TECHNOLOGY

Heated Debates

A History of the Development of the Space Shuttle's Thermal Protection System: 1970-1981

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INTRODUCTION

A documentary on the *Columbia* disaster, recently aired on British Television, concluded that the accident was the result of "flawed design." In a similar vein to commentary that followed the *Challenger* disaster in 1986, Nigel Henbest and Heather Couper's documentary located the causes of this "flawed design" and so by implication the accident itself, in the technical compromises that emerged from the political battles between NASA and the Nixon Administration during the 1969 to 1972 period.

Although pertinent, Henbest and Couper's mistake was to separate politics from technology: to place politics on the outside where it impinged on and was detrimental to technological progress. This led them to state that had Nixon's Administration allowed NASA to build its original two-stage Shuttle design, such a catastrophic failure would not have occurred. Such statements, as sociologist Bruno Latour rightly points out, "say nothing." They are simply tautologies that are "feasible only at the end of the road" long after history has distinguished success from failure.[1]

To understand the dynamics of technological change and in so doing, come to know our machines, it is necessary to dispel the myth that the technological is independent from the social. Although technological practitioners may strive to create order, system and control, through rational decision-making, technological development is a diverse, capricious, contradictory and messy process. Authors in the both the history and sociology of science and technology have shown that scientific knowledge and technological artifacts and systems have to be treated as socio-historical products: that the definition and creation of an object is also the definition and creation of its socio-technical context. To build and operate large complex technologies like the Shuttle, the protagonists have to enroll a variety of things, organizations and individuals into a range of associations and negotiations that are continually being enacted and re-enacted.[2] The aim of this paper then, is not to find fault or to lay blame, but in light of the recent *Columbia* disaster and as a guide to future commentary about it, to look back at the development of its thermal protection system and reveal both the difficulties and the socio-technical processes that were involved in its creation.

TECHNOLOGY AND CHOICE

The starting point of any history of technology is with the exposure of choice and controversy. In relation to the Shuttle's thermal protection system, one Shuttle observer noted in 1970 that: "If there is any clear cut lack of agreement among those planning the Space Shuttle, it is in the area of thermal protection." The problem of shielding the orbiter's primary structure from the intense heat induced by atmospheric drag on re-entry attracted such visible controversy because its solution was inextricably bound-up with the design of other major elements of the Shuttle. Airframe configuration, structure and materials could not be divorced from the selection of materials and structure of the thermal protection system. Equally, the weight and distribution of a thermal protection system could have adverse effects on the design of the propulsion system.[3]

NASA and its contractors explored four principal thermal protection design concepts in early 1970: replaceable ablator panels; metallic heat shields; non-metallic materials; and carbon-carbon hot structures.

Ablator technologies had been developed and utilized on the Mercury, Gemini and Apollo programmes. Essentially an ablator heat shield was a sacrificial outer layer that would burn up on re-entry. The concept employed materials that had almost no ability to transfer heat, but would turn white hot, char and then melt away without transmitting energy into the primary structure. Although the development of a low-density ablator system for Shuttle application would be uncomplicated and workable, engineers at the Ames Research Center did not regard it as feasible unless some of the design requirements imposed were relaxed. An expensive and complicated refit of the orbiter's thermal protection system after every flight was not in harmony with the Shuttle discourse on economic and routine access to space. The Office of Manned Space Flight's requirement that the Shuttle system perform routinely over 100 missions with a cost-effective level of refurbishment and maintenance placed a heavy demand on the design of a thermal protection system. The inter-related nature of the thermal protection system went further than its influence on other subsystems. The problems and solutions associated with thermal protection were integral to the overall justification of the programme. Without a reusable thermal protection system, the Shuttle programme was in grave danger of not being able to rationalize itself. Nevertheless, Ames continued its research into ablator techniques in case a backup would be required.[4]

Repeatedly withstanding the thermal environments of re-entry was the key determinant of a thermal protection system design. Coupled with this were other induced environments within which the system had to perform, such as acoustic loads, structural deflections induced by aerodynamic loads, the extreme heat and radiation of the Sun, the extreme cold of space, and the natural environments on Earth, such as salt, fog, wind and rain; and because the thermal protection system was to cover the exterior of the vehicle, it also had to provide an acceptable aerodynamic surface.[5]

Due to the inter-related nature of the thermal protection system, most contractors involved in Space Shuttle proposals exhibited a tendency towards combinations of metallic materials in their design proposals. McDonnell Douglas and Martin Marietta proposed a titanium alloy hot-structure for the wings and fuselage, with the lower surfaces covered with columbium shingles. The contractors proposed a cobalt superalloy for the control surfaces and the vertical tail was to be made of a nickel superalloy. North American Rockwell also adopted a radiant heat shield configuration constructed of various metallic superalloys including columbium-129Y, Haynes-188 and Inconel-718. Grumman/Boeing's design consisted of metallic panels

The Space Shuttle *Columbia* glides down over Rogers Dry Lake as it heads for a landing at Edwards Air Force Base at the conclusion of its first orbital mission.

Image courtesy of NASA

backed with micro-quartz insulation, except for the rudder, which was made of Inconel-718. Thus, in the early phases, design emphasis was on a thermal protection system that was an integral part of the load bearing structure, providing commonality between materials for airframe structure and thermal protection and with a minimum reliance on exotic materials.[6]

Nonetheless, a perception prevailed at the Office of Manned Space Flight that all the metallic heat shield concepts possessed some significant drawbacks. Many of the metallic materials required coatings, such as Sylvania R-512E, to provide oxidation protection. Application of the coatings would have to be so thorough, both inside and outside (including fasteners), that complicated inspection techniques between each flight would negate the advantages of commonality. Although superalloys that did not require any coatings, such as nickel chrome (TDNiCr), were also on the agenda as they could withstand temperatures up to 2,400 degrees F, the production rate of TDNiCr (around 10,000 pounds per year in 1970) was not sufficient to meet Shuttle demands. In addition, superalloys also showed a tendency to produce a rippling effect over the surface when repeatedly exposed to high temperatures, which could have a detrimental influence on aerodynamic stability. Overall, metallic concepts were complex. Design features to minimize thermal distortion, intricate panel-to-panel joints, as well as the additional insulation blanket that would be required to protect the primary structure of the orbiter, all conspired against a metallic thermal protection system.[7]

In contrast to the complexity of the metallic systems, the non-metallic heat shield concepts appeared to possess the advantage of design simplicity. Lockheed Missiles and Space Company's early Space Shuttle proposal had an orbiter constructed from conventional aluminum with a thermal protection system comprised of titanium on the upper surfaces and its proprietary silica system, called LI-1500, on the lower surface. The silica system captured NASA's attention. Composed of tiles fabricated from 99.6 percent pure amorphous silica fibers derived from common sand, the system had the potential of offering a low density, low maintenance, reusable thermal protection system that could be installed on a conventional airframe. While engineers recognized that a major development programme would have to be undertaken to bring the non-metallic materials out of the laboratory to a state of high production and vehicle application, the significant weight savings and inherent design simplicity influenced NASA to favor it as the primary material for the orbiter's thermal protection system.[8]

From 1970 to 1972, two non-metallic reusable materials were under investigation by NASA: a silica-base material (SiO2) and a mullite (3A12O3 SiO2). The various NASA Centers working on the thermal protection system initially expected mullite to exhibit a higher temperature capability because of its higher density; however, tests showed that the low-density silica possessed a superior thermal performance due to the small fiber diameter material used in its formulation. The contractors working with mullite, McDonnell Douglas and General Electric, failed to strengthen the material to levels compatible with the predicted thermal stresses of re-entry; thus Lockheed, the contractor working with silica, won the contract to supply the baseline material for the orbiter's thermal protection system in June 1973.[9]

Although the Office of Manned Space Flight favoured the silica system, this design decision conflicted with a programmatic decision dictated by the Air Force. During the design phase, the Office of Manned Space Flight adopted a delta wing planform to produce a high crossrange of 1,500 nautical miles either side of the orbiter's ground track. The Air Force's fiercely defended crossrange specification imposed an angle of attack of 30 degrees or lower to achieve the required hypersonic lift-to-drag ratio. A metallic hot structures system would have allowed for a shallower trajectory, but the silica system demanded that the initial entry angle of attack should be as high as possible (around 30 to 50 degrees) to minimize re-entry heating. To reduce re-entry heating and thus increase the lifespan of the thermal protection system, NASA and the Air Force arrived at a compromise position whereby the Office of Manned Space Flight chose an angle of attack profile of 40 degrees for all missions not requiring the high crossrange.[10]

For the wing's leading edge and the nose cap, carbon-carbon was the only known material that showed potential for providing reuse capability for these high temperature areas (greater than 2,300 degrees F). The Office of Manned Space Flight considered carbon-carbon a clear choice for the leading-edge applications because in test conditions it appeared far more durable than superalloys. Nevertheless, significant developments in coatings to prevent oxidation would be necessary if carbon-carbon was to become a multi-mission material.[11]

A timed exposure of the Space Shuttle *STS-1*, at Launch Pad A, Complex 39, turns the space vehicles and support facilities into a night-time fantasy of light. Structures to the left of the Shuttle are the fixed and the rotating service structure.

