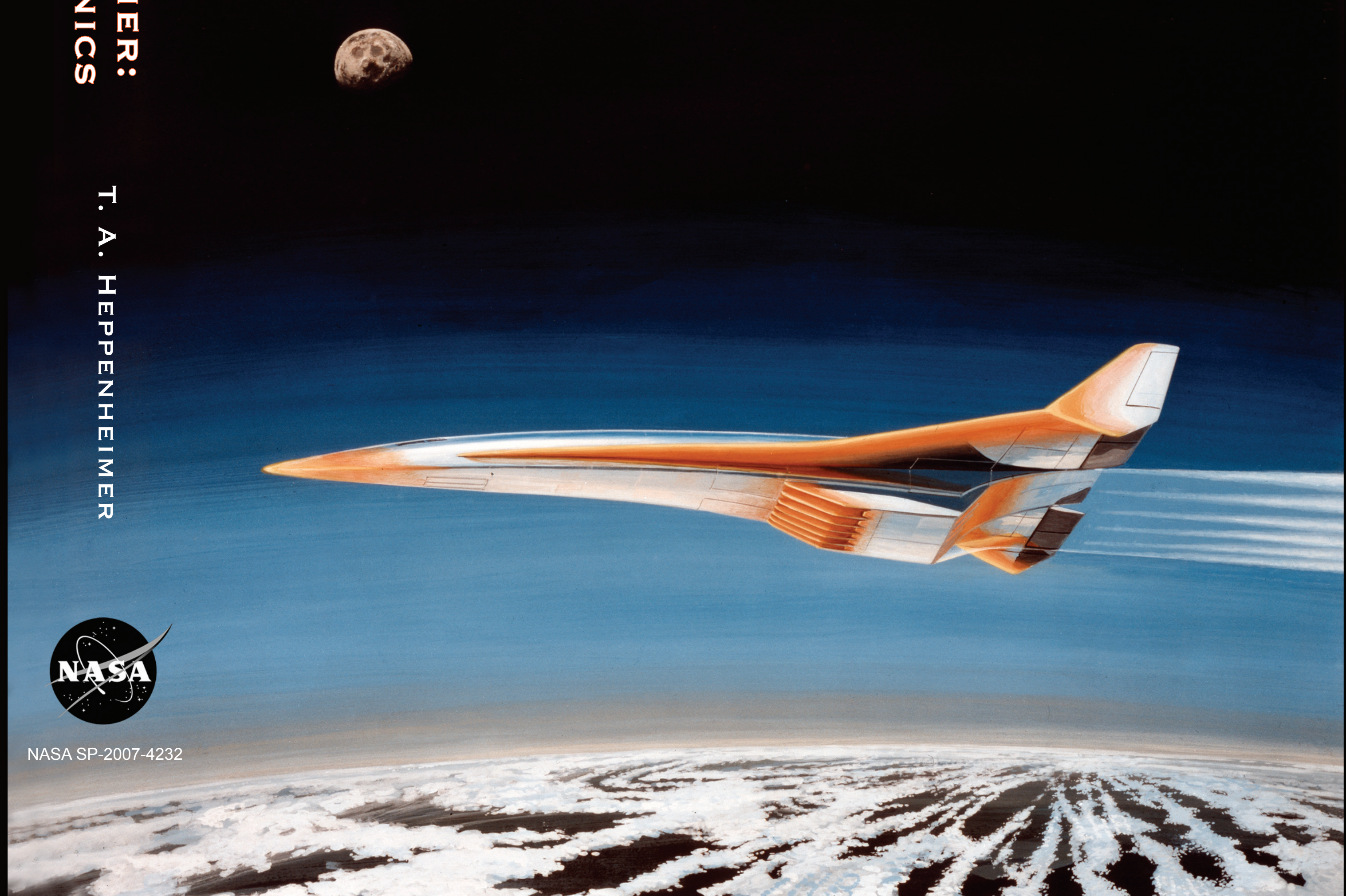
FACING THE HEAT BARRIER:
A HISTORY OF HYPERSONICS

T. A. HEPPENHEIMER



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Hypersonics is the study of flight at speeds where aerodynamic heating dominates the physics of the problem. Typically this is Mach 5 and higher. Hypersonics is an engineering science with close links to supersonics and engine design.

Within this field, many of the most important results have been experimental. The principal facilities have been wind tunnels and related devices, which have produced flows with speeds up to orbital velocity.

Why is it important? Hypersonics has had two major applications. The first has been to provide thermal protection during atmospheric entry. Success in this enterprise has supported ballistic-missile nose cones, has returned strategic reconnaissance photos from orbit and astronauts from the Moon, and has even dropped an instrument package into the atmosphere of Jupiter. The last of these approached Jupiter at four times the speed of a lunar mission returning to Earth.

Work with re-entry has advanced rapidly because of its obvious importance. The second application has involved high-speed propulsion and has sought to develop the scramjet as an advanced airbreathing ramjet. Scramjets are built to run cool and thereby to achieve near-orbital speeds. They were important during the Strategic Defense Initiative, when a set of these engines was to power the experimental X-30 as a major new launch vehicle. This effort fell short, but the X-43A, carrying a scramjet, has recently flown at Mach 9.65 by using a rocket.

Atmospheric entry today is fully mature as an engineering discipline. Still, the Jupiter experience shows that work with its applications continues to reach for new achievements. Studies of scramjets, by contrast, still seek full success, in which such engines can accelerate a vehicle without the use of rockets. Hence, there is much to do in this area as well. For instance, work with computers may soon show just how good scramjets can become.

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INTRODUCTION

As an approach to the concept of hypersonic flight, one may begin by thinking of a sequence of high-performing aircraft that have flown at successively higher speeds. At Mach 2, twice the speed of sound, typical examples included the F-104 fighter and the Concorde commercial airliner. Though dramatically rakish in appearance, they were built of aluminum, the most familiar of materials, and used afterburning turbojets for propulsion.[1]

At Mach 3 and higher, there was the Lockheed SR-71 that cruised at 85,000 feet. The atmosphere at such altitudes, three times higher than Mount Everest, has a pressure only one-fiftieth of that at sea level. Even so, this airplane experienced aerodynamic heating that brought temperatures above 500°F over most of its surface. In turn, this heating brought requirements that dominated the problems of engineering design. Aluminum was out as a structural material; it lost strength at that high temperature. Titanium had to be used instead. Temperature-resistant fuels and lubricants also became necessary. Even so, this aircraft continued to rely on afterburning turbojets for propulsion.[2]

At Mach 4, the heating became still more severe and the difficulties of design were more daunting. No version of the turbojet has served at such speeds; it has been necessary to use a ramjet or rocket. The X-7, a ramjet testbed craft of the 1950s, was built of steel and had better temperature resistance than the SR-71. Still, when it flew past Mach 4.3 in 1958, the heating became so severe that it produced structural failure and a breakup of the vehicle in flight.[3]

Yet Mach 4 still counts as merely supersonic flight, not as hypersonic. For more than half a century analysts have defined hypersonic speeds as Mach 5 and higher.[4] Only rocket-powered craft have flown so fast—and Mach 5 defines only the lower bound of the hypersonic regime. An important range of hypersonic speeds extends from Mach 20 to 25 and includes the velocities of long-range ballistic missiles and of satellites re-entering from orbit. Moreover, flight above Mach 35 was a matter of national concern during the Apollo program, for its piloted Command Module entered the atmosphere at such speeds when returning from the Moon.

Specifically, the hypersonic regime is defined as the realm of speed wherein the physics of flows is dominated by aerodynamic heating. This heating is far more intense than at speeds that are merely supersonic, even though these lesser velocities have defined the performance of the SR-71 and X-7.

Hypersonics nevertheless was a matter of practical military application before the term entered use. Germany's wartime V-2 rocket flew above Mach 5,[5] but steel proved suitable for its construction and aerodynamic heating played only a limited role in its overall design.[6] The Germans used wind-tunnel tests to ensure that this missile would remain stable in flight, but they did not view its speed regime as meriting a name of its own. Hsue-shen Tsien, an aerodynamicist at the California Institute of Technology, coined the term in 1946.[7] Since then, it has involved three significant areas of application.

The first was the re-entry problem, which came to the forefront during the mid-1950s. The Air Force by then was committed to developing the Atlas ICBM, which was to carry a nuclear warhead to Moscow. Left to itself, this warhead would have heated up like a meteor when it fell back into the atmosphere. It would not have burned up—it was too massive—but it certainly would have been rendered useless. Hence, it was necessary to devise a heat shield to protect it against this intense aerodynamic heating.

The successful solution to this problem opened the door to a host of other initiatives. The return of film-carrying capsules from orbit became routine, and turned strategic reconnaissance of the Soviet Union into an important element of national defense. Piloted space flight also became feasible, for astronauts now could hope to come back safely. Then, as the engineering methods for thermal protection were further improved, thoughts of a space shuttle began to flourish. They took shape as a reusable launch vehicle, the first of its kind.

Hypersonic technologies also became important as policy makers looked ahead to an era in which the speed and performance of fighters and bombers might increase without limit. This expectation led to the X-15. Though designed during the 1950s, this rocket-powered research airplane set speed and altitude marks that were not surpassed until the advent of the shuttle. Aerodynamic heating again defined its design requirements, and it was built of the nickel alloy Inconel X. It routinely withstood temperatures of 1200°F as it flew to Mach 6,[8] and reached altitudes high enough for some of its pilots to qualify as astronauts.

Only rocket engines could propel a vehicle at such speeds, but hypersonic propulsion has represented a third important area of application. Here the hope has persisted that innovative airbreathing engines—scramjets—might cope with intense aerodynamic heating while offering fuel economy far surpassing that of a rocket. Other work has emphasized airbreathing rockets, which could give improved performance by eliminating the need to carry liquid oxygen in a tank. These concepts have held their own importance. They lay behind the National Aerospace Plane (NASP) program of 1985-1995, which sought to lay groundwork for single-stage vehicles that were to use both types of engine and were to fly from a runway to orbit.

The Air Force historian Richard Hallion has written of a "hypersonic revolution," as if to place the pertinent technologies on par with the turbojet and liquid-propellant rocket.[9] The present book takes a more measured view. Work in hypersonics had indeed brought full success in the area of re-entry. Consequences have included strategic missiles, the Soviet and American man-in-space programs, the Corona program in strategic reconnaissance, Apollo, and the space shuttle. These activities deterred nuclear war, gained accurate estimates of the Soviet threat, sent astronauts to the Moon and brought them home, and flew to and from space in a reusable launch vehicle. This list covers many of the main activities of the postwar missile and space industry, and supports Hallion's viewpoint.

But in pursuing technical revolution, engineers succeed in actually solving their problems, as when the Apollo program sent men to the Moon. These people do not merely display brilliant ingenuity while falling short of success. Unfortunately, the latter has been the case in the important area of hypersonic propulsion.

The focus has involved the scramjet as a new engine. It has taken form as a prime mover in its own right, capable of standing alongside such engines as the turboprop and ramjet. Still, far more so than the other engines, the scramjet has remained in the realm of experiment. Turboprops powered the Lockheed Electra airliner, P-3 antisubmarine aircraft, and C-130 transport. Ramjets provided propulsion for the successful Bomarc and Talos antiaircraft missiles. But the scramjet has powered only such small experimental airplanes as the X-43A.

Why? From the outset, the scramjet has faced overwhelming competition from a successful alternative: the rocket. This has strongly inhibited funding and has delayed its development to a point at which it could be considered seriously. On paper, scramjets offer superior performance. They therefore drew attention in the mid-1980s, during the heyday of NASP, at a time when Air Force officials had become disenchanted with the space shuttle but faced huge prospective demand for access to space in President Reagan's Strategic Defense Initiative. For once, then, scramjets gained funding that served to push their development—and their performance fell well short of people's hopes.

Within this book, Chapter 1 covers the immediate postwar years, when America still had much to learn from the Europeans. It focuses on two individuals: Eugen Sänger, who gave the first proposal for a hypersonic bomber, and John Becker, who built America's first hypersonic wind tunnel.

Chapter 2 covers the first important area of hypersonic research and development, which supported the advent of strategic missiles during the 1950s. The focus was on solving the re-entry problem, and this chapter follows the story through flight tests of complete nose cones.

Chapter 3 deals with the X-15, which took shape at a time when virtually the whole of America's capability in hypersonics research was contained within Becker's 11-inch instrument. Today it is hard to believe that so bold and so successful a step in aviation research could stand on so slender a foundation. This chapter shows how it happened.

Chapter 4 introduces hypersonic propulsion and emphasizes the work of Antonio Ferri, an Italian aerodynamicist who was the first to give a credible concept for a scramjet engine. This chapter also surveys Aerospaceplane, a little-known program of paper studies that investigated the feasibility of flight to orbit using such engines.

The next two chapters cover important developments in re-entry that followed the ICBM. Chapter 5, "Widening Prospects for Re-Entry," shows how work in this area supported the manned space program while failing to offer a rationale for a winged spacecraft, Dyna-Soar. Chapter 6, "Hypersonics and the Shuttle," begins by outlining developments during the mid-1960s that made it plausible that NASA's reusable space transporter would be designed as a lifting body and built using hot structures. In fact, the shuttle orbiter came forth as a conventional airplane with delta wings, and was built with aluminum structure covered with thermal-protecting tiles. This discussion indicates how those things happened.

Chapter 7, "The Fading, the Comeback," shows how work with scramjets did not share the priority afforded to the topic of re-entry. Instead it faded, and by the late 1960s only NASA-Langley was still pursuing studies in this area. This ongoing effort nevertheless gave important background to the National Aerospace Plane—but it was not technical success that won approval for NASP. As noted, it was the Strategic Defense Initiative. Within the Strategic Defense Initiative, the scramjet amounted to a rabbit being pulled from a hat, to satisfy Air Force needs. NASP was not well-founded at the outset; it was more of a leap of faith.

Chapter 8, "Why NASP Fell Short," explains what happened. In summary, the estimated performance of its scramjet engine fell well below initial hopes, while the drag was higher than expected. Computational aerodynamics failed to give accurate estimates in critical technical areas. The ejector ramjet, a key element of the propulsion system, proved to lack the desired performance. In the area of materials, metallurgists scored an impressive success with a new type of titanium called Beta-21S. It had only half the density of the superalloys that had been slated for Dyna-Soar, but even greater weight savings would have been needed for NASP.

Finally, Chapter 9 discusses "Hypersonics After NASP." Recent developments include the X-33 and X-34 launch vehicles, which represent continuing attempts to build the next launch vehicle. Scramjets have lately taken flight, not only as NASA's X-43A but also in Russia and in Australia. In addition, the new topic of Large Eddy Simulation, in computational fluid mechanics, raises the prospect that analysts indeed may learn, at least on paper, just how good a scramjet may be.

What, in the end, can we conclude? During the past half-century, the field of hypersonics has seen three major initiatives: missile nose cones, the X-15, and NASP. Of these, only one—the X-15—reflected ongoing progress in aeronautics. The other two stemmed from advances in nuclear weaponry: the hydrogen bomb, which gave rise to the ICBM, and the prospect of an x-ray laser, which lay behind the Strategic Defense Initiative and therefore behind NASP.

This suggests that if hypersonics is to flourish anew, it will do so because of developments in the apparently unrelated field of nuclear technology.

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1 F-104: Gunston, *Fighters*, pp. 120-126. Concorde: Heppenheimer, *Turbulent*, pp. 202-203, 208.

2 Crickmore, *SR-71*, pp. 89-91, 95-99, 194.

3 Ritchie, "Evaluation."Steel: Miller, *X-Planes*, p. 119.

4 See, for example, Anderson, *History*, pp. 438-439.

5 Top speed of the V-2 is given as 1,600 meters per second (Dornberger, *V-2*, p. xix) and as 1,700 meters per second (Naval Research Laboratory, *Upper*, cited in Ley, *Rockets*, pp. 596-597); the speed of sound at the pertinent altitudes is 295 meters per second (Kuethe and Chow, *Foundations*, p. 518).

6 Ley, *Rockets*, p. 243; Neufeld, *Rocket*, pp. 85-94.

7 Tsien, "Similarity."

8 1200°F: NASA SP-2000-4518, diagram, p. 25.

9 Hallion, *Hypersonic*.

ABBREVIATIONS AND ACRONYMS

AAF	Army Air Forces
AAS	American Astronautical Society
ACES	Air Collection and Enrichment System
AEC	Atomic Energy Commission
AEDC	Arnold Engineering Development Center
AEV	Aerothermodynamic Elastic Vehicle (ASSET)
AFB	Air Force Base
AFSC	Air Force Systems Command
AGARD	Advisory Group for Aeronautical Research and Development
AIAA	American Institute for Aeronautics and Astronautics
AIM	Aerothermodynamic Integration Model (HRE)
APL	Applied Physics Laboratory (Johns Hopkins University)
APU	auxiliary power unit
ARDC	Air Research and Development Command (USAF)
ARS	American Rocket Society
ASD	Aeronautical Systems Division (USAF)
ASSET	Aerothermodynamic/elastic Structural Systems Environmental Tests
ASV	Aerothermodynamic Structural Vehicle (ASSET)
BMW	Bayerische Motoren-Werke
BTU	British Thermal Unit
CASI	Center for Aerospace Information
C_D	coefficient of drag
CDE	Concept Demonstrator Engine (NASP)
CFD	computational fluid dynamics
CFHT	Continuous Flow Hypersonic Tunnel (NACA-Langley)
CIA	Central Intelligence Agency
CIAM	Central Institute of Aviation Motors (Moscow)
C_L	coefficient of lift
CO_2	carbon dioxide
DARPA	Defense Advanced Research Projects Agency
DM	Deutschmark
DNS	Direct Numerical Simulation (CFD)
DOD	Department of Defense
DSB	Defense Science Board
DTIC	Defense Technical Information Center
DVL	Deutsche Versuchsanstalt für Luftfahrtforschung
ELV	expendable launch vehicle
°F	degrees Fahrenheit
FAI	Federation Aeronautique Internationale
FDL	Flight Dynamics Laboratory (USAF)
FY	Fiscal Year
g	force of gravity

GAO	General Accounting Office (United States Congress)
GASL	General Applied Science Laboratories, Inc.
GE	General Electric
HGS	homogeneous gas sample (shock tubes)
HRE	Hypersonic Research Engine
HXEM	Hyper-X Engine Module
HXFE	Hyper-X Flight Engine
HYWARDS	Hypersonic Weapons Research and Development Supporting System
IBM	International Business Machines
ICBM	intercontinental ballistic missile
IFTV	Incremental Flight Test Vehicle
ILRV	Integrated Launch and Re-entry Vehicle
ISABE	International Society for Air Breathing Propulsion
I_{sp}	specific impulse
ISTAR	Integrated System Test of an Airbreathing Rocket
K	degrees Kelvin
LACE	Liquid Air Cycle Engine
L/D	lift-to-drag ratio
LES	Large-Eddy Simulation (CFD)
LH_2	liquid hydrogen
LSCIR	Low Speed Component Integration Rig (Pratt & Whitney)
LSS	Low Speed System (NASP)
MBB	Messerschmitt-Boelkow-Blohm
MIT	Massachusetts Institute of Technology
MOL	Manned Orbiting Laboratory
MOU	Memorandum of Understanding
MSC	Manned Spacecraft Center (now Johnson Space Center)
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
NASP	National Aerospace Plane
NIFTA	Non-Integral Fuselage Tank Article (NASP)
NMASAP	NASP Materials and Structures Augmentation Program
OAL	Ordnance Astrophysics Laboratory
OMSF	Office of Manned Space Flight (NASA)
P & W	Pratt & Whitney
POBATO	propellants on board at takeoff
PRIME	Precision Recovery Including Maneuvering Entry
PROFAC	propulsive fluid accumulator
PSi	pounds per square inch
RCC	Reusable Carbon-Carbon
RENE	Rocket Engine Nozzle Ejector
ROLS	Recoverable Orbital Launch System
RSI	reusable surface insulation
SAB	Scientific Advisory Board (USAF)
SAGE	Semi-Automatic Ground Environment
SAM	Structures Assembly Model (HRE)
SAMPE	Society for Advancement of Materials and Process Engineering
SCRAM	Supersonic Combustion Ramjet Missile (APL)
SDI	Strategic Defense Initiative
SSME	Space Shuttle Main Engine
SSTO	single stage to orbit
SXPE	Subscale Parametric Engine (NASP)
TAV	Trans-Atmospheric Vehicle
TPS	thermal protection system
TZM	titanium-zirconium-molybdenum alloy
USAF	United States Air Force
VKF	Von Karman Facility (AEDC)
WADC	Wright Air Development Center (USAF)

1

FIRST STEPS IN HYPERSONIC RESEARCH

Today's world of high-speed flight is international, with important contributions having recently been made in Japan, Australia, and Russia as well as in the United States. This was even truer during World War II, when Adolf Hitler sponsored development programs that included early jet fighters and the V-2 missile. America had its own research center at NACA's Langley Memorial Aeronautical Laboratory, but in important respects America was little more than an apt pupil of the wartime Germans. After the Nazis surrendered, the U.S. Army brought Wernher von Braun and his rocket team to this country, and other leading researchers found themselves welcome as well.

Liftoff of a V-2 rocket. (U.S. Army)

Some of their best work had supported the V-2, using a pair of tunnels that operated at Mach 4.4. This was just short of hypersonic, but these facilities made a key contribution by introducing equipment and research methods that soon found use in studying true hypersonic flows. At Peenemunde, one set of experiments introduced a wind-tunnel nozzle of specialized design and reached Mach 8.8, becoming the first to achieve such a speed. Other German work included the design of a 76,000-horsepower installation that might have reached Mach 10.

The technical literature also contained an introductory discussion of a possible application. It appeared within a wartime report by Austria's Eugen Sänger, who had proposed to build a hypersonic bomber that would extend its range by repeatedly skipping off the top of the atmosphere like a stone skipping over water. This concept did not enter the mainstream of postwar weapons development, which gave pride of place to the long-range ballistic missile. Still, Sänger's report introduced skipping entry as a new mode of high-speed flight, and gave a novel suggestion as to how wings could increase the range of a rocket-powered vehicle.

Within Langley, ongoing research treated flows that were merely supersonic. However, the scientist John Becker wanted to go further and conduct studies of hypersonic flows. He already had spent several years at Langley, thereby learning his trade as an aerodynamicist. At the same time he still was relatively young, which meant that much of his career lay ahead of him. In 1947 he achieved a major advance in hypersonics by building its first important research instrument, an 11-inch wind tunnel that operated at Mach 6.9.

German Work with High-Speed Flows

At the Technische Hochschule in Hannover, early in the twentieth century, the physicist Ludwig Prandtl founded the science of aerodynamics. Extending earlier work by Italy's Tullio Levi-Civita, he introduced the concept of the boundary layer. He described it as a thin layer of air, adjacent to a wing or other surface, that clings to this surface and does not follow the free-stream flow. Drag, aerodynamic friction, and heat transfer all arise within this layer. Because the boundary layer is thin, the equations of fluid flow simplified considerably, and important aerodynamic complexities became mathematically tractable.[1]

As early as 1907, at a time when the Wright Brothers had not yet flown in public, Prandtl launched the study of supersonic flows by publishing investigations of a steam jet at Mach 1.5. He now was at Göttingen University, where he built a small supersonic wind tunnel. In 1911 the German government founded the Kaiser-Wilhelm-Gesellschaft, an umbrella organization that went on to sponsor a broad range of institutes in many areas of science and engineering. Prandtl proposed to set up a center at Göttingen for research in aerodynamics and hydrodynamics, but World War I intervened, and it was not until 1925 that this laboratory took shape.

After that, though, work in supersonics went forward with new emphasis. Jakob Ackeret, a colleague of Prandtl, took the lead in building supersonic wind tunnels. He was Swiss, and he built one at the famous Eidgenossische Technische Hochschule in Zurich. This attracted attention in nearby Italy, where the dictator Benito Mussolini was giving strong support to aviation. Ackeret became a consultant to the Italian Air Force and built a second wind tunnel in Guidonia, near Rome. It reached speeds approaching 2,500 miles per hour (mph), which far exceeded those that were available anywhere else in the world.[2]

These facilities were of the continuous-flow type. Like their subsonic counterparts, they ran at substantial power levels and could operate all day. At the Technische Hochschule in Aachen, the aerodynamicist Carl Wiesenberger took a different approach in 1934 by building an intermittent-flow facility that needed much less power. This "blowdown" installation relied on an evacuated sphere, which sucked outside air through a nozzle at speeds that reached Mach 3.3.

This wind tunnel was small, having a test-section diameter of only four inches. But it set the pace for the mainstream of Germany's wartime supersonic research. Wieselberger's assistant, Rudolf Hermann, went to Peenemunde, the center of that country's rocket development, where in 1937 he became head of its new Aerodynamics Institute. There he built a pair of large supersonic tunnels, with 16-inch test sections, that followed Aachen's blowdown principle. They reached Mach 4.4, but not immediately. A wind tunnel's performance depends on its nozzle, and it took time to develop proper designs. Early in 1941 the highest working speed was Mach 2.5; a nozzle for Mach 3.1 was still in development. The Mach 4.4 nozzles were not ready until 1942 or 1943.[3]

The Germans never developed a true capability in hypersonics, but they came close. The Mach 4.4 tunnels introduced equipment and methods of investigation that carried over to this higher-speed regime. The Peenemunde vacuum sphere was constructed of riveted steel and had a diameter of 40 feet. Its capacity of a thousand cubic meters gave run times of 20 seconds.[4] Humidity was a problem; at Aachen, Hermann had learned that moisture in the air could condense when the air cooled as it expanded through a supersonic nozzle, producing unwanted shock waves that altered the anticipated Mach number while introducing nonuniformities in the direction and velocity of flow. At Peenemunde he installed an air dryer that used silica gel to absorb the moisture in the air that was about to enter his supersonic tunnels.[5]

Configuration development was at the top of his agenda. To the modern mind the V-2 resembles a classic spaceship, complete with fins. It is more appropriate to say that spaceship designs resemble the V-2, for that missile was very much in the forefront during the postwar years, when science fiction was in its heyday.[6] The V-2 needed fins to compensate for the limited effectiveness of its guidance, and their design was trickier than it looked. They could not be too wide, or the V-2 would be unable to pass through railroad tunnels. Nor could they extend too far below the body of the missile, or the rocket exhaust, expanding at high altitude, would burn them off.

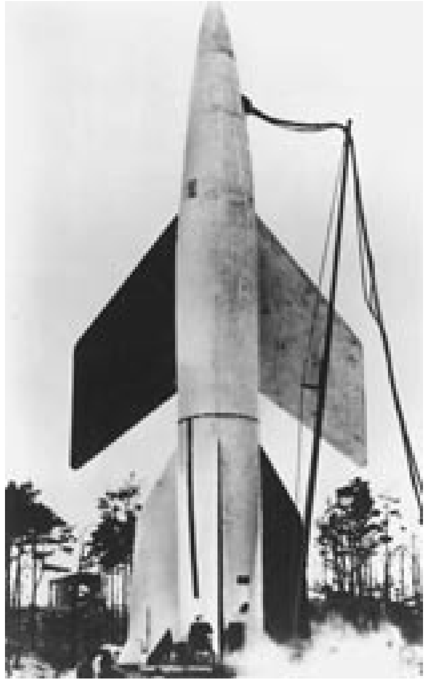
The historian Michael Neufeld notes that during the 1930s, "no one knew how to design fins for supersonic flight." The A-3, a test missile that preceded the V-2, had proven to be *too* stable; it tended merely to rise vertically, and its guidance system lacked the authority to make it tilt. Its fins had been studied in the Aachen supersonic tunnel, but this problem showed up only in flight test, and for a time it was unclear how to go further. Hermann Kurzweg, Rudolf Hermann's assistant, investigated low-speed stability building a model and throwing it off the roof of his home. When that proved unsatisfactory, he mounted it on a wire, attached it to his car, and drove down an autobahn at 60 mph.

The V-2 was to fly at Mach 5, but for a time there was concern that it might not top Mach 1. The sound barrier loomed as potentially a real barrier, difficult to pierce, and at that time people did not know how to build a transonic wind tunnel that would give reliable results. Investigators studied this problem by building heavy iron models of this missile and dropping them from a Heinkel He-111 bomber. Observers watched from the ground; in one experiment, Von Braun himself piloted a plane and dove after the model to observe it from the air. The design indeed proved to be marginally unstable in the transonic region, but the V-2 had the thrust to power past Mach 1 with ease.

A second test missile, the A-5, also contributed to work on fin design. It supported development of the guidance system, but it too needed fins, and it served as a testbed for further flight studies. Additional flight tests used models with length of five feet that were powered with rocket engines that flew with hydrogen peroxide as the propellant.

These tests showed that an initial fin design given by Kurzweg had the best subsonic stability characteristics. Subsequently, extensive wind-tunnel work both at Peenemunde and at a Zeppelin facility in Stuttgart covered the V-2's complete Mach range and refined the design. In this fashion, the V-2's fins were designed with only minimal support from Peenemunde's big supersonic wind tunnels.[7] But these tunnels came into their own later in the war, when investigators began to consider how to stretch this missile's range by adding wings and thereby turning it into a supersonic glider.

Once the Germans came up with a good configuration for the V-2, they stuck with it. They proposed to use it anew in a two-stage missile that again sported fins that look excessively large to the modern eye, and that was to cross the Atlantic to strike New York.[8] But there was no avoiding the need for a new round of wind-tunnel tests in studying the second stage of this intercontinental missile, the A-9, which was to fly with swept wings. As early as 1935 Adolf Busemann, another colleague of Prandtl, had proposed the use of such wings in supersonic flight.[9] Walter Dornberger, director of V-2 development, describes witnessing a wind-tunnel test of a model's stability.


A-4b missile ready for launch. (U.S. Army)

The model had "two knifelike, very thin, swept-back wings." Mounted at its center of gravity, it "rotated at the slightest touch." When the test began, a technician opened a valve to start the airflow. In Dornberger's words,

> "The model moved abruptly, turning its nose into the oncoming airstream. After a few quickly damping oscillations of slight amplitude, it lay quiet and stable in the air that hissed past it at 4.4 times the speed of sound. At the nose, and at the edges of the wing supports and guide mechanism, the shock waves could be clearly seen as they traveled diagonally backward at a sharp angle.
>
> As the speed of the airflow fell off and the test ended, the model was no longer lying in a stable position. It made a few turns around its center of gravity, and then it came to a standstill with the nose pointing downward. The experiment Dr. Hermann had wished to show me had succeeded perfectly. This projectile, shaped like an airplane, had remained absolutely stable at a supersonic speed range of almost 3,500 mph."[10]

Work on the A-9 languished for much of the war, for the V-2 offered problems aplenty and had far higher priority. But in 1944, as the Allies pushed the Germans out of France and the Russians closed in from the east, Dornberger and Von Braun faced insistent demands that they pull a rabbit from a hat and increase the V-2's range. The rabbit was the A-9, with its wings promising a range of 465 miles, some three times that of the standard V-2.[11]

Peenemunde's Ludwig Roth proceeded to build two prototypes. The V-2 was known to its builders as the A-4, and Roth's A-9 now became the A-4b, a designation that allowed it to share in the high priority of that mainstream program. The A-4b took shape as a V-2 with swept wings and with a standard set of fins that included slightly enlarged air vanes for better control. Certainly the A-4b needed all the help it could get, for the addition of wings had made it highly sensitive to winds.

The first A-4b launch took place late in December 1944. It went out of control and crashed as the guidance system failed to cope with its demands. Roth's rocketeers tried again a month later, and General Dornberger describes how this flight went much better:

"The rocket, climbing vertically, reached a peak altitude of nearly 50 miles at a maximum speed of 2,700 mph. [It] broke the sound barrier without trouble. It flew with stability and steered automatically at both subsonic and supersonic speeds. On the descending part of the trajectory, soon after the rocket leveled out at the upper limit of the atmosphere and began to glide, a wing broke. This structural failure resulted from excessive aerodynamic loads."[12]

This shot indeed achieved its research goals, for it was to demonstrate successful launch and acceleration through the sound barrier, overcoming drag from the wings, and it did these things. Gliding flight was not on the agenda, for while wind-tunnel tests could demonstrate stability in a supersonic glide, they could not guard against atmosphere entry in an improper attitude, with the A-4b tumbling out of control.[13]

Yet while the Germans still had lessons to learn about loads on a supersonic aircraft in flight, they certainly had shown that they knew their high-speed aerodynamics. One places their achievement in perspective by recalling that all through the 1950s a far wealthier and more technically capable United States pursued a vigorous program in rocket-powered aviation without coming close to the A-4b's performance. The best American flight, of an X-2 in 1956, approached 2,100 mph—and essentially duplicated the German failure as it went out of control, killing the pilot and crashing. No American rocket plane topped the 2,700 mph of the A-4b until the X-15 in 1961.[14]

Hence, without operating in the hypersonic regime, the Peenemunde wind tunnels laid important groundwork as they complemented such alternative research techniques as dropping models from a bomber and flying scale models under rocket power. Moreover, the Peenemunde aerodynamicist Siegfried Erdmann used his center's facilities to conduct the world's first experiments with a hypersonic flow.

In standard operation, at speeds up to Mach 4.4, the Peenemunde tunnels had been fed with air from the outside world, at atmospheric pressure. Erdmann knew that a hypersonic flow needed more, so he arranged to feed his tunnel with compressed air. He also fabricated a specialized nozzle and aimed at Mach 8.8, twice the standard value. His colleague Peter Wegener describes what happened:

"Everything was set for the first-ever hypersonic flow experiment. The highest possible pressure ratio across the test section was achieved by evacuating the sphere to the limit the remaining pump could achieve. The supply of the nozzle—in contrast to that at lower Mach numbers—was now provided by air at a pressure of about 90 atmospheres…. The experiment was initiated by opening the fast-acting valve. The flow of brief duration looked perfect as viewed via the optical system. Beautiful photographs of the flow about wedge-shaped models, cylinders, spheres, and other simple shapes were taken, photographs that looked just as one would expect from gas dynamics theory."[15]

These tests addressed the most fundamental of issues: How, concretely, does one operate a hypersonic wind tunnel? Supersonic tunnels had been bedeviled by condensation of water vapor, which had necessitated the use of silica gel to dry the air. A hypersonic facility demanded far greater expansion of the flow, with consequent temperatures that were lower still. Indeed, such flow speeds brought the prospect of condensation of the air itself.

Conventional handbooks give the liquefaction temperatures of nitrogen and oxygen, the main constituents of air, respectively as 77 K and 90 K. These refer to conditions at atmospheric pressure; at the greatly rarefied pressures of flow in a hypersonic wind tunnel, the pertinent temperatures are far lower.[16] In addition, Erdmann hoped that his air would "supersaturate," maintaining its gaseous state because of the rapidity of the expansion and hence of the cooling.

This did not happen. In Wegener's words, "Looking at the flow through the glass walls, one could see a dense fog. We know now that under the conditions of this particular experiment, the air had indeed partly condensed. The fog was made up of air droplets or solid air particles forming a cloud, much like the water clouds we see in the sky."[17] To prevent such condensation, it proved necessary not only to feed a hypersonic wind tunnel with compressed air, but to heat this air strongly.

