Why Space Research and Space Exploration?: NASA Ames Research Center Contributions To NASA's 50 Years

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Why explore? Among the many reasons, we explore because it fuels a useful scientific and technological foundation that enables a flourishing economy. Taking humans to the edge of their known world both requires new technology, and returns radical new insights into the world. Without exploration, science and engineering became routine and uninteresting. In this paper we will explore how the NASA Ames Research Center, which is nearly 70 years old, has contributed scientific and engineering expertise to the exploration missions at the heart of NASA over its 50 year history. We will cover Ames's work on the manned space programs, the Space Shuttle, aeronautics, lunar science, planetary exploration, Mars, and the prospects of life in the universe. We end with a cautionary tale of economic decline should exploration stop.

I. Why Explore?

This October, the NASA Ames Research Center celebrates its 50 years as one of the pillars of the National Aeronautics and Space Administration (NASA). Our Center stands as an extraordinary repository of high-tech equipment, research laboratories, and facilities to support humankind's conquest of the atmosphere and the exploration of space. That physical infrastructure supports what Ames truly is--a growing and evolving community of researchers and managers. It is a community with a fertile, open and pan-disciplinary culture, driven by

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people who have contributed all they know to all that NASA has accomplished over the past 50 years.

The Apollo encounter with our Moon was one of the defining events of the last century. Apollo forever changed the way we look at the Moon, at the Earth, and at NASA. Anyone over the age of 36 can look up at the Moon today and personally remember that twelve men once walked there. They can recall how thrilling were those late-night black-and-white images of the small plots of lunar soil around where the lunar landers camped. To anyone under the age of 36—and that includes many in NASA holding PhDs in space science, and some with star-struck kids of their own—they learned that the last man to have trod the lunar landscape did so before they were born. When these youngsters think about the Moon, and wonder why Americans have only returned to the Moon twice since then (once through the Lunar Prospector robotic probe developed by NASA researchers at Ames) perhaps they conclude that that early generation of explorers found the Moon an even more barren rock than they had imagined. Apollo changed how we think about our Moon.

When we all think about our Earth in our post-Apollo age, by comparison with the Moon, we see it as even more life-giving. Before Apollo school kids imagined the Earth like a brown Mercator projection lined with political divisions. After Apollo we envision the Earth--as first did the Apollo astronauts--as that fragile orb of interlaced green, blue and white suspended in the black vastness of space, a frightening thin layer of atmosphere keeping it alive. Life on Earth now inspires even more wonderment.

And when we think about NASA, there may also be a generational divide. Some envision NASA as that can-do team of brainy young men and women—some wearing thick black glasses and others wearing thick white space suits--who achieved what once seemed impossible, and did so before that decade was out. Perhaps those younger envision NASA as scientists in Shuttle-standard orange jump-suits, looking down upon Earth while floating free from gravity, but simply off to their jobs.

Of course, the story of NASA then, like the story of NASA today, is vastly more complicated and interesting once we look deeper. And as Ames' life with NASA reaches its 50th anniversary, it is worth exploring how the historical analogy to the Apollo years—and to the early Shuttle years--illuminates the NASA of today.

II. Ames Contributions to Mercury and Gemini

Apollo was a time of sweeping cultural change within NASA. Yet Ames probably changed the least, of all the Centers, as the NACA was absorbed into NASA in October 1958, and as NASA became preoccupied with Apollo in 1962. Smith DeFrance kept Ames the way he had built it, as director from its founding in 1939 though his retirement as director in 1966. DeFrance was succeeded as director by H. Julian Allen, a paradigm-shifting aerodynamicist completely imbued with the NACA spirit of relevant but free research. The first "A" in NASA stands for Aeronautics, and during the Apollo years Ames did much of the work that needed to be done on aircraft so that the new NASA centers could focus on space travel.

Ames still contributed much to NASA's early manned missions—in terms of science, technology and culture. During the Apollo years competition between centers was vigorous and heartfelt. The pie of increased funding was growing, regardless of how funding was apportioned. Every member of the new NASA felt free to contribute their best efforts to the mission, they could get support and protection from their center, and new ideas were welcome throughout the Administration. The culture was competitive largely because the intra-NASA peer review system, 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 new idea being offered. And there was enough money available that the thrust-and-parry of new ideas encountering peer-critique could usually be ended by cutting metal and strapping on sensors in order to prove the point. Ames representatives to the NASA committees charged with designing early spacecraft especially earned a reputation for their "show-me" attitude.

Furthermore, DeFrance and Allen enjoyed the freedom to manage their center, because James Webb in NASA headquarters respected their judgment. Research leaders within Ames also enjoyed the freedom to manage their groups because DeFrance and Allen continued the NACA tradition that all communication to and from headquarters—or to their scientific colleagues at Langley or Lewis--go through the director's office. NASA headquarters slowly opened up direct lines of communication to researchers within Ames—notably in the way it structured Ames' life sciences efforts—but DeFrance and Allen fought hard to minimize interference from Washington.