Image courtesy of NASA

TESTING AND MODEL DEVELOPMENT

The Thermal Protection Branch at NASA's Ames Research Center had been researching and testing reusable thermal protection materials since the mid-1960s. By 1970, it stepped this programme up, as Ames conducted tests on candidate insulation materials for the Shuttle. During these tests, two problems became evident. First, facilities were inadequate for accurate testing. The arc-jets at Ames, while able to produce the necessary high-temperatures, were incapable of sustained tests on large samples of heat shield materials; and second, because the facilities at Ames were inadequate, the Thermal Protection Branch considered that it could not analyze the results of the tests satisfactorily. Underlying the arguments coming from the Thermal Protection Branch in 1970 were proposals for expansion. There were already proposals circulating NASA in 1969 to shut Ames down. Larger facilities, more researches and a greater role in the Shuttle program would serve to both demarcate the work of Ames from its main internal competitor, the Langley Research Center, and ensure its continued survival.[12]

In part, Ames realized its strategy through the acquisition of a new 60-megawatt arc-jet facility in early 1975. Three times as powerful as any previous facility, its primary task over the next few years was to test the heat resistance of the orbiter's thermal protection system. Although Ames had yet to fully define the verification test programme, it considered that materials characterization would involve the classic practice of multiple tests to answer questions pertaining to life expectancy. The Office of Manned Space Flight's requirements had dictated that thermal protection material samples be subjected to 100 tests of 1,000 seconds each. In addition, tests would focus on heating the materials up to 2,500 degrees Fahrenheit and then raising the temperature in increments of 100 degrees Fahrenheit until destruction.[13] Although important, these tests provided only a limited interpretation of the environment within which the thermal protection system would operate. NASA and Lockheed engineers had to go much farther. If the Shuttle was to come back unscathed, they had to duplicate all re-entry conditions as accurately as possible.

Various aspects of re-entry heating phenomena had been under theoretical investigation by Walter Hohmann since the mid-1920s, but the first steps towards a quantitative understanding of re-entry dynamics did not materialise until the 1950s, with the advent of re-entry ballistic missile technology and advancements in supersonic and hypersonic flight. The air temperatures around the nose of a re-entering ballistic missile may reach tens of thousands of degrees. Shockwave compression outside of the boundary layer surface generates part of this heat, but it is the heat generated within the boundary layer, which is in contact with the missile's structure, that can melt or at the very least severely damage the vehicle. Classical aerodynamic boundary-layer theory had long dictated that streamline needle-nose shapes were required to reduce aerodynamic drag and thus minimize heat transfer to the vehicle's structure. However, Harry Julian Allen, an aerodynamicist at the Ames Aeronautical Laboratory (when it was part of the National Advisory Committee for Aeronautics), presented the radical idea in 1952, that re-entry shapes needed to be blunt. When a blunt-nosed missile enters the atmosphere a powerful bow shock wave builds up that generates much more heat outside the boundary layer than is the case with a sharp-pointed nose, thus dissipating the heat harmlessly into the surrounding air. In addition, because the vehicle's resistance to the tenuous upper atmosphere would be at its maximum, the vehicle would start to slow down sooner within the thinner atmosphere, which would also transfer less heat to the vehicle's surface.[14]

NASA's aerodynamicists had practice in the re-entry dynamics of blunt-nose vehicle configurations on the Mercury, Gemini and Apollo capsules during the 1960s. Nevertheless, inherent within the Shuttle's design lay numerous contradictions and nowhere did these contradictions reveal themselves more forcibly than in the aerodynamics of the return flight. With the advent of the Shuttle, NASA's aerodynamicists faced constructing a vehicle that had to realize many conflicting requirements. Not only was the Shuttle orbiter going to be the largest vehicle to perform the task of re-entry, it had to land on a runway like a conventional aircraft. This meant designing an aerodynamic configuration that would function through the entire atmospheric flight regime: from hypersonic through to subsonic and down to a landing velocity. Each speed regime demands quantifiable differences in aerodynamic design and those above Mach 6 were largely unknown.[15]

When NASA embarked on its Shuttle development programme, behind them lay a fairly mature discipline on the construction and flight characteristics of aircraft design. Aerodynamics had come a long way from its empirical roots at the start of the twentieth century. Experimental data, mathematical models and flight experience all supported a firm foundation of empirical and theoretical knowledge in aerodynamic design. However, supersonic and hypersonic flight (defined as the speed regime above Mach 5) brought with them major shifts in aerodynamic theory. Within these new environments the characteristics of fluid dynamics changed. Hypersonic airflow had to be viewed as compressible as opposed to incompressible, which was the case for subsonic aerodynamics. Aerodynamic engineers thus had to delve deeper into the physics and the chemistry of gases to deal with the new problems posed by re-entry, hypersonic and supersonic flight. Kinetic theory of gases, flow problems and radiation transfer all moved to center stage.[16]

The Air Force generated a great deal of knowledge on supersonic and hypersonic flight from its X-series of rocket planes. The Bell X-1 first broke the sound barrier in 1947, and the Air Force first entered hypersonic flight in 1959 with the X-15. The X-15 put into practice what engineers had learned from theory and from hypersonic wind tunnels tests. Although an Air Force program, the Langley and Ames Research Centers both contributed to the development of the X-15, with much of the work conducted on the Langley 11-inch hypersonic tunnel, which could reach Mach 6.8, the approximate speed goal of the X-15. From the X-15 spawned the X-20 Dyna-Soar, a plane that the Air Force intended to send aloft atop a ballistic rocket and then glide back to Earth to land like a conventional airplane. Conceived in 1943, again in 1950, designed in 1954 and adopted in 1957, the Dyna-Soar pushed at the envelope in design for hypersonic flight before the Secretary of Defense, Robert McNamara, finally recommended its cancellation in 1963.[17]

As North American Rockwell's Space Shuttle Manager, Bastian Hello reveals, the X-15 was an important program in founding a knowledge base for the Shuttle:

> I had a very, very stalwart group of chief engineers... The combination of having very seasoned, space-wise engineers who had graduated from the X-15 and then into the Apollo program, and then into Shuttle... finally led us... to a winning proposal. ...Clearly the X-15 program, there was an immense amount of experience that was gained from that program, which was a real pacesetter.

Nevertheless, it would be wrong to assume that the path from the X-15 to the Shuttle followed a straight line. On the question of the X-20, Bastian Hello recalled:

> For all I know, engineers working for our team at that time (1969-72) could well have graduated from the Dyna-Soar program without me knowing about it... but was there a guiding light that said this is what Boeing did on the Dyna-Soar and here's what they did right and here's what they did wrong? No. ... And I worked on... the X-24, the PRIME program, but they were rudimentary. We were ... still using ablative material on that thing, there wasn't the sophistication of the reusable tiles. ...But we used a very rudimentary honeycomb and inserted ablative material in it and smoothed that down to the exterior contours. ...But that had long been past by the time we came around to Apollo. We had already been through ablators on the underside of Mercury and on the underside of Apollo and we also understood what reusable things were on Apollo. ...So the whole thing had moved and it was a different game.[19]

To a very large degree, engineers designing the Shuttle had to begin with a blank sheet of paper. Indeed, the lack of wind tunnel data on the re-entry and flight characteristics of a reusable space vehicle concerned both NASA and the Air Force when they examined the issue in 1966. Del Tischler of the NASA Office of Advance Research and Technology also identified "aerodynamics-structures-thermal protection" as major problem areas for the proposed Shuttle in 1969. Again in 1974, the NASA Research and Technology Advisory Council raised concern over deficiencies in knowledge of the aerodynamics of reusable launch vehicle when it highlighted "inaccuracies in total heat-load prediction techniques now available to designers." The collection of more accurate wind tunnel data thus became a major priority because of concerns that theory was deficient, especially at the high angle of attack proposed for the orbiter's return flight.[20]

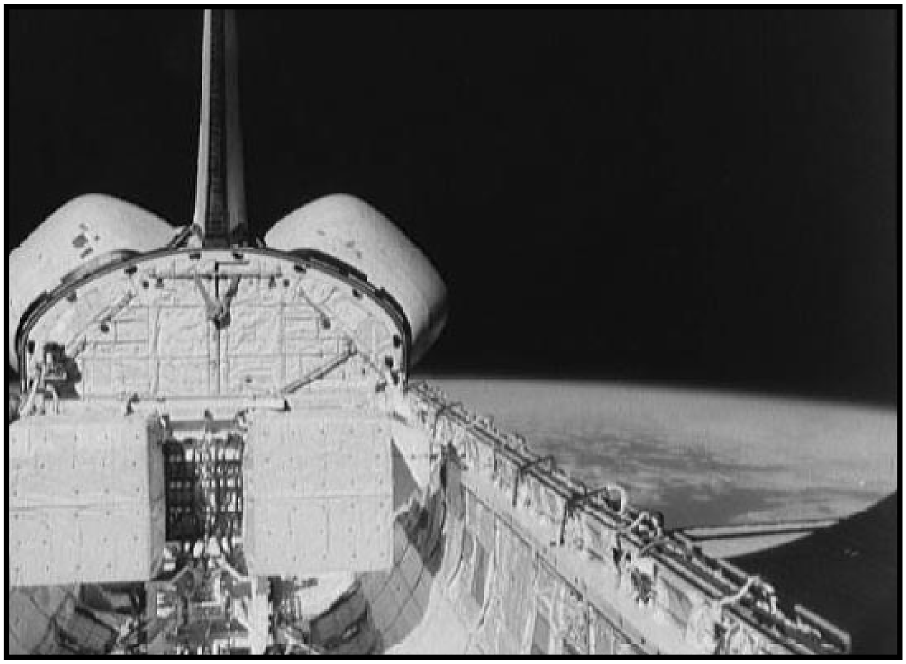
In hypersonic wind tunnel operations aerodynamicists assumed that the air streaming by the body behaved as a perfect gas, as defined by the laws of thermodynamics. However, in the regime of orbital re-entry speeds a strong shock wave generated near the nose of the body produces very large temperature and pressure increases that change the chemical composition of the streaming air, with the oxygen and nitrogen molecules dissociating and becoming electrically charged to form an ionized sheath around the re-entry vehicle. At this time, long duration hypersonic wind tunnel tests were not possible at temperatures above 3,000 degrees F, which meant that vehicle designers had to conduct intermittent testing to preserve the structural integrity of the facility.[21]

> Even so, full duplication of reentry temperatures, pressures, and velocities is beyond the reach of terrestrial test equipment, and partial simulation becomes a fact of life. Assessing the adequacy of the simulation and designing experiments to minimize the uncertainties become major challenges in providing reliable test results for the spacecraft designer to go on.[22]

