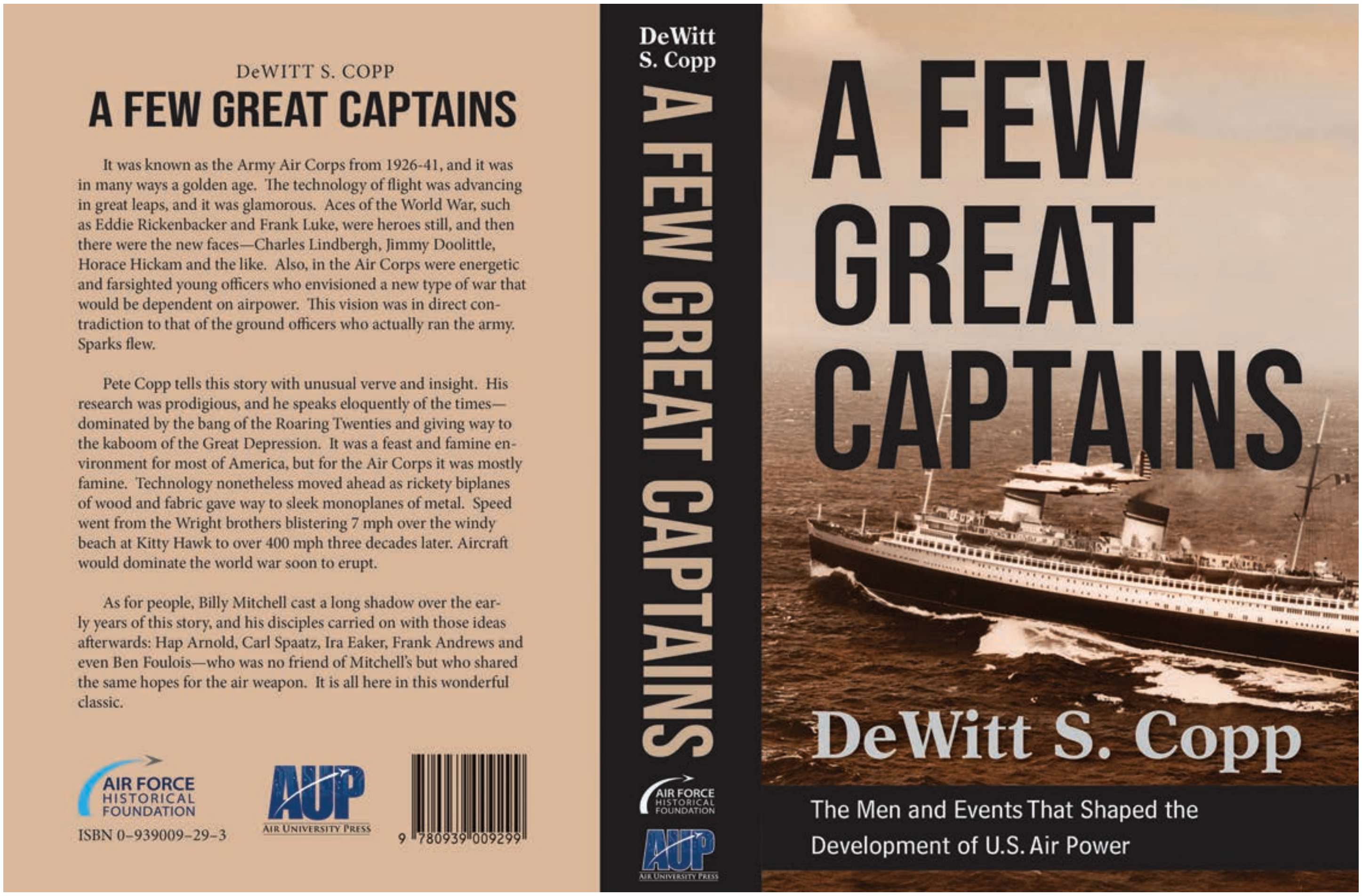
SPECIAL 2025 - Volume 72, Number 5
WWW.AFHISTORY.ORG

Journal of the Air Force Historical Foundation



In a joint program with the Air University Press, AFHF is proud to offer the newly published update of Pete Copp's air power classic (now expanded), *A Few Great Captains: The Men and the Events that Shaped the Development of U.S. Air Power*. The free digital version will be available soon from the Air University bookstore.