One thus is entitled to wonder whether the Germans would have obtained useful results from their most ambitious wind-tunnel project, a continuous-flow system that was designed to achieve Mach 7, with a possible extension to Mach 10. Its power ratings pointed to the advantage of blowdown facilities, such as those of Peenemunde. The Mach 4.4 Peenemunde installations used a common vacuum sphere, evacuation of which relied on pumps with a total power of 1,100 horsepower. Similar power levels were required to dry the silica gel by heating it, after it became moist. But the big hypersonic facility was to have a one-meter test section and demanded 76,000 horsepower, or 57 megawatts.[18]

Such power requirements went beyond what could be provided in straightforward fashion, and plans for this wind tunnel called for it to use Germany's largest hydroelectric plant. Near Kochel in Bavaria, two lakes—the Kochelsee and Walchensee—are separated in elevation by 660 feet. They stand close together, providing an ideal site for generating hydropower, and a hydro plant at that location had gone into operation in 1925, generating 120 megawatts. Since the new wind tunnel would use half of this power entirely by itself, the power plant was to be enlarged, with additional water being provided to the upper lake by a tunnel through the mountains to connect to another lake.[19]

In formulating these plans, as with the A-4b, Germany's reach exceeded its grasp. Moreover, while the big hypersonic facility was to have generous provision for drying its air, there was nothing to prevent the air from condensing, which would have thrown the data wildly off.[20] Still, even though they might have had to learn their lessons in the hard school of experience, Germany was well on its way toward developing a true capability in hypersonics by the end of World War II. And among the more intriguing concepts that might have drawn on this capability was one by the Austrian rocket specialist Eugen Sänger.

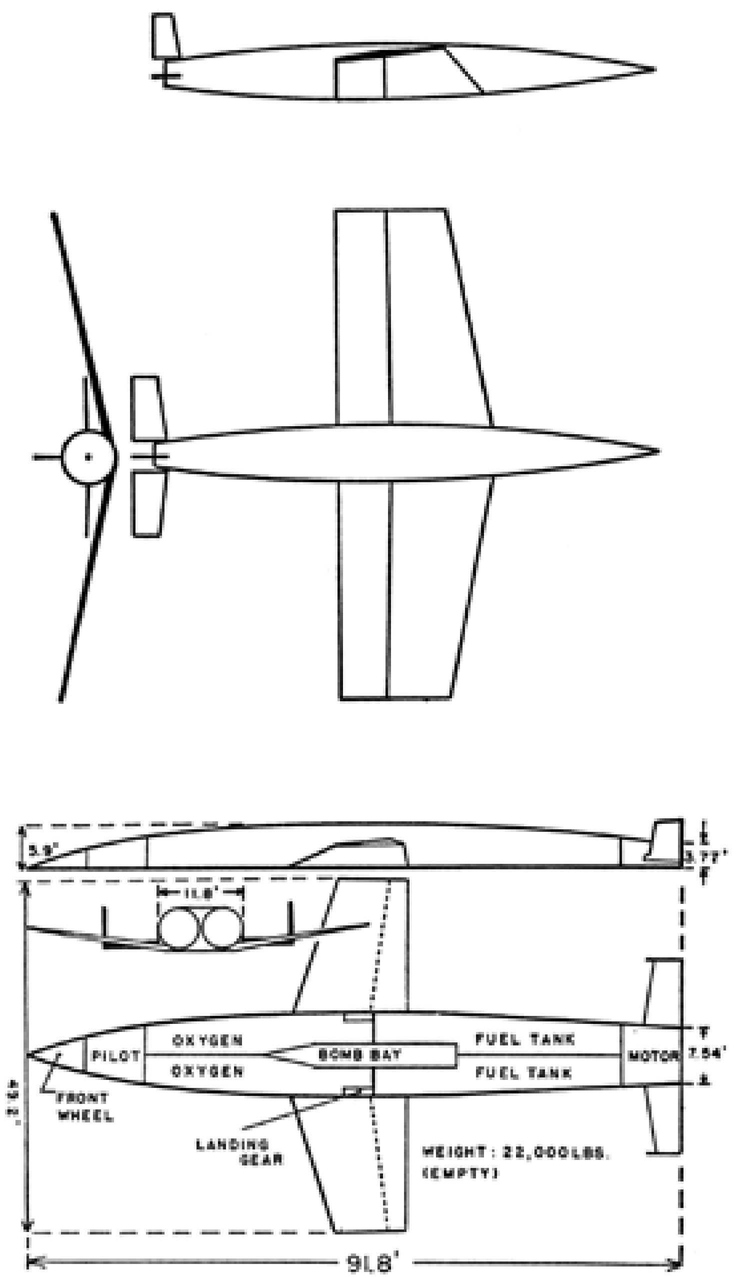
EUGEN SÄNGER

Born in 1905, he was of the generation that came of age as ideas of space flight were beginning to germinate. Sänger's own thoughts began to take shape while he was still in grammar school. His physics teacher gave him, as a Christmas present, a copy of a science-fiction novel, *Auf Zwei Planeten* ("On Two Planets"). "I was about 16 years old," Sänger later recalled. "Naturally I read this novel avidly, and thereafter dreamed of doing something like this in my own lifetime." He soon broadened his readings with the classic work of Hermann Oberth. "I had to pass my examination in mechanics," he continued, "and had, therefore, made a particular study of this and related subjects. Then I also started to check and recalculate in detail everything in Oberth's book, and I became convinced that here was something that one could take seriously."

He then attended the Technische Hochschule in Vienna, where he tried to win a doctoral degree in 1928 by submitting a dissertation on the subject of rocket-powered aircraft. He did not get very far, later recalling that his professor told him, "If you try, today, to take your doctor degree in spaceflight, you will most probably be an old man with a long beard before you have succeeded in obtaining it." He turned his attention to a more conventional topic, the structural design of wings for aircraft, and won his degree a year later. But his initial attempt at a dissertation had introduced him to the line of study that he pursued during the next decade and then during the war.

In 1933 he turned this dissertation into a book, *Raketenflugtechnik*. It was the first text in this new field. He wrote of a rocket plane burning liquid oxygen and petrol, which was to reach Mach 10 along with altitudes of 60 to 70 miles. This concept was significant at the time, for the turbojet engine had not yet been invented, and futurists, such as Aldous Huxley who wrote *Brave New World*, envisioned rockets as the key to high-speed flight in centuries to come.[21]

Sänger's altitudes became those of the X-15, a generation later. The speed of his concept was markedly higher. He included a three-view drawing. Its wings were substantially larger than those of eventual high-performance aircraft, although these wings gave his plane plenty of lift at low speed, during takeoff and landing. Its tail surfaces also were far smaller than those of the X-15, for he did not know about the



Rocket aircraft of Eugen Sänger. Top, the Silbervogel. Bottom, the Amerika-Bomber that was to use a skipping entry. Note that both were low-wing monoplanes. (Courtesy of Willy Ley)

stability problems that loomed in supersonic flight. Still, he clearly had a concept that he could modify through further study.

In 1934, writing in the magazine *Flug* ("Flight"), he used an exhaust velocity of 3,700 meters per second and gave a velocity at a cutoff of Mach 13. His *Silbervogel*, Silver Bird, now was a boost-glide vehicle, entering a steady glide at Mach 3.5 and covering 5,000 kilometers downrange while descending from 60 to 40 kilometers in altitude.

He stayed on at the Hochschule and conducted rocket research. Then in 1935, amid the Depression, he lost his job. He was in debt to the tune of DM 2,000, which he had incurred for the purpose of publishing his book, but he remained defiant as he wrote, "Nevertheless, my silver birds will fly!" Fortunately for him, at that time Hitler's Luftwaffe was taking shape, and was beginning to support a research establishment. Sänger joined the DVL, the German Experimental Institute for Aeronautics, where he worked as technical director of rocket research. He did not go to Peenemunde and did not deal with the V-2, which was in the hands of the Wehrmacht, not the Luftwaffe. But once again he was employed, and he soon was out of debt.

He also began collaborating with the mathematician Irene Bredt, whom he later married. His *Silbervogel* remained on his mind as he conducted performance studies with help from Bredt, hoping that this rocket plane might evolve into an *Amerika-Bomber*. He was aware that when transitioning from an initial ballistic trajectory into a glide, the craft was to re-enter the atmosphere at a shallow angle. He then wondered what would happen if the angle was too steep.

He and Bredt found that rather than enter a glide, the vehicle might develop so much lift that it would fly back to space on a new ballistic arc, as if bouncing off the atmosphere. Stones skipping over water typically make several such skips, and Sänger found that his winged craft would do this as well. With a peak speed of 3.73 miles per second, compared with 4.9 miles per second as the Earth's orbital velocity, it could fly halfway around the world and land in Japan, Germany's wartime ally. At 4.4 miles per second, the craft could fly completely around the world and land in Germany.[22]

Sänger wrote up their findings in a document of several hundred pages, with the title (in English) of "On a Rocket Propulsion for Long Distance Bombers." In December 1941 he submitted it for publication—and won a flat rejection the following March. This launched him into a long struggle with the Nazi bureaucracy, as he sought to get his thoughts into print.

His rocket craft continued to show a clear resemblance to his *Silbervogel* of the previous decade, for he kept the basic twin-tailed layout even as he widened the fuselage and reduced the size of the wings. Its bottom was flat to produce more lift, and his colleagues called it the *Platteisen*, the Flatiron. But its design proved to be

patentable, and in June 1942 he received a piece of bright news as the government awarded him a Reichspatent concerning "Gliding Bodies for Flight Velocities Above Mach 5." As he continued to seek publication, he won support from an influential professor, Walter Georgii. He cut the length of his manuscript in half. Finally, in September 1944 he learned that his document would be published as a Secret Command Report.

The print run came to fewer than a hundred copies, but they went to the people who counted. These included the atomic-energy specialist Werner Heisenberg, the planebuilder Willy Messerschmitt, the chief designer Kurt Tank at Focke-Wulf, Ernst Heinkel of Heinkel Aircraft, Ludwig Prandtl who still was active, as well as Wernher von Braun and his boss, General Dornberger. Some copies reached the Allies after the Nazi surrender, with three of them being taken to Moscow. There their content drew attention from the dictator Josef Stalin, who ordered a full translation. He subsequently decided that Sänger and Bredt were to be kidnapped and brought to Moscow.

At that time they were in Paris, working as consultants for the French air force. Stalin sent two agents after them, accompanied by his own son. They nevertheless remained safe; the Soviets never found them. French intelligence agents learned about the plot and protected them, and in any case, the Soviets may not have been looking very hard. One of them, Grigory Tokaty-Tokayev, was the chief rocket scientist in the Soviet air force. He defected to England, where he wrote his memoirs for the *Daily Express* and then added a book, *Stalin Means War*.

Sänger, for his part, remained actively involved with his rocket airplane. He succeeded in publishing some of the material from his initial report that he had had to delete. He also won professional recognition, being chosen in 1951 as the first president of the new International Astronautical Federation. He died in 1964, not yet 60. But by then the X-15 was flying, while showing more than a casual resemblance to his *Silbervogel* of 30 years earlier. His Silver Bird indeed had flown, even though the X-15 grew out of ongoing American work with rocket-powered aircraft and did not reflect his influence. Still, in January of that year—mere weeks before he died—the trade journal *Astronautics & Aeronautics* published a set of articles that presented new concepts for flight to orbit. These showed that the winged-rocket approach was alive and well.[23]

What did he contribute? He was not the first to write of rocket airplanes; that palm probably belongs to his fellow Austrian Max Valier, who in 1927 discussed how a trimotor monoplane of the day, the Junkers G-23, might evolve into a rocket ship. This was to happen by successively replacing the piston motors with rocket engines and reducing the wing area.[24] In addition, World War II saw several military rocket-plane programs, all of which were piloted. These included Germany's Me-163 and Natter antiaircraft weapons as well as Japan's Ohka suicide weapon, the

Cherry Blossom, which Americans called Baka, "Fool." The rocket-powered Bell X-1, with which Chuck Yeager first broke the sound barrier, also was under development well before war's end.[25]

Nor did Sänger's 1944 concept hold military value. It was to be boosted by a supersonic rocket sled, which would have been both difficult to build and vulnerable to attack. Even then, and with help from its skipping entry, it would have been a single-stage craft attaining near-orbital velocity. No one then, 60 years ago, knew how to build such a thing. Its rocket engine lay well beyond the state of the art. Sänger projected a mass-ratio, or ratio of fueled to empty weight, of 10—with the empty weight including that of the wings, crew compartment, landing gear, and bomb load. Structural specialists did not like that. They also did not like the severe loads that skipping entry would impose. And after all this *Sturm und drang*, the bomb load of 660 pounds would have been militarily useless.[26]

But Sänger gave a specific design concept for his rocket craft, presenting it in sufficient detail that other engineers could critique it. Most importantly, his skipping entry represented a new method by which wings might increase the effectiveness of a rocket engine. This contribution did not go away. The train of thought that led to the Air Force's Dyna-Soar program, around 1960, clearly reflected Sänger's influence. In addition, during the 1980s the German firm of Messerschmitt-Boelkow-Blohm conducted studies of a reusable wing craft that was to fly to orbit as a prospective replacement for America's space shuttle. The name of this two-stage vehicle was Sänger.[27]

NACA-Langley and John Becker

During the war the Germans failed to match the Allies in production of airplanes, but they were well ahead in technical design. This was particularly true in the important area of jet propulsion. They fielded an operational jet fighter, the Me-262, and while the Yankees were well along in developing the Lockheed P-80 as a riposte, the war ended before any of those jets could see combat. Nor was the Me-262 a last-minute work of desperation. It was a true air weapon that showed better speed and acceleration than the improved P-80A in flight test, while demonstrating an equal rate of climb.[28] Albert Speer, Hitler's minister of armaments, asserted in his autobiographical *Inside the Third Reich* (1970) that by emphasizing production of such fighters and by deploying the Wasserfall antiaircraft missile that was in development, the Nazis "would have beaten back the Western Allies' air offensive against our industry from the spring of 1944 on."[29] The Germans thus might have prolonged the war until the advent of nuclear weapons.

Wartime America never built anything resembling the big Mach 4.4 wind tunnels at Peenemunde, but its researchers at least constructed facilities that could compare with the one at Aachen. The American installations did not achieve speeds to match Aachen's Mach 3.3, but they had larger test sections. Arthur Kantrowitz, a young physicist from Columbia University who was working at Langley, built a nine-inch tunnel that reached Mach 2.5 when it entered operation in 1942. (Aachen's had been four inches.) Across the country, at NACA's Ames Aeronautical Laboratory, two other wind tunnels entered service during 1945. Their test sections measured one by three feet, and their flow speeds reached Mach 2.2.[30]

The Navy also was active. It provided $4.5 million for the nation's first really large supersonic tunnel, with a test section six feet square. Built at NACA-Ames, operating at Mach 1.3 to 1.8, this installation used 60,000 horsepower and entered service soon after the war.[31] The Navy also set up its Ordnance Aerophysics Laboratory in Daingerfield, Texas, adjacent to the Lone Star Steel Company, which had air compressors that this firm made available. The supersonic tunnel that resulted covered a range of Mach 1.25 to 2.75, with a test section of 19 by 27.5 inches. It became operational in June 1946, alongside a similar installation that served for high-speed engine tests.[32]

Theorists complemented the wind-tunnel builders. In April 1947 Theodore von Karman, a professor at Caltech who was widely viewed as the dean of American aerodynamicists, gave a review and survey of supersonic flow theory in an address to the Institute of Aeronautical Sciences. His lecture, published three months later in the *Journal of the Aeronautical Sciences*, emphasized that supersonic flow theory now was mature and ready for general use. Von Karman pointed to a plethora of available methods and solutions that not only gave means to attack a number of important design problems but also gave independent approaches that could permit cross-checks on proposed solutions.

John Stack, a leading Langley aerodynamicist, noted that Prandtl had given a similarly broad overview of subsonic aerodynamics a quarter-century earlier. Stack declared, "Just as Prandtl's famous paper outlined the direction for the engineer in the development of subsonic aircraft, Dr. von Karman's lecture outlines the direction for the engineer in the development of supersonic aircraft."[33]

Yet the United States had no facility, and certainly no large one, that could reach Mach 4.4. As a stopgap, the nation got what it wanted by seizing German wind tunnels. A Mach 4.4 tunnel was shipped to the Naval Ordnance Laboratory in White Oak, Maryland. Its investigators had fabricated a Mach 5.18 nozzle and had conducted initial tests in January 1945. In 1948, in Maryland, this capability became routine.[34] Still, if the U.S. was to advance beyond the Germans and develop the true hypersonic capability that Germany had failed to achieve, the nation would have to rely on independent research.

The man who pursued this research, and who built America's first hypersonic tunnel, was Langley's John Becker. He had been at that center since 1936; during the latter part of the war he was assistant chief of Stack's Compressibility Research Division. He specifically was in charge of Langley's 16-Foot High-Speed Tunnel, which had fought its war by investigating cooling problems in aircraft motors as well as the design of propellers. This facility contributed particularly to tests of the B-50 bomber and to the aerodynamic shapes of the first atomic bombs. It also assisted development of the Pratt & Whitney R-2800 Double Wasp, a widely used piston engine that powered several important wartime fighter planes, along with the DC-6 airliner and the C-69 transport, the military version of Lockheed's Constellation.[35]

It was quite a jump from piston-powered warbirds to hypersonics, but Becker willingly made the leap. The V-2, flying at Mach 5, gave him his justification. In a memo to Langley's chief of research, dated 3 August 1945, Becker noted that planned facilities were to reach no higher than Mach 3. He declared that this was inadequate: "When it is considered that all of these tunnels will be used, to a large extent, to develop supersonic missiles and projectiles of types which have already been operated at Mach numbers as high as 5.0, it appears that there is a definite need for equipment capable of higher test Mach numbers."

Within this memo, he outlined a design concept for "a supersonic tunnel having a test section four-foot square and a maximum test Mach number of 7.0." It was to achieve continuous flow, being operated by a commercially-available compressor of 2,400 horsepower. To start the flow, the facility was to hold air within a tank that was compressed to seven atmospheres. This air was to pass through the wind tunnel before exhausting into a vacuum tank. With pressure upstream pushing the flow and with the evacuated tank pulling it, airspeeds within the test section would be high indeed. Once the flow was started, the compressor would maintain it.

A preliminary estimate indicated that this facility would cost $350,000. This was no mean sum, and Becker's memo proposed to lay groundwork by first building a model of the big tunnel, with a test section only one foot square. He recommended that this subscale facility should "be constructed and tested before proceeding with a four-foot-square tunnel." He gave an itemized cost estimate that came to $39,550, including $10,000 for installation and $6,000 for contingency.

Becker's memo ended in formal fashion: "Approval is requested to proceed with the design and construction of a model supersonic tunnel having a one-foot-square test section at Mach number 7.0. If successful, this model tunnel would not only provide data for the design of economical high Mach number supersonic wind tunnels, but would itself be a very useful research tool."[36]

On 6 August, three days after Becker wrote this memo, the potential usefulness of this tool increased enormously. On that day, an atomic bomb destroyed Hiroshima. With this, it now took only modest imagination to envision nuclear-tipped V-2s as weapons of the future. The standard V-2 had carried only a one-ton conventional warhead and lacked both range and accuracy. It nevertheless had been

technically impressive, particularly since there was no way to shoot it down. But an advanced version with an atomic warhead would be far more formidable.

John Stack strongly supported Becker's proposal, which soon reached the desk of George Lewis, NACA's Director of Aeronautical Research. Lewis worked at NACA's Washington Headquarters but made frequent visits to Langley. Stack discussed the proposal with Lewis in the course of such a visit, and Lewis said, "Let's do it."

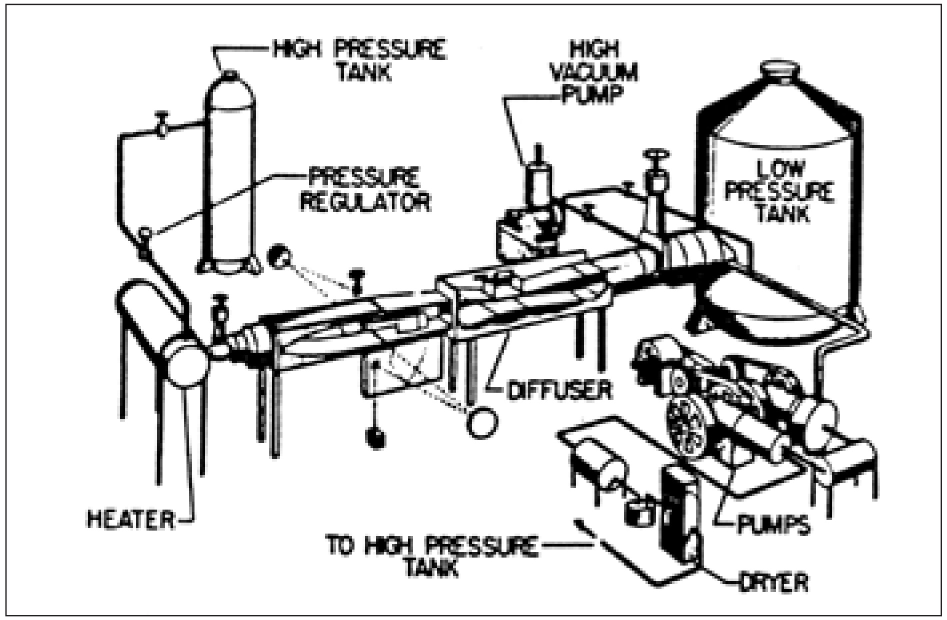
Just then, though, there was little money for new projects. NACA faced a postwar budget cut, which took its total appropriation from $40.9 million in FY 1945 to $24 million in FY 1946. Lewis therefore said to Stack, "John, you know I'm a sucker for a new idea, but don't call it a wind tunnel because I'll be in trouble with having to raise money in a formal way. That will necessitate Congressional review and approval. Call it a research project." Lewis designated it as Project 506 and obtained approval from NACA's Washington office on 18 December.[37]

A month later, in January 1946, Becker raised new issues in a memo to Stack. He was quite concerned that the high Mach would lead to so low a temperature that air in the flow would liquefy. To prevent this, he called for heating the air, declaring that "a temperature of 600ºF in the pressure tank is essential." He expected to achieve this by using "a small electrical heater."

The pressure in that tank was to be considerably higher than in his plans of August. The tank would hold a pressure of 100 atmospheres. Instead of merely starting the flow, with a powered compressor sustaining in continuous operation, this pressure tank now was to hold enough air for operating times of 40 seconds. This would resolve uncertainties in the technical requirements for continuous operation. Continuous flows were still on the agenda but not for the immediate future. Instead, this wind tunnel was to operate as a blowdown facility.

Here, in outline, was a description of the installation as finally built. Its test section was 11 inches square. Its pressure tank held 50 atmospheres. It never received a compressor system for continuous flow, operating throughout its life entirely as a blowdown wind tunnel. But by heating its air, it indeed operated routinely at speeds close to Mach 7.[38]

Taking the name of 11-Inch Hypersonic Tunnel, it operated successfully for the first time on 26 November 1947. It did not heat its compressed air directly within the pressure tank, relying instead on an electric resistance heater as a separate component. This heater raised the air to temperatures as high as 900ºF, eliminating air liquefaction in the test section with enough margin for Mach 8. Specialized experiments showed clearly that condensation took place when the initial temperature was not high enough to prevent it. Small particles promoted condensation by serving as nuclei for the formation of droplets. Becker suggested that such particles could have formed through the freezing of CO_2, which is naturally present in air. Subsequent research confirmed this conjecture.[39]



John Becker's 11-inch hypersonic wind tunnel. (NASA)

The facility showed initial early problems as well as a long-term problem. The early difficulties centered on the air heater, which showed poor internal heat conduction, requiring as much as five hours to reach a suitably uniform temperature distribution. In addition, copper tubes within the heater produced minute particles of copper oxide, due to oxidation of this metal at high temperature. These particles, blown within the hypersonic airstream, damaged test models and instruments. Becker attacked the problem of slow warmup by circulating hot air through the heater. To eliminate the problem of oxidation, he filled the heater with nitrogen while it was warming up.[40]

A more recalcitrant difficulty arose because the hot airflow, entering the nozzle, heated it and caused it to undergo thermal expansion. The change in its dimensions was not large, but the nozzle design was highly sensitive to small changes, with this expansion causing the dynamic pressure in the airflow to vary by up to 13 percent in the course of a run. Run times were as long as 90 seconds, and because of this, data taken at the beginning of a test did not agree with similar data recorded a minute later. Becker addressed this by fixing the angle of attack of each test model. He did not permit the angle to vary during a run, even though variation of this angle would have yielded more data. He also made measurements at a fixed time during each run.[41]

The wind tunnel itself represented an important object for research. No similar facility had ever been built in America, and it was necessary to learn how to use it most effectively. Nozzle design represented an early topic for experimental study. At Mach 7, according to standard tables, the nozzle had to expand by a ratio of 104.1 to 1. This nozzle resembled that of a rocket engine. With an axisymmetric design, a throat of one-inch diameter would have opened into a channel having a diameter slightly greater than 10 inches. However, nozzles for Becker's facility proved difficult to develop.

Conventional practice, carried over from supersonic wind tunnels, called for a two-dimensional nozzle. It featured a throat in the form of a narrow slit, having the full width of the main channel and opening onto that channel. However, for flow at Mach 7, this slit was to be only about 0.1 inch high. Hence, there was considerable interest in nozzles that might be less sensitive to small errors in fabrication.[42]

Initial work focused on a two-step nozzle. The first step was flat and constant in height, allowing the flow to expand to 10 inches wide in the horizontal plane and to reach Mach 4.36. The second step maintained this width while allowing the flow to expand to 10.5 inches in height, thus achieving Mach 7. But this nozzle performed poorly, with investigators describing its flow as "entirely unsatisfactory for use in a wind tunnel." The Mach number reached 6.5, but the flow in the test section was "not sufficiently uniform for quantitative wind-tunnel test purposes." This was due to "a thick boundary layer which developed in the first step" along the flat parallel walls set closely together at the top and bottom.[43]

A two-dimensional, single-step nozzle gave much better results. Its narrow slit-like throat indeed proved sensitive; this was the nozzle that gave the variation with time of the dynamic pressure. Still, except for this thermal-expansion effect, this nozzle proved "far superior in all respects" when compared with the two-step nozzle. In turn, the thermal expansion in time proved amenable to correction. This expansion occurred because the nozzle was made of steel. The commercially available alloy Invar had a far lower coefficient of thermal expansion. A new nozzle, fabricated from this material, entered service in 1954 and greatly reduced problems due to expansion of the nozzle throat.[44]

Another topic of research addressed the usefulness of the optical techniques used for flow visualization. The test gas, after all, was simply air. Even when it formed shock waves near a model under test, the shocks could not be seen with the unaided eye. Therefore, investigators were accustomed to using optical instruments when studying a flow. Three methods were in use: interferometry, schlieren, and shadowgraph. These respectively observed changes in air density, density gradient, and the rate of change of the gradient.

Such instruments had been in use for decades. Ernst Mach, of the eponymous Mach number, had used a shadowgraph as early as 1887 to photograph shock waves produced by a speeding bullet. Theodor Meyer, a student of Prandtl, used schlieren to visualize supersonic flow in a nozzle in 1908. Interferometry gave the most detailed photos and the most information, but an interferometer was costly and difficult to operate. Shadowgraphs gave the least information but were the least costly and easiest to use. Schlieren apparatus was intermediate in both respects and was employed often.[45]

Still, all these techniques depended on the flow having a minimum density. One could not visualize shock waves in a vacuum because they did not exist. Highly rarefied flows gave similar difficulties, and hypersonic flows indeed were rarefied. At Mach 7, a flow of air fell in pressure to less than one part in 4000 of its initial value, reducing an initial pressure of 40 atmospheres to less than one-hundredth of an atmosphere.[46] Higher test-section pressures would have required correspondingly higher pressures in the tank and upstream of the nozzle. But low test-section pressures were desirable because they were physically realistic. They corresponded to conditions in the upper atmosphere, where hypersonic missiles were to fly.

Becker reported in 1950 that the limit of usefulness of the schlieren method "is reached at a pressure of about 1 mm of mercury for slender test models at $M = 7.0$."[47] This corresponded to the pressure in the atmosphere at 150,000 feet, and there was interest in reaching the equivalent of higher altitudes still. A consultant, Joseph Kaplan, recommended using nitrogen as a test gas and making use of an afterglow that persists momentarily within this gas when it has been excited by an electrical discharge. With the nitrogen literally glowing in the dark, it became much easier to see shock waves and other features of the flow field at very low pressures.

"The nitrogen afterglow appears to be usable at static pressures as low as 100 microns and perhaps lower," Becker wrote.[48] This corresponded to pressures of barely a ten-thousandth of an atmosphere, which exist near 230,000 feet. It also corresponded to the pressure in the test section of a blowdown wind tunnel with air in the tank at 50 atmospheres and the flow at Mach 13.8.[49] Clearly, flow visualization would not be a problem.

Condensation, nozzle design, and flow visualization were important topics in their own right. Nor were they merely preliminaries. They addressed an important reason for building this tunnel: to learn how to design and use subsequent hypersonic facilities. In addition, although this 11-inch tunnel was small, there was much interest in using it for studies in hypersonic aerodynamics.

This early work had a somewhat elementary character, like the hypersonic experiments of Erdmann at Peenemunde. When university students take initial courses in aerodynamics, their textbooks and lab exercises deal with simple cases such as flow over a flat plate. The same was true of the first aerodynamic experiments with the 11-inch tunnel. The literature held a variety of theories for calculating lift, drag, and pressure distributions at hypersonic speeds. The experiments produced data

that permitted comparison with theory—to check their accuracy and to determine circumstances under which they would fail to hold.

One set of tests dealt with cone-cylinder configurations at Mach 6.86. These amounted to small and simplified representations of a missile and its nose cone. The test models included cones, cylinders with flat ends, and cones with cylindrical afterbodies, studied at various angles of attack. For flow over a cone, the British researchers Geoffrey I. Taylor and J. W. Maccoll published a treatment in 1933. This quantitative discussion was a cornerstone of supersonic theory and showed its merits anew at this high Mach number. An investigation showed that it held "with a high degree of accuracy."

The method of characteristics, devised by Prandtl and Busemann in 1929, was a standard analytical method for designing surfaces for supersonic flow, including wings and nozzles. It was simple enough to lend itself to hand computation, and it gave useful results at lower supersonic speeds. Tests in the 11-inch facility showed that it continued to give good accuracy in hypersonic flow. For flow with angle of attack, a theory put forth by Antonio Ferri, a leading Italian aerodynamicist, produced "very good results." Still, not all preexisting theories proved to be accurate. One treatment gave good results for drag but overestimated some pressures and values of lift.[50]

Boundary-layer effects proved to be important, particularly in dealing with hypersonic wings. Tests examined a triangular delta wing and a square wing, the latter having several airfoil sections. Existing theories gave good results for lift and drag at modest angles of attack. However, predicted pressure distributions were often in error. This resulted from flow separation at high angles of attack—and from the presence of thick laminar boundary layers, even at zero angle of attack. These finds held high significance, for the very purpose of a hypersonic wing was to generate a pressure distribution that would produce lift, without making the vehicle unstable and prone to go out of control while in flight.

The aerodynamicist Charles McLellan, who had worked with Becker in designing the 11-inch tunnel and who had become its director, summarized the work within the *Journal of the Aeronautical Sciences*. He concluded that near Mach 7, the aerodynamic characteristics of wings and bodies "can be predicted by available theoretical methods with the same order of accuracy usually obtainable at lower speeds, at least for cases in which the boundary layer is laminar."[51]

At hypersonic speeds, boundary layers become thick because they sustain large temperature changes between the wall and the free stream. Mitchel Bertram, a colleague of McLellan, gave an approximate theory for the laminar hypersonic boundary layer on a flat plate. Using the 11-inch tunnel, he showed good agreement between his theory and experiment in several significant cases. He noted that boundary-layer effects could increase drag coefficients at least threefold, when compared with values using theories that include only free-stream flow and ignore the boundary layer. This emphasized anew the importance of the boundary layer in producing hypersonic skin friction.[52]

These results were fundamental, both for aerodynamics and for wind-tunnel design. With them, the 11-inch tunnel entered into a brilliant career. It had been built as a pilot facility, to lay groundwork for a much larger hypersonic tunnel that could sustain continuous flows. This installation, the Continuous Flow Hypersonic Tunnel (CFHT), indeed was built. Entering service in 1962, it had a 31-inch test section and produced flows at Mach 10.[53]

Still, it took a long time for this big tunnel to come on line, and all through the 1950s the 11-inch facility continued to grow in importance. At its peak, in 1961, it conducted more than 2,500 test runs, for an average of 10 per working day. It remained in use until 1972.[54] It set the pace with its use of the blowdown principle, which eliminated the need for costly continuous-flow compressors. Its run times proved to be adequate, and the CFHT found itself hard-pressed to offer much that was new. It had been built for continuous operation but found itself used in a blowdown mode most of the time. Becker wrote that his 11-inch installation "far exceeded" the CFHT "in both the importance and quality of its research output." He described it as "the only 'pilot tunnel' in NACA history to become a major research facility in its own right."[55]

Yet while the work of this wind tunnel was fundamental to the development of hypersonics, in 1950 the field of hypersonics was not fundamental to anything in particular. Plenty of people expected that America in time would build missiles and aircraft for flight at such speeds, but in that year no one was doing so. This soon changed, and the key year was 1954. In that year the Air Force embraced the X-15, a hypersonic airplane for which studies in the 11-inch tunnel proved to be essential. Also in that year, advances in the apparently unrelated field of nuclear weaponry brought swift and emphatic approval for the development of the ICBM. With this, hypersonics vaulted to the forefront of national priority.

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1 Anderson, *History*, pp. 251-255.

2 Wegener, *Peenemunde*, pp. 23-24, 167; Von Karman and Edson, *Wind*, p. 221.

3 Wegener, *Peenemunde*, pp. 22-23; Neufeld, *Rocket*, pp. 87-88.

4 Neufeld, *Rocket*, p. 87.

5 Wegener, *Peenemunde*, pp. 24-25; Shapiro, *Compressible*, pp. 203-04.

6 See, for example, Miller and Durant, *Worlds*, pp. 9, 17, 23.

7 Neufeld, *Rocket*, pp. 86, 88-91 (quote, p. 89). Zeppelin: Wattendorf, *German*, p. 19.

8 Wegener, *Peenemunde*, photos following p. 84.

9 Von Karman and Edson, *Wind*, pp. 218-19.

10 Dornberger, *V-2*, pp. 122-23, 127-28.

11 Hallion, *Hypersonic*, pp. xvi, xviii; Neufeld, *Rocket*, pp. 248-50, 283.

12 Neufeld, *Rocket*, pp. 250-51; Dornberger, *V-2*, p. 268.

13 Neufeld, *Rocket*, p. 250.

14 NASA SP-4303, pp. 77, 316, 330.

15 Wegener, *Peenemunde*, p. 70.

16 Lukasiewicz, *Experimental*, pp. 71-76.

17 Wegener, *Peenemunde*, pp. 70-71.

18 Neufeld, *Rocket*, p. 87; Wegener, *Peenemunde*, p. 24; Wattendorf, *German*, p. 4.

19 Wegener, *Peenemunde*, pp. 32, 75, photos following p. 84.

20 Wattendorf, *German*, p. 4.

21 *Spaceflight*, May 1973, pp. 166-71 (quotes, pp. 168, 170); Huxley, *Brave*, pp. 58, 59, 61.

22 *Spaceflight,* May 1973, pp. 166, 171-72 (quote, p. 166); Ley, *Rockets*, pp. 533-537.

23 *Spaceflight*, May 1973, pp. 171-72, 175-76; Ley, *Rockets*, pp. 533-34, 535; Ordway and Sharpe, *Rocket Team*, pp. 327-28.

24 *Spaceflight,* May 1973, pp. 168-69.

25 Ley, *Rockets*, pp. 514-19, 524; Allen and Polmar, *Downfall*, pp. 103, 226.

26 Ordway and Sharpe, *Rocket Team*, p. 329; Jenkins, *Space Shuttle*, p. 2.

27 "Sänger." MBB brochure, August 1986.