Most of the hypersonic wind tunnel facilities that emerged during the 1950s and 1960s were located at the NASA Ames, Langley, and Lewis Centers. Ames and Langley had both worked on the problems associated with re-entry and had built up relatively large facilities for testing hypersonic cruise and re-entry flight, whereas Lewis had concentrated on propulsion aspects. Despite this impressive background, the Space Shuttle was to present one of the biggest challenges to NASA's wind tunnel complex. Indeed, wind tunnel support involved every major NASA facility as well as assistance from both the Air Force and industry. Over the entire programme, NASA employed at least 50 different wind tunnels and clocked upward of 100,000 hours (the equivalent of almost 25 years) of wind tunnel work. Not all of this work was devoted to the understanding of re-entry dynamics. Aerodynamic loads, structural heating, stability and control parameters, flutter/buffet boundaries, propulsion system integration, and the complex factors involved in controlling the separation of the twin solid rockets and external fuel tank, all presented problems that those working in the wind tunnel program had to solve.[23]

In the area of thermal protection, an important contribution came from the Langley 8-Foot High-Temperature Structures Tunnel, conceived in the late 1950s because the then existing hypersonic tunnels could not duplicate the structural problems encountered at these high velocities. Not completed until 1968, the tunnel came too late for Apollo, but it did provide ideal conditions for full-scale testing of the Shuttle's thermal protection system as it was large enough to test complete arrays of full sized tiles.[24]

For NASA's aerodynamicists one of their most difficult problems was



View of *STS-1* payload bay and aft section, which shows some of the missing thermal tiles from the orbital maneuvering system (OMS) pods which flank the vertical stabilizer at left edge of photograph.

Image courtesy of NASA

simulating turbulent flow in the laboratory. Understanding it was of great importance because maximum heating rates and material ablation would occur when turbulent flow became fully established.[25] As Johnson engineer Robert Ried, told a NASA technical conference in 1985:

> The phenomena of turbulent flow and boundary-layer transition have been under intense investigation for more than a century with somewhat limited success. This limitation is possibly measured by the anxiety which develops when engineers are required to predict boundary-layer transition outside the range of experimental data.[26]

In general there are two types of boundary layers, laminar and turbulent, and both are fundamentally different in character. Laminar flow takes place smoothly in parallel laminae, free of irregular eddying motion. Turbulent flow, by contrast, contains a large number of small eddies that move in a chaotic manner. As a result of the transverse mixing of gases, turbulent flow tends to be thicker than laminar flow and has higher velocities close to the surface. This effect causes the turbulent flow (all things being equal) to exert higher skin friction than the laminar flow and therefore cause extreme surface heating.[27]

Ames, Langley and Johnson tackled the problem of simulating turbulent flows and boundary-layer transition through the development of both simplified theoretical models and empirical evidence based on the previous experience and knowledge gleaned from the blunt re-entry capsules of Mercury, Gemini and Apollo. They could do this because geometrically similar bodies develop identical flow and shock patterns within the subsonic and supersonic speed regimes. Within the hypersonic speed regime, however, there is considerable interaction between the boundary-layer and the shock pattern. When this occurs the similitude requirements are more difficult to satisfy. To circumvent this problem the standard technique was to introduce simplified models using data from accurate predictions under incompressible flow conditions to provide predictions under compressible flow conditions using distortions of geometry to balance distortions of velocity. Aerodynamicists thus selected representative locations on the orbiter and then collected data from tests on models in a wind tunnel that were scaled-up to flight conditions by correlating boundary-layer transition and turbulent heating as a function of the Reynolds number behind a normal shock.[28] From these simplified models, Johnson mapped a re-entry trajectory that would be consistent with the thermal protection system's capabilities. The orbiter's re-entry configuration, however, was not a true blunt re-entry vehicle, nor was it a slender flight vehicle. The flow dynamics would vary along the orbiter from the high entropy of a blunt-body nose flow asymptotically toward a low entropy slender-body flow.[29] More complex models and analytical techniques were, therefore, required.

Although the Shuttle orbiter was not the first winged vehicle ever to fly through the hypersonic speed regime, it was going to be the first real technological test of theoretical high-speed flight above Mach 7. As Johnson's Director Christopher Kraft recalled:

> The ability to perform a re-entry from Mach 26 to touch down speeds...through the entire Mach number regime, particularly from Mach numbers of 10 to 1, that was...a technical feat...which nobody had ever done before; and one which there was no capability to run (a) test (on) in the world...in wind tunnels or anything else. We had to do that by rope and by mathematics and by guessing.[30]

So, despite the maturity of aerodynamics, precedents did not exist to facilitate many of the design requirements. Requirements for the orbiter's thermal protection system dictated a more accurate and intricate definition of re-entry heating than for any of NASA's previous vehicles. The three dimensional geometric complexity and the large scale of the orbiter posed a greater challenge to the definition of the re-entry flow-field and subsequent heating than had any previous system.[31]

Thus, along with the development of theoretical models, an array of instrumentation was required to recreate boundary-layer transition from laminar to turbulent flows in the laboratory. The foundation for the definition of the re-entry aerothermodynamics environments was the wind tunnel test data taken from scaled models of the orbiter, but wind tunnels, though invaluable tools, had their limits. The most pressing problem was the scaling-up of data without the introduction of some error or distortion. Although a range of techniques were available, such as pressurizing or cooling the air in the tunnel, chilling the models to cryogenic temperatures, or using helium instead of air, complex mathematical equations were also a necessary part of the prediction process.[32] Complementing wind tunnel activity, therefore, was an increase in the use of computer technology in computational fluid dynamics. Many of the engineers and managers at Ames were eager to enter what was then a new research field as Dean Chapman, Chief of Ames's Thermo- and Gas-Dynamics Division recalled:

> I'd been out of fluid mechanics for eight or nine years when I took over the division in 1969. When I reviewed the field and saw what computers were doing even then, it became clear to me that they could do a lot of things that I as an experimentalist never dreamed about, so I decided to press into that area.[33]

In 1970, the Theoretical Branch and the Hypersonic Free-Flight Branch combined to form the new Computational Fluid Dynamics Branch. Ames, however, had the poorest computer facilities within NASA and both Ames Director Hans Mark and Chapman sought to remedy this situation quickly. The collapse of the Air Force's Manned Orbital Laboratory Program left available an IBM 360-67, which was immediately acquisitioned by Ames in a most unusual manner. Hans Mark had Ames people in Sunnyvale on the very day that the Manned Orbital Laboratory closed down, pulling the computer out before the Air Force declared it surplus and installing it at Ames. The acquisition of the IBM 360-67 opened the door for an aggressive research programme by the Computational Fluid Dynamics Branch. In 1975, Ames acquired the Illiac IV (a supercomputer capable of performing 300 million calculations per second and storing one trillion bits of information at a time) through more usual channels. Mark and Chapman both saw the acquisition of Illiac as the deciding factor in establishing Ames as the NASA center for computational fluid dynamics. Its performance was so revolutionary that Mark, Chapman and Melvin Pirtle, head of the Illiac programme, argued that the relationship between wind tunnel testing and computational fluid dynamics was shifting in favour of the latter.[34]

Wind tunnel experiments and computational fluid dynamics nonetheless worked in parallel on the Shuttle program and generated a colossal amount of data on the re-entry environment to aid the design and fabrication of the thermal protection system. Indeed, there was so much data that by early 1976, "disquieting rumours" had begun to circulate around NASA that Rockwell International was not exercising sufficient caution and care in the review of the data. Concern soon arose within the Office of Space Flight over what steps both Johnson and Rockwell were taking to critically examine the data for errors. Thus, in early 1976 the Deputy Associate Administrator for Space Flight (Technical), Charles Donlan, assembled a team, which included Joe Weil from the Dryden Flight Research Center and members from Rockwell, to examine the issue.[35]

After three days of discussion and review, Charles Donlan reported that he was "satisfied that Rockwell had competent and knowledgeable people on the program" and that the "discrepancies in data and judgements" were being "freely aired between contractors and government personal." Although Joe Weil "expressed some skepticism," about whether the variations in aerodynamic parameters used in flight simulations were broad enough to demonstrate with 100% confidence the ability of the flight control system to handle uncertainties, Donlan sided with Rockwell.[36] Crucial to his decision was the role of Ames, as Donlan stated at the time:

> (Ames) is to be commended for its role in this area. (Ames) is not only performing invaluable tests on the (thermal protection tiles)

24 March 1979. Shuttle orbiter *Columbia* aboard a 747 jet transport touches down on KSC's Shuttle Landing Facility.

Image courtesy of NASA

> but serves as a **technical conscience** for the heating program. They have developed for example, a three dimensional flow model (unique in this field) that is being used to estimate orbiter temperatures...The results indicate that the less sophisticated modelling employed by Rockwell is yielding conservative temperature estimates over most of the body length.[37]

By this time, Ames was contributing around 40% of the entire Shuttle wind tunnel program in addition to its work in computational flight dynamics. The Center had thus come a long way from its precarious position at the end of 1969.

