020. To get on station, NASA would buy seats temporarily on Russian spacecraft until about 2016. Then NASA would rely on commercial launch vehicles, like the Atlas V and Delta IV launchers built by United Launch Alliance LLC or the Falcon 9 built by SpaceX, the Space Exploration Technologies Corporation.

To help this commercial spacecraft industry succeed NASA would "return to its NACA roots," a phrase used repeatedly by Pete Worden in explaining the Ames perspective on the new budget. The government would create a market for access to low Earth orbit, as it already had by investing in human suborbital flight. NASA would also invest a half-billion dollars in transformative technology for space exploration, help commercial firms solve their common problems, and invent the technology needed for space exploration decades in the future.

One example of that help, mentioned by Bolden in Congressional hearings, was the PICA heatshields developed by SpaceX for their Dragon crew capsule.²¹² PICA had been developed at Ames, successfully demonstrated on the Stardust return capsule in January 2006, and refined for the Orion crew capsule developed by Boeing for the Constellation program. Using a reimbursable space act agreement administered by the NASA Ames Space Portal, SpaceX consulted with Ames staff on the thermal and mechanical properties

of PICA, finite element modeling to improve it, ways of building and instrumenting an arc jet model, and a risk reduction strategy for validating it. SpaceX tested its variant, dubbed PICA-X, in the Ames arc jets and selected it for its Dragon crew capsule. Thermal protection engineering for the Constellation program, led by Ames, revived many American firms that made ablative materials and gave NASA new options for the future design of heatshields.

Other parts of Obama's proposal boded well for NASA Ames, in that they played to Ames' historic, but recently underfunded, research strengths. Aeronautics research would receive \$80 million. NASA would shift a half-billion dollars into space science and into monitoring the health of the Earth, especially through small Venture class missions. Ames would be the center of NASA's small spacecraft efforts. Robotic precursors would be sent to several destinations, and space life sciences would refocus on fundamental research. Whenever possible, NASA would pursue collaboration with international partners. NASA put education as a top priority.

Other developments showed that NASA would again value its basic research centers. All Center directors reported to the administrator. NASA empowered a new chief technologist to fund break-through technologies and to manage the innovative partnerships program which led interaction with commercial firms. Full cost recovery was cancelled; though full cost accounting remained. Center maintenance budgets were boosted by \$200 million, and Bolden created a new mission support directorate with a budget to fund the health of the NASA Centers.

It appeared that the Obama administration was aware of all Ames people hoped would get America back into space exploration. NASA shifted its paradigm in-line with the paradigm Ames had operated under for decades: support of industry and university partners, taking a longer-term view toward technology, a willingness to work with smaller budgets, and a dedication to space science and aeronautics research. All this would be possible by righting the imbalance induced by spending on the Constellation program.

However, NASA's proposed budget soon encountered strong resistance. Members of Congress representing the areas near the

Kennedy, Marshall and Johnson human space centers objected to much of NASA's plan, especially the cancellation of Constellation. President Obama flew to Florida and announced a jobs program and continued investment in the Orion crew capsule, which could be used aboard a commercial rocket. As NASA and Congress worked on a compromise budget, NASA Ames people remained optimistic about the prospects of a historic shift in how NASA equipped itself for space exploration.

As NASA tried to reshape itself, NASA Ames celebrated its 70th anniversary on December 20, 2009. In fact, Ames people celebrated for months as the Center invited former directors back to speak, held picnic lunches, and inducted a new class into its hall of fame. The celebration of Ames' past culminated in a gala dinner in January 2010 and the next week NASA Ames—its culture and all it had built over the past 70 years—found itself positioned at the center of America's space exploration future.

Acknowledgements

Jack Boyd has played a unique role in the history of Ames. Jack joined Ames in 1947 as an engineer working in supersonic aerodynamics. In 1966 he became technical assistant to Harvey Allen and since then—as he moved up to deputy director, associate director, NASA associate administrator for management, and other leadership posts—Jack has served as Ames’ institutional memory and the embodiment of its corporate ethos. As this book was written, he served as senior advisor to the Center director, helping make the Center’s past relevant to the shaping of its future. Jack also served as Center ombud, helping solve problems that arose where the Ames corporate culture has broken. Jack also served as senior advisor for history, available to give ready advice on how to interpret Ames’ multifaceted history. Jack lives the belief that a strong sense of the past is great grounding in the rush to forge the future.

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This is a work for hire, though the only restriction Ames placed on this manuscript was that it be done for their seventieth anniversary year. Some may say I failed to give adequate attention to certain projects, failed to credit to all those who dedicated their careers to the Center, or failed to appreciate the struggles they overcame. Many people reviewed this manuscript for errors, though any that remain are mine alone. Most made sure that I understood that the best scientists, engineers and managers will keep coming to Ames, not because of the history that I was tasked to portray—but to work with the best minds in their professions.

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²¹⁰Mark D. Bowles and Virginia P. Dawson, “The Advanced Turboprop Project: Radical Innovation in a Conservative Environment,” in Pamela E. Mack, ed., *From Engineering Science to Big Science: The NACA and NASA Collier Trophy Research Project Winners*, NASA SP-4219 (1998).

²¹¹“NASA Technology Comes to Earth,” (accessed 1 March 2010 at <http://www.bloomenergy.com/about/company-history/>).

Chapter 8: Conclusion

²¹²Charles F. Bolden, *Challenges and Opportunities in the NASA FY 2011 Budget Proposal: Testimony before the Subcommittee on Science and Space, Committee on Commerce, Science and Transportation, U.S. Senate*, (24 February 2010) (accessed 3 March 2010 at <http://commerce.senate.gov/public/>

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