28 Boyne, *Arrow*, p. 139.

29 Speer, *Inside*, pp. 364-66.

30 Anderson, *History*, p. 435; NASA: SP-440, pp. 51-52; SP-4305, p. 467.

31 NASA: SP-440, p. 52; SP-4302, pp. 63-64.

32 AIAA Paper 79-0219, pp. 3-4.

33 *Journal of the Aeronautical Sciences*, July 1947. pp. 373-409 (Stack quote, p. 406).

34 Hermann, "Supersonic," p. 439; Anspacher et al., *Legacy*, pp. 209-10.

35 Becker: Professional resume; NASA SP-4305, p. 54. R-2800 engine: "Dependable Engines" (Pratt & Whitney).

36 Memo, Becker to Chief of Research, 3 August 1945 (includes quotes); see also NASA SP-4305, pp. 344-346.

37 John Becker interview by Walter Bonney, March 1973 (quotes, p. 4). NACA budget: NASA SP-4305, p. 428. Project approval noted in memo, Becker to Stack, 16 January 1946.

38 Memo, Becker to Stack, 16 January 1946 (includes quotes).

39 *Journal of Applied Physics,* July 1950, pp. 619-21; NACA TN 3302. Air heater: NASA SP-4305, p. 471.

40 Becker, memo for record, 23 January 1948.

41 AIAA Paper 88-0230, p. 6.

42 NACA TN 2171, p. 3.

43 Ibid., pp. 6, 21 (quotes, pp. 1, 19).

44 NACA TN 2223 (quote, p. 11); AIAA Paper 88-0230, pp. 6-7.

45 Shapiro, *Compressible*, pp. 59-68. Photos by Mach and Meyer: Anderson, *History*, pp. 376, 382.

46 Shapiro, *Compressible*, table, p. 620.

47 *Journal of Applied Physics,* July 1950, pp. 619-28 (quote, p. 621).

48 Ibid. (quote, p. 622).

49 230,000 feet: Shapiro, *Compressible*, table, pp. 612-13. Mach 13.8: calculated from Shapiro, *Compressible*, eq. 4.14b, p. 83.

50 NACA RM L51J09 (quotes, p. 19).

51 NACA RM L51D17; *Journal of the Aeronautical Sciences,* October 1951, pp. 641-48 (quote, p. 648).

52 NACA TN 2773.

53 AIAA Paper 88-0230, pp. 8-9; NACA: SP-440, pp. 94-95; TM X-1130, p. 27.

54 AIAA Paper 88-0230, p. 7.

55 Becker, handwritten notes, January 1989 (includes quotes); NASA: SP-4305, p. 471; RP-1132, p. 256.

2

NOSE CONES AND RE-ENTRY

The ICBM concept of the early 1950s, called Atlas, was intended to carry an atomic bomb as a warhead, and there were two things wrong with this missile. It was unacceptably large and unwieldy, even with a warhead of reduced weight. In addition, to compensate for this limited yield, Atlas demanded unattainable accuracy in aim. But the advent of the hydrogen bomb solved both problems. The weight issue went away because projected H-bombs were much lighter, which meant that Atlas could be substantially smaller. The accuracy issue also disappeared. Atlas now could miss its target by several miles and still destroy it, by the simple method of blowing away everything that lay between the aim point and the impact point.

Studies by specialists, complemented by direct tests of early H-bombs, brought a dramatic turnaround during 1954 as Atlas vaulted to priority. At a stroke, its designers faced the re-entry problem. They needed a lightweight nose cone that could protect the warhead against the heat of atmosphere entry, and nothing suitable was in sight. The Army was well along in research on this problem, but its missiles did not face the severe re-entry environment of Atlas and its re-entry studies were not directly applicable.

The Air Force approached this problem systematically. It began by working with the aerodynamicist Arthur Kantrowitz, who introduced the shock tube as an instrument that could momentarily reproduce flow conditions that were pertinent. Tests with rockets, notably the pilotless X-17, complemented laboratory experiments. The solution to the problem of nose-cone design came from George Sutton, a young physicist who introduced the principle of ablation. Test nose cones soon were in flight, followed by prototypes of operational versions.

THE MOVE TOWARD MISSILES

In August 1945 it took little imagination to envision that the weapon of the future would be an advanced V-2, carrying an atomic bomb as the warhead and able to cross oceans. It took rather more imagination, along with technical knowledge, to see that this concept was so far beyond the state of the art as not to be worth pursuing. Thus, in December Vannevar Bush, wartime head of the Office of Scientific Research and Development, gave his views in congressional testimony:

> "There has been a great deal said about a 3,000 miles high-angle rocket. In my opinion, such a thing is impossible for many years. The people have been writing these things that annoy me, have been talking about a 3,000 mile high-angle rocket shot from one continent to another, carrying an atomic bomb and so directed as to be a precise weapon which would land exactly on a certain target, such as a city. I say, technically, I don't think anyone in the world knows how to do such a thing, and I feel confident that it will not be done for a very long period of time to come. I think we can leave that out of our thinking."[1]

Propulsion and re-entry were major problems, but guidance was worse. For intercontinental range, the Air Force set the permitted miss distance at 5,000 feet and then at 1,500 feet. The latter equaled the error of experienced bombardiers who were using radar bombsights to strike at night from 25,000 feet. The view at the Pentagon was that an ICBM would have to do as well when flying all the way to Moscow. This accuracy corresponded to hitting a golf ball a mile and having it make a hole in one. Moreover, each ICBM was to do this entirely through automatic control.[2]

The Air Force therefore emphasized bombers during the early postwar years, paying little attention to missiles. Its main program, such as it was, called for a missile that was neither ballistic nor intercontinental. It was a cruise missile, which was to solve its guidance problem by steering continually. The first thoughts dated to November 1945. At North American Aviation, chief engineer Raymond Rice and chief scientist William Bollay proposed to "essentially add wings to the V-2 and design a missile fundamentally the same as the A-9."

Like the supersonic wind tunnel at the Naval Ordnance Laboratory, here was another concept that was to carry a German project to completion. The initial design had a specified range of 500 miles,[3] which soon increased. Like the A-9, this missile—designated MX-770—was to follow a boost-glide trajectory and then extend its range with a supersonic glide. But by 1948 the U.S. Air Force had won its independence from the Army and had received authority over missile programs with ranges of 1,000 miles and more. Shorter-range missiles remained the concern of the Army. Accordingly, late in February, Air Force officials instructed North American to stretch the range of the MX-770 to a thousand miles.

A boost-glide trajectory was not well suited for a doubled range. At Wright Field, the Air Force development center, Colonel M. S. Roth proposed to increase the range by adding ramjets.[4] This drew on work at Wright, where the Power Plant Laboratory had a Nonrotating Engine Branch that was funding development of both ramjets and rocket engines. Its director, Weldon Worth, dealt specifically with ramjets.[5] A modification of the MX-770 design added two ramjet engines, mounting them singly at the tips of the vertical fins.[6] The missile also received a new name: Navaho. This reflected a penchant at North American for names beginning with "NA."[7]

Then, within a few months during 1949 and 1950, the prospect of world war emerged. In 1949 the Soviets exploded their first atomic bomb. At nearly the same time, China's Mao Zedong defeated the Nationalists of Chiang Kai-shek and proclaimed the People's Republic of China. The Soviets had already shown aggressiveness by subverting the democratic government of Czechoslovakia and by blockading Berlin. These new developments raised the prospect of a unified communist empire armed with the industry that had defeated the Nazis, wielding atomic weapons, and deploying the limitless manpower of China.

President Truman responded both publicly and with actions that were classified. In January 1950 he announced a stepped-up nuclear program, directing "the Atomic Energy Commission to continue its work on all forms of atomic weapons, including the so-called hydrogen or super bomb." In April he gave his approval to a secret policy document, NSC-68. It stated that the United States would resist communist expansion anywhere in the world and would devote up to twenty percent of the gross national product to national defense.[8] Then in June, in China's back yard, North Korea invaded the South, and America again was at war.

These events had consequences for the missile program, as the design and mission of Navaho changed dramatically during 1950. Bollay's specialists, working with Air Force counterparts, showed that they could anticipate increases in its range to as much as 5,500 nautical miles. Conferences among Air Force officials, held at the Pentagon in August, set this intercontinental range as a long-term goal. A letter from Major General Donald Putt, Director of Research and Development within the Air Materiel Command, became the directive instructing North American to pursue this objective. An interim version, Navaho II, with range of 2,500 nautical miles, appeared technically feasible. The full-range Navaho III represented a long-term project that was slated to go forward as a parallel effort.

The thousand-mile Navaho of 1948 had taken approaches based on the V-2 to their limit. Navaho II, the initial focus of effort, took shape as a two-stage missile with a rocket-powered booster. The booster was to use two such engines, each with thrust of 120,000 pounds. A ramjet-powered second stage was to ride it during initial ascent, accelerating to the supersonic speed at which the ramjet engines could produce their rated thrust. This second stage was then to fly onward as a cruise missile, at a planned flight speed of Mach 2.75.[9]

A rival to Navaho soon emerged. At Convair, structural analyst Karel Bossart held a strong interest in building an ICBM. As a prelude, he had built three rockets in the shape of a subscale V-2 and had demonstrated his ideas for lightweight structure in flight test. The Rand Corporation, an influential Air Force think tank, had been keeping an eye on this work and on the burgeoning technology of missiles. In December 1950 it issued a report stating that long-range ballistic missiles now were in reach. A month later the Air Force responded by giving Bossart, and Convair, a new study contract. In August 1951 he christened this missile Atlas, after Convair's parent company, the Atlas Corporation.

The initial concept was a behemoth. Carrying an 8,000-pound warhead, it was to weigh 670,000 pounds, stand 160 feet tall by 12 feet in diameter, and use seven of Bollay's new 120,000-pound engines. It was thoroughly unwieldy and represented a basis for further studies rather than a concept for a practical weapon. Still, it stood as a milestone. For the first time, the Air Force had a concept for an ICBM that it could pursue using engines that were already in development.[10]

For the ICBM to compete with Navaho, it had to shrink considerably. Within the Air Force's Air Research and Development Command, Brigadier General John Sessums, a strong advocate of long-range missiles, proposed that this could be done by shrinking the warhead. The size and weight of Atlas were to scale in proportion with the weight of its atomic weapon, and Sessums asserted that new developments in warhead design indeed would give high yield while cutting the weight.

He carried his argument to the Air Staff, which amounted to the Air Force's board of directors. This brought further studies, which indeed led to a welcome reduction in the size of Atlas. The concept of 1953 called for a length of 110 feet and a loaded weight of 440,000 pounds, with the warhead tipping the scale at only 3,000 pounds. The number of engines went down from seven to five.[11]

There also was encouraging news in the area of guidance. Radio guidance was out of the question for an operational missile; it might be jammed or the ground-based guidance center might be destroyed in an attack. Instead, missile guidance was to be entirely self-contained. All concepts called for the use of sensitive accelerometers along with an onboard computer, to determine velocity and location. Navaho was to add star trackers, which were to null out errors by tracking stars even in daylight. In addition, Charles Stark Draper of MIT was pursuing inertial guidance, which was to use no external references of any sort. His 1949 system was not truly inertial, for it included a magnetic compass and a Sun-seeker. But when flight-tested aboard a B-29, over distances as great at 1,737 nautical miles, it showed a mean error of only 5 nautical miles.[12]

For Atlas, though, the permitted miss distance remained at 1,500 feet, with the range being 5500 nautical miles. The program plan of October 1953 called for a leisurely advance over the ensuing decade, with research and development being completed only "sometime after 1964," and operational readiness being achieved in 1965. The program was to emphasize work on the major components: propulsion, guidance, nose cone, lightweight structure. In addition, it was to conduct extensive ground tests before proceeding toward flight.[13]

This concept continued to call for an atomic bomb as the warhead, but by then the hydrogen bomb was in the picture. The first test version, named Mike, detonated at Eniwetok Atoll in the Pacific on 1 November 1952. Its fireball spread so far and fast as to terrify distant observers, expanding until it was more than three miles across. "The thing was enormous," one man said. "It looked as if it blotted out the whole horizon, and I was standing 30 miles away." The weapons designer Theodore Taylor described it as "so huge, so brutal—as if things had gone too far. When the heat reached the observers, it stayed and stayed and stayed, not for seconds but for minutes." Mike yielded 10.4 megatons, nearly a thousand times greater than the 13 kilotons of the Hiroshima bomb of 1945.

Mike weighed 82 tons.[14] It was not a weapon; it was a physics experiment. Still, its success raised the prospect that warheads of the future might be smaller and yet might increase sharply in explosive power. Theodore von Karman, chairman of the Air Force Scientific Advisory Board, sought estimates from the Atomic Energy Commission of the size and weight of future bombs. The AEC refused to release this information. Lieutenant General James Doolittle, Special Assistant to the Air Force Chief of Staff, recommended creating a special panel on nuclear weapons within the SAB. This took form in March 1953, with the mathematician John von Neumann as its chairman. Its specialists included Hans Bethe, who later won the Nobel Prize, and Norris Bradbury who headed the nation's nuclear laboratory at Los Alamos, New Mexico.

In June this group reported that a thermonuclear warhead with the 3,000-pound Atlas weight could have a yield of half a megaton. This was substantially higher than that of the pure-fission weapons considered previously. It gave renewed strength to the prospect of a less stringent aim requirement, for Atlas now might miss by far more than 1,500 feet and still destroy its target.

Three months later the Air Force Special Weapons Center issued its own estimate, anticipating that a hydrogen bomb of half-megaton yield could weigh as little as 1,500 pounds. This immediately opened the prospect of a further reduction in the size of Atlas, which might fall in weight from 440,000 pounds to as little as 240,000. Such a missile also would need fewer engines.[15]

Also during September, Bruno Augenstein of the Rand Corporation launched a study that sought ways to accelerate the development of an ICBM. In Washington, Trevor Gardner was Special Assistant for Research and Development, reporting to the Air Force Secretary. In October he set up his own review committee. He recruited von Neumann to serve anew as its chairman and then added a dazzling array of talent from Caltech, Bell Labs, MIT, and Hughes Aircraft. In Gardner's words, "The aim was to create a document so hot and of such eminence that no one could pooh-pooh it."[16]

He called his group the Teapot Committee. He wanted particularly to see it call for less stringent aim, for he believed that a 1,500-foot miss distance was preposterous. The Teapot Committee drew on findings by Augenstein's group at Rand, which endorsed a 1,500-pound warhead and a three-mile miss distance. The formal Teapot report, issued in February 1954, declared "the military requirement" on miss distance "should be relaxed from the present 1,500 feet to at least two, and probably three, nautical miles." Moreover, "the warhead weight might be reduced as far as 1,500 pounds, the precise figure to be determined after the Castle tests and by missile systems optimization."[17]

The latter recommendation invoked Operation Castle, a series of H-bomb tests that began a few weeks later. The Mike shot of 1952 had used liquid deuterium, a form of liquid hydrogen. It existed at temperatures close to absolute zero and demanded much care in handling. But the Castle series was to test devices that used lithium deuteride, a dry powder that resembled salt. The Mike approach had been chosen because it simplified the weapons physics, but a dry bomb using lithium promised to be far more practical.

The first such bomb was detonated on 1 March as Castle Bravo. It produced 15 megatons, as its fireball expanded to almost four miles in diameter. Other Castle H-bombs performed similarly, as Castle Romeo went to 11 megatons and Castle Yankee, a variant of Romeo, reached 13.5 megatons. "I was on a ship that was 30 miles away," the physicist Marshall Rosenbluth recalls about Bravo, "and we had this horrible white stuff raining out on us." It was radioactive fallout that had condensed from vaporized coral. "It was pretty frightening. There was a huge fireball with these turbulent rolls going in and out. The thing was glowing. It looked to me like a diseased brain." Clearly, though, bombs of the lithium type could be as powerful as anyone wished—and these test bombs were readily weaponizable.[18]

The Castle results, strongly complementing the Rand and Teapot reports, cleared the way for action. Within the Pentagon, Gardner took the lead in pushing for Atlas. On 11 March he met with Air Force Secretary Harold Talbott and with the Chief of Staff, General Nathan Twining. He proposed a sped-up program that would nearly double the Fiscal Year (FY) 1955 Atlas budget and would have the first missiles ready to launch as early as 1958. General Thomas White, the Vice Chief of Staff, weighed in with his own endorsement later that week, and Talbott responded by directing Twining to accelerate Atlas immediately.

White carried the ball to the Air Staff, which held responsibility for recommending approval of new programs. He told its members that "ballistic missiles were here to stay, and the Air Staff had better realize this fact and get on with it." Then on 14 May, having secured concurrence from the Secretary of Defense, White gave Atlas the highest Air Force development priority and directed its acceleration "to the maximum extent that technology would allow." Gardner declared that White's order meant "the maximum effort possible with no limitation as to funding."[19]

This was a remarkable turnaround for a program that at the moment lacked even a proper design. Many weapon concepts have gone as far as the prototype

stage without winning approval, but Atlas gained its priority at a time when the accepted configuration still was the 440,000-pound, five-engine concept of 1953. Air Force officials still had to establish a formal liaison with the AEC to win access to information on projected warhead designs. Within the AEC, lightweight bombs still were well in the future. A specialized device, tested in the recent series as Castle Nectar, delivered 1.69 megatons but weighed 6,520 pounds. This was four times the warhead weight proposed for Atlas.

But in October the AEC agreed that it could develop warheads weighing 1,500 to 1,700 pounds, with a yield of one megaton. This opened the door to a new Atlas design having only three engines. It measured 75 feet long and 10 feet in diameter, with a weight of 240,000 pounds—and its miss distance could be as great as five miles. This took note of the increased yield of the warhead and further eased the problem of guidance. The new configuration won Air Force approval in December.[20]

APPROACHING THE NOSE CONE

An important attribute of a nose cone was its shape, and engineers were reducing drag to a minimum by crafting high-speed airplanes that displayed the ultimate in needle-nose streamlining. The X-3 research aircraft, designed for Mach 2, had a long and slender nose that resembled a church steeple. Atlas went even further, with an early concept having a front that resembled a flagpole. This faired into a long and slender cone that could accommodate the warhead.[21]

This intuitive approach fell by the wayside in 1953, as the NACA-Ames aerodynamicists H. Julian Allen and Alfred Eggers carried through an elegant analysis of the motion and heating of a re-entering nose cone. This work showed that they were masters of the simplifying assumption. To make such assumptions successfully represents a high art, for the resulting solutions must capture the most essential aspects of the pertinent physics while preserving mathematical tractability. Their paper stands to this day as a landmark. Quite probably, it is the single most important paper ever written in the field of hypersonics.

They calculated total heat input to a re-entry vehicle, seeking shapes that would minimize this. That part of the analysis enabled them to critique the assertion that a slender and sharply-pointed shape was best. For a lightweight nose cone, which would slow significantly in the atmosphere due to drag, they found a surprising result: the best shape, minimizing the total heat input, was blunt rather than sharp.

The next issue involved the maximum rate of heat transfer when averaged over an entire vehicle. To reduce this peak heating rate to a minimum, a nose cone of realistic weight might be either very sharp or very blunt. Missiles of intermediate slenderness gave considerably higher peak heating rates and "were definitely to be avoided."

This result applied to the entire vehicle, but heat-transfer rates were highest at the nose-cone tip. It was particularly important to minimize the heating at the tip, and again their analysis showed that a blunt nose cone would be best. As Allen and Eggers put it, "not only should pointed bodies be avoided, but the rounded nose should have as large a radius as possible."[22]

How could this be? The blunt body set up a very strong shock wave, which produced intense heating of the airflow. However, most of this heat was carried away in the flow. The boundary layer served to insulate the vehicle, and relatively little of this heat reached its surface. By contrast, a sharp and slender nose cone produced a shock that stood very close to this surface. At the tip, the boundary layer was too thin to offer protection. In addition, skin friction produced still more heating, for the boundary layer now received energy from shock-heated air flowing close to the vehicle surface.[23]

This paper was published initially as a classified document, but it took time to achieve its full effect. The Air Force did not adopt its principle for nose-cone design until 1956.[24] Still, this analysis outlined the shape of things to come. Blunt heat shields became standard on the Mercury, Gemini, and Apollo capsules. The space shuttle used its entire undersurface as a heat shield that was particularly blunt, raising its nose during re-entry to present this undersurface to the flow.

Yet while analysis could indicate the general shape for a nose cone, only experiment could demonstrate the validity of a design. At a stroke, Becker's Mach 7 facility, which had been far in the forefront only recently, suddenly became inadequate. An ICBM nose cone was to re-enter the atmosphere at speeds above Mach 20. Its kinetic energy would vaporize five times its weight of iron. Temperatures behind the bow shock would reach 9000 K, hotter than the surface of the Sun. Research scientist Peter Rose wrote that this velocity would be "large enough to dissociate all the oxygen molecules into atoms, dissociate about half of the nitrogen, and thermally ionize a considerable fraction of the air."[25]

Though hot, the 9000 K air actually would be cool, considering its situation, because its energy would go into dissociating molecules of gas. However, the ions and dissociated atoms were only too likely to recombine at the surface of the nose cone, thereby delivering additional heat. Such chemical effects also might trip the boundary layer from laminar to turbulent flow, with the rate of heat transfer increasing substantially as a result. In the words of Rose:

> "The presence of free-atoms, electrons, and molecules in excited states can be expected to complicate heat transfer through the boundary layer by additional modes of energy transport, such as atom diffusion, carrying the energy of dissociation. Radiation by transition from excited energy states may contribute materially to radiative heat transfer. There is also a possibility of heat transfer by electrons and ions. The existence of large amounts of energy in any of these forms will undoubtedly influence the familiar flow phenomena."[26]

Within the Air Force, the Aircraft Panel of the Scientific Advisory Board (SAB) issued a report in October 1954 that looked ahead to the coming decade:

> "In the aerodynamics field, it seems to us pretty clear that over the next 10 years the most important and vital subject for research and development is the field of hypersonic flows; and in particular, hypersonic flows with [temperatures at a nose-cone tip] which may run up to the order of thousands of degrees. This is one of the fields in which an ingenious and clever application of the existing laws of mechanics is probably not adequate. It is one in which much of the necessary physical knowledge still remains unknown at present and must be developed before we arrive at a true understanding and competence. The reason for this is that the temperatures which are associated with these velocities are higher than temperatures which have been produced on the globe, except in connection with the nuclear developments of the past 10 or 15 years and that there are problems of dissociation, relaxation times, etc., about which the basic physics is still unknown."[27]

The Atlas program needed a new experimental technique, one that could overcome the fact that conventional wind tunnels produced low temperatures due to their use of expanding gases, and hence the pertinent physics and chemistry associated with the heat of re-entry were not replicated. Its officials found what they wanted at a cocktail party.

This social gathering took place at Cornell University around Thanksgiving of 1954. The guests included university trustees along with a number of deans and senior professors. One trustee, Victor Emanuel, was chairman of Avco Corporation, which already was closely involved in work on the ICBM. He had been in Washington and had met with Air Force Secretary Harold Talbott, who told him of his concern about problems of re-entry. Emanuel raised this topic at the party while talking with the dean of engineering, who said, "I believe we have someone right here who can help you."[28]

That man was Arthur Kantrowitz, a former researcher at NACA-Langley who had taken a faculty position at Cornell following the war. While at Langley during the late 1930s, he had used a $5,000 budget to try to invent controlled thermonuclear fusion. He did not get very far. Indeed, he failed to gain results that were sufficient even to enable him to write a paper, leaving subsequent pioneers in controlled fusion to start again from scratch. Still, as he recalls, "I continued my interest in high temperatures with the hope that someday I could find something that I could use to do fusion."[29]

In 1947 this led him to the shock tube. This instrument produced very strong shocks in a laboratory, overcoming the limits of wind tunnels. It used a driving gas at high pressure in a separate chamber. This gas burst through a thin diaphragm to generate the shock, which traveled down a long tube that was filled with a test gas. High-speed instruments could observe this shock. They also could study a small model immersed within the hot flow at high Mach that streamed immediately behind the shock.[30]

When Kantrowitz came to the shock tube, it already was half a century old. The French chemist Paul Vieille built the first such devices prior to 1900, using them to demonstrate that a shock wave travels faster than the speed of sound. He proposed that his apparatus could prove useful in studying mine explosions, which took place in shafts that resembled his long tubes.[31]

The next important shock-tube researcher, Britain's William Payman, worked prior to World War II. He used diaphragm-bursting pressures as high as 1100 pounds per square inch and introduced high-speed photography to observe the shocked flows. He and his colleagues used the shock tube for experimental verification of equations in gasdynamics that govern the motion of shock waves.[32]

At Princeton University during that war, the physicist Walter Bleakney went further. He used shock tubes as precision instruments, writing, "It has been found that successive 'shots' in the tube taken with the same initial conditions reproduce one another to a surprising degree. The velocity of the incident shock can be reproduced to 0.1 percent." He praised the versatility of the device, noting its usefulness "for studying a great variety of problems in fluid dynamics." In addition to observations of shocks themselves, the instrument could address "problems of detonation and allied phenomena. The tube may be used as a wind tunnel with a Mach number variable over an enormous range." This was the role it took during the ICBM program.[33]

At Cornell, Kantrowitz initiated a reach for high temperatures. This demanded particularly high pressure in the upstream chamber. Payman had simply used compressed air from a thick-walled tank, but Kantrowitz filled his upstream chamber with a highly combustible mix of hydrogen and oxygen. Seeking the highest temperatures, he avoided choosing air as a test gas, for its diatomic molecules absorbed energy when they dissociated or broke apart, which limited the temperature rise. He turned instead to argon, a monatomic gas that could not dissociate, and reached 18,000 K.

He was a professor at Cornell, with graduate students. One of them, Edwin Resler, wrote a dissertation in 1951, "High Temperature Gases Produced by Strong Shock Waves." In Kantrowitz's hands, the versatility of this instrument appeared anew. With argon as the test gas, it served for studies of thermal ionization, a physical effect separate from dissociation in which hot atoms lost electrons and became electrically charged. Using nitrogen or air, the shock tube examined dissociation as well, which increased with the higher temperatures of stronger shocks. Higher Mach values also lay within reach. As early as 1952, Kantrowitz wrote that "it is possible to obtain shock Mach numbers in the neighborhood of 25 with reasonable pressures and shock tube sizes."[34]

Other investigators also worked with these devices. Raymond Seeger, chief of aerodynamics at the Naval Ordnance Laboratory, built one. R. N. Hollyer conducted experiments at the University of Michigan. At NACA-Langley, the first shock tube entered service in 1951. The Air Force also was interested. The 1954 report of the SAB pointed to "shock tubes and other devices for producing extremely strong shocks" as an "experimental technique" that could give new insights into fundamental problems of hypersonics.[35]

Thus, when Emanuel met Kantrowitz at that cocktail party, this academic physicist indeed was in a position to help the Atlas effort. He had already gained hands-on experience by conducting shock-tube experiments at temperatures and shock velocities that were pertinent to re-entry of an ICBM. Emanuel then staked him to a new shock-tube center, Avco Research Laboratory, which opened for business early in 1955.

Kantrowitz wanted the highest shock velocities, which he obtained by using lightweight helium as the driver gas. He heated the helium strongly by adding a mixture of gaseous hydrogen and oxygen. Too little helium led to violent burning with unpredictable detonations, but use of 70 percent helium by weight gave a controlled burn that was free of detonations. The sudden heating of this driver gas also ruptured the diaphragm.

Standard optical instruments, commonly used in wind-tunnel work, were available for use with shock tubes as well. These included the shadowgraph, schlieren apparatus, and Mach-Zehnder interferometer. To measure the speed of the shock, it proved useful to install ionization-sensitive pickups that responded to changes in electrical resistance as shock waves passed. Several such pickups, spaced along the length of the tube, gave good results at speeds up to Mach 16.

Within the tube, the shock raced ahead of the turbulent mix of driver gases. Between the shock and the driver gases lay a "homogeneous gas sample" (HGS), a cylindrical slug of test gas moving nearly with the speed of the shock. The measured speed of the shock, together with standard laws of gasdynamics, permitted a complete calculation of the pressure, temperature, and internal energy of the HGS. Even when the HGS experienced energy absorption due to dissociation of its constituent molecules, it was possible to account for this through a separate calculation.[36]

The HGS swept over a small model of a nose cone placed within the stress. The time for passage was of the order of 100 microseconds, with the shock tube thus operating as a "wind tunnel" having this duration for a test. This nevertheless was long enough for photography. In addition, specialized instruments permitted study of heat transfer. These included thin-gauge resistance thermometers for temperature measurements and thicker-gauge calorimeters to determine heat transfer rates.

Metals increase their electrical resistance in response to a temperature rise. Both the thermometers and the calorimeters relied on this effect. To follow the sudden temperature increase behind the shock, the thermometer needed a metal film that was thin indeed, and Avco researchers achieved a thickness of 0.3 microns. They did this by using a commercial product, Liquid Bright Platinum No. 05, from Hanovia Chemical and Manufacturing Company. This was a mix of organic compounds of platinum and gold, dissolved in oils. Used as a paint, it was applied with a brush and dried in an oven.

The calorimeters used bulk platinum foil that was a hundred times thicker, at 0.03 millimeters. This thickness diminished their temperature rise and allowed the observed temperature increase to be interpreted as a rate of heat transfer. Both the thermometers and calorimeters were mounted to the surface of nose-cone models, which typically had the shape of a hemisphere that faired smoothly into a cylinder at the rear. The models were made of Pyrex, a commercial glass that did not readily crack. In addition, it was a good insulator.[37]

The investigator Shao-Chi Lin also used a shock tube to study thermal ionization, which made the HGS electrically conductive. To measure this conductivity, Shao used a nonconducting shock tube made of glass and produced a magnetic field within its interior. The flow of the conducting HGS displaced the magnetic lines of force, which he observed. He calibrated the system by shooting a slug of metal having known conductivity through the field at a known speed. Measured HGS conductivities showed good agreement with values calculated from theory, over a range from Mach 10 to Mach 17.5. At this highest flow speed, the conductivity of air was an order of magnitude greater than that of seawater.[38]

With shock tubes generating new data, there was a clear need to complement the data with new solutions in aerodynamics and heat transfer. The original Allen-Eggers paper had given a fine set of estimates, but they left out such realistic effects as dissociation, recombination, ionization, and changes in the ratio of specific heats. Again, it was necessary to make simplifying assumptions. Still, the first computers were at hand, which meant that solutions did not have to be in closed form. They might be equations that were solvable electronically.

Recombination of ions and of dissociated diatomic molecules—oxygen and nitrogen—was particularly important at high Mach, for this chemical process could deliver additional heat within the boundary layer. Two simplified cases stood out. In "equilibrium flow," the recombination took place instantly, responding immediately to the changing temperature and pressure within the boundary layer. The extent of ionization and dissociation then were simple point functions of the temperature and pressure at any location, and they could be calculated directly.

The other limiting case was "frozen flow." One hesitates to describe a 9000 K airstream as "frozen," but here it meant that the chemical state of the boundary layer retained its condition within the free stream behind the bow shock. Essentially this means that recombination proceeded so slowly that the changing conditions within the boundary layer had no effect on the degrees of dissociation and ionization. These again could be calculated directly, although this time as a consequence of conditions behind the shock rather than in the boundary layer. Frozen flow occurred when the air was rarefied.

These approximations avoided the need to deal with the chemistry of finite reaction rates, wherein recombination would not instantly respond to the rapidly varying flow conditions across the thickness of a boundary layer but would lag behind the changes. In 1956 the aerodynamicist Lester Lees proposed a heat-transfer theory that specifically covered those two limiting cases.[39] Then in 1957, Kantrowitz's colleagues at Avco Research Laboratory went considerably further.

The Avco lab had access to the talent of nearby MIT. James Fay, a professor of mechanical engineering, joined with Avco's Frederick Riddell to treat anew the problem of heat transfer in dissociated air. Finite reaction-rate chemistry was at the heart of their agenda, and again they needed a simplifying assumption: that the airflow velocity was zero. However, this condition was nearly true at the forward tip of a nose cone, where the heating was most severe.

Starting with a set of partial differential equations, they showed that these equations reduced to a set of nonlinear ordinary differential equations. Using an IBM 650 computer, they found that a numerical solution of these nonlinear equations was reasonably straightforward. In dealing with finite-rate chemistry, they introduced a "reaction rate parameter" that attempted to capture the resulting effects. They showed that a re-entering nose cone could fall through 100,000 feet while transitioning from the frozen to the equilibrium regime. Within this transition region, the boundary layer could be expected to be partly frozen, near the free stream, and partly in equilibrium, near the wall.

The Fay-Riddell theory appeared in the February 1958 *Journal of the Aeronautical Sciences*. That same issue presented experimental results, also from Avco, that tested the merits of this treatment. The researchers obtained shock-tube data with shock Mach numbers as high as 17.5. At this Mach, the corresponding speed of 17,500 feet per second approached the velocity of a satellite in orbit. Pressures within the shock-tube test gas simulated altitudes of 20,000, 70,000, and 120,000 feet, with equilibrium flow occurring in the models' boundary layers even at the highest equivalent height above the ground.

Most data were taken with calorimeters, although data points from thin-gauge thermometers gave good agreement. The measurements showed scatter but fit neatly on curves calculated from the Fay-Riddell theory. The Lees theory underpredicted heat-transfer rates at the nose-cone tip, calling for rates up to 30 percent lower than those observed. Here, within a single issue of that journal, two papers from Avco gave good reason to believe that theoretical and experimental tools were at hand to learn the conditions that a re-entering ICBM nose cone would face during its moments of crisis.[40]

Still, this was not the same as actually building a nose cone that could survive this crisis. This problem called for a separate set of insights. These came from the U.S. Army and were also developed independently by an individual: George Sutton of General Electric.

ABLATION

In 1953, on the eve of the Atlas go-ahead, investigators were prepared to consider several methods for thermal protection of its nose cone. The simplest was the heat sink, with a heat shield of thick copper absorbing the heat of re-entry. An alternative approach, the hot structure, called for an outer covering of heat-resistant shingles that were to radiate away the heat. A layer of insulation, inside the shingles, was to protect the primary structure. The shingles, in turn, overlapped and could expand freely.