An important part of the design process was simplification. Simplification was a fundamental principle of aerodynamic design because of the inherent complexity and contradictory nature of the orbiter's return flight trajectory. As such, the sophisticated geometric techniques of past aerodynamicists were not appropriate solutions for the orbiter's design. As Space Shuttle Program Manager Robert Thompson, recalled:

> Aerodynamic oriented people...had done a lot of work on trying to shape (the) vehicle very cleverly so that it had good aerodynamic characteristics through the entire speed range; and it's a very broad speed range because you go from hypersonic speeds down to supersonic speeds to subsonic speeds and the aerodynamic characteristics change in those regimes, such that something shaped to fly good in one regime isn't necessarily good to fly in another. So we avoided getting into a lot of fancy shaping of the vehicle, or a lot of variable geometry kind of solutions by just brute forcing our way through...We actually used the control system on the vehicle to stabilize it in many cases. We didn't worry about giving it a basic airframe stability.[38]

The use of a computer-controlled flight control system permitted the required vehicle stability and handling qualities to be artificially produced. The integration of aerodynamic control requirements through an automated system was thus of major importance in meeting flying quality goals in all the flight regimes. It also allowed the thermal protection system design to comprise mainly of large flat areas, limiting curvature to smaller areas between the flat ones. This maximized the use of uniform dimension tiles, which would minimize both production and insulation costs.[39]

INTEGRATION AND FABRICATION

While the processes of theoretical modeling and wind tunnel testing in the area of re-entry aerothermodynamics progressed, production of the orbiter's thermal protection system got underway. Before full-scale production commenced, however, it had become apparent that the fragility of the proposed tiles presented a major systems integration problem with the external fuel tank. Introduced in late 1971, the external fuel tank represented the most significant deviation from NASA's original Shuttle design. Indeed, for Robert Thompson, the move to an expendable fuel tank was the single most important configuration decision made in the Shuttle programme:[40]

> I think the biggest thing that broke (the) logjam was our willingness to give up on everything being reusable: to take the propellants out of the orbiter. Propellants just made a mess out of trying to build the orbiter. You get them out and get them in a fairly simple tank...and then throw that aluminium tank away, looked like a good common sense way of going.[41]

In early 1974, the configuration of the external tank had been settled and hardware production begun, when Ames notified Marshall and external tank contractor Martin Marietta that if ice was allowed to form on the external tank then debris caused by the vibration of lift-off could damage their thermal protection system. As the External Tank Development Manager, James Odem remembered:

> We were well into the design of the tank when we realized just how fragile the insulation on the bottom of the orbiter was going to be. So then, we had to come up... with insulation on the tank that would withstand less than minus 400 degrees (Fahrenheit) on one side and still be above 32 degrees (Fahrenheit) on the outside so as not to create ice.[42]

The no "ice/debris" requirement meant that both Marshall and Martin Marietta had to design a thermal system that would cover the entire acreage of the tank, including all its feed lines, brackets and anything else that was on the outside. Several working sessions took place to evaluate various solutions to the icing problem, including de-icing sprays, thermal paints and heating blankets, or shrouds. As engineers debated these differing approaches, they narrowed their focus to the concept of a spray-on-foam that could cover the entire tank, including all the brackets and feed lines. NASA had previously employed spray-on-foams on the Apollo/Saturn vehicles as cryogenic tank insulators to create a suitable environment that would limit propellant boil-off and maintain the fuel quality. Accordingly, in June 1974, Marshall and Martin Marietta selected the same technology, the BX-250 spray-on-foam, for the external tank's thermal insulation design.[43]

Notwithstanding its advantages, by the end of 1974 the acceptability of BX-250 was in serious doubt. As James Odem recalled, during ascent the leading edge of the tank would have to withstand aerodynamic heating, as would the area between the orbiter and the tank:

> The insulation had to both insulate from an ice standpoint, but it had to withstand very high temperatures also. So those two are two absolutely opposing requirements, we...literally (had to) develop very light foam insulations that could withstand both aerodynamic heating as well as being a good (cryogenic) insulator.[44]

Initial solutions such as the inclusion of an ablator material, SLA-561, were not acceptable to Robert Thompson, leading to the introduction in November 1974 a new urethane modified isocyanurate foam material produced by the UpJohn Company: CPR-421. However, towards the end of 1975, Martin Marietta had to stop work on all CPR-421 activity because of toxicity problems, which by that point had become critical. Tests at the Southern Research Institute, conducted during January 1976, confirmed that the CPR-421 foam contained chemical components, which on pyrolysis could produce a toxic substance referred to as trimethylol propanephosphate. Some within NASA argued that pyrolysis on re-entry did not present a problem, as it was "safe to assume" that the Earth's atmosphere would "dilute the products of combustion tremendously." Nevertheless, Martin Marietta reformulated a new composition, CPR-488, which did not contain the phosphate component and was acceptable to Level 1 management.[45]

Meanwhile, in the area of thermal protection, the transition from laboratory production of the silica thermal protection system to full production was experiencing many scale-up problems. Control of the purity and consistency of the silica fibers presented NASA and Lockheed with their first major production problem. The silica fiber, a key ingredient in the production of the tile, came in an amorphorous form. Crystalline forms of the fiber, however, had a thermal expansion coefficient 30 times greater than the amorphorous form. A crucial element of the production process, therefore, was the transformation of the silica fiber from its amorphorous form to a crystalline structure, but this was not an easy procedure. Shrinkage and distortion of the sintered silica composites impeded the formation of crystalline structures that would be acceptable to NASA. To achieve the dimensional stability dictated by Shuttle requirements, a silica fiber greater than 99.6 per cent pure was necessary.[46]

Locating fibers with sufficient purity thus became a major concern of tile production. Lockheed's supplier (Johns-Mansville) was unable to meet all the purity requirements and so sought an alternate. However, silica fibers provided by other suppliers were much larger in diameter than those provided by Johns-Mansville, which was unacceptable. The exact diameter of the fiber was of crucial importance to the tile's thermal performance. Lockheed, therefore, decided to intervene in Johns-Mansville's production process and introduced extensive post-treatment and rigid process controls, from the selection of the sand used in making the fiber through to the fiberizing and cleaning process, to minimize contamination of the "sub-standard" fibers and bring the Johns-Manville fibers up to an acceptable standard.[47]

Another materials problem arose during the production phase of the thermal protection tile early in 1975. In the original design concept the thermal tile was going to be applied with multiple layers of borosilicate glass coatings to prevent moisture absorption, provide protection against handling damage and provide optical property control (solar absorption). During thermal testing Ames discovered that the multi-layer glass coatings had a tendency to crack or foam. Arc-jet tests at Ames revealed coating failures on approximately 40 per cent of the tiles when exposed to a succession of simulated re-entry environments. Possible causes of the coating failures included: problems with glass coating composition; processing cycle errors; glazing cycle errors; or problems with coating distribution.[48]

By 1975, however, NASA was suffering from budgetary problems, the seeds of which had been sown years earlier. Throughout 1972, the Office of Management and Budget indicated to NASA that it was in full accord with the settlement over the Shuttle.[49] For NASA, an important part of the 1972 settlement entailed a commitment.

NASA Administrator, James Fletcher, advised President Richard Nixon in July 1973:

> In January 1972 when you approved the Space Shuttle development, I stated that I could conduct the right kind of space programme...at a "constant budget" (sic) of $3.4 billion...I would have not recommended starting the Shuttle at a lower budget projection.[50]

NASA's interpretation of a constant budget was a guaranteed annual funding level $3.4 billion, in FY 1971 dollars, during the Shuttle's development. However, the Office of Management and Budget did not agree with this interpretation. The Office of Manage-ment and Budget immediately cut Fletcher's request for a $1 billion Shuttle reserve and they submitted NASA's FY 1973 budget in 1973 dollars so NASA lost any inflationary increments.[51]

In the months that followed Nixon's re-election, the Office of Management and Budget formulated plans to curb the growth in federal spending. Having permitted heavy spending in 1972, in part to assure a Nixon victory in the presidential elections, the Office of Management and Budget intended to reverse policy and work towards what they regarded as desirable economic goals. In December 1972, the Office of Management and Budget told NASA that it had to take a major cut in its FY 1974 funding as part of the overall budgetary squeeze.[52] As projections for FY 1975 did not appear to offer any alleviation, Fletcher advised Nixon of a pending crisis.

> It will not be possible to continue to run a balanced program...unless adequate funding is provided in FY 1975 and in future years... We...assumed (with Office of Management and Budget knowledge) that the reductions were only temporary, and that future years' budgets would again reach the required level. The programs we now have under way cannot be sustained at the FY 1973/74 levels, nor can they be sustained at the Office of Management and Budget projected level of $3.2 billion for FY 1975... Either the Shuttle will have to be cancelled and with it the only future plans for US men in space, or we will have to forgo one or more of the major areas of output.[53]

Despite NASA's supplications, the agency's total FY 1975 budget only just exceeded $3.2 billion.[54]

The combination of sustained funding cuts and emergent overruns from some of the Shuttle contractors were, by themselves, major contributors to the onset of financial difficulties at NASA. With the addition of an inflationary crisis, NASA's financial difficulties worsened.[55]

With rising costs of materials and labor, many of the Shuttle's contractors argued that it was difficult to continue development projects with dollars that bought substantially less than projected in 1972. NASA's FY 1975 funding was based on a 5% inflation factor, but by late 1974, overall levels of inflation on materials stood at around 9% and in some areas approached 10%.[56] In a push for retention of the constant budget, NASA continually advised the presidency and the executive branch of the political consequences of sustained funding cuts. As NASA Administrator, James Fletcher, informed Roy Ash, Director of the Office of Management and Budget in 1973:

> A great deal of support for the space program in general, and for the Shuttle in particular, hinges on program balance. Without this balance we would lose support for the remaining program in the Congress, by the public, and by the scientific and users communities.[57]

And a 1974 NASA position paper warned:

> A fiscally imposed slippage of the Shuttle development schedule by the Executive Branch for the third consecutive year may well result in termination of the program. Congress could take it as evidence of an internal Administration intent to create an untenable development environment that would lead inevitably to cancellation. Or Congress could take it as a lack of Administration determination and real commitment to preeminence that would provide an incentive to terminate the program by legislative fiat.[58]

By 1975, the General Accounting Office expressed grave doubts about NASA's ability to construct the Shuttle on time and within budget. Its main concern was that NASA's budget estimates and schedule goals appeared to be overly optimistic and as a result the agency might have understated its project estimates and overstated its reserves.[59]

In this projection, the General Accounting Office was correct. For the development of the thermal protection system, the result was a deferral of any detailed investigation into the problems they were encountering. Finding a solution to the cracking tiles thus had to wait until 1976. Eventually Ames's proposal, to use only a single-layer glass coating, received funding for qualification testing in mid-1976. After a lengthy verification program, NASA found that the single-layer coating did not foam during production and actually provided a better match with the thermal coefficient of the silica insulation material. The superior performance of the single-layer coating over the multi-layer coating in many of the tests ultimately persuaded NASA officials to change the design.[60]