The result was a cooperative spirit that allowed DeFrance and Allen to move many new types of researchers into the center without cultural conflict. One strategic enterprise dominated most of the centers set up by NASA, or reshaped by NASA. JPL came to focus on robotic explorers, Goddard on Earth observation, Marshall on propulsion, Kennedy on launch vehicles, Johnson on manned space flight. At Ames in the 1960s, as today, most all of NASA's strategic enterprises were pursued—aerospace, information technology, human factors, space and earth science, aeroflightdynamics. Each enterprise was weighted equally by the management of the center, and each looked for fertile areas to explore along their borderlands.

III. Life Sciences and Information Technology

Life sciences and information technology were prime examples of the inclusive research tradition at Ames. Life sciences, especially, grew at Ames over the past 45 years like a river—fed by streams, splitting around rocks, merging again around a new idea, sometimes branching and pooling, and accelerating as channels deepen. This perambulation into sundry research efforts frustrates attempts to write a linear history of the life sciences at Ames, though it made the ride all that more thrilling for those who lived that history. Ames people, like all those who built Silicon Valley into an epicenter of biotechnology and computing, persistently figured out ways to make their work both cutting-edge and cross-pollinating. There is nothing linear about how they have collaborated.

Ames began research on living subjects in the early 1950s when it started building simulators to improve the analog computers behind aircraft controls. With the birth of NASA in 1958, Ames was asked to invent and build more sophisticated simulators for studying how human pilots could control the coming spacecraft. From there, Ames developed expertise in the design of space suits that could support life in space while permitting a wide range of functionality. And Ames began its work in miniature biosensors that could monitor and diagnose the health of astronauts sealed, far away, in space suits and capsules.

NASA headquarters, seeing how well biologists adapted to the research environment at Ames, asked DeFrance to take on more life sciences work. DeFrance then hired Chuck Klein to coordinate those efforts, and Klein did a masterful job of growing the life sciences within the cooperative culture inherited from the NACA. Ames built for NASA a comprehensive laboratory for more fundamental studies of human adaptation to weightlessness, and built the Biosatellite capsules to carry the first pure biology experiments into space. University scientists working at Ames then used all NASA was learning about the chemical composition of the universe to theorize about what sparked life on Earth. Exobiology flourished at Ames as very fundamental science, though NASA applied it very concretely to study why the Moon did not support life.

NASA continued to find uses for the life sciences capabilities at Ames. Exobiologist teams built instruments for the Viking Lander in 1976 to study the prospects of life on Mars, and analyze the chemical composition of the planets passed by the Pioneer series of satellites. A series of ever more powerful infrared telescopes—like the Kuiper Airborne Observatory--returned new information about the chemical composition of the solar system and generated new insights on the formation of planets. Meanwhile NASA researchers at Ames continued their work on flight simulators—for new generations of piloted spacecraft and rotorcraft, and to study human adaptation to long stays in space. And they managed experiment packages sent aloft to study how other creatures adapted to microgravity—on Skylab, on the Shuttle Orbiter, and on a series of Cosmos/Bion flights with the Soviet space agency.

NASA researchers at Ames then brought their space biology work back home. They turned what they learned about the atmospheric observation of other planets to look at the ecosystem of the planet Earth with new technologies and new theories. Ames hosted a fleet of NASA science aircraft, like the DC-8 and the ER-2, that served as airborne platform available to carry interesting experiments devised by scientists at other centers, at universities, or from around the world. All of this work at Ames coalesced in the 1990s in a series of inclusive NASA projects—on astrobiology, air traffic systems, and telemedicine.

During the NACA years, Ames had been organized by facilities. By the mid-1960s it was organized by scientific discipline. By the mid-1990s it was organized by tasks which could only be solved by aligned efforts of many people.

Information technology at Ames started later than the life sciences, though its history also displays the same perambulation and service to NASA spaceflight missions. At first, the computers at Ames were mathematicians, mostly women, hired to work through equations and compile vast amounts of experimental data. Ames began using analog computing machines to simulate flight controls, and in the early 1960s added a few digital computers to compile wind tunnel data and handle administration. In 1972 Ames acquired the Illiac IV supercomputer, which Harvard Lomax used to create the field of computational fluid dynamics. Over the next two decades, NASA researchers at Ames bought and debugged almost every new generation of supercomputer. They also figured out how to share them, and invented protocols for distributed computing that underlay the development of the Internet. They also invented all types of CFD codes, software that graphically modelled how air flowed over an object and thus moved much of aircraft development from the wind tunnel into the computer. Ames applied its basic expertise in modelling air flows to model heat flows, chemical interactions, microorganisms, molecular structures, and the thermal evolution of the galaxies. The amount of computing time it takes Ames to do a model of global climate change, for example, continues to drop. When NASA researchers at Ames matched their computing power with new telecommunication technologies, they became experts in surface rovers, robotics, virtual landscapes and, connecting back to the life sciences, in air traffic systems and telemedicine.