A Few Great Captains is a terrific book, suitable for airmen of any rank. Pete Copp wrote a masterpiece that takes the Air Corps and its leaders, both senior and junior, through the tumultuous period of the 1920s and 30s. Ground-oriented Army leaders felt threatened by the new weapon of the airplane and therefore labored to control it and those who flew it. For their part, the airmen refused to be bridled by the ground zealots and instead foresaw a future where the airplane would dominate war. The visions of the airmen were not completely accurate, but they were far more so than those who saw the airplane as just another weapon to support ground operations.

This publication marks the Foundation's return to publishing and disseminating important, relevant, and readable history to all.

KNOW THE PAST...SHAPE THE FUTURE!

Journal of the Air Force Historical Foundation

SPECIAL 2025 - Volume 72, Number 5
WWW.AFHISTORY.ORG

know the past
.....Shape the Future

Last May, the Air Force Historical Foundation presented one of its Journal Article Awards to David K. Stumpf for "Old School" Technical Research. This Special Medal highlighted David's outstanding work on the evolution of the USAF Missile Program.

David K. Stumpf, Ph.D., is a retired plant biochemist living with his wife, Susan, in Tucson, Arizona. He has written three nuclear weapon histories: *Regulus the Forgotten Weapon*, a history of the Navy's Regulus I and II cruise missiles; *Titan II: A History of a Cold War Missile System* and *Minuteman: a technical history—The Missile that defined American Nuclear Warfare*, published February 2021. Dr. Stumpf volunteered at the Titan Missile Museum, Sahuarita, Arizona, as an historian and as a tour guide for 15 years. He was instrumental in the effort to gain National Historic Landmark status for the museum.

David has written many articles we have published in the Journal. All are excellent, are technically based, and are superior examples of technical research and writing that once formed the foundation of technical histories that documented the complex world of USAF missile systems. His research has been used by current missile projects as a measure of its efficacy. We here enclose six of them.

This "Special Stumpf Edition" began as a practice Journal project for our newly selected incoming editor, Paul "Abbie" Hoffman. I challenged the current editor, Richard Wolf, and Abbie to use David's collected works—including technical diagrams, detailed article notes, and outstanding photos—as an edition of collected works that the Foundation could digitally publish for use by those with specific interests in the evolution of the missile program.

This special edition is a tribute to David and his work, but it is more than that. David's research and writing represent the history of a technical subject that few today can document in an understandable and readable way.

Publications such as this one are an important part of AFHF's charter—to educate and promote the preservation and appreciation of the history and heritage of the U.S. Air Force, the U.S. Space Force, and the organizations and people that have come before. Our continued focus is on producing quality research and educational programs for our Airmen, Guardians, and the families of the U.S. Air Force and U.S. Space Force.

We hope that you appreciate the efforts of the author and the editors in creating this Special Edition for you. If you are so inclined, please make a small donation at the following link to cover the incidental costs of this groundbreaking edition of the JAFHF. https://afhistory.org/support/donate/#Donate

Features

FRONT COVER: A time exposure of eight Peacekeeper (LGM-118A) intercontinental ballistic missile reentry vehicles passing through clouds during a flight test. *(U.S. Air Force photo)*

BACK COVER: A Minuteman Upper Silo Simulation launch took place to test the capabilities of the Peacekeeper silo ejection process. *(U.S. Air Force photo)*