12 March 1979. Shuttle orbiter *Columbia* arriving at the Orbiter Processing Facility, KSC.
Image courtesy of NASA

Once these two key materials problems had been solved, full-scale production could begin. Technical matters, however, were not the only obstruction to tile production. Funding limitations in 1975 resulted in a substantial modification to the Shuttle program's schedule and deferment of further development of the thermal protection system until the funds were available to procure special tooling equipment. This delayed the completion of the production facility in Sunnyvale, California;[61] as Johnson's Director, Christopher Kraft recalled:

> We made a decision to put off building the tile factory, because we didn't have the money. We had to put the money into the schedule and we had to develop the schedule...and we just decided we could wait a couple of years.[62]

The Sunnyvale plant contained some of the most modern manufacturing equipment then available, including: precision controlled kilns and furnaces; numerically controlled milling machines; and the most up-to-date blending and slurry casting equipment. As with flow dynamics analysis, computers played an important role in the fabrication of the thermal protection system. Lockheed was able to plot orbiter configuration coordinates from a Rockwell engineering database and then convert them into computer programs, which drove the numerically controlled mills that machined the tiles into precise dimensions.[63]

APPLICATION AND MODIFICATION

By the end of 1978, application of the complex array of thermal protection tiles to the Shuttle orbiter *Columbia* was nearing completion. It was a complex process. Lockheed had formed most of the 33,000 tiles into individually specific shapes, determined by the aerodynamic and aerothermodynamics data that governed the computer-controlled milling machines. Thus, Lockheed had to stamp every tile with a number, which corresponded to a precise position on the orbiter. Rockwell than had to apply each tile individually, check for any differences in height that might induce turbulent flows, and carefully index them before they were "glued" to the structure. In addition, a gap of no less 0.010 inch had to be ensured between each tile to allow for thermal expansion and contraction and for the flexing of the orbiter's wing surface during flight. The application rate was slow and hindered further by the fragility of the tile material. On average, one technician applied one tile per week.[64]

As the planned September 1979 launch date approached, Rockwell found itself behind schedule with the tile application. To avoid adverse publicity, NASA Headquarters decided that technicians at Kennedy could attach the remainder of the tiles. So on March 24 1979, *Columbia* was airlifted atop NASA's Boeing 747 to the launch center with around 6,000 tiles left to install. The plan did not go as intended. Many tiles were lost during the flight from California to Kennedy. As a public relations exercise it was a disaster. It appeared to the media that if the most advanced spaceship in the world could not even fly from California to Florida without tiles falling off, then how was it supposed make the journey into space?[65] Most of the tiles that were lost were "dummies," applied because of concern about the effects of turbulence on the "actual" tiles fitted, but the event severely damaged NASA's reputation.

A Rockwell International technician mounts some of the ceramic-coated tiles on the external surface of *Columbia*, February 1980.

Image courtesy of NASA History Office

With the arrival of *Columbia* at Kennedy in late March 1979, President Carter announced: "The first great era of space is over. The second is about to begin." The statement, largely based on the assurances coming from NASA, was nonetheless premature. The shipment of *Columbia* to Kennedy was primarily political. As one Johnson Official, Herb Yarbrough, recalled when *Columbia* arrived Kennedy "it was not ready for delivery, but the program had a milestone and we had budget problems and not delivering on time wouldn't have helped that." March 1979 had been the predicted launch date for a number of years; thus getting the Shuttle to Kennedy by that date had become a key objective. Yet, it soon became apparent to those at Kennedy that the vehicle was nowhere near ready to fly. As Rockwell engineer (Kennedy Division), John Tribe, remembered:

"When the vehicle got here it wasn't finished. ...so we had a lot of work to do down here, it was almost like we had to finish building it."[66] And as Deputy Director of Space Shuttle Projects Management at Kennedy, Samuel Beddingfield, also recollected:

> Well, when the Shuttle got here and this has been kind of a tradition, an unfortunate tradition, that when the Rockwell people deliver a spacecraft down here to be launched it's never finished. It has a lot of work to be done on it, even though they claim that it's finished. Now when that one came in the tiles were a huge problem, the thermal protection system tiles. We lost a lot of them in transit, just flying it across the country. ...It ended up that we had to replace almost all the tiles on the whole vehicle and the work was not very well done, they had a lot of sloppy workers and there was (sic) a lot of other things that had to be tweaked. The landing gear was not working right, the brakes were not working right. So we practically rebuilt the thing down here; so it was a long time after it was delivered before the first flight and part of it is just being absolutely concerned with checking it out, making sure everything works. But a large part of it was that it just wasn't finished being built. They did the same thing on the Apollo space vehicle.[67]

Towards the end of 1979 NASA found that it had a large problem with the thermal protection system. Due to budget and schedule pressures, NASA had decided to move ahead with the tile fabrication and installation before Ames had completed the final aerodynamic loads and stress analysis. The design of the tiles derived from the initial predictions that had emerged from these studies. As the predictions became more refined, however, they highlighted a serious weakness in the strength of the tiles. As Space Shuttle Program Manager Robert Thompson, recalled: "One of the things that we got into a little bit of difficulty with, we didn't characterize the tile materials as thoroughly as we should have." And Johnson's Director Christopher Kraft remembered: "When we finally got the factory built and started producing the tiles, we got enough tiles to run a sufficient statistical sample, and low and behold, the strength was only half what we thought it was." Late in 1979, Johnson engineers suspected that somewhere between 10,000 and 12,000 tiles were below the "new" specifications. But, as the program turned into 1980, aerodynamic and aerothermodynamics data were predicting that up to 31,000 tiles would need retesting.[68]

The first problem Kennedy had was how to test the tiles while they were still on the orbiter. What Johnson came up with was a "proof-test device" that combined a vacuum chuck (which attached to a single tile), a pneumatic cylinder (which applied the specified load) and six pads (which would be attached to the surrounding tiles to react to the load). The device would then stick to the orbiter, rather like a plunger, and attempt to pull a single tile off within a specified load. If the tile stayed fixed, then it passed the test. If it came off, then clearly it did not. Although a simple and effective solution, a second problem emerged: what if the test itself weakened the tile? To solve this problem, Kennedy's engineers attached an acoustic sensor to the proof-test device to monitor the acoustic emissions from fiber breakage. This involved the establishment of a large-scale laboratory programme to arrive at criteria of failure. The program simulated the flight loads over 100 missions and monitored the changing acoustic signatures as the tiles failed.[69]

The next problem for Kennedy engineers was to determine what to do with the tiles that came off. Initially, the "repair" concept was to install a graphite sheet under the tiles to increase their adhesion to the orbiter. However, Kennedy abandoned this approach quite early for a simpler process known as "tile densification," which involved coating the surface facing the orbiter with a colloidal silica coat. This provided the tiles with a new surface that spread the loads more evenly. However, having been forced into a major modification of its tile application programme, NASA adopted the change with caution.[70] Many at NASA believed that the tile problems should never have occurred and laid the blame on Rockwell. George Jeffs, President of Rockwell International Aerospace Operations, told *Aviation Week and Space Technology*:

> I think it's a fair criticism that we didn't define the problems more clearly. ...We worked too hard on the quality of the material alone and waited too long for the thermal analysis while awaiting a detailed structural definition. Perhaps it was a bit too long to understand what the (orbiter structural deflections) might be and their effects in the tiles. I am troubled that we are suffering a lot of shots at our engineering reputation because of the bloody tiles, and we are doing everything we can to clean them up.[71]

Kennedy's engineers hoped that the data obtained from the "pull-tests" would enable a relaxation of requirements thus reducing the reapplication number. By the end of 1979, Kennedy had pulled off and reapplied over 12,000 tiles. Originally, the densification process was restricted to the black tiles along the bottom of the orbiter, but in early 1980, there was growing concern about "suspect" white tiles on *Columbia's* topside. In addition, aerodynamic and aerothermodynamics analysis had increased the load predictions yet again. This meant Kennedy had to retest all the tiles for a second time, including the 12,000 that had been through the densification process.[72]

In a tremendous effort to complete the work on *Columbia* in time for a

November 1979 launch, NASA moved over 2,000 workers from Palmdale, California, to Kennedy at a cost of over $1.8 million. A huge complex of temporary accommodation and facilities was established at Kennedy to house all the workers, who were working seven days a week, three shifts a day, to finish building *Columbia*. In addition, Kennedy also hired every man and women in Brevard County that wanted to work on the Space Shuttle, to work with the application of the thermal protection tiles, because it was such a labor intensive operation. Included in that workforce were over 320 high school graduates and college students on their summer vacation.[73] John Halsema recalled his experiences as a temporary technician, hired to install the thermal protection tiles.