The dawn of the Space Station effort in the mid-1980s shifted the emphasis of Ames work in information technology into intelligent systems, that is, computing systems that extend decision-making support into spacecraft far from Earth. NASA researchers at Ames developed systems to plan and schedule major NASA missions, systems to monitor and diagnose space vehicles and the equipment they carry, systems to analyze vast amounts of space science data, and systems to assist both ground-based scientists and astronaut-scientists in the conduct of experiments. Ames brought into use a host of specific applications arising from its basic work on intelligent systems. One program developed at Ames schedules Space Shuttle processing at KSC. A laptop-based experiment assistant was used by astronaut Shannon Lucid on a vestibular biology flight experiment. The Mars Exploration Rover science teams at JPL used a number of collaborative tools developed by NASA researchers at Ames. The NASA Ames computer complex is now used in real time during every Shuttle flight to analyze potential problems. Ames today has more people working on information technology than in any other federal laboratory, and NASA uses this capability extensively.

Aeronautics research remained an important function at Ames at it, likewise, continued to reflect the inclusive research approach that characterized Ames' development of the life science and information technology. During the 1950s Ames engineers had taken very inclusive views to solving all the problems of supersonic flight—using a variety of wind tunnels, simulators and flight tests--and devised some key solutions to making the jet age possible. These include the invention of the swept wing, studies of conical camber, and the Cooper-Harper Rating Scale of aircraft performance. Into the 1970s, Ames engineers tackled the myriad problems presented by VTOL (vertical take off and landing) aircraft, drawing from their expertise in rotorcraft and fixed wing aircraft at low speeds. This included wind tunnel tests of rotors, simulator studies of cockpit design, and flight tests of the XV-15 tilt-rotor and other aircraft. Because of its continuing collaboration with the Army, Ames has become an important center for basic research in helicopter aerodynamics.

Historically, it is also important to remember the fields Ames did not enter. DeFrance also made clear decisions on what Ames was not. Even when money was available, DeFrance demurred from taking on projects that did not leverage the research culture at Ames. For example, throughout the 1960s there were NASA engineers at Ames eager to take on management of complete space programs. NASA headquarters encouraged them. Program management then was a creative art, advancing rapidly at the time throughout science, industry, and government. Program management got most creative as it got closer to the engineers cutting metal or the scientists compiling the results, in understanding the dynamic tensions of piecing together all the people and the pieces. Ames did a great job managing its wind tunnel projects, then considered very high technology, and could have done well managing space projects.

Yet DeFrance demurred. Only the M2-F2 lifting body prototype, the Biosatellite, and the early Pioneers emerged as completed projects during his watch. In the late 1960s and afterward Ames managed a number of spacecraft projects, but never managed complete projects on the scale of the other centers. However, the projects that NASA people at Ames did manage—notably the Pioneer satellites, Space Shuttle biology experiment packages, the Galileo probe, the Lunar Prospector, a series of infrared telescopes—were remarkable for their low cost and timely performance, their collaboration with university sciences, and for the brilliance of their results.

DeFrance was also cautious about developing expertise at Ames that would not complement its existing strengths. For example, because of mathematical work and analog computing research at Ames culminating in the Kalman-Schmidt filter, a navigation algorithm, NASA people at Ames could have lead the work in the early 1960s on defining the flight envelope for the Apollo and deep space missions. DeFrance encouraged the aerodynamicists hired during the NACA years to branch into new areas, to re-invent their careers and to seek new relevance for their work. They were, after all, all very bright people who could make an impact wherever they turned their attention. While NASA would later task Ames to use its computing power to improve air and space navigation, at that time DeFrance thought navigation was too far afield from what NASA more clearly needed from Ames—leadership on thermal protection systems and space science.

IV. Ames Contributions to Apollo

Ames researchers quietly contributed to the Apollo mission. Public attention focused on the spectacular—powerful rockets, massive spaceports, mission control centers, and charismatic astronauts. Ames hosted none of these spectacles. Perhaps the most exciting photographs to emerge from that era, around Ames, were of tiny capsule models ablaze in a high-speed ballistic range or a high-temperature arc jet tunnel. Instead, behind the scenes, Ames researchers gathered knowledge about new scientific fields that needed to be known and tested their technologies with painstaking precision. And they did so with a style that was uniquely Ames. Researchers with many areas of expertise discussed their work persistently and freely, then cooperated to bring every tool they had to solve a very complex problem. And they were given the freedom to work quickly and to their own ideal of thoroughness.