A third approach, transpiration cooling, sought to take advantage of the light weight and high heat capacity of boiling water. The nose cone was to be filled with this liquid; strong g-forces during deceleration in the atmosphere were to press the water against the hot inner skin. The skin was to be porous, with internal steam pressure forcing the fluid through the pores and into the boundary layer. Once injected, steam was to carry away heat. It would also thicken the boundary layer, reducing its temperature gradient and hence its rate of heat transfer. In effect, the nose cone was to stay cool by sweating.[41]

Still, each of these approaches held difficulties. Though potentially valuable, transpiration cooling was poorly understood as a topic for design. The hot-structure concept raised questions of suitably refractory metals along with the prospect of losing the entire nose cone if a shingle came off. The heat-sink approach was likely to lead to high weight. Even so, it seemed to be the most feasible way to proceed, and early Atlas designs specified use of a heat-sink nose cone.[42]

The Army had its own activities. Its missile program was separate from that of the Air Force and was centered in Huntsville, Alabama, with the redoubtable Wernher von Braun as its chief. He and his colleagues came to Huntsville in 1950 and developed the Redstone missile as an uprated V-2. It did not need thermal protection, but the next missile would have longer range and would certainly need it.[43]

Von Braun was an engineer. He did not set up a counterpart of Avco Research Laboratory, but his colleagues nevertheless proceeded to invent their way toward a nose cone. Their concern lay at the tip of a rocket, but their point of departure came at the other end. They were accustomed to steering their missiles by using jet vanes, large tabs of heat-resistant material that dipped into the exhaust. These vanes then deflected the exhaust, changing the direction of flight. Von Braun's associates thus had long experience in testing materials by placing them within the blast of a rocket engine. This practice carried over to their early nose-cone work.[44]

The V-2 had used vanes of graphite. In November 1952, these experimenters began testing new materials, including ceramics. They began working with nose-cone models late in 1953. In July 1954 they tested their first material of a new type: a reinforced plastic, initially a hard melamine resin strengthened with glass fiber. New test facilities entered service in June 1955, including a rocket engine with thrust of 20,000 pounds and a jet diameter of 14.5 inches.[45]

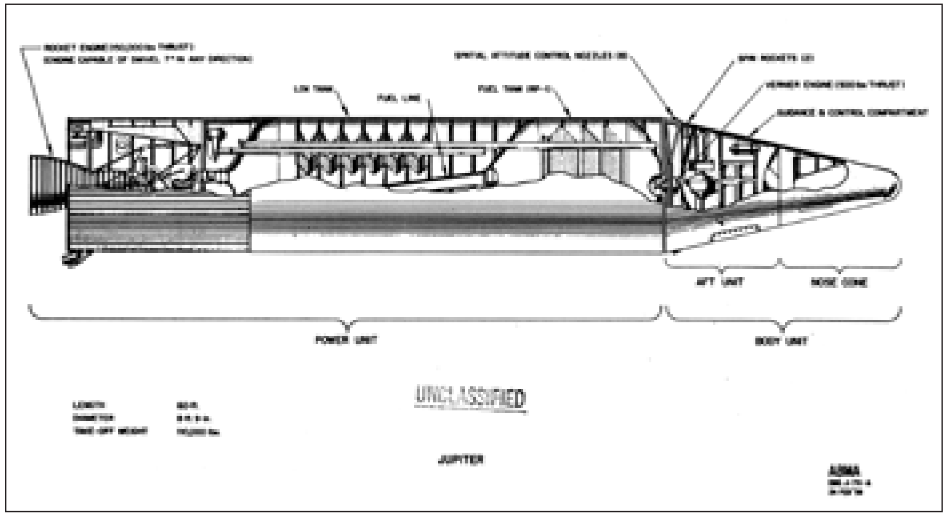
The pace accelerated after November of that year, as Von Braun won approval from Defense Secretary Charles Wilson to proceed with development of his next missile. This was Jupiter, with a range of 1,500 nautical miles.[46] It thus was markedly less demanding than Atlas in its thermal-protection requirements, for it was to re-enter the atmosphere at Mach 15 rather than Mach 20 and higher. Even so, the Huntsville group stepped up its work by introducing new facilities. These included a rocket engine of 135,000 pounds of thrust for use in nose-cone studies.

The effort covered a full range of thermal-protection possibilities. Transpiration cooling, for one, raised unpleasant new issues. Convair fabricated test nose cones with water tanks that had porous front walls. The pressure in a tank could be adjusted to deliver the largest flow of steam when the heat flux was greatest. But this technique led to hot spots, where inadequate flow brought excessive temperatures. Transpiration thus fell by the wayside.

Heat sink drew attention, with graphite holding promise for a time. It was light in weight and could withstand high temperatures. But it also was a good heat conductor, which raised problems in attaching it to a substructure. Blocks of graphite also contained voids and other defects, which made them unusable.

By contrast, hot structures held promise. Researchers crafted lightweight shingles of tungsten and molybdenum backed by layers of polished corrugated steel and aluminum, to provide thermal insulation along with structural support. When the shingles topped 3,250°F, the innermost layer stayed cool and remained below 200°F. Clearly, hot structures had a future.

The initial work with a reinforced plastic, in 1954, led to many more tests of similar materials. Engineers tested such resins as silicones, phenolics, melamines, Teflon, epoxies, polyesters, and synthetic rubbers. Filler materials included soft glass, fibers of silicon dioxide and aluminum silicate, mica, quartz, asbestos, nylon, graphite, beryllium, beryllium oxide, and cotton.



Jupiter missile with ablative nose cone. (U.S. Army)

Fiber-reinforced polymers proved to hold particular merit. The studies focused on plastics reinforced with glass fiber, with a commercially-available material, Micarta 259-2, demonstrating noteworthy promise. The Army stayed with this choice as it moved toward flight test of subscale nose cones in 1957. The first one used Micarta 259-2 for the plastic, with a glass cloth as the filler.[47]

In this fashion the Army ran well ahead of the Air Force. Yet the Huntsville work did not influence the Atlas effort, and the reasons ran deeper than interservice rivalry. The relevance of that work was open to question because Atlas faced a far more demanding re-entry environment. In addition, Jupiter faced competition from Thor, an Air Force missile of similar range. It was highly likely that only one would enter production, so Air Force designers could not merely become apt pupils of the Army. They had to do their own work, seeking independent approaches and trying to do better than Von Braun.

Amid this independence, George Sutton came to the re-entry problem. He had received his Ph.D. at Caltech in 1955 at age 27, jointly in mechanical engineering and physics. His only experience within the aerospace industry had been a summer job at the Jet Propulsion Laboratory, but he jumped into re-entry with both feet after taking his degree. He joined Lockheed and became closely involved in studying materials suitable for thermal protection. Then he was recruited by General Electric, leaving sunny California and arriving in snowy Schenectady, New York, early in 1956.

Heat sinks for Atlas were ascendant at that time, with Lester Lees's heat-transfer theory appearing to give an adequate account of the thermal environment. Sutton was aware of the issues and wrote a paper on heat-sink nose cones, but his work soon led him in a different direction. There was interest in storing data within a small capsule that would ride with a test nose cone and that might survive re-entry if the main cone were to be lost. This capsule needed its own thermal protection, and it was important to achieve light weight. Hence it could not use a heat sink. Sutton's management gave him a budget of $75,000 to try to find something more suitable.[48]

This led him to re-examine the candidate materials that he had studied at Lockheed. He also learned that other GE engineers were working on a related problem. They had built liquid propellant rocket engines for the Army's Hermes program, with these missiles being steered by jet vanes in the fashion of the V-2 and Redstone. The vanes were made from alternating layers of glass cloth and thermosetting resins. They had become standard equipment on the Hermes A-3, but some of them failed due to delamination. Sutton considered how to avoid this:

> "I theorized that heating would char the resin into a carbonaceous mass of relatively low strength. The role of the fibers should be to hold the carbonaceous char to virgin, unheated substrate. Here, low thermal conductivity was essential to minimize the distance from the hot, exposed surface to the cool substrate, to minimize the mass of material that had to be held by the fibers as well as the degradation of the fibers. The char itself would eventually either be vaporized or be oxidized either by boundary layer oxygen or by CO_2 in the boundary layer. The fibers would either melt or also vaporize. The question was how to fabricate the material so that the fibers interlocked the resin, which was the opposite design philosophy to existing laminates in which the resin interlocks the fibers. I believed that a solution might be the use of short fibers, randomly oriented in a soup of resin, which was then molded into the desired shape. I then began to plan the experiments to test this hypothesis."[49]

Sutton had no pipeline to Huntsville, but his plan echoed that of Von Braun. He proceeded to fabricate small model nose cones from candidate fiber-reinforced plastics, planning to test them by immersion in the exhaust of a rocket engine. GE was developing an engine for the first stage of the Vanguard program; prototypes were at hand, along with test stands. Sutton arranged for an engine to produce an exhaust that contained free oxygen to achieve oxidation of the carbon-rich char.

He used two resins along with five types of fiber reinforcement. The best performance came with the use of Refrasil reinforcement, a silicon-dioxide fiber. Both resins yielded composites with a heat capacity of 6,300 BTU per pound or greater. This was astonishing. The materials had a density of 1.6 times that of water. Yet they absorbed more than six times as much heat, pound for pound, as boiling water![50]

Here was a new form of thermal protection: ablation. An ablative heat shield could absorb energy through latent heat, when melting or evaporating, and through sensible heat, with its temperature rise. In addition, an outward flow of ablating volatiles thickened the boundary layer, which diminished the heat flux. Ablation promised all the advantages of transpiration cooling, within a system that could be considerably lighter and yet more capable.[51]

Sutton presented his experimental results in June 1957 at a technical conference held at the firm of Ramo-Wooldridge in Los Angeles. This company was providing technical support to the Air Force's Atlas program management. Following this talk, George Solomon, one of that firm's leading scientists, rose to his feet and stated that ablation was the solution to the problem of thermal protection.

The Army thought so too. It had invented ablation on its own, considerably earlier and amid far deeper investigation. Indeed, at the moment when Sutton gave his talk, Von Braun was only two months away from a successful flight test of a subscale nose cone. People might argue whether the Soviets were ahead of the United States in missiles, but there was no doubt that the Army was ahead of the Air Force in nose cones. Jupiter was already slated for an ablative cone, but Thor was to use heat sink, as was the intercontinental Atlas.

Already, though, new information was available concerning transition from laminar to turbulent flow over a nose cone. Turbulent heating would be far more severe, and these findings showed that copper, the best heat-sink material, was inadequate for an ICBM. Materials testing now came to the forefront, and this work needed new facilities. A rocket-engine exhaust could reproduce the rate of heat transfer, but in Kantrowitz's words, "a rocket is not hot enough."[52] It could not duplicate the temperatures of re-entry.

A shock tube indeed gave a suitably hot flow, but its duration of less than a millisecond was hopelessly inadequate for testing ablative materials. Investigators needed a new type of wind tunnel that could produce a continuous flow, but at temperatures far greater than were available. Fortunately, such an installation did not have to reproduce the hypersonic Mach numbers of re-entry; it sufficed to duplicate the necessary temperatures within the flow. The instrument that did this was the arc tunnel.

It heated the air with an electric arc, which amounted to a man-made stroke of lightning. Such arcs were in routine use in welding; Avco's Thomas Brogan noted that they reached 6500 K, "a temperature which would exist at the [tip] of a blunt body flying at 22,000 feet per second." In seeking to develop an arc-heated wind tunnel, a point of departure lay in West Germany, where researchers had built a "plasma jet."[53]

This device swirled water around a long carbon rod that served as the cathode. The motion of the water helped to keep the arc focused on the anode, which was also of carbon and which held a small nozzle. The arc produced its plasma as a mix of very hot steam and carbon vapor, which was ejected through the nozzle. This invention achieved pressures of 50 atmospheres, with the plasma temperature at the nozzle exit being measured at 8000 K. The carbon cathode eroded relatively slowly, while the water supply was easily refilled. The plasma jet therefore could operate for fairly long times.[54]

At NACA-Langley, an experimental arc tunnel went into operation in May 1957. It differed from the German plasma jet by using an electric arc to heat a flow of air, nitrogen, or helium. With a test section measuring only seven millimeters square, it was a proof-of-principle instrument rather than a working facility. Still, its plasma temperatures ranged from 5800 to 7000 K, which was well beyond the reach of a conventional hypersonic wind tunnel.[55]

At Avco, Kantrowitz paid attention when he heard the word "plasma." He had been studying such ionized gases ever since he had tried to invent controlled fusion. His first arc tunnel was rated only at 130 kilowatts, a limited power level that restricted the simulated altitude to between 165,000 and 210,000 feet. Its hot plasma flowed from its nozzle at Mach 3.4, but when this flow came to a stop when impinging on samples of quartz, the temperature corresponded to flight velocities as high as 21,000 feet per second. Tests showed good agreement between theory and experiment, with measured surface temperatures of 2700 K falling within three percent of calculated values. The investigators concluded that opaque quartz "will effectively absorb about 4000 BTU per pound for ICBM and [intermediate-range] trajectories."[56]

In Huntsville, Von Braun's colleagues found their way as well to the arc tunnel. They also learned of the initial work in Germany. In addition, the small California firm of Plasmadyne acquired such a device and then performed experiments under contract to the Army. In 1958 Rolf Buhler, a company scientist, discovered that when he placed a blunt rod of graphite in the flow, the rod became pointed. Other investigators attributed this result to the presence of a cool core in the arc-heated jet, but Sutton succeeded in deriving this observed shape from theory.

This immediately raised the prospect of nose cones that after all might be sharply pointed rather than blunt. Such re-entry bodies would not slow down in the upper atmosphere, perhaps making themselves tempting targets for antiballistic missiles, but would continue to fall rapidly. Graphite still had the inconvenient features noted previously, but a new material, pyrolytic graphite, promised to ease the problem of its high thermal conductivity.

Pyrolytic graphite was made by chemical vapor deposition. One placed a temperature-resistant form in an atmosphere of gaseous hydrocarbons. The hot surface broke up the gas molecules, a process known as pyrolysis, and left carbon on the surface. The thermal conductivity then was considerably lower in a direction normal to the surface than when parallel to it. The low value of this conductivity, in the normal direction, made such graphite attractive.[57]

Having whetted their appetites with the 130-kilowatt facility, Avco went on to build one that was two orders of magnitude more powerful. It used a 15-megawatt power supply and obtained this from a bank of 2,000 twelve-volt truck batteries, with motor-generators to charge them. They provided direct current for run times of up to a minute and could be recharged in an hour.[58]

With this, Avco added the high-power arc tunnel to the existing array of hypersonic flow facilities. These included aerodynamic wind tunnels such as Becker's, along with plasma jets and shock tubes. And while the array of ground installations proliferated, the ICBM program was moving toward a different kind of test: full-scale flight.

Flight Test

The first important step in this direction came in January 1955, when the Air Force issued a letter contract to Lockheed that authorized them to proceed with the X-17. It took shape as a three-stage missile, with all three stages using solid-propellant rocket motors from Thiokol. It was to reach Mach 15, and it used a new flight mode called "over the top."

The X-17 was not to fire all three stages to achieve a very high ballistic trajectory. Instead it started with only its first stage, climbing to an altitude of 65 to 100 miles. Descent from such an altitude imposed no serious thermal problems. As it re-entered the atmosphere, large fins took hold and pointed it downward. Below 100,000 feet, the two upper stages fired, again while pointing downward. These stages accelerated a test nose cone to maximum speed, deep within the atmosphere. This technique prevented the nose cone from decelerating at high altitude, which would have happened with a very high ballistic flight path. Over-the-top also gave good control of both the peak Mach and of its altitude of attainment.

The accompanying table summarizes the results. Following a succession of subscale and developmental flights that ran from 1955 into 1956, the program conducted two dozen test firings in only eight months. The start was somewhat shaky as no more than two of the first six X-17s gained full success, but the program soon settled down to routine achievement. The simplicity of solid-propellant rocketry enabled the flights to proceed with turnaround times of as little as four days. Launches required no more than 40 active personnel, with as many as five such flights taking place within the single month of October 1956. All of them flew from a single facility: Pad 3 at Cape Canaveral.[59]

X-17 FLIGHT TESTS

Date	*Nose-Cone Shape*	*Results*
17 Jul 1956	Hemisphere	Mach 12.4 at 40,000 feet.
27 Jul 1956	Cubic Paraboloid	Third stage failed to ignite.
18 Aug 1956	Hemisphere	Missile exploded 18 sec. after launch.
23 Aug 1956	Blunt	Mach 12.4 at 38,500 feet.
28 Aug 1956	Blunt	Telemetry lost prior to apogee.
8 Sep 1956	Cubic Paraboloid	Upper stages ignited while ascending.
1 Oct 1956	Hemisphere	Mach 12.1 at 36,500 feet.
5 Oct 1956	Hemisphere	Mach 13.7 at 54,000 feet.
13 Oct 1956	Cubic Paraboloid	Mach 13.8 at 58,500 feet.
18 Oct 1956	Hemisphere	Mach 12.6 at 37,000 feet.
25 Oct 1956	Blunt	Mach 14.2 at 59,000 feet.
5 Nov 1956	Blunt (Avco)	Mach 12.6 at 41,100 feet.
16 Nov 1956	Blunt (Avco)	Mach 13.8 at 57,000 feet.
23 Nov 1956	Blunt (Avco)	Mach 11.3 at 34,100 feet.
3 Dec 1956	Blunt (Avco)	Mach 13.8 at 47,700 feet.
11 Dec 1956	Blunt Cone (GE)	Mach 11.4 at 34,000 feet.
8 Jan 1957	Blunt Cone (GE)	Mach 11.5 at 34,600 feet.
15 Jan 1957	Blunt Cone (GE)	Upper stages failed to ignite.
29 Jan 1957	Blunt Cone (GE)	Missile destroyed by Range Safety.
7 Feb 1957	Blunt Cone (GE)	Mach 14.4 at 57,000 feet.
14 Feb 1957	Hemisphere	Mach 12.1 at 35,000 feet.
1 Mar 1957	Blunt Cone (GE)	Mach 11.4 at 35,600 feet.
11 Mar 1957	Blunt (Avco)	Mach 11.3 at 35,500 feet.
21 Mar 1957	Blunt (Avco)	Mach 13.2 at 54,500 feet.

Source: "Re-Entry Test Vehicle X-17," pp. 30, 32.

Many nose cones approached or topped Mach 12 at altitudes below 40,000 feet. This was half the speed of a satellite, at altitudes where airliners fly today. One places this in perspective by noting that the SR-71 cruised above Mach 3, one-fourth this speed, and at 85,000 feet, which was more than twice as high. Thermal problems dominated its design, with this spy plane being built as a titanium hot structure. The X-15 reached Mach 6.7 in 1967, half the speed of an X-17 nose cone, and at

102,000 feet. Its structure was Inconel X heat sink, and it had further protection from a spray-on ablative. Yet it sustained significant physical damage due to high temperatures and never again approached that mark.[60]

Another noteworthy flight involved a five-stage NACA rocket that was to accomplish its own over-the-top mission. It was climbing gently at 96,000 feet when the third stage ignited. Telemetry continued for an additional 8.2 seconds and then suddenly cut off, with the fifth stage still having half a second to burn. The speed was Mach 15.5 at 98,500 feet. The temperature on the inner surface of the skin was 2,500ºF, close to the melting point, with this temperature rising at nearly 5,300ºF per second.[61]

How then did X-17 nose cones survive flight at nearly this speed, but at little more than one-third the altitude? They did not. They burned up in the atmosphere. They lacked thermal protection, whether heat sink or ablative (which the Air Force, the X-17's sponsor, had not invented yet), and no attempt was made to recover them. The second and third stages ignited and burned to depletion in only 3.7 seconds, with the thrust of these stages being 102,000 and 36,000 pounds, respectively.[62] Acceleration therefore was extremely rapid; exposure to conditions of very high Mach was correspondingly brief. The X-17 thus amounted to a flying shock tube. Its nose cones lived only long enough to return data; then they vanished into thin air.

Yet these data were priceless. They included measurements of boundary-layer transition, heat transfer, and pressure distributions, covering a broad range of peak Mach values, altitudes, and nose-cone shapes. The information from this program complemented the data from Avco Research Laboratory, contributing materially to Air Force decisions that selected ablation for Atlas (and for Titan, a second ICBM), while retaining heat sink for Thor.[63]

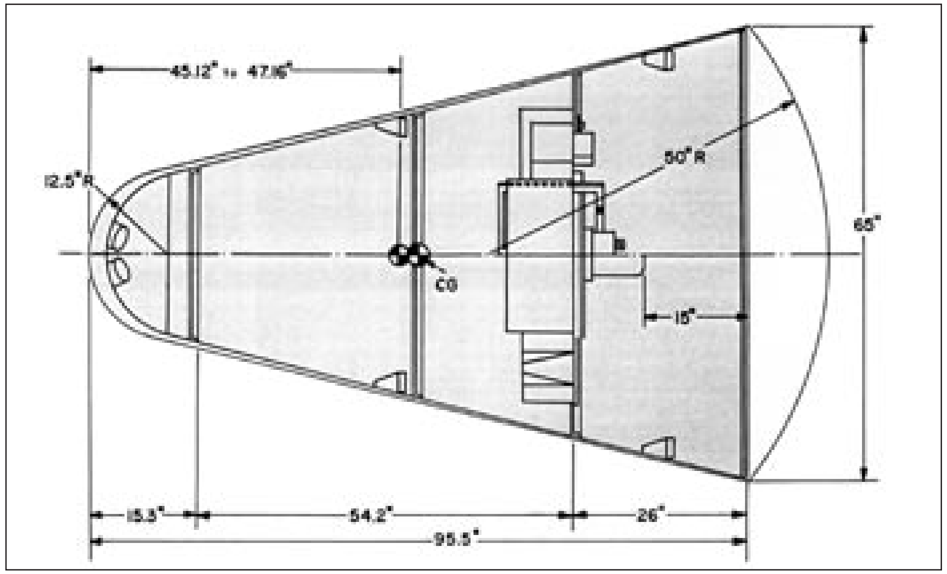
As the X-17 went forward during 1956 and 1957, the Army weighed in with its own flight-test effort. Here were no over-the-top heroics, no ultrashort moments at high Mach with nose cones built to do their duty and die. The Army wanted nothing less than complete tests of true ablating nose cones, initially at subscale and later at full scale, along realistic ballistic trajectories. The nose cones were to survive re-entry. If possible, they were to be recovered from the sea.

The launch vehicle was the Jupiter-C, another product of Von Braun. It was based on the liquid-fueled Redstone missile, which was fitted with longer propellant tanks to extend the burning time. Atop that missile rode two additional stages, both of which were built as clusters of small solid-fuel rockets.

The first flight took place from Cape Canaveral in September 1956. It carried no nose cone; this launch had the purpose of verifying the three-stage design, particularly its methods for stage separation and ignition. A dummy solid rocket rode atop this stack as a payload. All three stages fired successfully, and the flight broke all performance records. The payload reached a peak altitude of 682 miles and attained an estimated range of 3,335 miles.[64]

Thor missile with heat-sink nose cone. (U.S. Air Force)

Nose-cone tests followed during 1957. Each cone largely duplicated that of the Jupiter missile but was less than one-third the size, having a length of 29 inches and maximum diameter of 20 inches. The weight was 314 pounds, of which 83



Jupiter nose cone. (U.S. Army)

pounds constituted the mix of glass cloth and Micarta plastic that formed the ablative material. To aid in recovery in the ocean, each nose cone came equipped with a balloon for flotation, two small bombs to indicate position for sonar, a dye marker, a beacon light, a radio transmitter—and shark repellant, to protect the balloon from attack.[65]

The first nose-cone flight took place in May. Telemetry showed that the re-entry vehicle came through the atmosphere successfully and that the ablative thermal protection indeed had worked. However, a faulty trajectory caused this nose cone to fall 480 miles short of the planned impact point, and this payload was not recovered.

Full success came with the next launch, in August. All three stages again fired, pushing the nose cone to a range of 1,343 statute miles. This was shorter than the planned range of Jupiter, 1,725 miles, but still this payload experienced 95 percent of the total heat transfer that it would have received at the tip for a full-range flight. The nose cone also was recovered, giving scientists their first close look at one that had actually survived.[66]

In November President Eisenhower personally displayed it to the nation. The Soviets had stirred considerable concern by placing two Sputnik satellites in orbit, thus showing that they already had an ICBM. Speaking on nationwide radio and television, Ike sought to reassure the public. He spoke of American long-range bombers and then presented his jewel: “One difficult obstacle on the way to producing a useful long-range weapon is that of bringing a missile back from outer space without its burning up like a meteor. This object here in my office is the nose cone of an experimental missile. It has been hundreds of miles into outer space and back. Here it is, completely intact.”[67]

Jupiter then was in flight test and became the first missile to carry a full-size nose cone to full range.[68] But the range of Jupiter was far shorter than that of Atlas. The Army had taken an initial lead in nose-cone testing by taking advantage of its early start, but by the time of that flight—May 1958—all eyes were on the Air Force and on flight to intercontinental range.

Atlas also was in flight test during 1958, extending its range in small steps, but it still was far from ready to serve as a test vehicle for nose cones. To attain 5,000-mile range, Air Force officials added an upper stage to the Thor. The resulting rocket, the Thor-Able, indeed had the job of testing nose cones. An early model, from General Electric, weighed more than 600 pounds and carried 700 pounds of instruments.[69]

Two successful flights, both to full range, took place during July 1958. The first one reached a peak altitude of 1,400 miles and flew 5,500 miles to the South Atlantic. Telemetered data showed that its re-entry vehicle survived the fiery passage through the atmosphere, while withstanding four times the heat load of a Thor heat-sink nose cone. This flight carried a passenger, a mouse named Laska in honor of what soon became the 49th state. Little Laska lived through decelerations during re-entry that reached 60 g, due to the steepness of the trajectory, but the nose cone was not recovered and sank into the sea. Much the same happened two weeks later, with the mouse being named Wickie. Again the reentry vehicle came through the atmosphere successfully, but Wickie died for his country as well, for this nose cone also sank without being recovered.[70]

A new series of tests went forward during 1959, as General Electric introduced the RVX-1 vehicle. Weighing 645 pounds, 67 inches long with a diameter at the base of 28 inches, it was a cylinder with a very blunt nose and a conical afterbody for stability.[71] A flight in March used phenolic nylon as the ablator. This was a phenolic resin containing randomly oriented one-inch-square pieces of nylon cloth. Light weight was its strong suit; with a density as low as 72 pounds per cubic foot, it was only slightly denser than water. It also was highly effective as insulation. Following flight to full range, telemetered data showed that a layer only a quarter-inch thick could limit the temperature rise on the aft body, which was strongly heated, to less than 200ºF. This was well within the permissible range for aluminum, the most familiar of aerospace materials. For the nose cap, where the heating was strongest, GE installed a thick coating of molded phenolic nylon.[72]

Within this new series of flights, new guidance promised enhanced accuracy and a better chance of retrieval. Still, that March flight was not recovered, with another shot also flying successfully but again sinking beneath the waves. When the first recovery indeed took place, it resulted largely from luck.

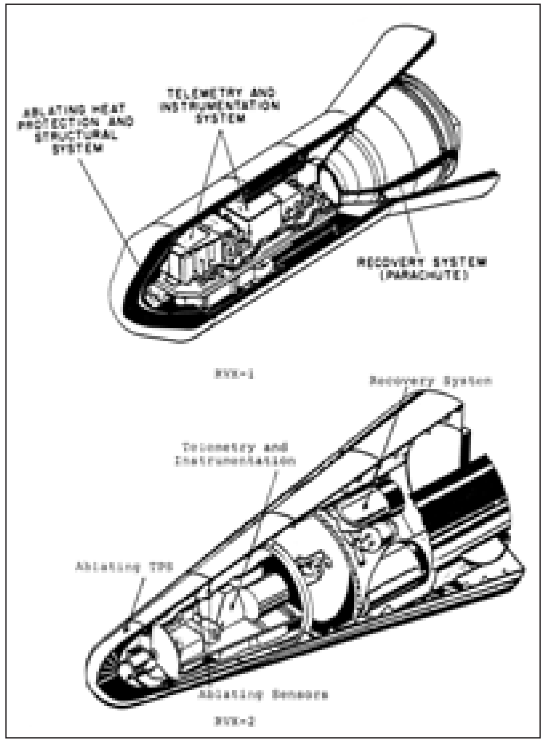
Early in April an RVX-1 made a flawless flight, soaring to 764 miles in altitude and sailing downrange to 4,944 miles. Peak speed during re-entry was Mach 20, or 21,400 feet per second. Peak heating occurred at Mach 16, or 15,000 feet per second, and at 60,000 feet. The nose cone took this in stride, but searchers failed to detect its radio signals. An Avco man in one of the search planes saved the situation by spotting its dye marker. Aircraft then orbited the position for three hours until a recovery vessel arrived and picked it up.[73]

It was the first vehicle to fly to intercontinental range and return for inspection. Avco had specified its design, using an ablative heat shield of fused opaque quartz. Inspection of the ablated surface permitted comparison with theory, and the results were described as giving "excellent agreement." The observed value of maximum ablated thickness was 9 percent higher than the theoretical value. The weight loss of ablated material agreed within 20 percent, while the fraction of ablated material that vaporized during re-entry was only 3 percent higher than the theoretical value. Most of the differences could be explained by the effect of impurities on the viscosity of opaque quartz.[74]

A second complete success was achieved six weeks later, again with a range of 5,000 miles. Observers aboard a C-54 search aircraft witnessed the re-entry, acquired the radio beacon, and then guided a recovery ship to the site.[75] This time the nose-cone design came from GE. That company's project engineer, Walter Schafer, wanted to try several materials and to instrument them with breakwire sensors. These were wires, buried at various depths within the ablative material, that would break as it eroded away and thus disclose the rate of ablation. GE followed a suggestion from George Sutton and installed each material as a 60-degree segment around the cylinder and afterbody, with the same material being repeated every 180 degrees for symmetry.[76]

Within the fast-paced world of nose-cone studies, each year had brought at least one new flight vehicle. The X-17 had flown during 1956. For the Jupiter-C, success had come in 1957. The year 1958 brought both Jupiter and the Thor-Able. Now, in 1959, the nose-cone program was to gain final success by flying full-size re-entry vehicles to full range aboard Atlas.

The program had laid important groundwork in November 1958, when this missile first flew to intercontinental distance. The test conductor, with the hopeful name of Bob Shotwell, pushed the button and the rocket leaped into the night. It traced an arc above the Moon as it flew across the starry sky. It dropped its twin booster engines; then, continuing to accelerate, the brilliant light of its main engine faded. Now it seemed to hang in the darkness like a new star, just below Orion. Shotwell and his crew contained their enthusiasm for a full seven minutes; then they erupted in shouts. They had it; the missile was soaring at 16,000 miles per hour, bound for a spot near the island of St. Helena in the South Atlantic, a full 6,300 miles from the Cape. In Shotwell's words, "We knew we had done it. It was going like a bullet; nothing could stop it."[77]



Nose cones used in flight test. Top, RVX-1; bottom, RVX-2. (U.S. Air Force)

Atlas could carry far heavier loads than Thor-Able, and its first nose cone reflected this. It was the RVX-2, again from General Electric, which had the shape of a long cone with a round tip. With a length of 147 inches and a width at the base of 64 inches, it weighed some 2,500 pounds. Once more, phenolic nylon was used for thermal protection. It flew to a range of 5,047 miles in July 1959 and was recovered. It thereby became the largest object to have been brought back following re-entry.[78]

Attention now turned to developmental tests of a nose cone for the operational Atlas. This was the Mark 3, also from GE. Its design returned to the basic RVX-1 configuration, again with a blunt nose at the front of a cylinder but with a longer conical afterbody. It was slightly smaller than the RVX-2, with a length of 115 inches, diameter at the cylinder of 21 inches, and diameter at the base of 36 inches. Phenolic nylon was specified throughout for thermal protection, being molded under high pressure for the nose cap and tape-wound on the cylinder and afterbody. The Mark 3 weighed 2,140 pounds, making it somewhat lighter than the RVX-2. The low density of phenolic nylon showed itself anew, for of this total weight, only 308 pounds constituted ablative material.[79]

The Mark 3 launches began in October 1959 and ran for several months, with this nose cone entering operational service the following April.[80] The flights again were full -range, with one of them flying 5,000 miles to Ascension Island and another going 6,300 miles. Re-entry speeds went as high as 22,500 feet per second. Peak heat transfer occurred near Mach 14 and 40,000 feet in altitude, approximating the conditions of the X-17 tests. The air at that height was too thin to breathe, but the nose cone set up a shock wave that compressed the incoming flow, producing a wind resistance with dynamic pressure of more than 30 atmospheres. Temperatures at the nose reached 6,500°F.[81]

Each re-entry vehicle was extensively instrumented, mounting nearly two dozen breakwire ablation sensors along with pressure and temperature sensors. The latter were resistance thermometers employing 0.0003-inch tungsten wire, reporting temperatures to 2000°F with an accuracy of 25 to 50°F. The phenolic nylon showed anew that it had the right stuff, for it absorbed heat at the rate of 3,000 BTU per pound, making it three times as effective as boiling water. A report from GE noted, "all temperature sensors located on the cylindrical section were at locations too far below the initial surface to register a temperature rise."[82]

With this, the main effort in re-entry reached completion, and its solution—ablation—had proved to be relatively simple. The process resembled the charring of wood. Indeed, Kantrowitz recalls Von Braun suggesting that it was possible to build a nose cone of lightweight balsa soaked in water and frozen. In Kantrowitz's words, "That might be a very reasonable ablator."[83]

Experience with ablation also contrasted in welcome fashion with a strong tendency of advanced technologies to rely on highly specialized materials. Nuclear energy used uranium-235, which called for the enormous difficulty of isotope separation, along with plutonium, which had to be produced in a nuclear reactor and then be extracted from highly radioactive spent fuel. Solid-state electronics depended on silicon or germanium, but while silicon was common, either element demanded refinement to exquisite levels of purity.

Ablation was different. Although wood proved inappropriate, once the basic concept was in hand the problem became one of choosing the best candidate from a surprisingly wide variety of possibilities. These generally were commercial plastics that served as binders, with the main heat resistance being provided by glass or silica. Quartz also worked well, particularly after being rendered opaque, while pyrolytic graphite exemplified a new material with novel properties.

The physicist Steven Weinberg, winner of a Nobel Prize, stated that a researcher never knows how difficult a problem is until the solution is in hand. In 1956 Theodore von Karman had described re-entry as "perhaps one of the most difficult problems one can imagine. It is certainly a problem that constitutes a challenge to the best brains working in these domains of modern aerophysics."[84] Yet in the end, amid all the ingenuity of shock tubes and arc tunnels, the fundamental insights derived from nothing deeper than testing an assortment of candidate materials in the blast of rocket engines.

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2 MacKenzie, *Inventing*, pp. 113-14. 1,500 feet: Neufeld, *Ballistic*, pp. 69-102 passim.

3 North American Aviation Report AL-1347, pp. 1-6 (quote, p. 4); Fahrney, *History*, p. 1291, footnote 3.

4 North American Aviation Report AL-1347, pp. 38-39; Colonel Roth: Letter, Colonel M. S. Roth to Power Plant Lab, Air Materiel Command, USAF, 11 February 1948.

5 Author interview, Colonel Edward Hall 29 August 1996, Folder 18649, NASA Historical Reference Collection, NASA History Division, Washington, D.C. 20546.

6 North American Aviation Report AL-1347, p. 39.

7 Other North American Aviation names of that era included the NAKA, NALAR, and NASTY battlefield missiles, the Navion private plane, and the NATIV research rocket; see "Thirty Years of Rocketdyne," photo, "Armament Rockets," 1962; Murray, *Atwood*, pp. 32, 44.

8 Rhodes, *Dark Sun*, p. 407 (includes quote); Manchester, *Caesar*, p. 642.

9 "Standard Missile Characteristics: XSM-64 Navaho"; Report AL-1347, op. cit., p. 88; *Development of the Navaho*, pp. 30-31; Augenstein, "Rand"; Fahrney, *History*, pp. 1296-98. General Putt: Letter, Major General Donald Putt to Commanding General, Air Materiel Command, USAF, 21 August 1950.

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11 Ibid., pp. 70-79.

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15 Von Karman and Edson, *Wind*, pp. 300-01; Neufeld, *Ballistic*, p. 98.

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17 AIAA Paper 67-838, pp. 12-13; Neufeld, *Ballistic*, p. 102 (quotes, p. 259).

18 Rhodes, *Dark Sun*, pp. 482-84, 541-42 (quote, p. 541).

19 Neufeld, *Ballistic*, pp. 104-06, 117 (quotes, pp. 105, 106); Rhodes, *Dark Sun*, p. 542.

20 Neufeld, *Ballistic*, p. 117; Emme, *History*, p. 151. Dimensions: Ley, *Rockets*, p. 400.

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24 Neufeld, *Ballistic*, p. 79.

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26 Rose, "Physical," p. 1.