> When I started working...we were in a big push to get the Shuttle finished. ...We started working a tremendous amount of hours...after my initial training, we started working 12 hours a day for five days a week and 8 hours a day on Saturday and Sunday. ...We had to be at work at five in the morning and we got off at 5:45. ...I think everybody at that period of time had a real personal feeling about working on the Space Shuttle. Most of the people that were hired temporarily here, grew up here and so they were in the same situation I was, they had (grown up) watching rockets take-off. ...All of us were young, in our late teens to early twenties...there were a few of the old hands that had been technicians during the Apollo program and they were kind of the corporate memory and we got to hear what it was like during the big pushes during the Apollo era.[74]

For the temporary technicians, working on the Shuttle was an "interesting and enjoyable" experience. Although the hours were long, for many it fulfilled their dreams of getting up close to a space vehicle. For the full-timers at Kennedy, getting the Shuttle ready to fly was turning into a nightmare, as John Tribe recalled:

> Those were some black days, ...I wondered if we'd ever fly. It just seem like that every time we started to put things back together there would be another (modification), or another crisis would occur, so that we had to go and start taking it apart again.[75]

The sheer amount of people engaged in the test, densification, tile removal and reapplication process, created serious food service, toilet and accommodation problems during 1979 and 1980. Kennedy had to erect a complex of trailers outside the Orbiter Processing Facility to support a workforce spread over three shifts working 24 hours a day, seven days a week. At any one time, over 200 people were working directly on or in the vicinity of *Columbia*, a number that was far higher than the facility had been designed for. Thus, the work platform access was not always available for tile work so Kennedy had to set up jury-rigged catwalks, strung up by ropes, to reach the otherwise inaccessible areas. The whole process for each tile from removal to densification to reapplication took about 14 days. In the summer of 1979, the average application rate, with a workforce of 800, was 450 tiles per week.[76]

As the programme moved through 1980, it became apparent that the tile problem was much more serious than had been anticipated and concern soon focused on the "special tiles" around the wing leading edge, the windshield, the undercarriage doors, the tail, and tiles in other areas that did not have square or rectangular shapes. These special tiles were often located in areas that would endure very complex airflows that Ames could not analyze easily and they were not amenable to the pull-test technique. Thus, NASA had to go back to wind tunnel testing on the tiles. However, this was both expensive and time consuming, so NASA decided to select only certain locations from several of the most complex air flow fields to build up a data set. To reinforce the analysis, Ames aerodynamicists correlated the scale model tests in the wind tunnel with similar airflows on fighter aircraft. Engineers attached some of the tiles to wing sections on an F-15 and an F-104 and then flew the aircraft through flight conditions up to 1.4 times the severity of those expected on the Shuttle.[77]

The test programme, completed in January 1981, forced NASA Headquarters to revise the first launch date for March 1981. However, the tests showed up serious flaws in the special tiles. Ames engineers speculated from the data that the high pressures of ascent could lift the windshield tiles from their moorings. As with all the tiles, Lockheed had machined the windshield tiles from a block of ceramic in such a way as to ensure that all the fibers run in parallel to the Shuttle's surface; principally because analysis had demonstrated that a parallel grain orientation would minimize the heat transfer to the orbiter's aluminium skin. However, this grain orientation caused a reduction in the tiles' strength because of the relatively low number of vertical fibers. The first solution, therefore, was to machine new tiles with the fibers running perpendicular to the orbiter's surface. This would provide strength, but would also reduce thermal efficiency. Thus, a second solution was also necessary. On further analysis, Ames thermal engineers found that the orbiter window would act as a heat sink, so they decided that by bonding the part of the tile that overhung the window directly to the glass this would increase the thermal capacity of the tile.[78]

After two years of testing and redesign, NASA's confidence in the thermal protection tiles grew and by March 1981, many of the problems seemed solved. However, few outside NASA shared this confidence and as *Columbia* prepared for its first flight in April 1981, the question of the tile's performance was still a matter of doubt.[79]

Columbia's first flight eventually took place on April 12, 1981. NASA had scheduled the first launch for April 10, but the back-up flight computer failed 20 minutes before lift-off, moving the launch to two days later.[80] This time everything went according to plan and *Columbia* climbed into the sky on the Sunday morning with no problems. However, once in orbit, a potentially serious problem emerged. Television monitor cameras, fitted to observe the payload bay doors open, caught sight of missing tiles on the orbital maneuvering system pods. This in itself was alarming to NASA, but what concerned Mission Control most was if tiles on the bottom of the orbiter were also missing. NASA spent all of April 13 attempting to find a solution, but as Hans Mark recalled:

> There was, of course, not much that we could really do. If there were indeed tiles missing from the portion of *Columbia* that would experience the highest heating rates, then we would only find out by making the attempt to bring her back to Earth. So we made our best calculations and estimates, but, in the final analysis we had to...hope for the best.[81]

Columbia returned safely on that occasion and went on to fly many more missions before showing us all the dangers and risks involved in space flight.

AUTONOMOUS OR INTERDEPENDENT

As historian of technology Thomas Hughes once noted, patterns of technological change only appear inevitable because large technological systems have embedded within them the characteristics of the past. Such massive systems, he claimed, have inertia analogous to that of the physical world in that their mass of technical and organizational components tends to maintain their steady growth in a particular direction. This momentum institutionalizes the dynamics of technological change; it veils any internal controversies from public view and presents technology as an autonomous thing, which is beyond politics and society.[82] Thus, commentators often articulate technological failure in terms of the dichotomy between technical and political decisions, between 'objectivity' and interests, where political compromise diverts 'value-free' technological progress from its 'true' and 'natural' course.

Authors in the social construction of technology, however, have shown that interests, dispute, controversy, negotiation and compromise, i.e. politics, are a normal part of technology building: that social matters are never absent from technological production, but intrinsic to it. Indeed, they have shown that social interests operate as contributory causes of action and form part of the motives for technological change. Technology is thus a negotiated space where actors play out their own agendas. Technological artifacts and systems cannot exist without the social interactions within and among different groups. They require assemblages of people and things to bring them into existence, to negotiate their meaning, purpose and functioning.[83]

Macro politics, of course, played a central role in shaping NASA's Space Shuttle. Budget restrictions, cost overruns and inflation were all significant shapers of both the technology and of development practice. However, central to the social constructivists' approach is the idea that social processes influence what it means for a technology to be deemed working. Important here is the concept of "interpretative flexibility." Interpretative flexibility changes a seemingly unambiguous thing into several different things simultaneously, dependant upon a multiplicity of human viewpoints. This fluidity of interpretation is often most obvious during the design stage, where a myriad of choices are open to the technology builders. However, interpretative flexibility operates along the entire life of a technology and, as highlighted above, is especially prevalent during technological testing.[84]

Testing performs a vital role in the development, fabrication and operation of technology. Yet, in comparison to its equivalent in the sciences, the experiment, the test has received little attention from the social studies of technology. In technically complex projects, like the Shuttle, many different groups of engineers are involved in the testing processes. All the components are, at first separated and tested in isolation, before integrated into the system as a whole. As with other elements of the program, therefore, testing was a process of negotiation: between groups of engineers; between engineers and managers; and between the engineers and the technology. The Shuttle engineers pushed for the maximum technical performance from the components for which they were responsible. Confidence that the Shuttle would work was reached gradually, through a succession of 'successful' tests taken together. However, the knowledge accrued through testing was invariably open to dispute and the value of the results, and the accuracy of the measurements, were often open to question.[85]

Similarity relationships and similitude requirements lay at the heart of testing. With the development of the thermal protection system, the operational environment dictated that Ames could only accomplish certain tests using scale models in artificial conditions created from theoretical assumptions, empirical knowledge, engineering judgment and a reliance on instrumentation. The systems, therefore, did not undergo the 'actual test' until the Shuttle flew as a whole for the first time. The arc tests on the thermal protection system, although an indicator of heat resistance, did not represent the total operational environment through which the system had to work. In addition to the arc tests, Ames's engineers had to simulate the complex airflows of re-entry: the most difficult of which was boundary-layer transitions from laminar to turbulent flows. Recreating turbulent flows in the laboratory was not an easy task. Because of their chaotic nature, similitude requirements were difficult to meet and the 'validity' of results depended upon the acceptance of the engineering community about the claims of the similarity relationship. This acceptance only came after controversy and only after investigation by senior management was confidence restored.[86]

Negotiation about the operational environment was, therefore, a pervasive part of the testing process. Results accrued through one set of tests did not always correspond with results from another set of tests. This was the case when budgetary and schedule pressures drove the decision to move ahead with the tile fabrication and installation program before Ames had completed its aerodynamic and re-entry analysis. Contention soon arose about the structural integrity of the tiles and confidence in the tile systems plummeted after the final aerodynamic, and aerothermodynamics data indicated that the re-entry and ascent environments were far more severe than first considered. The 'pull-test,' initiated by Kennedy, was an attempt to restore this confidence, but the result was a redesign of the tiles.

In essence then, what the above paper has aimed to highlight is what many working under the rubric of science and technology studies have argued: that technology forms part of a 'seamless web' of society, politics, ideology and economics. The development of a technological artifact or system is not simply a technical activity but is also intrinsically a social one. When technologies fail, therefore, we should not be surprised to find politics embedded in the systems we create.

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REFERENCES:

[1] Nigel Henbest, Heather Couper, *Space Shuttle: The Human Time Bomb?* Pioneer Productions, Aired on Channel 4, March 15, 2003; Bruno Latour, *Aramis or the Love of Technology* (Cambridge, Massachusetts: Harvard University Press, 1999): 78.

[2] Bruno Latour, *Pandora's Hope* (Cambridge, Massachusetts: Harvard University Press, 1999); Donald MacKenzie, *Inventing Accuracy* (Cambridge, Massachusetts: MIT Press, 1993); Trevor Pinch, *The Social Construction of Technology: A Review,* Robert Fox, ed. *Technological Change: Methods and Themes in the History of Technology* (London: Harwood Academic Publishers, 1996): 17-35; Trevor Pinch and Weibe Bijker, "The Social Construction of Facts and Artefacts," *Social Studies of Science 14*, (1984): 399-441.

[3] Marcel LaFollette, Jeffrey Stine, *Contemplating Choice: Historical Perspectives on Innovation and Application of Technology*, Marcel LaFollette, Jeffrey Stine, ed. *Technology and Choice: Readings from Technology and Culture* (Chicago: The University of Chicago Press, 1991): 1-17; William Normyle, "Shuttle Poses Dominant Challenge," *Aviation Week and Space Technology* (June 22, 1970): 99.

[4] Robert Freitag, interview with Brian Woods, Virginia, June 5, 1995; Robert Dotts, Donald Curry, Donald Tillian, "Orbiter Thermal Protection System," Norman Chaffee, ed. *Space Shuttle Technical Conference* (Houston, Texas, NASA, JSC, Conference Publication 2342, 1985): 1062; Mike Gray, *Angle of Attack* (New York: W.W. Norton, 1992): 212-215; Hans Mark, interview with Brian Woods, Texas, September 8, 1995; Letter from Hans Mark to Roy Jackson, February 15, 1972, Archives at the NASA History Office, Washington DC; NASA, Space Shuttle Program Requirements Document: Level 1. Archives at the NASA History Office, Washington DC: 4; David Baker, "Evolution of the Space Shuttle," *Spaceflight* (September 1976): 311; Anon 1, "Shuttle May Use Low-Cost Ablatives," *Aviation Week and Space Technology (*October 5, 1970): 56.