Ames developed some key Apollo technologies, most importantly technologies to allow the astronauts to return safely to earth. Building upon what was already two decades of research on re-entry physics and material science—a discipline today known as aerothermodynamics—NASA researchers at Ames devised the basic shape of the Apollo capsule and its thermal protection system. Today, almost sixty-five years later, all spacecraft are still derived from essential insights earned at Ames.

Before Ames began its work many thought that a spacecraft re-entering the Earth's atmosphere at meteoric speeds would, like a meteor, burn into a fireball. Those who speculated about spacecraft design suggested pointy cone-shape tips of hardened metal to pierce the atmosphere with the least possible friction and the slowest possible melting. Harvey Allen stepped outside the conventional thought, and took an entirely fresh approach. In 1948 Allen advanced the blunt-body concept, which was further developed by Al Eggers and Dean Chapman.

They conceptualized that, with a blunt body, atmospheric air would still heat up as it crossed the bigger bow shock wave in front of the spacecraft. However, that air would be heated at a distance from the spacecraft then pass harmlessly around it and into the wake of gas behind the body. With less heat near the spacecraft, different types of heatshield materials could be imagined. Such a radical idea met with resistance, so Ames set about to prove it to the rest of the aerospace community.

Ames then used its practical expertise in wind-tunnels and its theoretical expertise in hypersonics and built free-flight tunnels to determine which precise blunt body shape would be best during re-entry. These ballistic ranges shot tiny metal models into an onrush of air to reach the actual velocities at which they would enter the atmosphere, while delicate instruments recorded the results. These test runs led Thomas Canning to discover that the best shape for retaining a laminar boundary layer, and thus minimizing heat transfer to the capsule, was a nearly flat front face to the blunt body. They also checked these shapes for lift and drag and for aerodynamic stability—so a capsule would not start to tumble. Based on these tests, NASA selected this shape for the Mercury, Gemini, and Apollo capsules.

Once Ames demonstrated which specific blunt-body shape worked best, work began on picking the best materials to protect it with. Since no known materials could insulate against that kind of heat, Morris Rubesin, Constantine Pappas, John Howe and other NASA researchers at Ames developed an ablative heat shield. Ablation meant that the heat shield material was slowly consumed by burning and vaporization, but as it burned it transfered heat into the atmosphere and away from the underlying metal frame of the spacecraft. Surface transpiration also reduced skin friction, which kept the spacecraft more aerodynamically stable.

Ames people then invented and built arc jet tunnels to prove which were the best specific ablative materials. Arc jets are a type of wind tunnel which generate very hot gas flows for minutes so that re-entry heat can be simulated both in terms of temperature and chemistry. Aerospace firms then designed ablative heat shields for the Apollo capsules, and these were then tested again in Ames' arc jet complex. The result was superb performance from all the Apollo spacecraft during their re-entry into their home atmosphere.

V. Ames Contributions to the Space Shuttle

As with Apollo, Ames' contribution to the Space Shuttle included both shaping the technological choices and analyzing the scientific results to make the most of what we learned from each flight.

In much the same way that Ames' research defined the basic shape of the Apollo capsules, Ames work on lifting bodies by Clarence Syvertson and Alfred Eggers also defined the shape of the Space Shuttle Orbiter. The lifting body program represented perhaps the waning of the

NACA spirit within NASA. Three former NACA centers—Ames, Langley, and Dryden—each offered competitive proposals for what the design should look like. They critiqued each other's designs, collected wind tunnel data to justify their changes, then built inexpensive prototypes to test in the air. Competition was intense, but there was a common direction, and they trusted and respected each other. By collaborating they freed up funding for more research, and when the nation was ready to commit to building the Space Shuttle in the early 1970s NASA had in place strong tools for teamwork.

The Shuttle Orbiter is also basically a blunt re-entry body, complicated with aerodynamic control surfaces. The Orbiter approaches re-entry at a very high 40 degree angle of attack to present its entire blunt underside as it rushes into the increasingly dense air at 25 times the speed of sound. After a long and fiery re-entry, the Orbiter dissipates speed through a series of sweeping S turns. Once the Orbiter goes subsonic, its angle of attack is reduced so that while landing—unpowered-- it can be piloted like an airplane. Ames people, with the same spirit of fluid cooperation, made possible each step in this complicated landing process through differing flight regimes.

As with the Apollo spacecraft, Ames started by anticipating the airflow environment around the Shuttle during re-entry. Hot gases that envelop the Orbiter reach temperatures as high as 25,000 degrees Fahrenheit, and heat the underside tiles of the Orbiter to as much as 2,500 degrees Fahrenheit. Before later Ames researchers devised the 3-dimensional real-gas computational fluid dynamic codes to make such calculations more precise for each part of the Orbiter, they painstakingly estimated the rates and intensity of heating over the entire surface of the Shuttle. Though the specifications for constructing the Orbiter thermal protection systems simplified the definition of the expected heating, Ames researchers demonstrated that the tiles must work better than specification. These calculations were followed by tunnel tests to verify the shape of the bow shock wave and suggest modifications to the Orbiter shape.