27 Hallion, *Hypersonic*, pp. xxiii, xxvi.

28 *Time*, 13 June 1960 (includes quote). Arthur Kantrowitz: Author interview, 22 June 2001.

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44 Ley, *Rockets*, pp. 237, 245.

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54 ARS Paper 724-58.

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60 This flight is further discussed in ch. 6.

61 NASA RP-1028, p. 488.

62 Miller, *X-Planes*, pp. 215, 217.

63 Ibid., p. 213; *Journal of Spacecraft and Rockets*, January-February 1982, p. 6.

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72 DTIC AD-342828, pp. 16-19; AD-362539, pp. 11, 83.

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79 DTIC AD-362539, pp. 11, 39.

80 Hallion, *Hypersonic*, p. lxxii.

81 DTIC AD-362539, pp. 11-12. Peak heating occurred approximately at maximum dynamic pressure, at Mach 14 (see p. 12). Altitude, 40,000 feet, is from Figs. 2.6.

82 DTIC AD-362539, pp. 9, 12-13 (quote, p. 9).

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3

The X-15

Across almost half a century, the X-15 program stands out to this day not only for its achievements but for its audacity. At a time when the speed record stood right at Mach 2, the creators of the X-15 aimed for Mach 7—and nearly did it.* Moreover, the accomplishments of the X-15 contrast with the history of an X-planes program that saw the X-1A and X-2 fall out of the sky due to flight instabilities, and in which the X-3 fell short in speed because it was underpowered.[1]

The X-15 is all the more remarkable because its only significant source of aerodynamic data was Becker's 11-inch hypersonic wind tunnel. Based on that instrument alone, the Air Force and NACA set out to challenge the potential difficulties of hypersonic piloted flight. They succeeded, with this aircraft setting speed and altitude marks that were not surpassed until the advent of the space shuttle.

It is true that these agencies worked at a time of rapid advance, when performance was leaping forward at rates never approached either before or since. Yet there was more to this craft than a can-do spirit. Its designers faced specific technical issues and overcame them well before the first metal was cut.

The X-3 had failed because it proved infeasible to fit it with the powerful turbojet engines that it needed. The X-15 was conceived from the start as relying on rocket power, which gave it a very ample reserve.

Flight instability was already recognized as a serious concern. Using Becker's hypersonic tunnel, the aerodynamicist Charles McLellan showed that the effectiveness of tail surfaces could be greatly increased by designing them with wedge-shaped profiles.[2]

The X-15 was built particularly to study problems of heating in high-speed flight, and there was the question of whether it might overheat when re-entering the atmosphere following a climb to altitude. Calculations showed that the heating would remain within acceptable bounds if the airplane re-entered with its nose high. This would present its broad underbelly to the oncoming airflow. Here was a new application of the Allen-Eggers blunt-body principle, for an airplane with its nose up effectively became blunt.

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*Official flight records are certified by the Federation Aeronautique Internationale. The cited accomplishments lacked this distinction, but they nevertheless represented genuine achievements.

The plane's designers also benefited from a stroke of serendipity. Like any airplane, the X-15 was to reduce its weight by using stressed-skin construction; its outer skin was to share structural loads with internal bracing. Knowing the stresses this craft would encounter, the designers produced straightforward calculations to give the requisite skin gauges. A separate set of calculations gave the skin thicknesses that were required for the craft to absorb its heat of re-entry without weakening. The two sets of skin gauges were nearly the same! This meant that the skin could do double duty, bearing stress while absorbing heat. It would not have to thicken excessively, thus adding weight, to cope with the heat.

Yet for all the ingenuity that went into this preliminary design, NACA was a very small tail on a very large dog in those days, and the dog was the Air Force. NACA alone lacked the clout to build anything, which is why one sees military insignia on photos of the X-planes of that era. Fortuitously, two new inventions—the twin-spool and the variable-stator turbojet—were bringing the Air Force face to face with a new era in flight speed. Ramjet engines also were in development, promising still higher speed. The X-15 thus stood to provide flight-test data of the highest importance—and the Air Force grabbed the concept and turned it into reality.

ORIGINS OF THE X-15

Experimental aircraft flourished during the postwar years, but it was hard for them to keep pace with the best jet fighters. The X-1, for instance, was the first piloted aircraft to break the sound barrier. But only six months later, in April 1948, the test pilot George Welch did this in a fighter plane, the XP-86.[3] The layout of the XP-86 was more advanced, for it used a swept wing whereas the X-1 used a simple straight wing. Moreover, while the X-1 was a highly specialized research airplane, the XP-86 was a prototype of an operational fighter.

Much the same happened at Mach 2. The test pilot Scott Crossfield was the first to reach this mark, flying the experimental Douglas Skyrocket in November 1953.[4] Just then, Alexander Kartveli of Republic Aviation was well along in crafting the XF-105. The Air Force had ordered 37 of them in March 1953. It first flew in December 1955; in June 1956 an F-105 reached Mach 2.15. It too was an operational fighter, in contrast to the Skyrocket of two and a half years earlier.

Ramjet-powered craft were to do even better. Navaho was to fly near Mach 3. An even more far-reaching prospect was in view at that same Republic Aviation, where Kartveli was working on the XF-103. It was to fly at Mach 3.7 with its own ramjet, nearly 2,500 miles per hour (mph), with a sustained ceiling of 75,000 feet.[5]

Yet it was already clear that such aircraft were to go forward in their programs without benefit of research aircraft that could lay groundwork. The Bell X-2 was in development as a rocket plane designed to reach Mach 3, but although first thoughts of it dated to 1945, the program encountered serious delays. The airplane did not so much as fly past Mach 1 until 1956.[6]

Hence in 1951 and 1952, it already was too late to initiate a new program aimed at building an X-plane that could provide timely support for the Navaho and XF-103. The X-10 supported Navaho from 1954 to 1957, but it used turbojets rather than ramjets and flew at Mach 2.There was no quick and easy way to build aircraft capable of Mach 3, let alone Mach 4; the lagging X-2 was the only airplane that might do this, however belatedly. Yet it was already appropriate to look beyond the coming Mach 3 generation and to envision putative successors.

Maxwell Hunter, at Douglas Aircraft, argued that with fighter aircraft on their way to Mach 3, antiaircraft missiles would have to fly at Mach 5 to Mach 10.[7] In addition, Walter Dornberger, the wartime head of Germany's rocket program, now was at Bell Aircraft. He was directing studies of Bomi, Bomber Missile, a two-stage fully reusable rocket-powered bomber concept that was to reach 8,450 mph, or Mach 12.[8] At Convair, studies of intercontinental missiles included boost-glide concepts with much higher speeds.[9] William Dorrance, a company aerodynamicist, had not been free to disclose the classified Atlas concept to NACA but nevertheless declared that data at speeds up to Mach 20 were urgently needed.[10] In addition, the Rand Corporation had already published reports that envisioned spacecraft in orbit. The documents proposed that such satellites could serve for weather observation and for military reconnaissance.[11]

At Bell Aircraft, Robert Woods, a co-founder of the company, took a strong interest in Dornberger's ideas. Woods had designed the X-1, the X-1A that reached Mach 2.4, and the X-2. He also was a member of NACA's influential Committee on Aerodynamics. At a meeting of this committee in October 1951, he recommended a feasibility study of a "V-2 research airplane, the objective of which would be to obtain data at extreme altitudes and speeds and to explore the problems of re-entry into the atmosphere."[12] He reiterated this recommendation in a letter to the committee in January 1952. Later that month, he received a memo from Dornberger that outlined an "ionospheric research plane," capable of reaching altitudes of "more than 75 miles."[13]

NACA Headquarters sent copies of these documents to its field centers. This brought responses during May, as several investigators suggested means to enhance the performance of the X-2. The proposals included a rocket-powered carrier aircraft with which this research airplane was to attain "Mach numbers up to almost 10 and an altitude of about 1,000,000 feet,"[14] which the X-2 had certainly never been meant to attain. A slightly more practical concept called for flight to 300,000 feet.[15] These thoughts were out in the wild blue, but they showed that people at least were ready to think about hypersonic flight.

Accordingly, at a meeting in June 1952, the Committee on Aerodynamics adopted a resolution largely in a form written by another of its members, the Air Force science advisor Albert Lombard:

> WHEREAS, The upper stratosphere is the important new flight region for military aircraft in the next decade and certain guided missiles are already under development to fly in the lower portions of this region, and
> WHEREAS, Flight in the ionosphere and in satellite orbits in outer space has long-term attractiveness to military operations….
> RESOLVED, That the NACA Committee on Aerodynamics recommends that (1) the NACA increase its program dealing with problems of unmanned and manned flight in the upper stratosphere at altitudes between 12 and 50 miles, and at Mach numbers between 4 and 10, and (2) the NACA devote a modest effort to problems associated with unmanned and manned flights at altitudes from 50 miles to infinity and at speeds from Mach number 10 to the velocity of escape from the Earth's gravity.

Three weeks later, in mid-July, the NACA Executive Committee adopted essentially the same resolution, thus giving it the force of policy.[16]

Floyd Thompson, associate director of NACA-Langley, responded by setting up a three-man study team. Their report came out a year later. It showed strong fascination with boost-glide flight, going so far as to propose a *commercial* aircraft based on a boost-glide Atlas concept that was to match the standard fares of current airliners. On the more immediate matter of a high-speed research airplane, this group took the concept of a boosted X-2 as a point of departure, suggesting that such a vehicle could reach Mach 3.7. Like the million-foot X-2 and the 300,000-foot X-2, this lay beyond its thermal limits. Still, this study pointed clearly toward an uprated X-2 as the next step.[17]

The Air Force weighed in with its views in October 1953. A report from the Aircraft Panel of its Scientific Advisory Board (SAB) discussed the need for a new research airplane of very high performance. The panelists stated that "the time was ripe" for such a venture and that its feasibility "should be looked into."[18] With this plus the report of the Langley group, the question of such a research plane went on the agenda of the next meeting of NACA's Interlaboratory Research Airplane Panel. It took place at NACA Headquarters in Washington in February 1954.

It lasted two days. Most discussions centered on current programs, but the issue of a new research plane indeed came up. The participants rejected the concept of an uprated X-2, declaring that it would be too small for use in high-speed studies. They concluded instead "that provision of an entirely new research airplane is desirable."[19]

This decision led quickly to a new round of feasibility studies at each of the four NACA centers: Langley, Ames, Lewis, and the High-Speed Flight Station. The study conducted at Langley was particularly detailed and furnished much of the basis for the eventual design of the X-15. Becker directed the work, taking responsibility for trajectories and aerodynamic heating. Maxime Faget addressed issues of propulsion. Three other specialists covered the topics of structures and materials, piloting, configuration, stability, and control.[20]

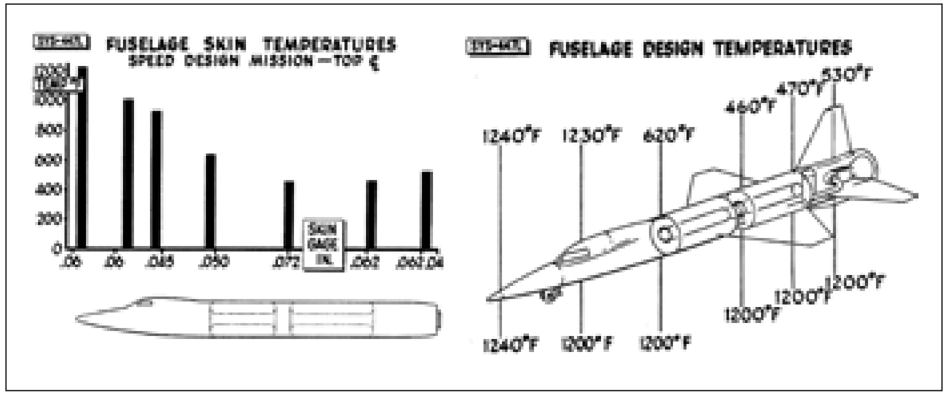
A performance analysis defined a loaded weight of 30,000 pounds. Heavier weights did not increase the peak speed by much, whereas smaller concepts showed a marked falloff in this speed. Trajectory studies then showed that this vehicle could reach a range of speeds, from Mach 5 when taking off from the ground to Mach 10 if launched atop a rocket-powered first stage. If dropped from a B-52 carrier, it would attain Mach 6.3.[21]

Concurrently with this work, prompted by a statement written by Langley's Robert Gilruth, the Air Force's Aircraft Panel recommended initiation of a research airplane that would reach Mach 5 to 7, along with altitudes of several hundred thousand feet. Becker's group selected a goal of Mach 7, noting that this would permit investigation of "extremely wide ranges of operating and heating conditions." By contrast, a Mach 10 vehicle "would require a much greater expenditure of time and effort" and yet "would add little in the fields of stability, control, piloting problems, and structural heating."[22]

A survey of temperature-resistant superalloys brought selection of Inconel X for the primary aircraft structure. This was a proprietary alloy from the firm of International Nickel, comprising 72.5 percent nickel, 15 percent chromium, 1 percent columbium, and iron as most of the balance. Its principal constituents all counted among the most critical materials used in aircraft construction, being employed in small quantities for turbine blades in jet engines. But Inconel X was unmatched in temperature resistance, holding most of its strength and stiffness at temperatures as high as 1200°F.[23]

Could a Mach 7 vehicle re-enter the atmosphere without exceeding this temperature limit? Becker's designers initially considered that during reentry, the airplane should point its nose in the direction of flight. This proved impossible; in Becker's words, "the dynamic pressures quickly exceeded by large margins the limit of 1,000 pounds per square foot set by structural considerations, and the heating loads became disastrous."

Becker tried to alleviate these problems by using lift during re-entry. According to his calculations, he obtained more lift by raising the nose—and the problem became far more manageable. He saw that the solution lay in having the plane enter the atmosphere with its nose high, presenting its flat undersurface to the air. It then would lose speed in the upper atmosphere, easing both the overheating and the aerodynamic pressure. The Allen-Eggers paper had been in print for nearly a year, and in Becker's words, "it became obvious to us that what we were seeing here was a new manifestation of H. J. Allen's 'blunt-body' principle. As we increased the angle of attack, our configuration in effect became more 'blunt.'" Allen and Eggers had



X-15 skin gauges and design temperatures. Generally, the heaviest gauges were required to meet the most severe temperatures. (NASA)

developed their principle for missile nose cones, but it now proved equally useful when applied to a hypersonic airplane.[24]

The use of this principle now placed a structural design concept within reach. To address this topic, Norris Dow, the structural analyst, considered the use of a heat-sink structure. This was to use Inconel X skin of heavy gauge to absorb the heat and spread it through this metal so as to lower its temperature. In addition, the skin was to play a structural role. Like other all-metal aircraft, the nascent X-15 was to use stressed-skin construction. This gave the skin an optimized thickness so that it could carry part of the aerodynamic loads, thus reducing the structural weight.

Dow carried through a design exercise in which he initially ignored the issue of heating, laying out a stressed-skin concept built of Inconel X with skin gauges determined only by requirements of mechanical strength and stiffness. A second analysis then took note of the heating, calculating new gauges that would allow the skin to serve as a heat sink. It was clear that if those gauges were large, adding weight to the airplane, then it might be necessary to back off from the Mach 7 goal so as to reduce the input heat load, thereby reducing the required thicknesses.

When Dow made the calculations, he received a welcome surprise. He found that the weight and thickness of a heat-absorbing structure were nearly the same as those of a simple aerodynamic structure! This meant that a hypersonic airplane, designed largely from consideration of aerodynamic loads, could provide heat-sink thermal protection as a bonus. It could do this with little or no additional weight.[25]

This, more than anything, was the insight that made the X-15 possible. Designers such as Dow knew all too well that ordinary aircraft aluminum lost strength beyond Mach 2, due to aerodynamic heating. Yet if hypersonic flight was to mean anything, it meant choosing a goal such as Mach 7 and then reaching this goal through the clever use of available heat-resistant materials. In Becker's study, the Allen-Eggers blunt-body principle reduced the re-entry heating to a level that Inconel X could accommodate.

The putative airplane still faced difficult issues of stability and control. Early in 1954 these topics were in the forefront, for the test pilot Chuck Yeager had nearly crashed when his X-1A fell out of the sky due to a loss of control at Mach 2.44. This problem of high-speed instability reflected the natural instability, at all Mach numbers, of a simple wing-body vehicle that lacked tail surfaces. Such surfaces worked well at moderate speeds, like the feathers of an arrow, but lost effectiveness with increasing Mach. Yeager's near-disaster had occurred because he had pushed just beyond a speed limit set by such considerations of stability. These considerations would be far more severe at Mach 7.[26]

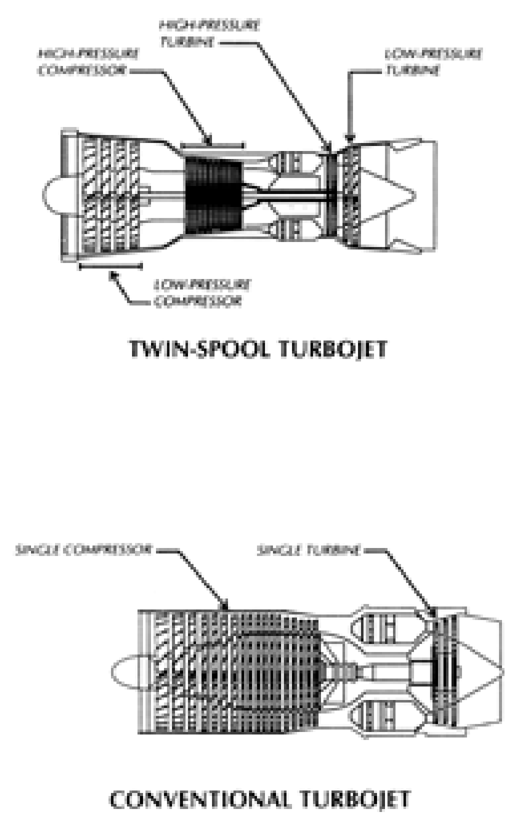
Another Langley aerodynamicist, Charles McLellan, took up this issue by closely examining the airflow around a tail surface at high Mach. He drew on recent experimental results from the Langley 11-inch hypersonic tunnel, involving an airfoil with a cross section in the shape of a thin diamond. Analysis had indicated that most of the control effectiveness of this airfoil was generated by its forward wedge-shaped portion. The aft portion contributed little to its overall effectiveness because the pressures on that part of the surface were lower. Experimental tests had confirmed this.

McLellan now proposed to respond to the problem of hypersonic stability by using tail surfaces having airfoils that would be wedge-shaped along their entire length. In effect, such a surface would consist of a forward portion extending all the way to the rear. Subsequent tests in the 11-inch tunnel confirmed that this solution worked. Using standard thin airfoils, the new research plane would have needed tail surfaces nearly as large as the wings. The wedge shape, which saw use in the operational X-15, reduced their sizes to those of conventional tails.[27]

The group's report, dated April 1954, contemplated flight to altitudes as great as 350,000 feet, or 66 miles. (The X-15 went to 354,200 feet in 1963.)[28] This was well above the sensible atmosphere, well into an altitude range where flight would be ballistic. This meant that at that early date, Becker's study was proposing to accomplish piloted flight into space.

The Air Force and High-Speed Flight

This report did not constitute a design. However, it gave good reason to believe that such a design indeed was feasible. It also gave a foundation for briefings at which supporters of hypersonic flight research could seek to parlay the pertinent calculations into a full-blown program that would actually build and fly the new research planes. To do this, NACA needed support from the Air Force, which had a budget 300 times greater than NACA's. For FY 1955 the Air Force budget was $16.6 billion; NACA's was $56 million.[29]

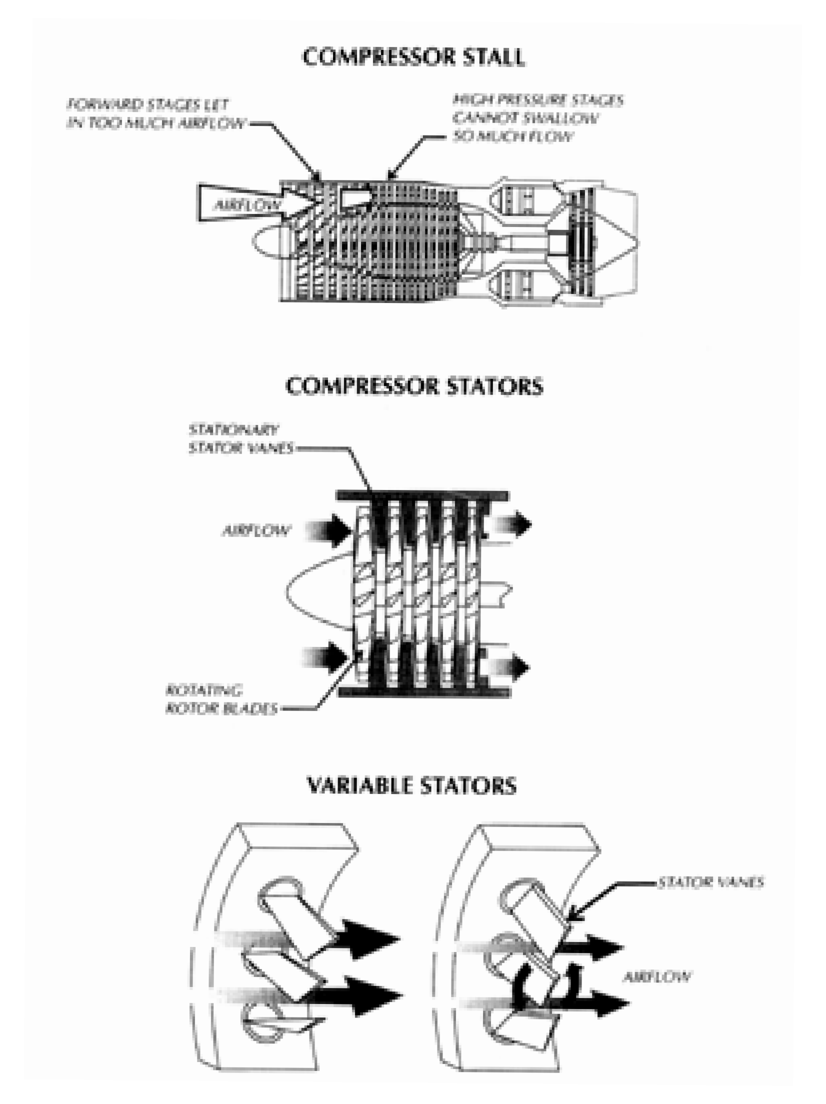


Twin-spool turbojet, amounting to two engines in one. It avoided compressor stall because its low-pressure compressor rotated somewhat slowly during acceleration, and hence pulled in less air. (Art by Don Dixon and Chris Butler)

Fortunately, at that very moment the Air Force was face to face with two major technical innovations that were upsetting all conventional notions of military flight. They faced the immediate prospect that aircraft would soon be flying at temperatures at which aluminum would no longer suffice. The inventions that brought this issue to the forefront were the dual-spool turbojet and the variable-stator turbojet—which call for a digression into technical aspects of jet propulsion.

Jet engines have functioned at speeds as high as Mach 3.3. However, such an engine must accelerate to reach that speed and must remain operable to provide control when decelerating from that speed. Engine designers face the problem of "compressor stall," which arises because compressors have numerous stages or rows of blades and the forward stages take in more air than the rear stages can accommodate. Gerhard Neumann of General Electric, who solved this problem, states that when a compressor stalls, the airflow pushes forward "with a big bang and the pilot loses all his thrust. It's violent; we often had blades break off during a stall."

An interim solution came from Pratt & Whitney, as the "twin-spool" engine. It separated the front and rear compressor stages into two groups, each of which could be made to spin at a proper speed. To do this, each group had its own turbine to provide power. A twin-spool turbojet thus amounted to putting one such engine inside another one. It worked; it prevented compressor stall, and it also gave high internal pressure that promoted good fuel economy. It thus was selected for long-range aircraft, including jet bombers and early commercial jet airliners. It also powered a number of fighters.



Gerhard Neumann's engine for supersonic flight. Top, high performance appeared unattainable because when accelerating, the forward compressor stages pulled in more airflow than the rear ones could swallow. Center, Neumann approached this problem by working with the stators, stationary vanes fitted between successive rows of rotating compressor blades. Bottom, he arranged for stators on the front stages to turn, varying their angles to the flow. When set crosswise to the flow, as on the right, these variable stators reduced the amount of airflow that their compressor stages would pull in. This solved the problem of compressor stall, permitting flight at Mach 2 and higher. (Art by Don Dixon and Chris Butler)

The F-104, which used variable stators. (U. S. Air Force)

But the twin-spool was relatively heavy, and there was much interest in avoiding compressor stall with a lighter solution. It came from Neumann in the form of the "variable-stator" engine. Within an engine's compressor, one finds rows of whirling blades. One also finds "stators," stationary vanes that receive airflow from those blades and direct the air onto the next set of blades. Neumann's insight was that the stators could themselves be adjusted, varied in orientation. At moderate speeds, when a compressor was prone to stall, the stators could be set crosswise to the flow, blocking it in part. At higher speeds, close to an engine's peak velocity, the stators could turn to present themselves edge-on to the flow. Very little of the airstream would be blocked, but the engine could still work as designed.[30]

The twin-spool approach had demanded nothing less than a complete redesign of the entire turbojet. The variable-stator approach was much neater because it merely called for modification of the forward stages of the compressor. It first flew as part of the Lockheed F-104, which was in development during 1953 and which then flew in March 1954. Early versions used engines that did not have variable stators, but the F-104A had them by 1958. In May of that year this aircraft reached 1,404 mph, setting a new world speed record, and set a similar altitude mark at 91,249 feet.[31]

To place this in perspective, one must note the highly nonuniform manner in which the Air Force increased the speed of its best fighters after the war. The advent of jet propulsion itself brought a dramatic improvement. The author Tom Wolfe notes that "a British jet, the Gloster Meteor, jumped the official world speed record from 469 to 606 in a single day."[32] That was an increase of nearly thirty percent, but after that, things calmed down. The Korean War-era F-86 could break the sound barrier in a dive, but although it was the best fighter in service during that war, it definitely counted as subsonic. When the next-generation F-100A flew supersonic in level flight in May 1953, the event was worthy of note.[33]

By then, though, both the F-104 and F-105 were on order and in development. A twin-spool engine was already powering the F-100A, while the F-104 was to fly with variable stators. At a stroke, then, the Air Force found itself in another great leap upward, with speeds that were not to increase by a mere thirty percent but were to double.

There was more. There had been much to learn about aerodynamics in crafting earlier jets; the swept wing was an important example of the requisite innovations. But the new aircraft had continued to use aluminum structures. Still, the F-104 and F-105 were among the last aircraft that were to be designed using this metal alone. At higher speeds, it would be necessary to use other materials as well.

Other materials were already part of mainstream aviation, even in 1954. The Bell X-2 had probably been the first airplane to be built with heat-resistant metals, mounting wings of stainless steel on a fuselage of the nickel alloy K Monel. This gave it a capability of Mach 3.5. Navaho and the XF-103 were both to be built of steel and titanium, while the X-7, a ramjet testbed, was also of steel.[34] But all these craft were to fly near Mach 3, whereas the X-15 was to reach Mach 7. This meant that in an era of accelerating change, the X-15 was plausibly a full generation ahead of the most advanced designs that were under development.

The Air Force already had shown its commitment to support flight at high speed by building the Arnold Engineering Development Center (AEDC). Its background dated to the closing days of World War II, when leaders in what was then the Army Air Forces became aware that Germany had been well ahead of the United States in the fields of aerodynamics and jet propulsion. In March 1946, Brigadier General H. I. Hodes authorized planning an engineering center that would be the Air Force's own.

This facility was to use plenty of electrical power to run its wind tunnels, and a committee selected three possible locations. One was Grand Coulee near Spokane, Washington, but was ruled out as being too vulnerable to air attack. The second was Arizona's Colorado River, near Hoover Dam. The third was the hills north of Alabama, where the Tennessee Valley Authority had its own hydro dams. Senator Kenneth McKellar, the president pro tempore of the Senate and chairman of its

Armed Services Committee, won the new AEDC for his home state of Tennessee by offering to give the Air Force an existing military base, the 40,000-acre Camp Forrest. It was located near Tullahoma, far from cities and universities, but the Air Force was accustomed to operating in remote areas. It accepted this offer in April 1948, with the firm of ARO, Inc. providing maintenance and operation.[35]

There was no interest in reproducing the research facilities of NACA, for the AEDC was to conduct its own activities. Engine testing was to be a specialty, and the first facility at this center was an engine test installation that had been "liberated" from the German firm of BMW. But the Air Force soon was installing its own equipment, achieving its first supersonic flow within its Transonic Model Tunnel early in 1953. Then, during 1954, events showed that AEDC was ready to conduct engineering development on a scale well beyond anything that NACA could envision.[36]

That year saw the advent of the 16-Foot Propulsion Wind Tunnel, with a test section 16 feet square. NACA had larger tunnels, but this one approached Mach 3.5 and reached Mach 4.75 under special operating conditions. A Mach of 4.75 had conventionally been associated with the limited run times of blowdown tunnels, but this tunnel, known as 16S, was a continuous-flow facility. It was unparalleled for exercising full-scale engines for realistic durations over the entire supersonic range.[37]

In December 1956 it tested the complete propulsion package of the XF-103, which had a turbojet with an afterburner that functioned as a ramjet. This engine had a total length of 39 feet. But the test section within 16S had a length of 40 feet, which gave room to spare.[38] In addition, the similar Engine Test Facility accommodated the full-scale SRJ47 engine of Navaho, with a 51-inch diameter that made it the largest ramjet engine ever built.[39]

The AEDC also jumped into hypersonics with both feet. It already had an Engine Test Facility, a Gas Dynamics Facility (renamed the Von Karman Gas Dynamics Facility in 1959), and a Propulsion Wind Tunnel, the 16S. During 1955 it added a ramjet center to the Engine Test Facility, which many people regarded as a fourth major laboratory.[40] Hypersonic wind tunnels were also on the agenda. Two 50-inch installations were in store, to operate respectively at Mach 8 and Mach 10. Both were continuous-flow facilities that used a 92,500-horsepower compressor system. Tunnel B, the Mach 8 facility, became operational in October 1958. Tunnel C, the Mach 10 installation, prevented condensation by heating its air to 1,450°F using a combustion heater and a 12-megawatt resistance heater. It entered operation in May 1960.[41]

The AEDC also conducted basic research in hypersonics. It had not intended to do that initially; it had expected to leave such studies to NACA, with its name reflecting its mission of engineering development. But the fact that it was off in the wilds of Tullahoma did not prevent it from attracting outstanding scientists, some of whom went on to work in hypersonics.

Facilities such as Tunnels B and C could indeed attain hypersonic speeds, but the temperatures of the flows were just above the condensation point of liquid air. There was much interest in achieving far greater temperatures, both to add realism at speeds below Mach 10 and to obtain Mach numbers well beyond 10. Beginning in 1953, the physicist Daniel Bloxsom used the exploding-wire technique, in which a powerful electric pulse vaporizes a thin wire, to produce initial temperatures as high as 5900 K.

This brought the advent of a new high-speed flow facility: the hotshot tunnel. It resembled the shock tube, for the hot gas was to burst a diaphragm and then reach high speeds by expanding through a nozzle. But its run times were considerably longer, reaching one-twentieth of a second compared to less than a millisecond for the shock tube. The first such instrument, Hotshot 1, had a 16-inch test section and entered service early in 1956. In March 1957, the 50-inch Hotshot 2 topped "escape velocity."[42]

Against this background, the X-15 drew great interest. It was to serve as a full-scale airplane at Mach 7, when the best realistic tests that AEDC could offer was full-scale engine test at Mach 4.75. Indeed, a speed of Mach 7 was close to the Mach 8 of Tunnel B. The X-15 also could anchor a program of hypersonic studies that soon would have hotshot tunnels and would deal with speeds up to orbital velocity and beyond. And while previous X-planes were seeing their records broken by jet fighters, it would be some time before any other plane flew at such speeds.

The thermal environment of the latest aircraft was driving designers to the use of titanium and steel. The X-15 was to use Inconel X, which had still better properties. This nickel alloy was to be heat-treated and welded, thereby developing valuable shop-floor experience in its use. In addition, materials problems would be pervasive in building a working X-15. The success of a flight could depend on the proper choice of lubricating oil.

The performance of the X-15 meant that it needed more than good aerodynamics. The X-2 was already slated to execute brief leaps out of the atmosphere. Thus, in September 1956 test pilot Iven Kincheloe took it to 126,200 feet, an altitude at which his ailerons and tail surfaces no longer functioned.[43] In the likely event that future interceptors were to make similar bold leaps, they would need reaction controls—which represented the first really new development in the field of flight control since the Wright Brothers.[44] But the X-15 was to use such controls and would show people how to do it.

The X-15 would also need new flight instruments, including an angle-of-attack indicator. Pilots had been flying with turn-and-bank indicators for some time, with these gyroscopic instruments enabling them to determine their attitude while flying blind. The X-15 was to fly where the skies were always clear, but still it needed to determine its angle with respect to the oncoming airflow so that the pilot could set up a proper nose-high attitude. This instrument would face the full heat load of reentry and had to work reliably.

It thus was not too much to call the X-15 a flying version of AEDC, and high-level Air Force representatives were watching developments closely. In May 1954 Hugh Dryden, Director of NACA, wrote a letter to Lieutenant General Donald Putt, who now was the Air Force's Deputy Chief of Staff, Development. Dryden cited recent work, including that of Becker's group, noting that these studies "will lead to specific preliminary proposals for a new research airplane." Putt responded with his own letter, stating that "the Scientific Advisory Board has done some thinking in this area and has formally recommended that the Air Force initiate action on such a program."[45]

The director of Wright Air Development Center (WADC), Colonel V. R. Haugen, found "unanimous" agreement among WADC reviews that the Langley concept was technically feasible. These specialists endorsed Langley's engineering solutions in such areas as choice of material, structure, thermal protection, and stability and control. Haugen sent his report to the Air Research and Development Command (ARDC), the parent of WADC, in mid-August. A month later Major General F. B. Wood, an ARDC deputy commander, sent a memo to Air Force Headquarters, endorsing the NACA position and noting its support at WADC. He specifically recommended that the Air Force "initiate a project to design, construct, and operate a new research aircraft similar to that suggested by NACA without delay."[46]

Further support came from the Aircraft Panel of the Scientific Advisory Board. In October it responded to a request from the Air Force Chief of Staff, General Nathan Twining, with its views:

> "[A] research airplane which we now feel is ready for a program is one involving manned aircraft to reach something of the order of Mach 5 and altitudes of the order of 200,000 to 500,000 feet. This is very analogous to the research aircraft program which was initiated 10 years ago as a joint venture of the Air Force, the Navy, and NACA. It is our belief that a similar co-operative arrangement would be desirable and appropriate now."[47]

The meetings contemplated in the Dryden-Putt correspondence were also under way. There had been one in July, at which a Navy representative had presented results of a Douglas Aircraft study of a follow-on to the Douglas Skyrocket. It was to reach Mach 8 and 700,000 feet.[48]

Then in October, at a meeting of NACA's Committee on Aerodynamics, Lockheed's Clarence "Kelly" Johnson challenged the entire postwar X-planes program. His XF-104 was already in flight, and he pulled no punches in his written statement:

> "Our present research airplanes have developed startling performance only by the use of rocket engines and flying essentially in a vacuum. Testing airplanes designed for transonic flight speeds at Mach numbers between 2 and 3 has proven, mainly, the bravery of the test pilots and the fact that where there is no drag, the rocket engine can propel even mediocre aerodynamic forms at high Mach numbers.
>
> I am not aware of any aerodynamic or power plant improvements to air-breathing engines that have resulted from our very expensive research airplane program. Our modern tactical airplanes have been designed almost entirely on NACA and other wind-tunnel data, plus certain rocket model tests…."[49]

Drawing on Lockheed experience with the X-7, an unpiloted high-speed missile, he called instead for a similar unmanned test aircraft as the way to achieve Mach 7. However, he was a minority of one. Everyone else voted to support the committee's resolution:

> BE IT HEREBY RESOLVED, That the Committee on Aerodynamics endorses the proposal of the immediate initiation of a project to design and construct a research airplane capable of achieving speeds of the order of Mach number 7 and altitudes of several hundred thousand feet….[50]

The Air Force was also on board, and the next step called for negotiation of a Memorandum of Understanding, whereby the participants—which included the Navy—were to define their respective roles. Late in October representatives from the two military services visited Hugh Dryden at NACA Headquarters, bringing a draft of this document for discussion. It stated that NACA was to provide technical direction, the Air Force would administer design and construction, and the Air Force and Navy were to provide the funds. It concluded with the words, "Accomplishment of this project is a matter of national urgency."[51]

The draft became the final MOU, with little change, and the first to sign it was Trevor Gardner. He was a special assistant to the Air Force Secretary and had midwifed the advent of Atlas a year earlier. James Smith, Assistant Secretary of the Navy for Air, signed on behalf of that service, while Dryden signed as well. These signatures all were in place two days before Christmas of 1954. With this, the groundwork was in place for the Air Force's Air Materiel Command to issue a Request for Proposal and for interested aircraft companies to begin preparing their bids.[52]

As recently as February, all that anyone knew was that this new research aircraft, if it materialized, would be something other than an uprated X-2. The project had taken form with considerable dispatch, and the key was the feasibility study of Becker's group. An independent review at WADC confirmed its conclusions, whereupon Air Force leaders, both in uniform and in mufti, embraced the concept. Approval at the Pentagon then came swiftly.