[5] Dotts et al., *Space Shuttle Technical Conference, Part 2*, 1062-1081.

[6] Dennis Jenkins, *Space Shuttle* (Wisconsin: Motorbooks, 1993): 76, 79, 93; Baker, 264-265.

[7] Normyle, 96-121; Dotts, et al., *Space Shuttle Technical Conference, Part 2*, 1062-1081.

[8] Anon 2, "Non-Metallics Studied for Shuttle," *Aviation Week and Space Technology* January 18, (1971): 36-39; Jenkins, 89; Samuel Beddingfield, interview with Brian Woods, Florida, July 31, 1995; Anon 2, 36-39; Dotts, et al., *Space Shuttle Technical Conference, Part 2*, 1062-1081; Jenkins, 119.

[9] William Hieronymus, "Two Reusable Materials Studied for Orbiter Thermal Protection," *Aviation Week and Space Technology* (August 23, 1973): 16-18; Dotts, et al., *Space Shuttle Technical Conference, Part 2*, 1062-1081.

[10] James Young, Jimmy Underwood, Ernest Hillje, Arthur Whitnah, Paul Romere, Joe Gamble, Barney Roberts, George Ware, William Scallion, Bernard Spencer, James Arrington, Deloy Olsen, "The Aerodynamic Challenges of the Design and Development of the Space Shuttle," Norman Chaffee, ed. *Space Shuttle Technical Conference, Part 1* (Houston, Texas: NASA, JSC, Conference Publication 2342, 1985): 209-263; Frank Reagan, *Re-Entry Vehicle Dynamics* (New York: American Institute of Aeronautics and Astronautics, Inc, 1984).

[11] Dotts, et al., *Space Shuttle Technical Conference, Part 2*, 1062-1081.

[12] Elizabeth Muenger, *Searching the Horizon: A History of Ames Research Center* (Washington DC: NASA, Scientific and Technical Information Branch, 1985): 168-173; Donald D. Baals and William R. Corliss, *Wind Tunnels of NASA* (Washington DC, NASA Scientific and Technical Information Branch, 1981): 85; Hans Mark, Arnold Levine, *The Management of Research Institutions: A Look at Government Laboratories* (Washington DC: NASA, Scientific and Technical Information Division, 1984): 81-81.

[13] Arc-jet facilities preheat the test gas in the stilling chamber upstream of the nozzle by means of a continuous electric arc. The heated gas is then injected under pressure into the nozzle. Though the arc-jet is an extremely valuable facility for testing spacecraft heat-shield materials, the test stream is subject to contamination from the arc. Benjamin Elson, "New Unit to Test Shuttle Thermal Guard," *Aviation Week and Space Technology* March 31 (1975): 52.

[14] Richard Hallion, *The Path to the Space Shuttle: The Evolution of Lifting Re-entry Technology.* (History Office, Air Force Flight Test Center, November 1983); Baals and Corliss, 75; Walter Vincenti, workshop presentation at the University of Edinburgh, May 20, 1998; Elson, 52. Jerry Grey, *Enterprise* (New York: William Morrow, 1979): 103-105; David Halliday, Robert Resnik, *Physics: Parts 1 and 2* (New York: John Wiley & Sons, Third Edition, 1978): chapter 18.

[15] Robert Thompson, interview with Brian Woods, Texas, September 9 1995; Christopher Kraft, interview with Brian Woods, Texas, September 1 1995; Raymond Dupree, interview with Brian Woods, Alabama, August 21 1995.

[16] Walter Vincenti, *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History* (Baltimore: The John Hopkins University Press, 1993): especially chapter 1; Walter Vincenti, workshop presentation at the University of Edinburgh, May 20, 1998; Elson, 52. Jerry Grey, *Enterprise,* 103-105; Halliday, and Resnik, *Physics: Parts 1 and 2,* chapter 18.

[17] Walter McDougall, *The Heavens and the Earth: A Political History of the Space Age* (New York: Basic Books, 1985): 164, 166, 190-91, 339-41; Baals and Corliss, 107-109; Roy F. Houchin, "The Diplomatic Demise of Dyna-Soar,' *Aerospace Historian*, Winter (1988): 274-280.

[18] Bastian Hello, interview with Brian Woods, Maryland, April 27 1995.

[19] Ibid.

[20] Supporting Space Research and Technology Panel Aeronautics and Astronautics Coordinating Board, Report to the Ad Hoc Committee on Reusable Launch Vehicle Technology, September 14, 1966; Memorandum from George Mueller, Associate Administrator Office of Manned Space Flight to Acting Associate Administrator, Office of Advanced Research and Technology, August 25, 1969; Minutes of Meeting: NASA Research and Technology Advisory Council, Committee on Space Vehicles, September 25-26, 1974, Archives at NASA

History Office, Washington DC.

[21] Baals and Corliss, 81.

[22] Ibid., 81.

[23] Ibid., 86, 117-121.

[24] Ibid., 95-96.

[25] Stanley Berger, *Laminar Wakes* (New York: American Elsevier Publishing Co Inc, 1971): preface; Elson, 52.

[26] Robert Ried, "'Orbiter Entry Aerothermodynamics," Norman Chaffee, ed., *Space Shuttle Technical Conference: Part 2* (Houston, Texas: NASA, JSC, Conference Publication 2342, 1985): 1055.

[27] Walter Vincenti, *What Engineers Know and How They Know It*, 37-39.

[28] An important similarity parameter for viscosity has long been the Reynolds number. Formulated by Osborne Reynolds in the late 19th Century while studying the flow of water in pipes and channels, the Reynolds number is a dimensionless number that expresses the ratio of inertial forces to viscous forces and is given by the equation Re = velocity x density x characteristic length/viscosity coefficient. The Reynolds number is significant because it allows aerodynamic engineers and naval architects to translate results obtained from scale model experiments to full-scale conditions. If the Reynolds number is the same (i.e. the model is operated in the same fluid as the prototype) then similarity is achieved. For example, if a model is 1/10 the size of a full-size aircraft, then the air density (the number of atmospheres) inside the tunnel must be increased by a factor of 10 to get wind tunnel results that are valid in regular atmospheric conditions with a full-size aircraft.

[29] Ried, pp 1051-1061; Berger, preface, 3-6; B. Kent Joosten, 'Descent Guidance and Mission Planning for the Space Shuttle,' Norman Chaffee, ed., *Space Shuttle Technical Conference: Part 1* (Houston, Texas: NASA, JSC, Conference Publication 2342, 1985): 113-124.

[30] Christopher Kraft, interview with Brian Woods, Texas, September 1 1995.

[31] Young, et al., *Space Shuttle Technical Conference, Part 1*, 209-263; Ried, 1051-1061.

[32] Ibid; Paul Ceruzzi, *Beyond the Limits: Flight Enters the Computer Age* (Cambridge, Massachusetts: MIT Press, 1989): chapter 7.

[33] Dean Chapman, quoted in Muenger, p 173.

[34] Hans Mark, Arnold Levine, 81; Muenger, 173-176; Ceruzzi, chapter 7; Dean Chapman, Hans Mark, Melvin Pirtle, "Computers vs Wind Tunnels for Aerodynamic Flow Simulations," *Astronautics and Aeronautics* (April 1975): 22-35.

[35] Memorandum from Charles Donlan to the Associate Administrator for Space Flight, February 19, 1976; Memorandum from Charles Donlan to the Associate Administrator for Space Flight, March 25, 1976, Archives at the NASA History Office, Washington DC.

[36] Memorandum from Charles Donlan to the Associate Administrator for Space Flight, March 25, 1976, Archives at the NASA History Office, Washington DC.

[37] Ibid, my emphasis.

[38] Robert Thompson, interview with Brian Woods, Texas, September 9 1995.

[39] Ibid; Young, et al., *Space Shuttle Technical Conference, Part 1*, 209-263.

[40] Robert Thompson, *Von Karman Lecture: The Space Shuttle - Some Key Program Decisions* (Reno, Nevada: AIAA 22nd Aerospace Sciences Meeting, AIAA-84-0574 January 9-12, 1984): 3-4.

[41] Robert Thompson, interview with Brian Woods, Texas, September 9 1995.

[42] James Odem, interview with Brian Woods, Huntsville, August 21, 1995.

[43] Ibid; R.H. Gray, memorandum for distribution, May 7, 1974, Archives at the Kennedy Space Centre, Florida; Letter from Robert Thompson to Shuttle Projects Office Manager, Kennedy, November 4, 1974, Archives at the Kennedy Space Centre, Florida; Frederick Bachtel, Jerold Vaniman, James Stucey, Carroll Cray, Bernard Widofsky, 'Thermal Design of the Space Shuttle External Tank,' Norman Chaffee, ed. *Space Shuttle Technical Conference Part 2* (Houston, Texas, NASA, JSC, Conference Publication 2342, 1985): 1041-1050.

[44] James Odem, interview with Brian Woods, Huntsville, August 21, 1995.

[45] Ibid; Letter from Robert Thompson to Shuttle Projects Office Manager, Kennedy, November 4, 1974, Archives at the Kennedy Space Center, Florida; Space Shuttle: 1975 *Status Report for the Committee on Science and Technology, US House of Representatives* (Washington DC: US Government Printing Office, February 1975): 94; Frederick Bachtel, et al. *Space Shuttle Technical Conference Part 2*, 1041-1050; NASA Position Paper, no date, Archives at the Kennedy Space Centre, Florida: 2.

[46] The sintering process involves the heating metal or ceramic powders, under high pressure and temperatures so that the powder grains liquefy and bond to form strong shapes. Dotts, et al., *Space Shuttle Technical Conference, Part 2*, 1062-1081.