Its mission defined the Space Shuttle as reusable, which meant it could not have an ablative heat shield that burned away. Yet Ames' work on ablation had led into work on ceramic tiles which deflected heat from the Shuttle Orbiters. Using their arc jets, researchers from Ames and JSC evaluated all likely candidate materials for use as Shuttle tiles. One of these was the LI-900 silica tile developed by Lockheed Missiles and Space Company nearby in Sunnyvale. NASA selected this as the baseline material for a vigorous tile improvement program to come, led by

Howard Goldstein. In 1973, Ames showed how the purity of the silica fibers in the tiles affected their shape and thus their performance. Ames invented a black borosilicate glass coating called Reaction Cured Glass that radiated heat back into the shockwave and was adopted by the Shuttle program managers in 1977. These improved tiles could be glowing on their surface at 2,300 degrees Fahrenheit while the back face, only a few inched below the surface, would never exceed 250 degrees Fahrenheit. The Orbiter, which is essentially an aluminum airplane, could now fly at hypersonic speeds.

To support NASA's Shuttle work, Ames upgraded its arc jet facilities so that they could simulate re-entry heating for tens of minutes. In the mid-1970s, the Ames facilities group brought online the 60-megawatt Interaction Heating Facility, which produced heating three times hotter and on larger models than any other arc jet. Compressed air passed through a constriction arc heater, invented by Ames, which was essentially a standing lightning bolt. Using a semi-elliptical nozzle, Ames could test a 2 by 2 foot section of tiles. By varying the composition of the heated gas, and using special instrumentation, Ames could also study the rapidly shifting reaction chemistry between the tile and the superheated gas.

Through the intensity and comprehensiveness of its effort, Ames became a world leader in thermal protection materials. When the first Orbiter, the Columbia, encountered a tile strength problem in 1978, Ames had already invented a stronger version of the silicon carbide tile, called the LI-2200. Ames then invented a new class of tiles, called Fibrous Refractory Composite Insulation (FRCI 12) that provided greater durability and a 500 pound overall weight savings. As hot gas flows between the tiles became recognized as a serious problem, Ames developed a gap filler. The gap filler was essentially a ceramic cloth impregnated with silicon polymer, and was applied to all the Orbiters. The upper side of the Orbiter also needs insulation, though it stays much cooler during re-entry. Ames worked with Johns Manville to develop a flexible silica blanket insulation. When the Shuttle first flew in 1981 it was covered by a patchwork of thermal protection materials, each type optimized to the particular stress re-entry placed on it.

Hans Mark served as Ames center director from 1969 through 1977, the formative years of the Shuttle program. Mark came from outside Ames, and led the center to more directly engage work on the Shuttle program. Ames formed a Shuttle Project Office, led by Victor Stevens and Bob Nysmith, that coordinated all its work on the Shuttle. JSC served as the lead center for the Shuttle program, and tasked to Ames more than half of all wind tunnel testing of designs leading to the Shuttle. Ames accomplished more than 10,000 hours of testing, using every wind tunnel it had, even before construction began on the first Shuttle in 1972. More than 25,000 hours of testing came after. Almost half of all testing was done in the 3.5-foot hypersonic wind tunnel, which could simulate flight at Mach 5, 7, and 10. During the entire development of the Shuttle, NASA conducted tests in more than fifty different wind tunnels, run by the government, universities, and by industry. The Shuttle program both proved the value of a coordinated wind tunnel infrastructure, while also exposing the limits of tunnel testing and justifying Ames' investment in CFD.

The ascent stack—that is, the Shuttle mated with the main engines as it stood on the launch pad—created enormously complex aerodynamics, followed by shock-shock interactions as it all hurtled faster into space. Ames did much to improve the ascent stack configuration. Ames also used its 14-foot wind tunnel to study the airflow interference around the Boeing 747 as it was mated with the Orbiter. The 747 was used to launch the Enterprise—a full-scale model of the Orbiter--to test its glide-landing performance. Later NASA used the 747 to ferry the orbiter from its landing spot at Dryden back to the Kennedy Space Center for relaunch. NASA also built a 36 percent scale model of the Orbiter, reaching 44 feet long, for tests in Ames' 40 by 80 foot wind tunnel. This model was tested primarily to study the scheduling of speed breaks and the affect of thermal protection systems on the Orbiter's low-speed aerodynamics. Almost every facet of Shuttle flight was analyzed and honed at Ames.