In turn, this decisiveness demonstrated a willingness to take risks. It is hard today to accept that the Pentagon could endorse this program on the basis of just that one study. Moreover, the only hypersonic wind tunnel that was ready to provide supporting research was Becker's 11-inch instrument; the AEDC hypersonic tunnels were still several years away from completion. But the Air Force was in no mood to hold back or to demand further studies and analyses.

This service was pursuing a plethora of initiatives in jet bombers, advanced fighters, and long-range missiles. Inevitably, some would falter or find themselves superseded, which would lead to charges of waste. However, Pentagon officials knew that the most costly weapons were the ones that America might need and not have in time of war. Cost-benefit analysis had not yet raised its head; Robert McNamara was still in Detroit as a Ford Motor executive, and Washington was not yet a city where the White House would deliberate for well over a decade before ordering the B-1 bomber into limited production. Amid the can-do spirit of the 1950s, the X-15 won quick approval.

X-15: THE TECHNOLOGY

Four companies competed for the main contract, covering design and construction of the X-15: Republic, Bell, Douglas, and North American. Each of them brought a substantial amount of hands-on experience with advanced aircraft. Republic, for example, had Alexander Kartveli as its chief designer. He was a highly imaginative and talented man whose XF-105 was nearly ready for first flight and whose XF-103 was in development. Republic had also built a rocket plane, the XF-91. This was a jet fighter that incorporated the rocket engine of the X-1 for an extra boost in combat. It did not go into production, but it flew in flight tests.

Still, Republic placed fourth in the competition. Its concept rated "unsatisfactory" as a craft for hypersonic research, for it had a thin outer fuselage skin that appeared likely to buckle when hot. The overall proposal rated no better than average in a number of important areas, while achieving low scores in Propulsion System and Tanks, Engine Installation, Pilot's Instruments, Auxiliary Power, and Landing Gear. In addition, the company itself was judged as no more than "marginal" in the key areas of Technical Qualifications, Management, and Resources. The latter included availability of in-house facilities and of an engineering staff not committed to other projects.[53]

Bell Aircraft, another contender, was the mother of research airplanes, having built the X-1 series as well as the X-2. This firm therefore had direct experience both with advanced heat-resistant metals and with the practical issues of powering piloted aircraft using liquid-fuel rocket engines. It even had an in-house group that was building such engines. Bell also was the home of the designers Robert Woods and Walter Dornberger, with the latter having presided over the V-2.

Dornberger's Bomi concept already was introducing the highly useful concept of hot structures. These used temperature-resistant alloys such as stainless steel. Wings might be covered with numerous small and very hot metal panels, resembling shingles, that would radiate heat away from the aircraft. Overheating would be particularly severe along the leading edges of wings; these could be water-cooled. Insulation could protect an internal structure that would withstand the stresses and forces of flight; active cooling could protect a pilot's cockpit and instrument compartment. Becker described these approaches as "the first hypersonic aircraft hot structures concepts to be developed in realistic meaningful detail."[54]

Even so, Bell ranked third. Historian Dennis Jenkins writes that within the proposal, "almost every innovation they proposed was hedged in such a manner as to make the reader doubt that it would work. The proposal itself seemed rather poorly organized and was internally inconsistent (i.e., weights and other figures frequently differed between sections)."[55] Yet the difficulties ran deeper and centered on the specifics of its proposed hot structure.

Bell adopted the insulated-structure approach, with the primary structure being of aluminum, the most familiar of aircraft materials and the best understood. Corrugated panels of Inconel X, mounted atop the aluminum, were to provide insulation. Freely-suspended panels of this alloy, contracting and expanding with ease, were to serve as the outer skin.

Yet this concept was quite unsuitable for the X-15, both on its technical merits and as a tool for research. A major goal of the program was to study aircraft structures at elevated temperatures, and this would not be possible with a primary structure of cool aluminum. There were also more specific deficiencies, as when Bell's thermal analysis assumed that the expanding panels of the outer shell would prevent leakage of hot air from the boundary layer. However, the evaluation made the flat statement, "leakage is highly probable." Aluminum might not withstand the resulting heating, with the loss of even one such panel leading perhaps to destructive heating. Indeed, the Bell insulated structure appeared so sensitive that it could be trusted to successfully complete only three of 13 reference flights.[56]

Another contender, Douglas Aircraft, had shared honors with Bell in building previous experimental aircraft. Its background included the X-3 and the Skyrocket, which meant that Douglas also had people who knew how to integrate a liquid rocket engine with an airplane. This company's concept came in second.

Its design avoided reliance on insulated structures, calling instead for use of a heat sink. The material was to be a lightweight magnesium alloy that had excellent

The North American X-15. (NASA)

heat capacity. Indeed, its properties were so favorable that it would reach temperatures of only 600ºF, while an Inconel X heat-sink airplane would go to 1,200ºF.

Again, though, this concept missed the point. Managers *wanted* a vehicle that could cope successfully with temperatures of 1,200ºF, to lay groundwork for operational fighters that could fly well beyond Mach 3. In addition, the concept had virtually no margin for temperature overshoots. Its design limit of 600ºF was right on the edge of a regime of which its alloy lost strength rapidly. At 680ºF, its strength could fall off by 90 percent. With magnesium being flammable, there was danger of fire within the primary structure itself, with the evaluation noting that "only a small area raised to the ignition temperature would be sufficient to destroy the aircraft."[57]

Then there was North American, the home of Navaho. That missile had not flown, but its detailed design was largely complete and specified titanium in hot areas. This meant that that company knew something about using advanced metals. The firm also had a particularly strong rocket-engine group, which split off during 1955 to form a new corporate division called Rocketdyne. Indeed, engines built by that association had already been selected for Atlas.[58]

North American became the winner. It paralleled the thinking at Douglas by independently proposing its own heat-sink structure, with the material being Inconel X. This concept showed close similarities to that of Becker's feasibility study a year earlier. Still, this was not to say that the deck was stacked in favor of Becker's approach. He and his colleagues had pursued conceptual design in a highly impromptu fashion. The preliminary-design groups within industry were far more experienced, and it had appeared entirely possible that these experts, applying their seasoned judgment, might come up with better ideas. This did not happen. Indeed, the Bell and Douglas concepts failed even to meet an acceptable definition of the new research airplane. By contrast, the winning concept from North American amounted to a particularly searching affirmation of the work of Becker's group.[59]

How had Bell and Douglas missed the boat? The government had set forth performance requirements, which these companies both had met. In the words of the North American proposal, "the specification performance can be obtained with very moderate structural temperatures." However, "the airplane has been designed to tolerate much more severe heating in order to provide a practical temperature band within which exploration can be conducted."

In Jenkins's words, "the Bell proposal…was terrible—you walked away not entirely sure that Bell had committed themselves to the project. The exact opposite was true of the North American proposal. From the opening page you knew that North American understood what was trying to be accomplished with the X-15 program and had attempted to design an airplane that would help accomplish the task—not just meet the performance specifications (which did not fully describe the intent of the program)."[60] That intent was to build an aircraft that could accomplish research at 1,200ºF and not merely meet speed and altitude goals.

The overall process of proposal evaluation cast the competing concepts in sharp relief, heightening deficiencies and emphasizing sources of potential difficulty. These proposals also received numerical scores, while another basis for comparison involved estimated program costs:

North American	81.5 percent	$56.1 million
Douglas Aircraft	80.1	36.4
Bell Aircraft	75.5	36.3
Republic Aviation	72.2	47.0

North American's concept thus was far from perfect, while Republic's represented a serious effort. In addition, it was clear that the Air Force—which was to foot most of the bill—was willing to pay for what it would get. The X-15 program thus showed budgetary integrity, with the pertinent agencies avoiding the temptation to do it on the cheap.[61]

On 30 September 1955, letters went out to North American as well as to the unsuccessful bidders, advising them of the outcome of the competition. With this, engineers now faced the challenge of building and flying the X-15 as a practical exercise in hypersonic technology. Accordingly, it broke new ground in such areas as metallurgy and fabrication, onboard instruments, reaction controls, pilot training, the pilot's pressure suit, and flight simulation.[62]

Inconel X, a nickel alloy, showed good ductility when fully annealed and had some formability. When severely formed or shaped, though, it showed work-hardening, which made the metal brittle and prone to crack. Workers in the shop addressed this problem by forming some parts in stages, annealing the workpieces by heating them between each stage. Inconel X also was viewed as a weldable alloy, but some welds tended to crack, and this problem resisted solution for some time. The solution lay in making welds that were thicker than the parent material. After being ground flat, their surfaces were peened—bombarded with spherical shot—and rolled flush with the parent metal. After annealing, the welds often showed better crack resistance than the surrounding Inconel X.

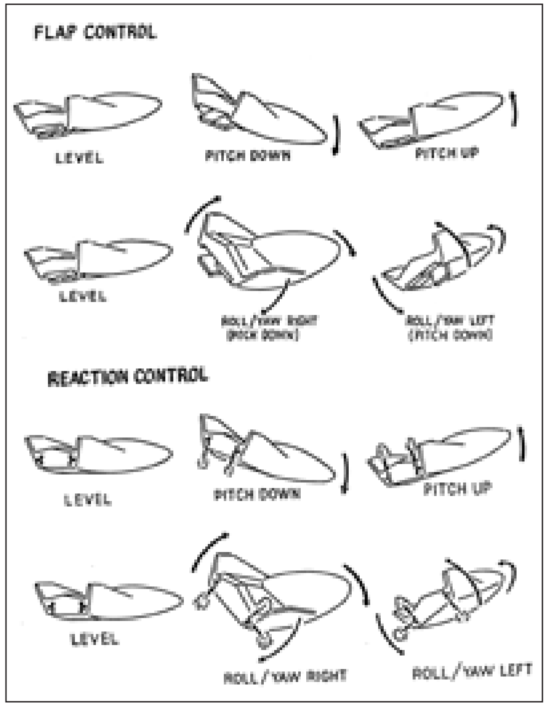
A titanium alloy was specified for the internal structure of the wings. It proved difficult to weld, for it became brittle by reacting with oxygen and nitrogen in the air. It therefore was necessary to enclose welding fixtures within enclosures that could be purged with an inert gas such as helium and to use an oxygen-detecting device to determine the presence of air. With these precautions, it indeed proved possible to weld titanium while avoiding embrittlement.[63]

Greases and lubricants posed their own problems. Within the X-15, journal and antifriction bearings received some protection from heat and faced operating temperatures no higher than 600°F. This nevertheless was considerably hotter than engineers were accustomed to accommodating. At North American, candidate lubricants underwent evaluation by direct tests in heated bearings. Good greases protected bearing shafts for 20,000 test cycles and more. Poor greases gave rise to severe wearing of shafts after as few as 350 cycles.[64]

In contrast to conventional aircraft, the X-15 was to fly out of the sensible atmosphere and then re-enter, with its nose high. It also was prone to yaw while in near-vacuum. Hence, it needed a specialized instrument to determine angles of attack and of sideslip. This took form as the "Q-ball," built by the Nortronics Division of Northrop Aircraft. It fitted into the tip of the X-15's nose, giving it the appearance of a greatly enlarged tip of a ballpoint pen.

The ball itself was cooled with liquid nitrogen to withstand air temperatures as high as 3,500°F. Orifices set within the ball, along yaw and pitch planes, measuring differential pressures. A servomechanism rotated the ball to equalize these pressures by pointing the ball's forward tip directly into the onrushing airflow. With the direction of this flow thus established, the pilot could null out any sideslip. He also could raise the nose to a desired angle of attack. "The Q-ball is a go-no go item," the test pilot Joseph Walker told *Time* magazine in 1961. "Only if she checks okay do we go."[65]

To steer the aircraft while in flight, the X-15 mounted aerodynamic controls. These retained effectiveness at altitudes well below 100,000 feet. However, they lost effectiveness between 90,000 and 100,000 feet. The X-15 therefore incorporated reaction controls, which were small thrusters fueled with hydrogen peroxide. Nose-mounted units controlled pitch and yaw. Other units, set near the wingtips, gave control of roll.



Attitude control of a hypersonic airplane using aerodynamic controls and reaction controls. (U.S. Air Force)

No other research airplane had ever flown with such thrusters, although the X-1B conducted early preliminary experiments and the X-2 came close to needing them in 1956. During a flight in September of that year, the test pilot Iven Kincheloe took it to 126,200 feet. At that altitude, its aerodynamic controls were useless. Kincheloe flew a ballistic arc, experiencing near-weightlessness for close to a minute. His airplane banked to the left, but he did not try to counter this movement, for he knew that his X-2 could easily go into a deadly tumble.[66]

In developing reaction controls, an important topic for study involved determining the airplane handling qualities that pilots preferred. Initial investigations used an analog computer as a flight simulator. The "airplane" was disturbed slightly; a man used a joystick to null out the disturbance, achieving zero roll, pitch, and yaw. These experiments showed that pilots wanted more control authority for roll than for pitch or yaw. For the latter, angular accelerations of 2.5 degrees per second squared were acceptable. For roll, the preferred control effectiveness was two to four times greater.

Flight test came next. The X-2 would have served splendidly for this purpose, but only two had been built, with both being lost in accidents. At NACA's High-Speed Flight Station, investigators fell back on the X-1B, which was less capable but still useful. In preparation for its flights with reaction controls, the engineers built a simulator called the Iron Cross, which matched the dimensions and inertial characteristics of this research plane. A pilot, sitting well forward along the central arm, used a side-mounted control stick to actuate thrusters that used compressed nitrogen. This simulator was mounted on a universal joint, which allowed it to move freely in yaw, pitch, and roll.

Reaction controls went into the X-1B late in 1957. The test pilot Neil Armstrong, who walked on the Moon 12 years later, made three flights in this research plane before it was grounded in mid-1958 due to cracks in its fuel tank. Its peak altitude during these three flights was 55,000 feet, where its aerodynamic controls readily provided backup. The reaction controls then went into an F-104, which reached 80,000 feet and went on to see much use in training X-15 pilots. When the X-15 was in flight, these pilots had to transition from aerodynamic controls to reaction controls and back again. The complete system therefore provided overlap. It began blending in the reaction controls at approximately 85,000 feet, with most pilots switching to reaction controls exclusively by 100,000 feet.[67]

Since the war, with aircraft increasing in both speed and size, it had become increasingly impractical for a pilot to exert the physical strength to operate a plane's ailerons and elevators merely by moving the control stick in the cockpit. Hydraulically-boosted controls thus were in the forefront, resembling power steering in a car. The X-15 used such hydraulics, which greatly eased the workload on a test pilot's muscles. These hydraulic systems also opened the way for stability augmentation systems of increasing sophistication.

Stability augmentation represented a new refinement of the autopilot. Conventional autopilots used gyroscopes to detect deviations from a plane's straight and level course. These instruments then moved an airplane's controls so as to null these deviations to zero. For high-performance jet fighters, the next step was stability augmentation. Such aircraft often were unstable in flight, tending to yaw or roll; indeed, designers sometimes enhanced this instability to make them more maneuverable. Still, it was quite wearying for a pilot to have to cope with this. A stability augmentation system made life in the cockpit much easier.

Such a system used rate gyros, which detected rates of movement in pitch, roll, and yaw at so many degrees per second. The instrument then responded to these rates, moving the controls somewhat like before to achieve a null. Each axis of this control had "gain," defining the proportion or ratio between a sensed rate of angular motion and an appropriate deflection of ailerons or other controls. Fixed-gain systems worked well; there also were variable-gain arrangements, with the pilot setting the value of gain within the cockpit. This addressed the fact that the airplane might need more gain in thin air at high altitude, to deflect these surfaces more strongly.[68]

The X-15 program built three of these aircraft. The first two used a stability augmentation system that incorporated variable gain, although in practice these aircraft flew well with constant values of gain, set in flight.[69] The third replaced it with a more advanced arrangement that incorporated something new: adaptive gain. This was a variable gain, which changed automatically in response to flight conditions. Within the Air Force, the Flight Control Laboratory at WADC had laid groundwork with a program dating to 1955. Adaptive-gain controls flew aboard F-94 and F-101 test aircraft. The X-15 system, the Minneapolis Honeywell MH-96, made its first flight in December 1961.[70]

How did it work? When a pilot moved the control stick, as when changing the pitch, the existing value of gain in the pitch channel caused the aircraft to respond at a certain rate, measured by a rate gyro. The system held a stored value of the optimum pitch rate, which reflected preferred handling qualities. The adaptive-gain control compared the measured and desired rates and used the difference to determine a new value for the gain. Responding rapidly, this system enabled the airplane to maintain nearly constant control characteristics over the entire flight envelope.[71]

The MH-96 made it possible to introduce the X-15's blended aerodynamic and reaction controls on the same control stick. This blending occurred automatically in response to the changing gains. When the gains in all three channels—roll, pitch, and yaw—reached 80 percent of maximum, thereby indicating an imminent loss of effectiveness in the aerodynamic controls, the system switched to reaction controls. During re-entry, with the airplane entering the sensible atmosphere, the system returned to aerodynamic control when all the gains dropped to 60 percent.[72]

The X-15 flight-control system thus stood three steps removed from the conventional stick-and-cable installations of World War II. It used hydraulically-boosted controls; it incorporated automatic stability augmentation; and with the MH-96, it introduced adaptive gain. Fly-by-wire systems lay ahead and represented the next steps, with such systems being built both in analog and digital versions.

Analog fly-by-wire systems exist within the F-16A and other aircraft. A digital system, as in the space shuttle, uses a computer that receives data both from the pilot and from the outside world. The pilot provides input by moving a stick or sidearm controller. These movements do not directly actuate the ailerons or rudder, as in days of old. Instead, they generate signals that tell a computer the nature of the desired maneuver. The computer then calculates a gain by applying control laws, which take account of the plane's speed and altitude, as measured by onboard instruments. The computer then sends commands down a wire to hydraulic actuators co-mounted with the controls to move or deflect these surfaces so as to comply with the pilot's wishes.[73]

The MH-96 fell short of such arrangements in two respects. It was analog, not digital, and it was a control system, not a computer. Like other systems executing automatic control, the MH-96 could measure an observed quantity such as pitch rate, compare it to a desired value, and drive the difference to zero. But the MH-96 was wholly incapable of implementing a control law, programmed as an algebraic expression that required values of airspeed and altitude. Hence, while the X-15 with

MH-96 stood three steps removed from the fighters of the recent war, it was two steps removed from the digital fly-by-wire control of the shuttle.

The X-15 also used flight simulators. These served both for pilot training and for development of onboard systems, including the reaction controls and the MH-96. The most important flight simulator was built by North American. It replicated the X-15 cockpit and included actual hydraulic and control-system hardware. Three analog computers implemented equations of motion that governed translation and rotation of the X-15 about all three axes, transforming pilot inputs into instrument displays.[74]

Flight simulators dated to the war. The famous Link Trainer introduced over half a million neophytes to their cockpits. The firm of Link Aviation added analog computers in 1949, within a trainer that simulated flight in a jet fighter.[75] In 1955, when the X-15 program began, it was not at all customary to use flight simulators to support aircraft design and development. But program managers turned to such simulators because they offered effective means to study new issues in cockpit displays, control systems, and aircraft handling qualities.

Flight simulation showed its value quite early. An initial X-15 design proved excessively unstable and difficult to control. The cure lay in stability augmentation. A 1956 paper stated that this had "heretofore been considered somewhat of a luxury for high-speed aircraft," but now "has been demonstrated as almost a necessity," in all three axes, to ensure "consistent and successful entries" into the atmosphere.[76]

The North American simulator, which was transferred to the NACA Flight Research Center, became critical in training X-15 pilots as they prepared to execute specific planned flights. A particular mission might take little more than 10 minutes, from ignition of the main engine to touchdown on the lakebed, but a test pilot could easily spend 10 hours making practice runs in this facility. Training began with repeated trials of the normal flight profile, with the pilot in the simulator cockpit and a ground controller close at hand. The pilot was welcome to recommend changes, which often went into the flight plan. Next came rehearsals of off-design missions: too much thrust from the main engine, too high a pitch angle when leaving the stratosphere.

Much time was spent practicing for emergencies. The X-15 had an inertial reference unit that used analog circuitry to display attitude, altitude, velocity, and rate of climb. Pilots dealt with simulated failures in this unit, attempting to complete the normal mission or, at least, execute a safe return. Similar exercises addressed failures in the stability augmentation system. When the flight plan raised issues of possible flight instability, tests in the simulator used highly pessimistic assumptions concerning stability of the vehicle. Other simulated missions introduced in-flight failures of the radio or Q-ball. Premature engine shutdowns imposed a requirement for safe landing on an alternate lakebed, which was available for emergency use.[77]

The simulations indeed were realistic in their cockpit displays, but they left out an essential feature: the g-loads, produced both by rocket thrust and by deceleration during re-entry. In addition, a failure of the stability augmentation system, during re-entry, could allow the airplane to oscillate in pitch or yaw. This would change its drag characteristics, imposing a substantial cyclical force.

To address such issues, investigators installed a flight simulator within the gondola of a centrifuge at the Naval Air Development Center in Johnsville, Pennsylvania. The gondola could rotate on two axes while the centrifuge as a whole was turning. It not only produced g-forces, but its g-forces increased during the simulated rocket burn. The centrifuge imposed such forces anew during reentry, while adding a cyclical component to give the effect of a yaw or pitch oscillation.[78]

Not all test pilots rode the centrifuge. William "Pete" Knight, who stood among the best, was one who did not. His training, coupled with his personal coolness and skill, enabled him to cope even with an extreme emergency. In 1967, during a planned flight to 250,000 feet, an X-15 experienced a complete electrical failure while climbing through 107,000 feet at Mach 4. This failure brought the shutdown of both auxiliary power units and hence of both hydraulic systems. Knight, the pilot, succeeded in restarting one of these units, which restored hydraulic power. He still had zero electrical power, but with his hydraulics, he now had both his aerodynamic and reaction controls. He rode his plane to a peak of 173,000 feet, re-entered the atmosphere, made a 180-degree turn, and glided to a safe landing on Mud Lake near Tonopah, Nevada.[79]

During such flights, as well as during some exercises in the centrifuge, pilots wore a pressure suit. Earlier models had already been good enough to allow the test pilot Marion Carl to reach 83,235 feet in the Douglas Skyrocket in 1953. Still, some of those versions left much to be desired. *Time* magazine, in 1952, discussed an Air Force model that allowed a pilot to breathe, but "with difficulty. His hands, not fully pressurized, swell up with blue venous blood. His throat is another trouble spot; the medicos have not yet learned how to pressurize a throat without strangling its owner."[80]

The David G. Clark Company, a leading supplier of pressure suits for Air Force flight crews, developed a greatly improved model for the X-15. Such suits tended to become rigid and hard to bend when inflated. This is also true of a child's long balloon, with an internal pressure that only slightly exceeds that of the atmosphere. The X-15 suit was to hold five pounds per square inch of pressure, or 720 pounds per square foot. The X-15 cockpit had its own counterbalancing pressure, but it could (and did) depressurize at high altitude. In such an event, the suit was to protect the test pilot rather than leave him immobile.

The solution used an innovative fabric that contracted in circumference while it stretched in length. With proper attention to the balance between these two effects, the suit maintained a constant volume when pressurized, enhancing a pilot's freedom of movement. Gloves and boots were detachable and zipped to this fabric. The helmet was joined to the suit with a freely-swiveling ring that gave full mobility to the head. Oxygen flowed into the helmet; exhalant passed through valves in a neck seal and pressurized the suit. Becker later described it as "the first practical full-pressure suit for pilot protection in space."[81]

Thus accoutered, protected for flight in near-vacuum, X-15 test pilots rode their rockets as they approached the edge of space and challenged the hypersonic frontier. They returned with results galore for project scientists—and for the nation.

X-15: Some Results

During the early 1960s, when the nation was agog over the Mercury astronauts, the X-15 pointed to a future in which piloted spaceplanes might fly routinely to orbit. The men of Mercury went water-skiing with Jackie Kennedy, but within their orbiting capsules, they did relatively little. Their flights were under automatic control, which left them as passengers along for the ride. Even a monkey could do it. Indeed, a chimpanzee named Ham rode a Redstone rocket on a suborbital flight in January 1961, three months before Alan Shepard repeated it before the gaze of an astonished world. Later that year another chimp, Enos, orbited the Earth and returned safely. The much-lionized John Glenn did this only later.[82]

In the X-15, by contrast, only people entered the cockpit. A pilot fired the rocket, controlled its thrust, and set the angle of climb. He left the atmosphere, soared high over the top of the trajectory, and then used reaction controls to set up his re-entry. All the while, if anything went wrong, he had to cope with it on the spot and work to save himself and the plane. He maneuvered through re-entry, pulled out of his dive, and began to glide. Then, while Mercury capsules were using parachutes to splash clumsily near an aircraft carrier, the X-15 pilot goosed his craft onto Rogers Dry Lake like a fighter.

All aircraft depend on propulsion for their performance, and the X-15's engine installations allow the analyst to divide its career into three eras. It had been designed from the start to use the so-called Big Engine, with 57,000 pounds of thrust, but delays in its development brought a decision to equip it with two XLR11 rocket engines, which had served earlier in the X-1 series and the Douglas Skyrocket. Together they gave 16,000 pounds of thrust.

Flights with the XLR11s ran from June 1959 to February 1961. The best speed and altitude marks were Mach 3.50 in February 1961 and 136,500 feet in August 1961. These closely matched the corresponding numbers for the X-2 during 1956: Mach 3.196, 126,200 feet.[83] The X-2 program had been ill-starred—it had had two operational aircraft, both of which were destroyed in accidents. Indeed, these research aircraft made only 20 flights before the program ended, prematurely, with the loss of the second flight vehicle. The X-15 with XLR11s thus amounted to X-2s that had been brought back from the dead, and that belatedly completed their intended flight program.

The Big Engine, the Reaction Motors XLR99, went into service in November 1960. It launched a program of carefully measured steps that brought the fall of one Mach number after another. A month after the last flight with XLR11s, in March 1961, the pilot Robert White took the X-15 past Mach 4. This was the first time a piloted aircraft had flown that fast, as White raised the speed mark by nearly a full Mach. Mach 5 fell, also to Robert White, four months later. In November 1961 White did it again, as he reached Mach 6.04. Once flights began with the Big Engine, it took only 15 of them to reach this mark and to double the maximum Mach that had been reached with the X-2.

Altitude flights were also on the agenda. The X-15 climbed to 246,700 feet in April 1962, matched this mark two months later, and then soared to 314,750 feet in July 1962. Again White was in the cockpit, and the Federation Aeronautique Internationale, which keeps the world's aviation records, certified this one as the absolute altitude record for its class. A year later, without benefit of the FAI, the pilot Joseph Walker reached 354,200 feet. He thus topped 100 kilometers, a nice round number that put him into space without question or cavil.[84]

The third era in the X-15's history took shape as an extension of the second one. In November 1962, with this airplane's capabilities largely demonstrated, a serious landing accident caused major damage and led to an extensive rebuild. The new aircraft, designated X-15A-2, retained the Big Engine but sported external tankage for a longer duration of engine burn. It also took on an ablative coating for enhanced thermal protection.

It showed anew the need for care in flight test. In mid-1962, and for that matter in 1966, the X-2's best speed stood at 4,104 miles per hour, or Mach 5.92. (Mach number depends on both vehicle speed and air temperature. The flight to Mach 6.04 reached 4,093 miles per hour.) Late in 1966, flying the X-15A-2 without the ablator, Pete Knight raised this to Mach 6.33. Engineers then applied the ablator and mounted a dummy engine to the lower fin, with Knight taking this craft to Mach 4.94 in August 1967. Then in October he tried for more.

But the X-15A-2, with both ablator and dummy engine, now was truly a new configuration. Further, it had only been certified with these additions in the flight to Mach 4.94 and could not be trusted at higher Mach. Knight took the craft to Mach 6.72, a jump of nearly two Mach numbers, and this proved to be too much. The ablator, when it came back, was charred and pitted so severely that it could not be restored for another flight. Worse, shock-impingement heating burned the engine off its pylon and seared a hole in the lower fin, disabling the propellant ejec-

X-15 with dummy Hypersonic Research Engine mounted to the lower fin. (NASA)

tion system and threatening the craft's vital hydraulics. No one ever tried to fly faster in the X-15.[85]

It soon retired with honor, for in close to 200 powered flights, it had operated as a true instrument of hypersonic research. Its flight log showed nearly nine hours above Mach 3, close to six hours above Mach 4, and 87 minutes above Mach 5.[86] It served as a flying wind tunnel and made an important contribution by yielding data that made it possible to critique the findings of experiments performed in ground-based tunnels. Tunnel test sections were small, which led to concern that their results might not be reliable when applied to full-size hypersonic aircraft. Such discrepancies appeared particularly plausible because wind tunnels could not reproduce the extreme temperatures of hypersonic flight.

The X-15 set many of these questions to rest. In Becker's words, "virtually all of the flight pressures and forces were found to be in excellent agreement with the low-temperature wind-tunnel predictions."[87] In addition to lift and drag, this good agreement extended as well to wind-tunnel values of "stability derivatives," which governed the aircraft's handling qualities and its response to the aerodynamic controls. Errors due to temperature became important only beyond Mach 10 and were negligible below such speeds.

B-52 mother ship with X-15A-2. The latter mounted a dummy scramjet and carried external tanks as well as ablative thermal protection. (NASA)

But the X-15 brought surprises in boundary-layer flow and aerodynamic heating. There was reason to believe that this flow would remain laminar, being stabilized in this condition by heat flow out of the boundary layer. This offered hope, for laminar flow, as compared to turbulent, meant less skin-friction drag and less heating. Instead, the X-15 showed mostly turbulent boundary layers. These resulted from small roughnesses and irregularities in the aircraft skin surface, which tripped the boundary layers into turbulence. Such skin roughness commonly produced turbulent boundary layers on conventional aircraft. The same proved to be true at Mach 6.

The X-15 had a conservative thermal design, giving large safety margins to cope with the prevailing lack of knowledge. The turbulent boundary layers might have brought large increases in the heat-transfer rates, limiting the X-15's peak speed. But in another surprise, these rates proved to be markedly lower than expected. As a consequence, the measured skin temperatures often were substantially less than had been anticipated (based on existing theory as well as on wind-tunnel tests). These flight results, confirmed by repeated measurements, were also validated with further wind-tunnel work. They resisted explanation by theory, but a new empirical model used these findings to give a more accurate description of hypersonic heating. Because this model predicted less heating and lower temperatures, it permitted design of vehicles that were lighter in weight.[88]

An important research topic involved observation of how the X-15 itself would stand up to thermal stresses. The pilot Joseph Walker stated that when his craft was accelerating and heating rapidly, "the airplane crackled like a hot stove." This resulted from buckling of the skin. The consequences at times could be serious, as when hot air leaked into the nose wheel well and melted aluminum tubing while in flight. On other occasions, such leaks destroyed the nose tire.[89]

Fortunately, such problems proved manageable. For example, the skin behind the wing leading edge showed local buckling during the first flight to Mach 5.3. The leading edge was a solid bar of Inconel X that served as a heat sink, with thin slots or expansion joints along its length. The slots tripped the local airflow into turbulence, with an accompanying steep rise in heat transfer. This created hot spots, which led to the buckling. The cure lay in cutting additional expansion slots, covering them with thin Inconel tabs, and fastening the skin with additional rivets. The wing leading edge faced particularly severe heating, but these modifications prevented buckling as the X-15 went beyond Mach 6 in subsequent flights.

Buckling indeed was an ongoing problem, and an important way to deal with it lay in the cautious step-by-step program of advance toward higher speeds. This allowed problems of buckling to appear initially in mild form, whereas a sudden leap toward record-breaking performance might have brought such problems in forms so severe as to destroy the airplane. This caution showed its value anew as buckling problems proved to lie behind an ongoing difficulty in which the cockpit canopy windows repeatedly cracked.

An initial choice of soda-lime glass for these windows gave way to alumino-silicate glass, which had better heat resistance. The wisdom of this decision became clear in 1961, when a soda-lime panel cracked in the course of a flight to 217,000 feet. However, a subsequent flight to Mach 6.04 brought cracking of an alumino-silicate panel that was far more severe. The cause again was buckling, this time in the retainer or window frame. It was made of Inconel X; its buckle again produced a local hot spot, which gave rise to thermal stresses that even this heat-resistant glass could not withstand. The original retainers were replaced with new ones made of titanium, which had a significantly lower coefficient of thermal expansion. Again the problem disappeared.[90]

The step-by-step test program also showed its merits in dealing with panel flutter, wherein skin panels oscillated somewhat like a flag waving in the breeze. This brought a risk of cracking due to fatigue. Some surface areas showed flutter at conditions no worse than Mach 2.4 and dynamic pressure of 650 pounds per square foot, a rather low value. Wind-tunnel tests verified the flight results. Engineers reinforced the panels with skin doublers and longitudinal stiffeners to solve the problem. Flutter did not reappear, even at the much higher dynamic pressure of 2,000 pounds per square foot.[91]

Caution in flight test also proved beneficial in dealing with the auxiliary power units (APUs). The APU, built by General Electric, was a small steam turbine driven by hydrogen peroxide and rotating at 51,200 revolutions per minute. Each X-15 airplane mounted two of them for redundancy, with each unit using gears to drive an electric alternator and a pump for the hydraulic system. Either APU could carry the full electrical and hydraulic load, but failure of both was catastrophic. Lacking hydraulic power, a pilot would have been unable to operate his aerodynamic controls.

Midway through 1962 a sudden series of failures in a main gear began to show up. On two occasions, a pilot experienced complete gear failure and loss of one APU, forcing him to rely on the second unit as a backup. Following the second such flight, the other APU gear also proved to be badly worn. The X-15 aircraft then were grounded while investigators sought the source of the problem.