Air Force Historical Foundation
P.O. Box 405
Mechanicsville, MD 20659
(301) 736-1959

E-mail: angelabear@afhistory.org
On the Web at http://www.afhistory.org

Journal of the Air Force Historical Foundation

The Journal of the
Air Force Historical Foundation
Special 2025 Volume 72 Number 5

Editor
Richard I. Wolf

Editor Incoming
Paul Hoffman

Book Review Editor
Scott A. Willey

Advertising
Dik A. Daso

Circulation
Angela J. Bear

Journal of the Air Force Historical Foundation (ISSN 1044-016X) is produced for Spring, Summer, Fall, and Winter by the Air Force Historical Foundation.

Prospective contributors should consult the **GUIDELINES FOR CONTRIBUTORS** at the back of this journal. Unsolicited manuscripts will be returned only on specific request. The Editor cannot accept responsibility for any damage to or loss of the manuscript. The Editor reserves the right to edit manuscripts and letters.

Address **LETTERS** and **manuscripts** to:

Journal of the Air Force
Historical Foundation
70 Shannon Way
Upton, MA 01568
e-mail: airpowerhistory@yahoo.com

Correspondence regarding missed issues or changes of address should be addressed to the **CIRCULATION OFFICE**:

Journal of the Air Force
Historical Foundation
P.O. Box 405
Mechanicsville, MD 20659
(301) 736-1959
e-mail: angelabear@afhistory.org