Ames also helped the Shuttle designers reach a compromise between a simple blunt shape for better thermodynamics and protruding aerodynamic surfaces for better landing. Ames researchers devised new ways to improve handling characteristics without changing the basic configuration of the Orbiter. In the 2-foot transonic tunnel, Ames worked through a potentially troublesome panel flutter problem. Ames used its 12-foot tunnel to demonstrate that unpowered landings could be made at speeds of at least 200 knots, and collaborated with Dryden on flight tests. Ames modified a Gulfstream 2 business jet by adding direct-lift flaps and side force generators to test Orbiter handling qualities and to train the pilot astronauts. Ames' Convair CV990 was used to prove that the Shuttle did not need a back up jet engine to power a fly-around in case it missed its landing. All of this reflected well on Ames' traditional expertise in aeronautics.

Simulating the Shuttle landing on earth also drew upon Ames' traditional expertise in flight simulation. The simulations were easier than, say, the Apollo landings on the Moon, in that it would glide in like an airplane, but the margin of error was small and many more pilots needed to be trained. Ames began landing simulations in the early 1970s using its Flight Simulator for Advanced Aircraft. The large motion envelop of the FSAA provided realistic cockpit accelerations so that pilot astronauts could experience the feel of g-forces while landing the Shuttle. Prior to their first flights, all pilot astronauts spent many hours training in the FSAA, which in turn helped NASA engineers identify handling qualities that needed improving. Using the FSAA, NASA identified the need for a heads-up display, and for its alpha-numeric symbology, that became the primary guidance system for Orbiter landings. Ames further tested this pilot workspace in the Space Shuttle Vehicle Simulation Cockpit.

During the first landing test flight, in July 1977, the Enterprise experienced a pilot-induced oscillation—that is, a longitudinal porpoising, caused by a control system problem, that worsened due to pilot overcontrol. During this flight, pilot Fred Haise had enough confidence and simulator training to simply let go of the control and let the oscillations naturally dampen out. Ames and JSC engineers then launched a major investigation into Orbiter control systems using the FSAA.

Ames opened its Vertical Motion Simulator in 1980, and it quickly became the best simulator for Shuttle design and pilot training. JSC engineers and astronaut flight crews used the VMS intensively to improve landing procedures and flight rules. During these piloted flight simulations, a close working relationship developed between the engineers from JSC, the astronaut crews, and Ames VMS researchers. Everyday, from early morning to late at night, T-38 aircraft assigned to the pilot astronauts would be parked on the ramp outside the VMS building. In addition to looking at future design improvements under investigation by Ames and JSC engineers, these pilots would encounter every conceivable failure mode. When they were done, they were prepared for a wide array of possible landing failures. The VMS also supported redesign of the Orbiter brakes, nose wheel steering, display system, drag parachute, flight control automation for extended duration orbit, and return-to-flight studies following the Challenger accident.

Once the Shuttle was flying, it was regularly overhauled and updated. The emerging science of computational fluid dynamics especially contributed to Shuttle improvements. Some of the earliest CFD codes established numerical benchmarks for the aerodynamics and shock wave profiles of Shuttle lift-off and re-entry, and CFD directed the redesign of the Shuttle main engine and the ascent stack. A second generation of thermal protection tile, called Toughened Unipeice Fibrous Insulation (TUFI) was added to the aft heat shield and body flaps which were struck by debris kicked up during landings, thus minimizing maintenance in the Orbiter Processing Facility.

VI. Ames Contributions to Lunar Exploration

Upon their return home, the Apollo astronauts had much good information to convey. Ames had formed a space sciences division, in 1962, to build a community of lunar scientists. Ames scientists analyzed samples of rock and soil taken from the Moon, studied the lunar craters, and measured lunar magnetic fields.

Apollo astronauts spent a total of 340 hours on the lunar surface and carried back to Earth more than 840 pounds of lunar rock. Only at Ames and JSC did NASA build lunar receiving facilities to analyze soil samples returned from the Moon. JSC would identify and isolate hazardous materials in the samples; Ames would explore the essential composition of the lunar materials. So Ames built a very clean laboratory and outfitted it with unique equipment. They observed the carbon chemistry of the samples, and concluded that they did not contain life. This led them to question what kind of carbon chemistry happens in the absence of life. They discovered that the Moon was being constantly bombarded with solar wind and micrometeorites, which left the Moon with a carbon chemistry dominated by the energetic interaction of the Sun, the Moon and cosmic debris.

Ames space scientists also devised magnetometers to study the Moon’s composition and its magnetic fields. Four Apollo missions flew Ames magnetometers to different sites on the surface of the Moon, and two portable magnetometers carried aboard the lunar rovers measured magnetic fields while in motion. These revealed much about the Moon’s geophysics and geological history. For example, the Moon did not have two-pole magnetism like Earth, but did have a stronger field than expected. They also revealed that the Moon was a solid mass, without a molten core like the Earth. Transient magnetic fields were induced by changes in the solar wind. 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.