They traced it to a lubricating oil, one type of which had a tendency to foam when under reduced pressure. The gear failures coincided with an expansion of the altitude program, with most of the flights above 100,000 feet having taken place during 1962 and later. When the oil turned to foam, it lost its lubricating properties. A different type had much less tendency to foam; it now became standard. Designers also enclosed the APU gearbox within a pressurized enclosure. Subsequent flights again showed reliable APU operation, as the gear failures ceased.[92]

Within the X-15 flight-test program, the contributions of its research pilots were decisive. A review of the first 44 flights, through November 1961, showed that 13 of them would have brought loss of the aircraft in the absence of a pilot and of redundancies in onboard systems. The actual record showed that all but one of these missions had been successfully flown, with the lone exception ending in an emergency landing that also went well.[93]

Still there were risks. The dividing line between a proficient flight and a disastrous one, between life and death for the pilot, could be narrow indeed, and the man who fell afoul of this was Major Mike Adams. His career in the cockpit dated to the Korean War. He graduated from the Experimental Test Pilot School, ranking first in his class, and then was accepted for the Aerospace Research Pilot School. Yeager himself was its director; his faculty included Frank Borman, Tom Stafford, and Jim McDivitt, all of whom went on to win renown as astronauts. Yeager and his selection board picked only the top one percent of this school's applicants.[94]

Adams made his first X-15 flight in October 1966. The engine shut down prematurely, but although he had previously flown this craft only in a simulator, he successfully guided his plane to a safe landing on an emergency dry lakebed. A year later, in the fall of 1967, he trained for his seventh mission by spending 23 hours in the simulator. The flight itself took place on 15 November.

As he went over the top at 266,400 feet, his airplane made a slow turn to the right that left it yawing to one side by 15 degrees.[95] Soon after, Adams made his mistake. His instrument panel included an attitude indicator with a vertical bar. He could select between two modes of display, whereby this bar could indicate either sideslip angle or roll angle. He was accustomed to reading it as a yaw or sideslip angle—but he had set it to display roll.

"It is most probable that the pilot misinterpreted the vertical bar and flew it as a sideslip indicator," the accident report later declared. Radio transmissions from the ground might have warned him of his faulty attitude, but the ground controllers had no data on yaw. Adams might have learned more by looking out the window, but he had been carefully trained to focus on his instruments. Three other cockpit indicators displayed the correct values of heading and sideslip angle, but he apparently kept his eyes on the vertical bar. He seems to have felt vertigo, which he had trained to overcome by concentrating on that single vertical needle.[96]

Mistaking roll for sideslip, he used his reaction controls to set up a re-entry with his airplane yawed at ninety degrees. This was very wrong; it should have been pointing straight ahead with its nose up. At Mach 5 and 230,000 feet, he went into a spin. He fought his way out of it, recovering from the spin at Mach 4.7 and 120,000 feet. However, some of his instruments had been knocked badly awry. His inertial reference unit was displaying an altitude that was more than 100,000 feet higher than his true altitude. In addition, the MH-96 flight-control system made a fatal error.

It set up a severe pitch oscillation by operating at full gain, as it moved the horizontal stabilizers up and down to full deflection, rapidly and repeatedly. This system should have reduced its gain as the aircraft entered increasingly dense atmosphere, but instead it kept the gain at its highest value. The wild pitching produced extreme nose-up and nose-down attitudes that brought very high drag, along with decelerations as great as 15 g. Adams found himself immobilized, pinned in his seat by forces far beyond what his plane could withstand. It broke up at 62,000 feet, still traveling at Mach 3.9. The wings and tail came off; the fuselage fractured into three pieces. Adams failed to eject and died when he struck the ground.[97]

"We set sail on this new sea," John Kennedy declared in 1962, "because there is new knowledge to be gained, and new rights to be won." Yet these achievements came at a price, which Adams paid in full.[98]

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2 NACA RM L54F21.

3 Gunston, *Fighters*, pp. 156-57; Anderson, *History*, pp. 430, 432.

4 NASA SP-4303, pp. 67-69.

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7 NASA RP-1028, p. 237.

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12 Miller, *X-Planes*, p. 22; NASA SP-4305, p. 350. Quote: Minutes, Committee on Aerodynamics, 4 October 1951, p. 16.

13 Letter, Woods to Committee on Aerodynamics, 8 January 1952; memo, Dornberger to Woods, 18 January 1952 (includes quotes).

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30 Heppenheimer, *Turbulent*, pp. 149-51, 197-200 (quote, p. 197).

31 Gunston, *Fighters*, pp. 121-22.

32 Wolfe, *Right Stuff*, p. 39.

33 Gunston, *Fighters*, pp. 155-64, 170-76.

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39 "History of the Arnold Engineering Development Center," 1 July to 1 December 1957; "Standard Missile Characteristics: XSM-64 Navaho," p. 3.

40 "History of the Arnold Engineering Development Center," 1 July to 1 December 1955; 1 July to 1 December 1959.

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42 DTIC AD-098980; *Quarterly Review:* Summer 1959, p. 81; Fall 1959, p. 57.

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85 Ibid., pp. 189-95; NASA SP-4303, pp. 121-22.

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4

FIRST THOUGHTS OF HYPERSONIC PROPULSION

Three new aircraft engines emerged from World War II: the turbojet, the ramjet, and the liquid rocket. The turbojet was not suitable for hypersonic flight, but the rocket and the ramjet both gave rise to related airbreathing concepts that seemed to hold promise.

Airbreathing rockets drew interest, but it was not possible to pump in outside air with a conventional compressor. Such rockets instead used liquid hydrogen fuel as a coolant, to liquefy air, with this liquid air being pumped to the engine. This arrangement wasted cooling power by also liquefying the air's nonflammable hydrogen, and so investigators sought ways to remove this nitrogen. They wanted a flow of nearly pure liquid oxygen, taken from the air, for use as the oxidizer.

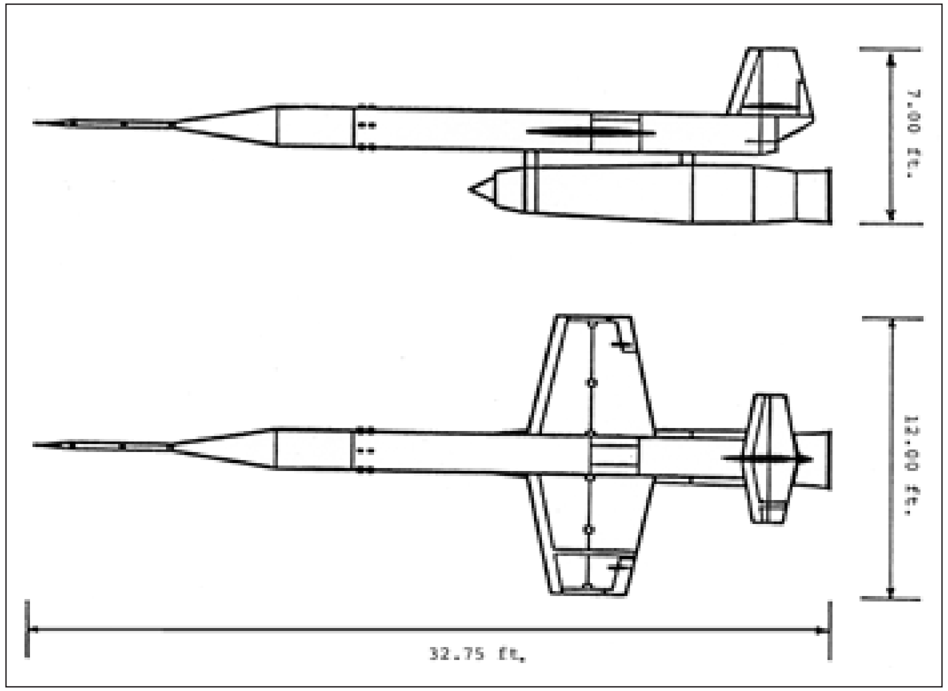
Ramjets provided higher flight speeds than turbojets, but they too had limits. Antonio Ferri, one of Langley's leading researchers, took the lead in conceiving of ramjets that appeared well suited to flight at hypersonic and perhaps even orbital speeds, at least on paper. Other investigators studied combined-cycle engines. The ejector ramjet, for one, sought to integrate a rocket with a ramjet, yielding a single compact unit that might fly from a runway to orbit.

Was it possible to design a flight vehicle that in fact would do this? Ferri thought so, as did his colleague Alexander Kartveli of Republic Aviation. Air Force officials encouraged such views by sponsoring a program of feasibility studies called Aerospaceplane. Designers at several companies contributed their own ideas.

These activities unfolded within a world where work with conventional rockets was advancing vigorously.[1] In particular, liquid hydrogen was entering the mainstream of rocket engineering.[2] Ramjets also won acceptance as standard military engines, powering such missiles as Navaho, Bomarc, Talos, and the X-7. With this background, for a time some people believed that even an Aerospaceplane might prove feasible.

RAMJETS AS MILITARY ENGINES

The ramjet and turbojet relied on fundamentally the same thermodynamic cycle. Both achieved compression of inflowing air, heated the compressed flow by burning



The X-7. (U.S. Air Force)

fuel, and obtained thrust by allowing the hot airflow to expand through a nozzle. The turbojet achieved compression by using a rotating turbocompressor, which inevitably imposed a requirement to tap a considerable amount of power from its propulsive jet by placing the turbine within the flow. A ramjet dispensed with this turbomachinery, compressing the incoming flow by the simple method of processing it through a normal or oblique shock. This brought the promise of higher flight speed. However, a ramjet paid for this advantage by requiring an auxiliary boost, typically with a rocket, to accelerate it to speeds at which this shock could form.[3]

The X-7 served as a testbed for development of ramjet engines as mainstream propulsion units. With an initial concept that dated to December 1946, it took shape as a three-stage flight vehicle. The first stage, a B-29 and later a B-50 bomber, played the classic role of lifting the aircraft to useful altitudes. Such bombers also served in this fashion as mother ships for the X-1 series, the X-2, and in time the X-15. For the X-7, a solid propellant rocket served as the second stage, accelerating the test aircraft to a speed high enough for sustained ramjet operation. The ramjet engine, slung beneath its fuselage, provided further acceleration along with high-speed cruise. Recovery was achieved using a parachute and a long nose spike that pierced the ground like a lance. This enabled the X-7 to remain upright, which protected the airframe and engine for possible re-use.

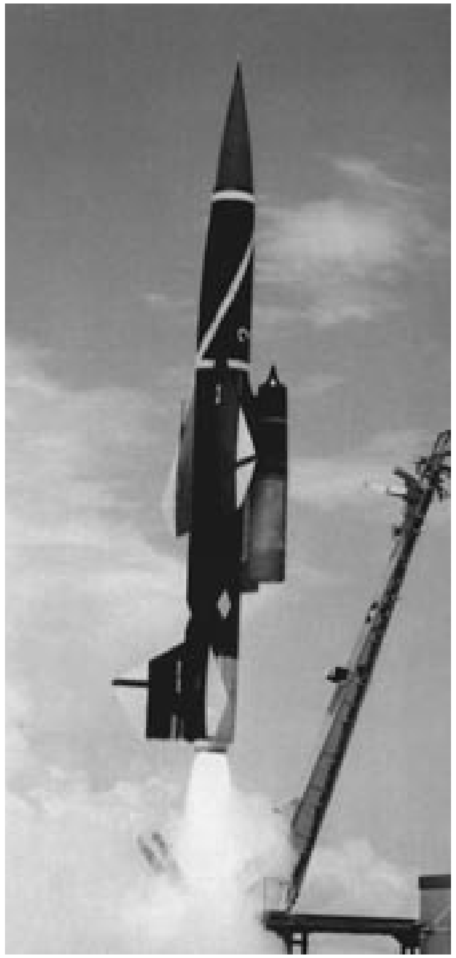
The X-7 craft were based at Holloman Air Force Base in New Mexico, which was an early center for missile flight test. The first flight took place in April 1951, with a ramjet of 20-inch diameter built by Wright Aeronautical. The X-7 soon took on the role of supporting developmental tests of a 28-inch engine built by the Marquardt Company and intended for use with the Bomarc missile. Flights with this 28-inch design began in December 1952 and achieved a substantial success the following April. The engine burned for some 20 seconds; the vehicle reached 59,500 feet and Mach 2.6. This exceeded the Mach 2.44 of the X-1A rocket plane in December 1953, piloted by Chuck Yeager. Significantly, although the X-7 was unpiloted, it remained aerodynamically stable during this flight. By contrast, the X-1A lost stability and fell out of the sky, dropping 51,000 feet before Yeager brought it back under control.[4]

The X-7 soon became a workhorse, running off some one hundred missions between 1955 and the end of the program in July 1960. It set a number of records, including range and flight time of 134 miles and 552 seconds, respectively. Its altitude mark of 106,000 feet, achieved with an airbreathing ramjet, compared with 126,200 feet for the rocket-powered X-2 research airplane.[5]

Other achievements involved speed. The vehicle had been built of heat-treated 4130 steel, with the initial goal being Mach 3. The program achieved this—and simply kept going. On 29 August 1957 it reached Mach 3.95 with a 28-inch Marquardt engine. Following launch from a B-50 at 33,700 feet, twin solid motors mounted beneath the wings boosted the craft to Mach 2.25. These boosters fell away; the ramjet ignited, and the vehicle began to climb at a 20-degree angle before leveling out at 54,500 feet. It then went into a very shallow dive. The engine continued to operate, as it ran for a total of 91 seconds, and acceleration continued until the craft attained its peak Mach at fuel exhaustion. It was recovered through use of its parachute and nose spike, and temperature-sensitive paints showed that it had experienced heating to more than 600°F. This heating also brought internal damage to the engine.[6]

Even so, the X-7 was not yet at the limit of its capabilities. Fitted with a 36-inch ramjet, again from Marquardt, it flew to Mach 4.31 on 17 April 1958. This time the drop from the B-50 came at 28,500 feet, with the engine igniting following rocket boost to Mach 1.99. It operated for 70.9 seconds, propelling the vehicle to a peak altitude of 60,000 feet. By then it was at Mach 3.5, continuing to accelerate as it transitioned to level flight. It reached its maximum Mach—and sustained a sharp drop in thrust three seconds later, apparently due to an engine tailpipe failure. Breakup of the vehicle occurred immediately afterward, with the X-7 being demolished.[7]

This flight set a record for airbreathing propulsion that stands to this day. Its speed of 2,881 miles per hour (mph) compares with the record for an afterburning



The Bomarc. (U.S. Air Force)

turbojet of 2,193 mph, set in an SR-71 in 1976.[8] Moreover, while the X-7 was flying to glory, the Bomarc program that it supported was rolling toward operational deployment.

The name "Bomarc" derives from the contractors Boeing and the Michigan Aeronautical Research Center, which conducted early studies. It was a single-stage, ground-launched antiaircraft missile that could carry a nuclear warhead. A built-in liquid-propellant rocket provided boost; it was replaced by a solid rocket in a later version. Twin ramjets sustained cruise at Mach 2.6. Range of the initial operational model was 250 miles, later extended to 440 miles.[9]

Specifications for this missile were written in September 1950. In January 1951 an Air Force letter contract designated Boeing as the prime contractor, with Marquardt Aircraft winning a subcontract to build its ramjet. The development of this engine went forward rapidly. In July 1953 officials of the Air Force's Air Materiel Command declared that work on the 28-inch engine was essentially complete.[10]

Flight tests were soon under way. An Air Force review notes that a test vehicle "traveled 70 miles in 1.5 minutes to complete a most successful test of 17 June 1954." The missile "cruised at Mach 3+ for 15 seconds and reached an altitude of 56,000 feet." In another flight in February 1955, it reached a peak altitude of 72,000 feet as its ramjet burned for 245 seconds. This success brought a decision to order Bomarc into production. Four more test missiles flew with their ramjets later that year, with all four scoring successes.[11]

Other activity turned Bomarc from a missile into a weapon system, integrating it with the electronic Semi-Automatic Ground Environment (SAGE) that controlled air defense within North America. In October 1958, Bomarcs scored a spectacular success. Controlled remotely from a SAGE center 1,500 miles away, two missiles homed in on target drones that were more than 100 miles out to sea. The Bomarcs dived on them and made intercepts. The missiles were unarmed, but one of them actually rammed its target. A similar success occurred a year later when a Bomarc made a direct hit on a Regulus 2 supersonic target over the Gulf of Mexico. The missile first achieved operational status in September 1959. Three years later, Bomarc was in service at eight Air Force sites, with deployment of Canadian squadrons following. These missiles remained on duty until 1972.[12]

The Talos. (National Archives and Records Administration)

Paralleling Bomarc, the Navy pursued an independent effort that developed a ship-based antiaircraft missile named Talos, after a mythical defender of the island of Crete. It took shape at a major ramjet center, the Applied Physics Laboratory (APL) of Johns Hopkins University. Like Bomarc, Talos was nuclear-capable; *Jane's* gave its speed as Mach 2.5 and its range as 65 miles.

An initial version first flew in 1952, at New Mexico's White Sands Missile Range. A prototype of a nuclear-capable version made its own first flight in December 1953. The Korean War had sparked development of this missile, but the war ended in mid-1953 and the urgency diminished. When the Navy selected the light cruiser USS *Galveston* for the first operational deployment of Talos, the conversion of this ship became a four-year task. Nevertheless, Talos finally joined the fleet in 1958, with other cruisers installing it as well. It remained in service until 1980.[13]

One military ramjet project, that of Navaho, found itself broken in mid-stride. Although the ultimate version was to have intercontinental range, the emphasis during the 1950s was on an interim model with range of 2,500 miles, with the missile cruising at Mach 2.75 and 76,800 feet. The missile used a rocket-powered booster with liquid-fueled engines built by Rocketdyne. The airplane-like Navaho mounted two 51-inch ramjets from Wright Aeronautical, which gave it the capability to demonstrate long-duration supersonic cruise under ramjet power.[14]

The Navaho. (Smithsonian Institution No. 77-10905)

Flight tests began in November 1956, with launches of complete missiles taking place at Cape Canaveral. The first four were flops; none even got far enough to permit ignition of the ramjets. In mid-July of 1957, three weeks after the first launch of an Atlas, the Air Force canceled Navaho. Lee Atwood, president of North American Aviation, recalls that Atlas indeed had greater promise: “Navaho would approach its target at Mach 3; a good antiaircraft missile might shoot it down. But Atlas would come in at Mach 20. There was no way that anyone would shoot *it* down.”

There nevertheless was hardware for several more launches, and there was considerable interest in exercising the ramjets. Accordingly, seven more Navahos were launched during the following 18 months, with the best flight taking place in January 1958.

The missile accelerated on rocket power and leveled off, the twin ramjet engines ignited, and it stabilized in cruise at 64,000 feet. It continued in this fashion for half an hour. Then, approaching the thousand-mile mark in range, its autopilot initiated a planned turnaround to enable this Navaho to fly back uprange. The turn was wide, and ground controllers responded by tightening it under radio control. This disturbed the airflow near the inlet of the right ramjet, which flamed out. The missile lost speed, its left engine also flamed out, and the vehicle fell into the Atlantic. It had been airborne for 42 minutes, covering 1,237 miles.[15]

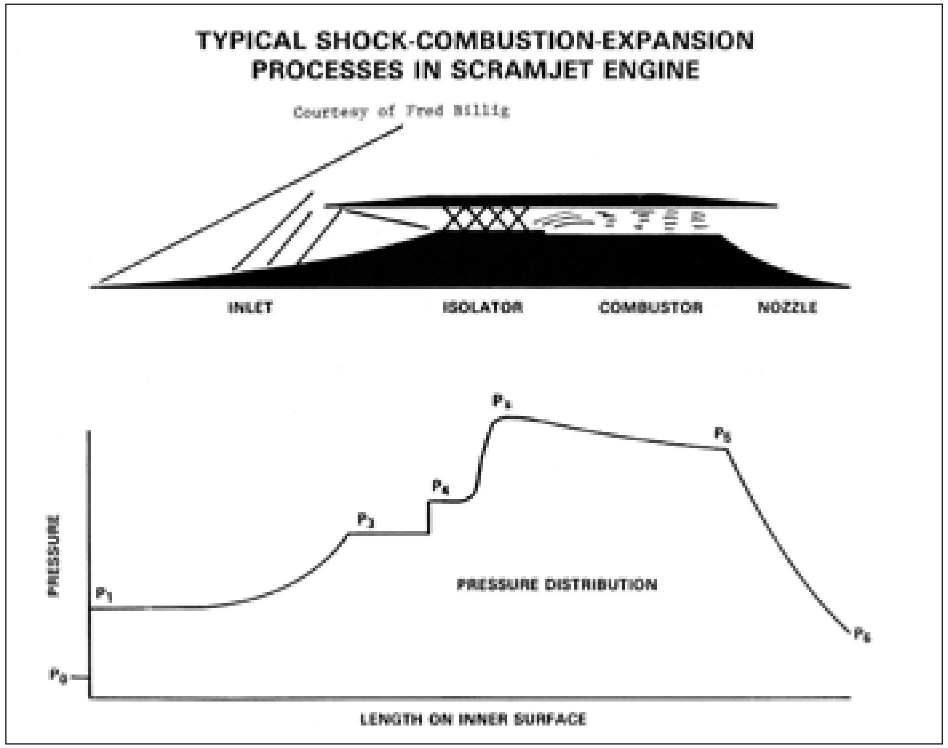
Because the program had been canceled and the project staff was merely flying off its leftover hardware, there were no funds to address what clearly was a serious inlet problem. Still, Navaho at least had flown. By contrast, another project—the Air Force’s XF-103 fighter, which aimed at Mach 3.7—never even reached the prototype stage.

The XF-103 in artist’s rendering. (U.S. Air Force)

Its engine, also from Wright Aeronautical, combined a turbojet and ramjet within a single package. The ramjet doubled as an afterburner, with internal doors closing off the ramjet’s long inlet duct. Conversion to pure ramjet operation took seven seconds. This turboramjet showed considerable promise. At Arnold Engineering Development Center, an important series of ground tests was slated to require as much as six weeks. They took only two weeks, with the engine running on the first day.

Unfortunately, the XF-103 outstayed its welcome. The project dated to 1951; it took until December 1956 to carry out the AEDC tests. Much of the reason for this long delay involved the plane’s highly advanced design, which made extensive use of titanium. Still, the Mach 1.8 XF-104 took less than 18 months to advance from the start of engineering design to first flight, and the XF-103 was not scheduled to fly until 1960. The Air Force canceled it in August 1957, and aviation writer Richard DeMeis pronounced its epitaph: “No matter how promising or outstanding an aircraft may be, if development takes inordinately long, the mortality rate rises in proportion.”[16]

Among the five cited programs, three achieved operational status, with the X-7 actually outrunning its initial planned performance. The feasibility of Navaho was never in doubt; the inlet problem was one of engineering development, not one that would call its practicality into question. Only the XF-103 encountered serious problems of technology that lay beyond the state of the art. The ramjet of the 1950s thus was an engine whose time had come, and which had become part of mainstream design.

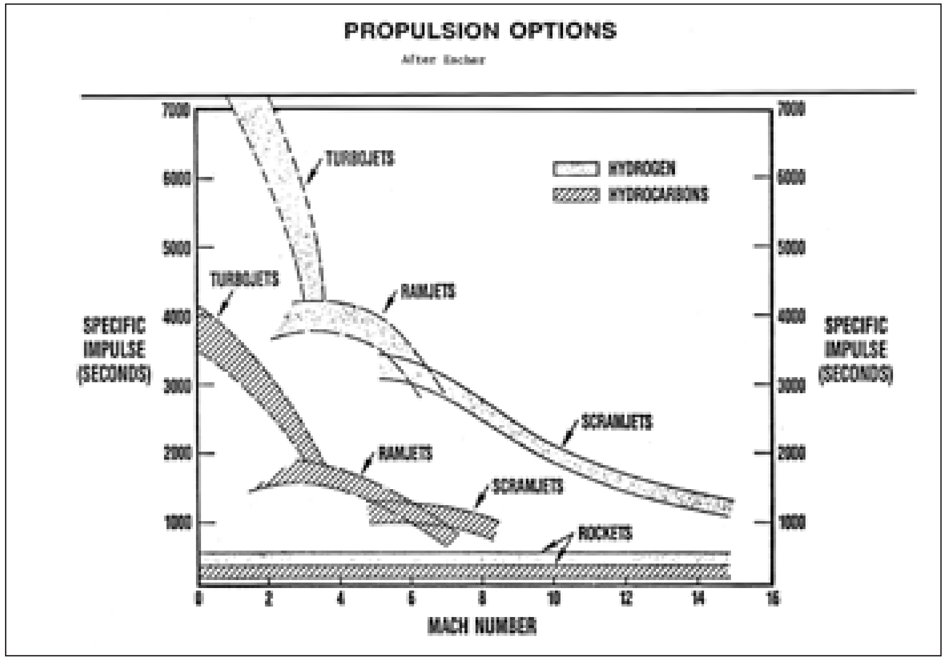


The scramjet. Oblique shocks in the isolator prevent disturbances in the combustor from propagating upstream, where they would disrupt flow in the inlet. (Courtesy of Frederick Billig)

There was a ramjet industry, featuring the firms of Marquardt Aviation and Wright Aeronautical. Facilities for developmental testing existed, not only at these companies but at NACA-Lewis and the Navy's Ordnance Aerophysics Laboratory, which had a large continuous-flow supersonic wind tunnel. With this background, a number of investigators looked ahead to engines derived from ramjets that could offer even higher performance.

Origins of the Scramjet

The airflow within a ramjet was subsonic. This resulted from its passage through one or more shocks, which slowed, compressed, and heated the flow. This was true even at high speed, with the Mach 4.31 flight of the X-7 also using a subsonic-combustion ramjet. Moreover, because shocks become stronger with increasing Mach, ramjets could achieve greater internal compression of the flow at higher speeds. This increase in compression improved the engine's efficiency.



Comparative performance of scramjets and other engines. Airbreathers have very high performance because they are "energy machines," which burn fuel to heat air. Rockets have much lower performance because they are "momentum machines," which physically expel flows of mass. (Courtesy of William Escher)

Still, there were limits to a ramjet's effectiveness. Above Mach 5, designers faced increasingly difficult demands for thermal protection of an airframe and for cooling of the ramjet duct. With the internal flow being very hot, it became more difficult to add still more heat by burning fuel, without overtaxing the materials or the cooling arrangements. If the engine were to run lean to limit the temperature rise in the combustor, its thrust would fall off. At still higher Mach levels, the issue of heat addition through combustion threatened to become moot. With high internal temperatures promoting dissociation of molecules of air, combustion reactions would not go to completion and hence would cease to add heat.

A promising way around this problem involved doing away with a requirement for subsonic internal flow. Instead this airflow was to be supersonic and was to sustain combustion. Right at the outset, this approach reduced the need for internal cooling, for this airflow would not heat up excessively if it was fast enough. This relatively cool internal airflow also could continue to gain heat through combustion. It would avoid problems due to dissociation of air or failure of chemical reactions in combustion to go to completion. On paper, there now was no clear upper limit to speed. Such a vehicle might even fly to orbit.

Yet while a supersonic-combustion ramjet offered tantalizing possibilities, right at the start it posed a fundamental issue: was it feasible to burn fuel in the duct of such an engine without producing shock waves? Such shocks could produce severe internal heating, destroying the benefits of supersonic combustion by slowing the flow to subsonic speeds. Rather than seeking to achieve shock-free supersonic combustion in a duct, researchers initially bypassed this difficulty by addressing a simpler problem: demonstration of combustion in a supersonic free-stream flow.

The earliest pertinent research appears to have been performed at the Applied Physics Laboratory (APL), during or shortly after World War II. Machine gunners in aircraft were accustomed to making their streams of bullets visible by making every twentieth round a tracer, which used a pyrotechnic. They hoped that a gunner could walk his bullets into a target by watching the glow of the tracers, but experience showed that the pyrotechnic action gave these bullets trajectories of their own. The Navy then engaged two research centers to look into this. In Aberdeen, Maryland, Ballistic Research Laboratories studied the deflection of the tracer rounds themselves. Near Washington, DC, APL treated the issue as a new effect in aerodynamics and sought to make use of it.

Investigators conducted tests in a Mach 1.5 wind tunnel, burning hydrogen at the base of a shell. A round in flight experienced considerable drag at its base, but the experiments showed that this combustion set up a zone of higher pressure that canceled the drag. This work did not demonstrate supersonic combustion, for while the wind-tunnel flow was supersonic, the flow near the base was subsonic. Still, this work introduced APL to topics that later proved pertinent to supersonic-combustion ramjets (which became known as scramjets).[17]

NACA's Lewis Flight Propulsion Laboratory, the agency's center for studies of engines, emerged as an early nucleus of interest in this topic. Initial work involved theoretical studies of heat addition to a supersonic flow. As early as 1950, the Lewis investigators Irving Pinkel and John Serafini treated this problem in a two-dimensional case, as in flow over a wing or past an axisymmetric body. In 1952 they specifically treated heat addition under a supersonic wing. They suggested that this might produce more lift than could be obtained by burning the same amount of fuel in a turbojet to power an airplane.[18]

This conclusion immediately raised the question of whether it was possible to demonstrate supersonic combustion in a wind tunnel. Supersonic tunnels produced airflows having very low pressure, which added to the experimental difficulties. However, researchers at Lewis had shown that aluminum borohydride could promote the ignition of pentane fuel at air pressures as low as 0.03 atmosphere. In 1953 Robert Dorsch and Edward Fletcher launched a research program that sought to ignite pure borohydride within a supersonic flow. Two years later they declared that they had succeeded. Subsequent work showed that at Mach 3, combustion of this fuel under a wing more than doubled the lift.[19]

Also at Lewis, the aerodynamicists Richard Weber and John MacKay published the first important open-literature study of theoretical scramjet performance in 1958. Because they were working entirely with equations, they too bypassed the problem of attaining shock-free flow in a supersonic duct by simply positing that it was feasible. They treated the problem using one-dimensional gas dynamics, corresponding to flow in a duct with properties at any location being uniform across the diameter. They restricted their treatment to flow velocities from Mach 4 to 7.

They discussed the issue of maximizing the thrust and the overall engine efficiency. They also considered the merits of various types of inlet, showing that a suitable choice could give a scramjet an advantage over a conventional ramjet. Supersonic combustion failed to give substantial performance improvements or to lead to an engine of lower weight. Even so, they wrote that "the trends developed herein indicate that the [scramjet] will offer superior performance at higher hypersonic flight speeds."[20]

An independent effort proceeded along similar lines at Marquardt, where investigators again studied scramjet performance by treating the flow within an engine duct using one-dimensional gasdynamic theory. In addition, Marquardt researchers carried out their own successful demonstration of supersonic combustion in 1957. They injected hydrogen into a supersonic airflow, with the hydrogen and the air having the same velocity. This work overcame objections from skeptics, who had argued that the work at NACA-Lewis had not truly demonstrated supersonic combustion. The Marquardt experimental arrangement was simpler, and its results were less equivocal.[21]

The Navy's Applied Physics Laboratory, home of Talos, also emerged as an early center of interest in scramjets. As had been true at NACA-Lewis and at Marquardt, this group came to the concept by way of external burning under a supersonic wing. William Avery, the leader, developed an initial interest in supersonic combustion around 1955, for he saw the conventional ramjet facing increasingly stiff competition from both liquid rockets and afterburning turbojets. (Two years later such competition killed Navaho.) Avery believed that he could use supersonic combustion to extend the performance of ramjets.

His initial opportunity came early in 1956, when the Navy's Bureau of Ordnance set out to examine the technological prospects for the next 20 years. Avery took on the task of assembling APL's contribution. He picked scramjets as a topic to study, but he was well aware of an objection. In addition to questioning the fundamental feasibility of shock-free supersonic combustion in a duct, skeptics considered that a hypersonic inlet might produce large pressure losses in the flow, with consequent negation of an engine's thrust.

Avery sent this problem through Talos management to a young engineer, James Keirsey, who had helped with Talos engine tests. Keirsey knew that if a hypersonic ramjet was to produce useful thrust, it would appear as a small difference between two large quantities: gross thrust and total drag. In view of uncertainties in both these numbers, he was unable to state with confidence that such an engine would work. Still he did not rule it out, and his "maybe" gave Avery reason to pursue the topic further.

Avery decided to set up a scramjet group and to try to build an engine for test in a wind tunnel. He hired Gordon Dugger, who had worked at NACA-Lewis. Dugger's first task was to decide which of several engine layouts, both ducted and unducted, was worth pursuing. He and Avery selected an external-burning configuration with the shape of a broad upside-down triangle. The forward slope, angled downward, was to compress the incoming airflow. Fuel could be injected at the apex, with the upward slope at the rear allowing the exhaust to expand. This approach again bypassed the problem of producing shock-free flow in a duct. The use of external burning meant that this concept could produce lift as well as thrust.

Dugger soon became concerned that this layout might be too simple to be effective. Keirsey suggested placing a very short cowl at the apex, thereby easing problems of ignition and combustion. This new design lent itself to incorporation within the wings of a large aircraft of reasonably conventional configuration. At low speeds the wide triangle could retract until it was flat and flush with the wing undersurface, leaving the cowl to extend into the free stream. Following acceleration to supersonic speed, the two shapes would extend and assume their triangular shape, then function as an engine for further acceleration.

Wind-tunnel work also proceeded at APL. During 1958 this center had a Mach 5 facility under construction, and Dugger brought in a young experimentalist named Frederick Billig to work with it. His first task was to show that he too could demonstrate supersonic combustion, which he tried to achieve using hydrogen as his fuel. He tried electric ignition; an APL history states that he "generated gigantic arcs," but "to no avail." Like the NACA-Lewis investigators, he turned to fuels that ignited particularly readily. His choice, triethyl aluminum, reacts spontaneously, and violently, on contact with air.

"The results of the tests on 5 March 1959 were dramatic," the APL history continues. "A vigorous white flame erupted over the rear of [the wind-tunnel model] the instant the triethyl aluminum fuel entered the tunnel, jolting the model against its support. The pressures measured on the rear surface jumped upward." The device produced less than a pound of thrust. But it generated considerable lift, supporting calculations that had shown that external burning could increase lift. Later tests showed that much of the combustion indeed occurred within supersonic regions of the flow.[22]

By the late 1950s small scramjet groups were active at NACA-Lewis, Marquardt, and APL. There also were individual investigators, such as James Nicholls of the University of Michigan. Still it is no small thing to invent a new engine, even as an extension of an existing type such as the ramjet. The scramjet needed a really high-level advocate, to draw attention within the larger realms of aerodynamics and propulsion. The man who took on this role was Antonio Ferri.

He had headed the supersonic wind tunnel in Guidonia, Italy. Then in 1943 the Nazis took control of that country and Ferri left his research to command a band of partisans who fought the Nazis with considerable effectiveness. This made him a marked man, and it was not only Germans who wanted him. An American agent, Moe Berg, was also on his trail. Berg found him and persuaded him to come to the States. The war was still on and immigration was nearly impossible, but Berg persuaded William Donovan, the head of his agency, to seek support from President Franklin Roosevelt himself. Berg had been famous as a baseball catcher in civilian life, and when Roosevelt learned that Ferri now was in the hands of his agent, he remarked, "I see Berg is still catching pretty well."[23]

At NACA-Langley after the war, he rose in management and became director of the Gas Dynamics Branch in 1949. He wrote an important textbook, *Elements of Aerodynamics of Supersonic Flows* (Macmillan, 1949). Holding a strong fondness for the academic world, he took a professorship at Brooklyn Polytechnic Institute in 1951, where in time he became chairman of his department. He built up an aerodynamics laboratory at Brooklyn Poly and launched a new activity as a consultant. Soon he was working for major companies, drawing so many contracts that his graduate students could not keep up with them. He responded in 1956 by founding a company, General Applied Science Laboratories (GASL). With financial backing from the Rockefellers, GASL grew into a significant center for research in high-speed flight.[24]

He was a formidable man. Robert Sanator, a former student, recalls that "you had to really want to be in that course, to learn from him. He was very fast. His mind was constantly moving, redefining the problem, and you had to be fast to keep up with him. He expected people to perform quickly, rapidly." John Erdos, another ex-student, adds that "if you had been a student of his and later worked for him, you could never separate the professor-student relationship from your normal working relationship." He remained Dr. Ferri to these people, never Tony, even when they rose to leadership within their companies.[25]

He came early to the scramjet. Taking this engine as his own, he faced its technical difficulties squarely and asserted that they could be addressed, giving examples of approaches that held promise. He repeatedly emphasized that scramjets could offer performance far higher than that of rockets. He presented papers at international conferences, bringing these ideas to a wider audience. In turn, his strong professional reputation ensured that he was taken seriously. He also performed experiments as he sought to validate his claims. More than anyone else, Ferri turned the scramjet from an idea into an invention, which might be developed and made practical.