[47] Ibid.; Lockheed Missiles and Space Co., Inc., Space Systems Division, "Summary of High Temperature Reusable Surface Insulation Program," *Space Shuttle 1976 Status Report for the Committee on Science and Technology US House of Representatives* (Washington DC: US Government Printing Office, October 1975): 325-329.

[48] Ibid.

[49] Memorandum from Willis Shapely to George Low, July 26, 1972; Letter from James Fletcher to Roy Ash, Director of the Office of Management and Budget, July 13, 1973; Letter from James Fletcher to Richard Nixon, July 13, 1973, Archives at the NASA History Office, Washington DC.

[50] Letter from James Fletcher to Richard Nixon, July 13, 1973, Archives at the NASA History Office, Washington DC.

[51] Robert Thompson, interview with Brian Woods, Texas, September 7, 1995; NASA's total appropriation for FY 1973 was $3,407,636,000. Ihor Gawdiak, Helen Fedor, *NASA Historical Data Book Volume IV* (Washington DC: NASA History Office, 1994): Table: 4-12, p 133.

[52] James Reichley, *Conservatives in an Age of Change* (Washington DC: Brookings Institute, 1981): 227; Letter from James Fletcher to Roy Ash, Director of OMB, July 13, 1973, Archives at the NASA History Office, Washington DC; Letter from James Fletcher to Richard Nixon, July 13, 1973, Archives at the NASA History Office, Washington DC; Gawdiak, Fedor, *NASA Historical Data Book Volume IV*, Table: 4-13, p 134. NASA's total appropriation for FY 1974 stood at $3,039,700,000.

[53] Letter from James Fletcher to Richard Nixon, July 13, 1973, Archives at the NASA History Office, Washington DC.

[54] Gawdiak, Fedor, *NASA Historical Data Book Volume IV*, Table: 4-14, p 135. NASA's total appropriation for FY 1975 stood at $3,231,093,000.

[55] Itoh Makoto, *The World Crisis and Japanese Capitalism* (London: MacMillan Press, 1990): 32-34, 50-57; Eric Hobsbawm, *The Age of Extremes: The Short Twentieth Century 1914-91* (London: Michael Joseph Ltd, 1994): chapter 9.

[56] K. Johnsen, "Inflation Boosts Labor Demands," *Aviation Week and Space Technology* (July 23 1974): 12-13; Craig Covault, "Inflation Forcing Shuttle Changes," *Aviation Week and Space Technology* September 23 (1974): 20-22; Barry Casebolt, "Overrun on Costs Of Shuttle Studied," *The Huntsville Times* April 14, (1974): 5-6.

[57] Letter from James Fletcher to Roy Ash, Director OMB, July 13, 1973, Archives at the NASA History Office, Washington DC.

[58] NASA position paper, 18 October 1974, Archives at the NASA History Office, Washington DC: p 2.

[59] GAO, *Staff Study: Space Transportation System* (Washington DC: General Accounting Office Distribution Center, 1975): 3, 21, 24.

[60] W.H. Morita, ed. *Space Shuttle System Summary* (Rockwell International, SSV80-1, May 1980): 110; Lockheed Missiles and Space Co., Inc., Space Systems Division, 325-329; Dotts, et al., *Space Shuttle Technical Conference, Part 2,* 1062-1081.

[61] Lockheed Missiles and Space Co., Inc., Space Systems Division, 325-329.

[62] Christopher Kraft, interview with Brian Woods, Texas, September 1, 1995.

[63] Dotts, et al., *Space Shuttle Technical Conference Part 2*, 1062-1081.

[64] Anon 3, "Thermal Tiles Applied to Orbiter 102," *Aviation Week and Space Technology* (November 27, 1978): 64; Anon 4, "F-15 Used in Shuttle Tile Test," *Aviation Week and Space Technology* February 25, (1980): 23; Gregg Easterbrook, "The Spruce Goose of Outer Space," *The Washington Monthly 12* (1980): 32-48.

[65] Bruce Smith, "Loss of Tiles Delays Orbiter Ferry Flight," *Aviation Week and Space Technology* March 19, (1979): 21-22; Transcript from NBC 6:30 pm News, NBC TV, December 21, 1979 (NASA History Office Archive, Washington DC).

[66] Jimmy Carter, quoted in NASA Activities, May, 1979, Archives at the NASA History Office, Washington DC; Herb Yarbrough, interview with Brian Woods, Texas,

September 5, 1995; Anon 5, "KSC Personnel Face Real Challenge," *Spaceport News*, 18 (1979): 3, 6; John Tribe, interview, with Brian Woods, Florida, July 28, 1995.

[67] Samuel Beddingfield, interview with Brian Woods, Florida, July 31, 1995.

[68] Robert Thompson, Von Karman Lecture, 11-12; Robert Thompson, interview with Brian Woods, Texas, September 9, 1995; Christopher Kraft, interview with Brian Woods, Texas, September 1, 1995; Robert Frosch, Press Briefing on Dr. Frosch's Conversation with President Carter Regarding the Space Shuttle, November 14, 1979, Archives at NASA History Office, Washington DC; Anon 6 "NASA, Contractor Push New Tile Tests," *Aviation Week and Space Technology* (October 15, 1979): 44; Craig Covault, "Kennedy Center Starts Shuttle Stacking," *Aviation Week and Space Technology* (November 5, 1979): 18-19; Craig Covault, "Shuttle Project Faces New Problems," *Aviation Week and Space Technology* (December 10, 1979): 20-21; Anon 7, "Orbiter Protective Tiles Assume Structural Role," *Aviation Week and Space Technology* (February 25, 1980): 22-24.

[69] William Schneider, Glenn Miller, "The Challenging 'Scales of the Bird': Shuttle Tile Structural Integrity," Norman Chaffee, ed. *Space Shuttle Technical Conference, Part 1* (Houston, Texas: NASA, JSC, Conference Publication 2342, 1985): 403-413.

[70] Ibid; Craig Covault, "Kennedy Center Starts Shuttle Stacking," 18-19.

[71] George Jeffs, quoted in Anon 7, 22.

[72] Ibid; Craig Covault, "'Kennedy Center Starts Shuttle Stacking," 18-19; Craig Covault, "'NASA Presses to Hold Shuttle Schedule," *Aviation Week and Space Technology* (July 21, 1980): 16-17; Craig Covault, "NASA Tightens Shuttle Schedule Again," *Aviation Week and Space Technology (*August 11, 1980): 27-28; Schneider, Miller, 403-413.

[73] John Tribe, interview, with Brian Woods, Florida, July 28, 1995; R. Jeffrey Smith, "'Shuttle Problems Compromise Space Program," *Science* 206, (1979): 910-914; Arlen Large, "America's Space Shuttle Lemon," *Wall Street Journal* (January 31, 1980): p 14; Deborah Kyle, "The Space Shuttle: Ahead of Its Time--Or Biding It?" *Armed Forces Journal International* (July, 1980): 44, 56; S. Diamond, "NASA Wasted Billions, Federal Audit Discloses," *New York Times* (April 23, 1986).

[74] John Halsema, interview with Brian Woods, Florida, July 26, 1995.

[75] John Tribe, interview, with Brian Woods, Florida, July 28, 1995

[76] John Halsema, interview with Brian Woods, Florida, July 26, 1995; John Tribe, interview with Brian Woods, Florida, July 28, 1995; Samuel Beddingfield, interview with Brian Woods, Florida, July 31, 1995.

[77] Anon 4, 23; Anon 8, "Space Shuttle Tile Tests Completed," *Aviation Week and Space Technology* (January 19, 1981): 30.

[78] Schneider, Miller, 403-413.

[79] Christopher Kraft, interview with Brian Woods, Texas, September 1, 1995.

[80] John Garman, "'The "Bug" Heard 'Round the World," *Software Engineering Notes* (6 October 1981): 3-10.

[81] Hans Mark, *Space Station: A Personal Journey* (Durham: Duke University Press, 1987): 124-125.

[82] Thomas Hughes, *American Genesis: A Century of Invention and Technological Enthusiasm 1870-1970* (New York: Viking, 1989): 459-461. See also Donald MacKenzie, *Inventing Accuracy*; Steven Yearley, *Science Technology and Social Change* (London: Unwin Hyman Ltd, 1988).

[83] Barry Barnes, *Interests and the Growth of Knowledge* (London: Routledge, 1977); Barry Barnes, David Bloor and John Henry, *Scientific Knowledge: A Sociological Analysis* (London: Athlone, 1996); Trevor Pinch, *The Social Construction of Technology: A Review,* 17-35.

[84] Trevor Pinch and Weibe Bijker, 399-441; John Law, Michel Callon, 'The Life and Death of an Aircraft: A Network Analysis of Technical Change,' Wiede Bijker, John Law, ed. *Shaping Technology/Building Society: Studies in Sociotechnical Change* (Cambridge, Massachusetts: MIT Press, 1992): 21-52; Ronald Kline, Trevor Pinch, "Users as Agents of Technological Change: The Social Construction of the Automobile in the United States," *Technology and Culture 37* (1996): 763-795.

[85] Trevor Pinch, 'Testing - One, two, Three ... Testing! Towards a Sociology of Testing,' *Science, Technology, and Human Values 18* (1993): 25-41; Donald MacKenzie, "From Kwajalein to Armageddon? Testing and the Social Construction of Missile Accuracy," David Gooding, Trevor Pinch, Simon Schaffer, ed. *The Use of Experiment: Studies in the Natural Sciences* (Cambridge: Cambridge University Press, 1989).

[86] Ibid; Donald MacKenzie, "How do we Know the Properties of Artifacts? Applying the Sociology of Knowledge to Technology," Robert Fox, ed. *Technological Change*, 247-63; Pinch, *Science, Technology, and Human Values 18*, (1993): 25-41; Vincenti, *What Engineers Know and How They Know It,* chapter 5.