VII. Ames Contributions to Planetary Exploration

NASA Ames also made major contributions to planetary science, through its work on robotic explorers. NASA Ames managed the Pioneer series of spacecraft, beginning with the Pioneers 6 through 9. These were identical spacecraft launched in the mid-1960s in orbit around the sun, and for many years returned crucial data on solar radiation, and on the Earth's relationship with its star.

Pioneers 10 and 11 explored the outer edges of our solar system. These were almost identical spacecraft, light, simple, and inexpensive, and built at Ames by legendary project manager Charles Hall. The Pioneers were the first spacecraft to travel through the asteroid belt, do close observations of Jupiter and Saturn, gather data on interplanetary space, and leave our solar system. Pioneer 10 was launched in March 1972, and Pioneer 11 in April 1973, and continued transmitting scientific data as they reached the edge of the heliopause. In addition to conveying the first glimpse of the outer solar system, they showed that the bulkier spacecraft to come could also make that voyage.

The Pioneer Venus mission, again managed by Charlie Hall, consisted of two separate spacecraft. The orbiter was inserted into Venus orbit on December 4, 1978, and the 4 different probes transported on the multiprobe bus entered the atmosphere of Venus on December 9, 1978. The orbiter carried 17 experiment packages to map and characterize the geology of Venus. The probes, dropped into the atmosphere at 4 different spots, returned valuable information about its composition, which taught us both about the carbon-dense atmosphere of Venus and the evolution of atmosphere of Earth.

The probes showed that NASA Ames scientists had devised an ingenious method for doing basic planetary science with what they learned during the re-entry testing of the Apollo spacecraft. Al Seiff, in a brilliant bit of scientific opportunism, proposed sending small spacecraft to Mars and Venus to gather the first hard data on their atmospheres. Seiff inverted the re-entry problem. Rather than developing a new vehicle to better enter Earth's known environment, he proposed dropping a blunt-body vehicle of known aerodynamic characteristics into an unknown atmosphere.

First, of course, Ames tested the concept. They started by sending various gases—of the sort that might enshroud other planets--through ballistic ranges and arc-jets to see how blunt bodies reacted to them. In 1971, Sieff managed the Planetary Atmospheres Entry Test into Earth's atmosphere, to demonstrate that one well-designed probe could gather data on the structure of an upper atmosphere based on aerodynamic responses during hypersonic entry, could directly measure the temperature and pressure of a lower atmosphere once slowed with a parachute, and could gather data on an atmosphere's chemical composition through mass spectroscopy analysis of the hot bow shock wave. And a probe could telemeter all this data back to NASA before smashing into the planet surface. Working closely with colleagues at JPL, Langley, Goddard and industry, Ames sent probes into the atmospheres of Mars with the Viking in 1976, of Venus with Pioneer Venus in 1978, and Jupiter with Galileo in 1995. For very little money they returned spectacular data on the composition of planetary atmospheres.

NASA Ames completed design and fabrication of the Galileo probe in 1986, though it waited a decade for a ride aboard the Space Shuttle. On December 7, 1995 the Galileo probe descended into the atmosphere of Jupiter and, before it was destroyed by mounting pressure, returned valuable data on the chemical composition and physical structure of the gas giant. It marked another milestone in NASA Ames work on planetary probes pioneered by Al Seiff. NASA Ames managed the probe project, designed its heat shield, and built most of the science packages aboard. And all that was learned about the atmosphere of this planet gave us new insights into the changing atmosphere and climate of Earth.

VIII. Ames Contributions to Mars Exploration

NASA Ames has also advanced our understanding of Mars, beginning with the Viking Lander biological laboratory. Two identical Viking Landers soft-landed on the surface of Mars—one on July 20, 1976, the other on September 3, 1976. Both carried a sophisticated biological laboratory which was designed and built at NASA Ames, by the life sciences division headed by Chuck Klein. The laboratory included a gas exchange experiment, a labeled release experiment, a pyrolytic release experiment, and a gas chromatograph. In addition, the Viking Landers transmitted images of the surface, took surface samples and analyzed them for composition, studied atmospheric composition and meteorology, and deployed seismometers. The laboratory detected no present signs of life, though the question of whether life ever existed remained open. Furthermore, the lander was encased in a bioshield to prevent contamination of the Martian surface, and advancing the state of the art in planetary protection technology.

NASA Ames also played a key role in the mission planning, done in the early 1990s, that led to the Mars Exploration Rovers later in that decade. Ames also made key contributions to the missions, in the thermal protection systems for the entry system, in testing the parachute, in site selection, and in managing the science operations.