His path to the scramjet began during the 1950s, when his work as a consultant brought him into a friendship with Alexander Kartveli at Republic Aviation. Louis Nucci, Ferri's longtime colleague, recalls that the two men "made good sparks. They were both Europeans and learned men; they liked opera and history." They also complemented each other professionally, as Kartveli focused on airplane design while Ferri addressed difficult problems in aerodynamics and propulsion. The two men worked together on the XF-103 and fed off each other, each encouraging the other to think bolder thoughts. Among the boldest was a view that there were no natural limits to aircraft speed or performance. Ferri put forth this idea initially; Kartveli then supported it with more detailed studies.[26]

The key concept, again, was the scramjet. Holding a strong penchant for experimentation, Ferri conducted research at Brooklyn Poly. In September 1958, at a conference in Madrid, he declared that steady combustion, without strong shocks, had been accomplished in a supersonic airstream at Mach 3.0. This placed him midway in time between the supersonic-combustion demonstrations at Marquardt and at APL.[27]

Shock-free flow in a duct continued to loom as a major problem. The Lewis, Marquardt, and APL investigators had all bypassed this issue by treating external combustion in the supersonic flow past a wing, but Ferri did not flinch. He took the problem of shock-free flow as a point of departure, thereby turning the ducted scramjet from a wish into a serious topic for investigation.

In supersonic wind tunnels, shock-free flow was an everyday affair. However, the flow in such tunnels achieved its supersonic Mach values by expanding through a nozzle. By contrast, flow within a scramjet was to pass through a supersonic inlet and then be strongly heated within a combustor. The inlet actually had the purpose of producing a shock, an oblique one that was to slow and compress the flow while allowing it to remain supersonic. However, the combustion process was only too likely to produce unwanted shocks, which would limit an engine's thrust and performance.

Nicholls, at Michigan, proposed to make a virtue of necessity by turning a combustor shock to advantage. Such a shock would produce very strong heating of the flow. If the fuel and air had been mixed upstream, then this combustor shock could produce ignition. Ferri would have none of this. He asserted that "by using a suitable design, formation of shocks in the burner can be avoided."[28]

Specifically, he started with a statement by NACA's Weber and MacKay on combustors. These researchers had already written that the combustor needed a diverging shape, like that of a rocket nozzle, to overcome potential limits on the airflow rate due to heat addition ("thermal choking"). Ferri proposed that within such a combustor, "fuel is injected parallel to the stream to eliminate formation of shocks…. The fuel gradually mixes with the air and burns…and the combustion process can take place without the formation of shocks." Parallel injection might take place by building the combustor with a step or sudden widening. The flow could expand as it passed the step, thereby avoiding a shock, while the fuel could be injected at the step.[29]

Ferri also made an intriguing contribution in dealing with inlets, which are critical to the performance of scramjets. He did this by introducing a new concept called "thermal compression." One approaches it by appreciating that a process of heat addition can play the role of a normal shock wave. When an airflow passes through such a shock, it slows in speed and therefore diminishes in Mach, while its temperature and pressure go up. The same consequences occur when a supersonic airflow is heated. It therefore follows that a process of heat addition can substitute for a normal shock.[30]

Practical inlets use oblique shocks, which are two-dimensional. Such shocks afford good control of the aerodynamics of an inlet. If heat addition is to substitute for an oblique shock, it too must be two-dimensional. Heat addition in a duct is one-dimensional, but Ferri proposed that numerous small burners, set within a flow, could achieve the desired two-dimensionality. By turning individual burners on or off, and by regulating the strength of each one's heating, he could produce the desired pattern of heating that in fact would accomplish the substitution of heating for shock action.[31]

Why would one want to do this? The nose of a hypersonic aircraft produces a strong bow shock, an oblique shock that accomplishes initial compression of the airflow. The inlet rides well behind the nose and features an enclosing cowl. The cowl, in turn, has a lip or outer rim. For best effectiveness, the inlet should sustain a "shock-on-lip" condition. The shock should not impinge within the inlet, for only the lip is cooled in the face of shock-impingement heating. But the shock also should not ride outside the inlet, or the inlet will fail to capture all of the shock-compressed airflow.

To maintain the shock-on-lip condition across a wide Mach range, an inlet requires variable geometry. This is accomplished mechanically, using sliding seals that must not allow leakage of very hot boundary-layer air. Ferri's principle of thermal compression raised the prospect that an inlet could use fixed geometry, which was far simpler. It would do this by modulating its burners rather than by physically moving inlet hardware.

Thermal compression brought an important prospect of flexibility. At a given value of Mach, there typically was only one arrangement of a variable-geometry inlet that would produce the desired shock that would compress the flow. By contrast, the thermal-compression process might be adjusted at will simply by controlling the heating. Ferri proposed to do this by controlling the velocity of injection of the fuel. He wrote that "the heat release is controlled by the mixing process, [which] depends on the difference of velocity of the air and of the injected gas." Shock-free internal flow appeared feasible: "The fuel is injected parallel to the stream to eliminate formation of shocks [and] the combustion process can take place without the formation of shocks." He added,

> "The preliminary analysis of supersonic combustion ramjets…indicates that combustion can occur in a fixed-geometry burner-nozzle combination through a large range of Mach numbers of the air entering the combustion region. Because the Mach number entering the burner is permitted to vary with flight Mach number, the inlet and therefore the complete engine does not require variable geometry. Such an engine can operate over a large range of flight Mach numbers and, therefore, can be very attractive as an accelerating engine."[32]

There was more. As noted, the inlet was to produce a bow shock of specified character, to slow and compress the incoming air. But if the inflow was too great, the inlet would disgorge its shock. This shock, now outside the inlet, would disrupt the flow within the inlet and hence in the engine, with the drag increasing and the thrust falling off sharply. This was known as an unstart.

Supersonic turbojets, such as the Pratt & Whitney J58 that powered the SR-71 to speeds beyond Mach 3, typically were fitted with an inlet that featured a conical spike at the front, a centerbody that was supposed to translate back and forth to adjust the shock to suit the flight Mach number. Early in the program, it often did not work.[33] The test pilot James Eastham was one of the first to fly this spy plane, and he recalls what happened when one of his inlets unstarted.

> "An unstart has your full and undivided attention, right then. The airplane gives a very pronounced yaw; then you are very preoccupied with getting the inlet started again. The speed falls off; you begin to lose altitude. You follow a procedure, putting the spikes forward and opening the bypass doors. Then you would go back to the automatic positioning of the spike—which many times would unstart it again. And when you unstarted on one side, sometimes the other side would also unstart. Then you really had to give it a good massage."[34]

The SR-71 initially used a spike-positioning system from Hamilton Standard. It proved unreliable, and Eastham recalls that at one point, "unstarts were literally stopping the whole program."[35] This problem was eventually overcome through development of a more capable spike-positioning system, built by Honeywell.[36] Still, throughout the development and subsequent flight career of the SR-71, the positioning of inlet spikes was always done mechanically. In turn, the movable spike represented a prime example of variable geometry.

Scramjets faced similar issues, particularly near Mach 4. Ferri's thermal-compression principle applied here as well—and raised the prospect of an inlet that might fight against unstarts by using thermal rather than mechanical arrangements. An inlet with thermal compression then might use fixed geometry all the way to orbit, while avoiding unstarts in the bargain.

Ferri presented his thoughts publicly as early as 1960. He went on to give a far more detailed discussion in May 1964, at the Royal Aeronautical Society in London. This was the first extensive presentation on hypersonic propulsion for many in the audience, and attendees responded effusively.

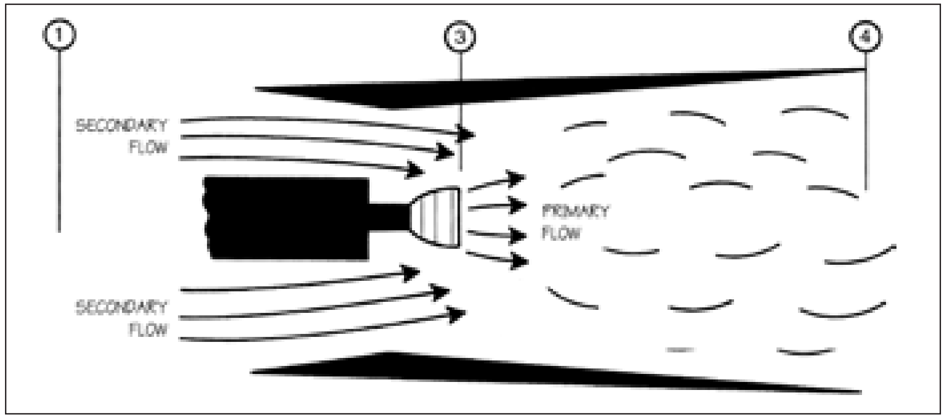
One man declared that "this lecture opened up enormous possibilities. Where they had, for lack of information, been thinking of how high in flight speed they could stretch conventional subsonic burning engines, it was now clear that they should be thinking of how far down they could stretch supersonic burning engines." A. D. Baxter, a Fellow of the Society, added that Ferri "had given them an insight into the prospects and possibilities of extending the speed range of the airbreathing engine far beyond what most of them had dreamed of; in fact, assailing the field which until recently was regarded as the undisputed regime of the rocket."[37]

Not everyone embraced thermal compression. "The analytical basis was rather weak," Marquardt's Arthur Thomas commented. "It was something that he had in his head, mostly. There were those who thought it was a lot of baloney." Nor did Ferri help his cause in 1968, when he published a Mach 6 inlet that offered "much better performance" at lower Mach "because it can handle much higher flow." His paper contained not a single equation.[38]

But Fred Billig was one who accepted the merits of thermal compression and gave his own analyses. He proposed that at Mach 5, thermal compression could increase an engine's specific impulse, an important measure of its performance, by 61 percent. Years later he recalled Ferri's "great capability for visualizing, a strong physical feel. He presented a full plate of ideas, not all of which have been realized."[39]

COMBINED-CYCLE PROPULSION SYSTEMS

The scramjet used a single set of hardware and operated in two modes, sustaining supersonic combustion as well as subsonic combustion. The transition involved a process called "swallowing the shock." In the subsonic mode, the engine held a train of oblique shocks located downstream of the inlet and forward of the combustor. When the engine went over to the supersonic-combustion mode, these shocks passed through the duct and were lost. This happened automatically, when the flight



Ejector ramjet. Primary flow from a ducted rocket entrains a substantial secondary flow of external air. (U.S. Air Force)

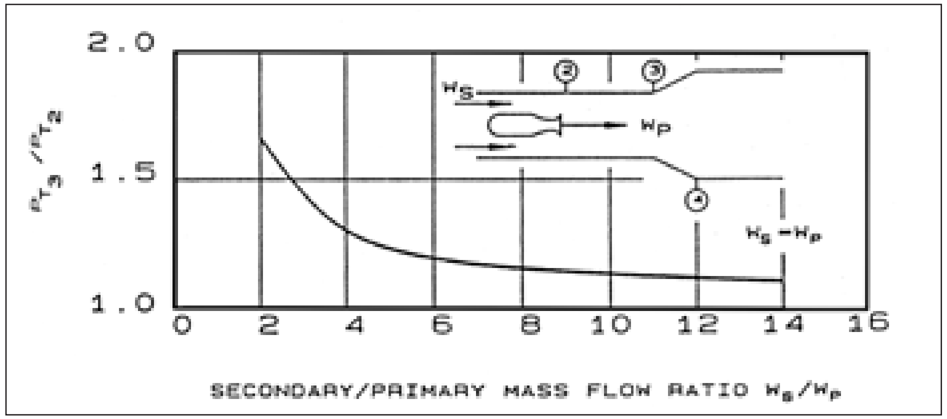
vehicle topped a critical speed and the engine continued to burn with no diminution of thrust.

The turboramjet arrangement of the XF-103 also operated in two modes, serving both as a turbojet and as a ramjet. Here, however, the engine employed two sets of hardware, which were physically separate. They shared a common inlet and nozzle, while the ramjet also served as the turbojet's afterburner. But only one set of equipment operated at any given time. Moreover, they were mounted separately and were not extensively integrated.[40]

System integration was the key concept within a third class of prime mover: the combined-cycle engine, which sought to integrate two separate thrust-producing cycles within a single set of hardware. In contrast to the turboramjet of the XF-103, engines of this type merged their equipment rather than keeping them separate. Two important concepts that did this were the ejector ramjet, which gave thrust even when standing still, and the Liquid Air Cycle Engine (LACE), which was an airbreathing rocket.

The ejector ramjet amounted to a combined-cycle system derived from a conventional ramjet. It used the ejector principle, whereby the exhaust of a rocket motor, placed within a duct, entrains a flow of air through the duct's inlet. This increases the thrust by converting thermal energy, within the hot exhaust, to mechanical energy. The entrained air slows and cools the exhaust. The effect is much the same as when designers improve the performance of a turbojet engine by installing a fan.

Ejectors date back to the nineteenth century. Horatio Phillips, a pioneer in aeronautical research, used a steam ejector after 1870 to build a wind tunnel. His ejector was a ring of pipe pierced with holes and set within a duct with the holes facing downstream. Pressurized steam, expanding through the holes, entrained an airflow within the duct that reached speeds of 40 mph, which served his studies.[41] Nearly a century later ejectors were used to evacuate chambers that conducted rocket-engine tests in near-vacuum, with the ejectors rapidly pumping out the rocket exhaust. Ejectors also flew, being used with both the F-104 and the SR-71. Significantly, the value of an ejector could increase with Mach. On the SR-71, for instance, it contributed only 14 percent of the total thrust at Mach 2.2, but accounted for 28 percent at Mach 3.2.[42]



Performance of an ejector. Even with minimal flow of entrained air, the pressure ratio is much lower than that of a turbojet. A pressure ratio of 1.5 implied low efficiency. (Courtesy of William Escher)

Jack Charshafian of Curtiss-Wright, director of development of ramjets for Navaho, filed a patent disclosure for an ejector rocket as early as 1947. By entraining outside air, it might run fuel-rich and still burn all its fuel. Ejector concepts also proved attractive to other aerospace pioneers, with patents being awarded to Alfred Africano, a founder of the American Rocket Society; to Hans von Ohain, an inventor of the turbojet; and to Helmut Schelp, who stirred early interest in military turbojets within the Luftwaffe.[43]

A conventional ramjet needed a boost to reach speeds at which its air-ramming effect would come into play, and the hardware requirements approached those of a complete and separate flight vehicle. The turbojet of the XF-103 exemplified what was necessary, as did the large rocket-powered booster of Navaho. But after 1960 the ejector ramjet brought the prospect of a ramjet that could produce thrust even when on the runway. By placing small rocket engines in a step surrounding a duct, a designer could leave the duct free of hardware. It might even sustain supersonic combustion, with the engine converting to a scramjet.

The ejector ramjet also promised to increase the propulsive efficiency by improving the match between flight speed and exhaust speed. A large mismatch greatly reduces the effectiveness of a propulsive jet. There would be little effective thrust, for instance, if one had a jet velocity of 10,000 feet per second while flying in the atmosphere at 400 feet per second. The ejector promised to avoid this by slowing the overall flow.

The ejector ramjet thus offered the enticing concept of a unified engine that could propel a single-stage vehicle from a runway to orbit. It would take off with ejector-boosted thrust from its rocket, accelerate through the atmosphere by using the combination as an ejector-boosted ramjet and scramjet, and then go over completely to rocket propulsion for the final boost to orbit.

Yet even with help from an ejector, a rocket still had a disadvantage. A ramjet or scramjet could use air as its oxidizer, but a rocket had to carry heavy liquid oxygen in an onboard tank. Hence, there also was strong interest in airbreathing rockets. Still, it was not possible to build such a rocket through a simple extension of principles applicable to the turbojet, for there was a serious mismatch between pressures available through turbocompression and those of a rocket's thrust chamber.

In the SR-71, for instance, a combination of inlet compression and turbocompression yielded an internal pressure of approximately 20 pounds per square inch (psi) at Mach 3 and 80,000 feet. By contrast, internal pressures of rocket engines started in the high hundreds of psi and rapidly ascended into the thousands for high performance. Unless one could boost the pressure of ram air to that level, no airbreathing rocket would ever fly.[44]

The concept that overcame this difficulty was LACE. It dated to 1954, and Randolph Rae of the Garrett Corporation was the inventor. LACE used liquid hydrogen both as fuel and as a refrigerant, to liquefy air. The temperature of the liquid hydrogen was only 21 K, far below that at which air liquefies. LACE thus called for incoming ram air to pass through a heat exchanger that used liquid hydrogen as the coolant. The air would liquefy, and then a pump could raise its pressure to whatever value was desired. In this fashion, LACE bypassed the restrictions on turbocompression of gaseous air. In turn, the warmed hydrogen flowed to the combustion chamber to burn in the liquefied air.[45]

At the outset, LACE brought a problem. The limited thermal capacity of liquid hydrogen brought another mismatch, for the system needed eight times more liquid hydrogen to liquefy a given mass of air than could burn in that mass. The resulting hydrogen-rich exhaust still had a sufficiently high velocity to give LACE a prospective advantage over a hydrogen-fueled rocket using tanked oxygen. Even so, there was interest in "derichening" the fuel-air mix, by making use of some of this extra hydrogen. An ejector promised to address this issue by drawing in more air to burn the hydrogen. Such an engine was called a ramLACE or scramLACE.[46]

A complementary strategy called for removal of nitrogen from the liquefied air, yielding nearly pure liquid oxygen as the product. Nitrogen does not support combustion, constitutes some three-fourths of air by weight, and lacks the redeeming quality of low molecular weight that could increase the exhaust velocity. Moreover, a hydrogen-fueled rocket could give much better performance when using oxygen rather than air. With oxygen liquefying at 90 K while nitrogen becomes a liquid at 77 K, at atmospheric pressure the prospect existed of using this temperature difference to leave the nitrogen unliquefied. Nor would it be useless; it could flow within a precooler, an initial heat exchanger that could chill the inflowing air while reserving the much colder liquid hydrogen for the main cooler.

It did not appear feasible in practice to operate a high-capacity LACE air liquefier with the precision in temperature that could achieve this. However, a promising approach called for use of fractional distillation of liquid air, as a variant of the process used in oil refineries to obtain gasoline from petroleum. The distillation process promised fine control, allowing the nitrogen to boil off while keeping the oxygen liquid. To increase the throughput, the distillation was to take place within a rotary apparatus that could impose high g-loads, greatly enhancing the buoyancy of the gaseous nitrogen. A LACE with such an air separator was called ACES, Air Collection and Enrichment System.[47]

When liquid hydrogen chilled and liquefied the nitrogen in air, that hydrogen went only partially to waste. In effect, it transferred its coldness to the nitrogen, which used it to advantage in the precooler. Still, there was a clear prospect of greater efficiency in the heat-transfer process if one could remove the nitrogen directly from the ram air. A variant of ACES promised to do precisely this, using chemical separation of oxygen. The process relied on the existence of metal oxides that could take up additional oxygen when heated by the hot ram air and then release this oxygen when placed under reduced pressure. Only the oxygen then was liquefied. This brought the increased efficiency, for the amount of liquid hydrogen used as a coolant was reduced. This enhanced efficiency also translated into conceptual designs for chemical-separation ACES units that could be lighter in weight and smaller in size than rotary-distillation counterparts.[48]

Turboramjets, ramjets, scramjets, LACE, ramLACE and scramLACE, ACES: with all these in prospect, designers of paper engines beheld a plenitude of possibilities. They also carried a strong mutual synergism. A scramjet might use a type of turboramjet for takeoff, again with the scramjet duct also functioning as an afterburner. Alternately, it might install an internal rocket and become a scramLACE. It could use ACES for better performance, while adopting the chemical-separation process to derichen the use of hydrogen.

It did not take long before engineers rose to their new opportunities by conceiving of new types of vehicles that were to use these engines, perhaps to fly to orbit as a single stage. Everyone in aerospace was well aware that it had taken only 30 years to progress from Lindbergh in Paris to satellites in space. The studies that explored the new possibilities amounted to an assertion that this pace of technical advance was likely to continue.

AEROSPACEPLANE

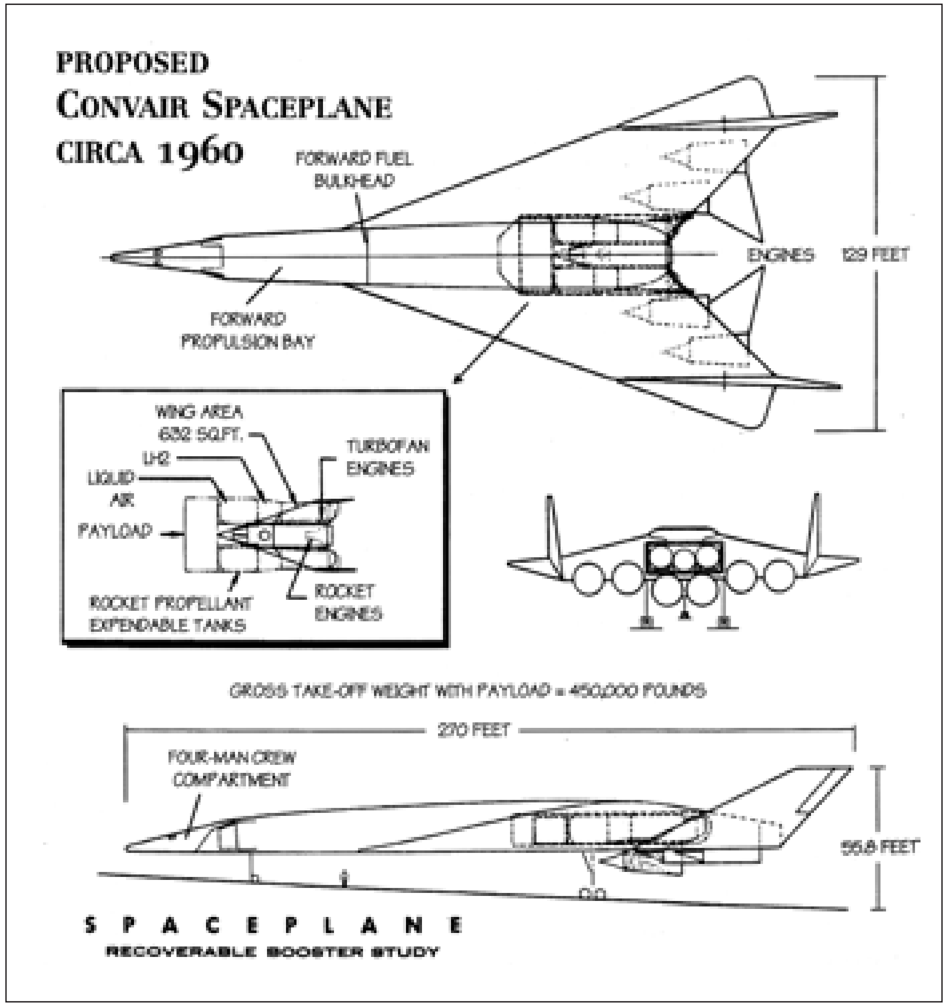
"I remember when Sputnik was launched," says Arthur Thomas, a leader in early work on scramjets at Marquardt. The date was 4 October 1957. "I was doing analysis of scramjet boosters to go into orbit. We were claiming back in those days that we could get the cost down to a hundred dollars per pound by using airbreathers." He adds that "our job was to push the frontiers. We were extremely excited and optimistic that we were really on the leading edge of something that was going to be big."[49]

At APL, other investigators proposed what may have been the first concept for a hypersonic airplane that merited consideration. In an era when the earliest jet airliners were only beginning to enter service, William Avery leaped beyond the supersonic transport to the hypersonic transport, at least in his thoughts. His colleague Eugene Pietrangeli developed a concept for a large aircraft with a wingspan of 102 feet and length of 175 feet, fitted with turbojets and with the Dugger-Keirsey external-burning scramjet, with its short cowl, under each wing. It was to accelerate to Mach 3.6 using the turbojets, then go over to scramjet propulsion and cruise at Mach 7. Carrying 130 passengers, it was to cross the country in half an hour and achieve a range of 7,000 miles. Its weight of 600,000 pounds was nearly twice that of the Boeing 707 Intercontinental, largest of that family of jetliners.[50]

Within the Air Force, an important prelude to similar concepts came in 1957 with Study Requirement 89774. It invited builders of large missiles to consider what modifications might make them reusable. It was not hard to envision that they might return to a landing on a runway by fitting them with wings and jet engines, but most such rocket stages were built of aluminum, which raised serious issues of thermal protection. Still, Convair at least had a useful point of departure. Its Atlas used stainless steel, which had considerably better heat resistance.[51]

The Convair concept envisioned a new version of this missile, fitted out as a reusable first stage for a launch vehicle. Its wings were to use the X-15's structure. A crew compartment, set atop a rounded nose, recalled that company's B-36 heavy bomber. To ease the thermal problem, designers were aware that this stage, having burned its propellants, would be light in weight. It therefore could execute a hypersonic glide while high in the atmosphere, losing speed slowly and diminishing the rate of heating.[52]

It did not take long before Convair officials began to view this reusable Atlas as merely a first step into space, for the prospect of LACE opened new vistas. Beginning late in 1957, using a combination of Air Force and in-house funding, the company launched paper studies of a new concept called Space Plane. It took shape as a large single-stage vehicle with highly-swept delta wings and a length of 235 feet. Propulsion was to feature a combination of ramjets and LACE with ACES, installed as separate engines, with the ACES being distillation type. The gross weight at takeoff, 450,000 pounds, was to include 270,000 pounds of liquid hydrogen.



Convair's Space Plane concept. (Art by Dennis Jenkins)

Space Plane was to take off from a runway, using LACE and ACES while pumping the oxygen-rich condensate directly to the LACE combustion chambers. It would climb to 40,000 feet and Mach 3, cut off the rocket, and continue to fly using hydrogen-fueled ramjets. It was to use ACES for air collection while cruising at Mach 5.5 and 66,000 feet, trading liquid hydrogen for oxygen-rich liquid air while taking on more than 600,000 pounds of this oxidizer. Now weighing more than a million pounds, Space Plane would reach Mach 7 on its ramjets, then shut them down and go over completely to rocket power. Drawing on its stored oxidizer, it could fly to orbit while carrying a payload of 38,000 pounds.

The concept was born in exuberance. Its planners drew on estimates "that by 1970 the orbital payload accumulated annually would be somewhere between two million and 20 million pounds." Most payloads were to run near 10,000 pounds, thereby calling for a schedule of three flights per day. Still the concept lacked an important element, for if scramjets were nowhere near the state of the art, at Convair they were not even the state of the imagination.[53] Space Plane, as noted, used ramjets with subsonic combustion, installing them in pods like turbojets on a B-52. Scramjets lay beyond the thoughts of other companies as well. Thus, Northrop expected to use LACE with its Propulsive Fluid Accumulator (PROFAC) concept, which also was to cruise in the atmosphere while building up a supply of liquefied air. Like Space Plane, PROFAC also specified conventional ramjets.[54]

But Republic Aviation was home to the highly imaginative Kartveli, with Ferri being just a phone call away. Here the scramjet was very much a part of people's thinking. Like the Convair designers, Kartveli looked ahead to flight to orbit with a single stage. He also expected that this goal was too demanding to achieve in a single jump, and he anticipated that intermediate projects would lay groundwork. He presented his thoughts in August 1960 at a national meeting of the Institute of Aeronautical Sciences.[55]

The XF-103 had been dead and buried for three years, but Kartveli had crafted the F-105, which topped Mach 2 as early as 1956 and went forward into production. He now expected to continue with a Mach 2.3 fighter-bomber with enough power to lift off vertically as if levitating and to cruise at 75,000 feet. Next on the agenda was a strategic bomber powered by nuclear ramjets, which would use atomic power to heat internal airflow, with no need to burn fuel. It would match the peak speed of the X-7 by cruising at Mach 4.25, or 2,800 mph, and at 85,000 feet.[56]

Kartveli set Mach 7, or 5,000 mph, as the next goal. He anticipated achieving this speed with another bomber that was to cruise at 120,000 feet. Propulsion was to come from two turbojets and two ramjets, with this concept pressing the limits of subsonic combustion. Then for flight to orbit, his masterpiece was slated for Mach 25. It was to mount four J58 turbojets, modified to burn hydrogen, along with four scramjets. Ferri had convinced him that such engines could accelerate this craft all the way to orbit, with much of the gain in speed taking place while flying at 200,000 feet. A small rocket engine might provide a final boost into space, but Kartveli placed his trust in Ferri's scramjets, planning to use neither LACE nor ACES.[57]

These concepts drew attention, and funding, from the Aero Propulsion Laboratory at Wright-Patterson Air Force Base. Its technical director, Weldon Worth, had been closely involved with ramjets since the 1940s. Within a world that the turbojet had taken by storm, he headed a Nonrotating Engine Branch that focused on ramjets and liquid-fuel rockets. Indeed, he regarded the ramjet as holding the greater

promise, taking this topic as his own while leaving the rockets to his deputy, Lieutenant Colonel Edward Hall. He launched the first Air Force studies of hypersonic propulsion as early as 1957. In October 1959 he chaired a session on scramjets at the Second USAF Symposium on Advanced Propulsion Concepts.

In the wake of this meeting, he built on the earlier SR-89774 efforts and launched a new series of studies called Aerospaceplane. It did not aim at anything so specific as a real airplane that could fly to orbit. Rather, it supported design studies and conducted basic research in advanced propulsion, seeking to develop a base for the evolution of such craft in the distant future. Marquardt and GASL became heavily involved, as did Convair, Republic, North American, GE, Lockheed, Northrop, and Douglas Aircraft.[58]

The new effort broadened the scope of the initial studies, while encouraging companies to pursue their concepts to greater depth. Convair, for one, had issued single-volume reports on Space Plane in October 1959, April 1960, and December 1960. In February 1961 it released an 11-volume set of studies, with each of them addressing a specific topic such as Aerodynamic Heating, Propulsion, Air Enrichment Systems, Structural Analysis, and Materials.[59]

Aerospaceplane proved too hot to keep under wraps, as a steady stream of disclosures presented concept summaries to the professional community and the general public. *Aviation Week*, hardly shy in these matters, ran a full-page article in October 1960:

> USAF PLANS RADICAL SPACE PLANE
> Studies costing $20 million sought in next budget, Earth-to-orbit vehicle would need no large booster.[60]

At the *Los Angeles Times*, the aerospace editor Marvin Miles published headlined stories of his own. The first appeared in November:

> LOCKHEED WORKING ON PLANE ABLE TO GO INTO ORBIT ALONE
> Air Force Interested in Project[61]

Two months later another of his articles ran as a front-page headline:

> HUGE BOOSTER NOT NEEDED BY AIR FORCE SPACE PLANE
> Proposed Wing Vehicle Would Take Off, Return Like Conventional Craft

It particularly cited Convair's Space Plane, with a *Times* artist presenting a view of this craft in flight.[62]

Participants in the new studies took to the work with enthusiasm matching that of Arthur Thomas at Marquardt. Robert Sanator, a colleague of Kartveli at Republic, recalls the excitement: "This one had everything. There wasn't a single thing in it that was off-the-shelf. Whatever problem there was in aerospace—propulsion, materials, cooling, aerodynamics—Aerospaceplane had it. It was a lifetime work and it had it all. I naturally jumped right in."[63]

Aerospaceplane also drew attention from the Air Force's Scientific Advisory Board, which set up an ad hoc committee to review its prospects. Its chairman, Alexander Flax, was the Air Force's chief scientist. Members specializing in propulsion included Ferri, along with Seymour Bogdonoff of Princeton University, a leading experimentalist; Perry Pratt of Pratt & Whitney, who had invented the twin-spool turbojet; NASA's Alfred Eggers; and the rocket specialist George P. Sutton. There also were hands-on program managers: Robert Widmer of Convair, builder of the Mach 2 B-58 bomber; Harrison Storms of North American, who had shaped the X-15 and the Mach 3 XB-70 bomber.[64]

This all-star group came away deeply skeptical of the prospects for Aerospaceplane. Its report, issued in December 1960, addressed a number of points and gave an overall assessment:

> The proposed designs for Aerospace Plane…appear to violate no physical principles, but the attractive performance depends on an estimated combination of optimistic assumptions for the performance of components and subsystems. There are practically no experimental data which support these assumptions.

On LACE and ACES:

> We consider the estimated LACE-ACES performance very optimistic. In several cases complete failure of the project would result from any significant performance degradation from the present estimates…. Obviously the advantages claimed for the system will not be available unless air can be condensed *and purified* very rapidly during flight. The figures reported indicate that about 0.8 ton of air per second would have to be processed. In conventional, i.e., ordinary commercial equipment, this would require a distillation column having a cross section on the order of 500 square feet…. It is proposed to increase the capacity of equipment of otherwise conventional design by using centrifugal force. This may be possible, but as far as the Committee knows this has never been accomplished.

On other propulsion systems:

> When reduced to a common basis and compared with the best of current technology, all assumed large advances in the state-of-the-art…. On the basis of the best of current technology, none of the schemes could deliver useful payloads into orbits.

On vehicle design:

> We are gravely concerned that too much emphasis may be placed on the more glamorous aspects of the Aerospace Plane resulting in neglect of what appear to be more conventional problems. The achievement of low structural weight is equally important…as is the development of a highly successful propulsion system.

Regarding scramjets, the panel was not impressed with claims that supersonic combustion had been achieved in existing experiments:

> These engine ideas are based essentially upon the feasibility of diffusion deflagration flames in supersonic flows. Research should be immediately initiated using existing facilities…to substantiate the feasibility of this type of combustion.

The panelists nevertheless gave thumbs-up to the Aerospaceplane effort as a continuing program of research. Their report urged a broadening of topics, placing greater emphasis on scramjets, structures and materials, and two-stage-to-orbit configurations. The array of proposed engines were "all sufficiently interesting so that research on all of them should be continued and emphasized."[65]

As the studies went forward in the wake of this review, new propulsion concepts continued to flourish. Lockheed was in the forefront. This firm had initiated company-funded work during the spring of 1959 and had a well-considered single-stage concept two years later. An artist's rendering showed nine separate rocket nozzles at its tail. The vehicle also mounted four ramjets, set in pods beneath the wings.

Convair's Space Plane had used separated nitrogen as a propellant, heating it in the LACE precooler and allowing it to expand through a nozzle to produce thrust. Lockheed's Aerospace Plane turned this nitrogen into an important system element, with specialized nitrogen rockets delivering 125,000 pounds of thrust. This certainly did not overcome the drag produced by air collection, which would have turned the vehicle into a perpetual motion machine. However, the nitrogen rockets made a valuable contribution.[66]