IX. Ames Contributions to Astrobiology

Because of its tradition of collaboration among diverse groups of intelligent and dedicated people, Ames stands today as a multi-disciplinary research and development center. Nearly half its funding supports basic research, and the other half supports advanced development of key components of software, aircraft and spacecraft. And because NASA scientists at Ames are passionate about their own pursuit of knowledge, much of Ames' funding and organization supports a wide array of education programs to teach and inspire the next generation of explorers.

Astrobiology stands as a prime example of how NASA managers at Ames re-integrated almost all of NASA's strategic enterprises. Exobiology as a discipline had become more routine in its institutional structure—with individual scientists applying for limited grants, and banded together mostly by the equipment and overhead they shared. NASA scientists at Ames, like David Morrison and Scott Hubbard, when faced with a budgetary setback in the early 1990s, responded with a plan to create a discipline of astrobiology through an inclusive institute. They decided to build a discipline, just as others in NASA built rockets and spacecraft. What they included as "astrobiology" was work done in many places, from many unique perspectives, and all of it aligned by the Astrobiology Institute into something relevant and usable. When NASA engineers needed help identifying landing sites for the Mars rover, astrobiologists could respond. Throughout, the Institute kept the diverse band of researchers focused on the biggest questions about life in the universe.

Astrobiology is simply the latest evidence that Ames people share a collaborative spirit with their colleagues on Center, and with scientists and engineers in universities and in industry. This collaborative tradition has served Ames people well whenever the nation called upon them to work closely and quickly with their colleagues throughout the other NASA centers.

X. Why Explore?

What happens to civilizations that do not seize the opportunity to explore when they can? China had that opportunity during its Ming dynasty in the early 1400s. Ming literally means "brilliant." China then stood at the height of its wealth and power, had consolidated control of its territory, and the arts and science were flourishing. An enlightened young ruler, Zhu Di, who became the Yung Lo emporer in 1403, wanted the world to know it. Zheng He, a court eunuch and a Muslim from central Asia proposed an ambitious series of ocean explorations. Yung Lo gave it his full backing.

The emperor committed a force of 62 ships and 28,000 men for the initial voyage to India in 1405. The Jewel Ships were reportedly 400 feet long (compared with 85 feet for Columbus' flagship, the *Santa Maria*), with 9 masts and 12 sails made of bamboo slats. They had sternpost rudders and multiple watertight compartments. They were also outfitted with magnetic compasses, then cutting edge technology. These maritime expeditions to India, Arabia, and Africa were far more ambitious than the Europe attempts several decades later. Zheng He's seven voyages (like the seven voyages of Apollo) illumined an unknown world. They returned a wealth of scientific data, as well as curiosities—exotic birds, ostriches, lions, zebras, giraffes, and precious stones. They did not come to colonize, and only in a few instances used force. Their goal was an expansion of Chinese influence and trade opportunities.

However, their success was not permanent. Trade blossomed, though Zheng He never set up lasting commercial networks. All the trade profits went directly to the court, while government revenues continued to come from land. Meanwhile, taxes rose to pay for skirmishes against the Mongols in the north and for building the city of Beijing. The Yung Lo emporer died in 1424. Zheng He launched one more expedition, though he died on the voyage home. When that expedition arrived back in Nanking in 1433, the expeditions ended abruptly. A new emperor declared that "not an inch of plank" would go down to the sea. In 1436 an imperial decree was issued against ocean voyages, and soon it became a capital offense to construct a multi-masted ship.

China, traditionally an introspective culture, completely turned its back on the outside world. The knowledge acquired (like the Moon rocks) were considered a poor substitute for a consolidated economy. The Beijing-Hanzou grand canal was repaired and agriculture was restored as the foundation of the economy. China quickly dissipated their technological momentum, and with it lost much economic significance. Many speculate on what the world might look like today if Zheng He had followed-up on his success in the Indian Ocean by turning east and crossing the Pacific. Since then, and until recently, China had been a net importer of technology. Loss of exploration—as both a use and source of knowledge—led to a loss of technological primacy, and was a prelude to China's loss of national independence.

There are disturbing parallels between the Chinese experience 600 years ago, and the current American dilemma of finding money for its space program. Space exploration provides one impetus to maintaining a premier place in the world economy, to provide intellectual stimulation and to protect national security. Today, the Chinese are becoming very active in space exploration while we are pursuing other priorities. Now that China is an economic extrovert, it is again celebrating the history of Zheng He.

Throughout history, humankind has been extending our range. Humans have ranged over most of our Earth's surface and its oceans, throughout our atmosphere, and beyond it to the Moon. As a people we can flourish only so long as we continue to explore our world, and extend that range. Though our range may not be infinite, it is incredibly vaster than we now know. Not all human civilizations have explored and extended their range, but those who can either do or die off.

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XI. Guide to Presentation Charts

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