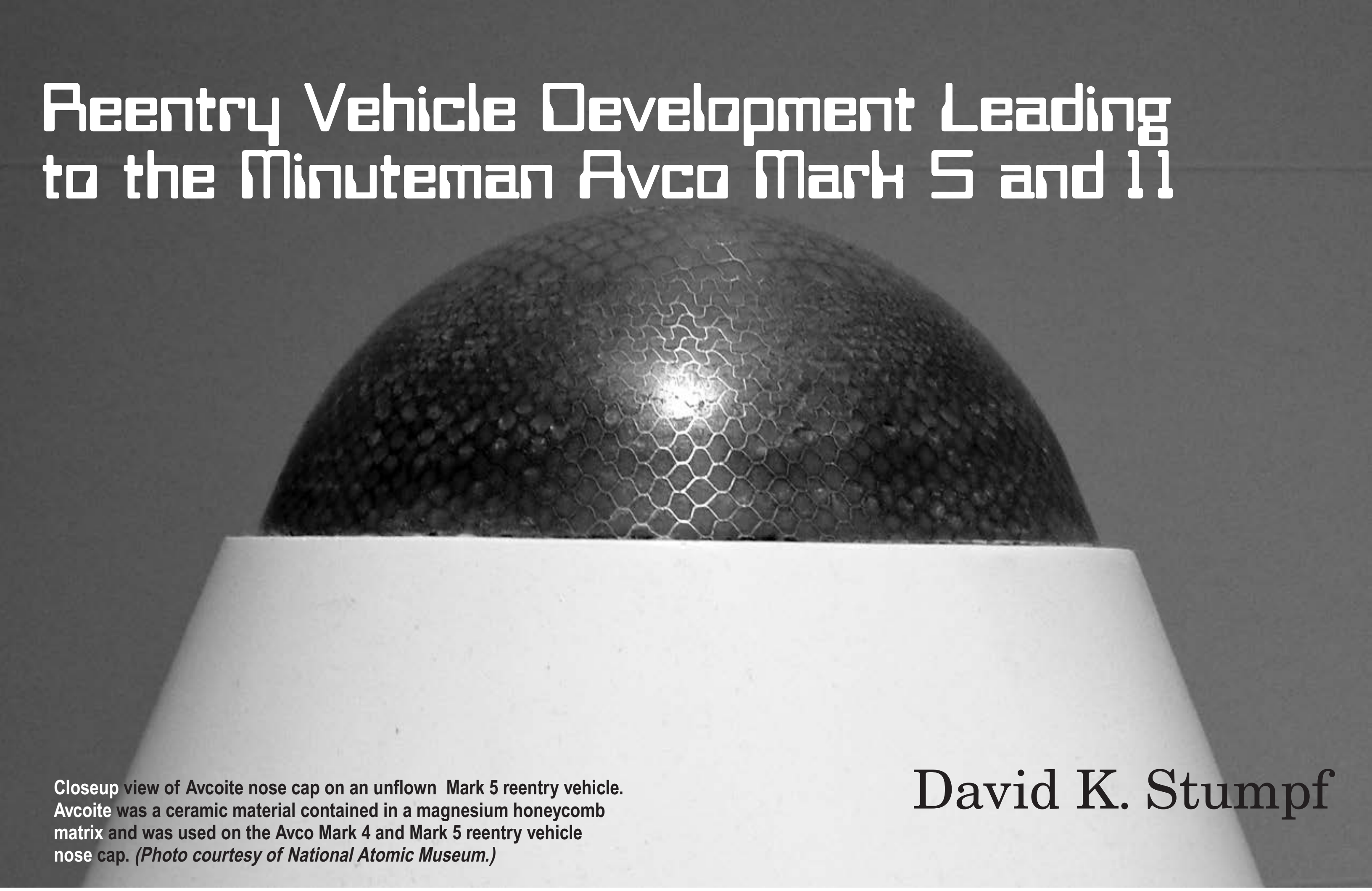
ADVERTISING

Executive Director
P.O. Box 405
Mechanicsville, MD 20659
(301) 736-1959
e-mail: xd@afhistory.org

Periodicals postage paid at Mechanicsville, MD 20659 and additional mailing offices.

Postmaster: Please send change of address to the Circulation Office.

Reentry Vehicle Development Leading to the Minuteman Avco Mark 5 and 11



Closeup view of Avcoite nose cap on an unflown Mark 5 reentry vehicle. Avcoite was a ceramic material contained in a magnesium honeycomb matrix and was used on the Avco Mark 4 and Mark 5 reentry vehicle nose cap. *(Photo courtesy of National Atomic Museum.)*

David K. Stumpf

The Minuteman Intercontinental Ballistic Missile (ICBM) has been deployed for over fifty years. As one of two second generation ICBMs, Minuteman represented the ultimate solution to the concept of land-based offensive strategic weapons. The solid propellant propulsion system provided for a nearly instantaneous response while reducing maintenance efforts and costs significantly below those of the first generation cryogenic oxidizer Atlas and Titan I. Even the second generation Titan II with its storable liquid propellants and comparable response time was cumbersome in comparison.

Development of the business end of all the ICBMs, the reentry vehicles, likewise went from the first generation heatsink thermal protection system to the second generation ablative reentry vehicles enabling larger payloads (the reentry vehicle was lighter) to be carried as well as improving accuracy. This article discusses the evolution of reentry vehicle design and fabrication leading up to and including the Minuteman Mark 5 and Mark 11 reentry vehicles. Detailing the earliest efforts of the Army, Navy and Air Force reentry vehicle approaches puts the development of the Minuteman Mark 5 and Mark 11 reentry vehicles into the proper historical perspective. The discussion of the Army's effort covers only the Jupiter IRBM program and its pioneering work on ablation. The Navy's contribution was a much different approach to the heatsink concept with the discussion ending with the Polaris A-1 and A-2 as the follow-on programs closely resembled the later Air Force approach. Due to classification issues caused by current world events, the third generation Air Force reentry vehicle designs are not discussed in this article though they have been described in great detail in an earlier article by Lin.[1]

Early Research

While bombardment rockets have been used for centuries, it was not until the creation of the German V-2 (also known as the A-4) that the warhead needed thermal protection due to reentry into the Earth's atmosphere.[2,] Since the entire V-2 impacted the target, there was no true separable reentry vehicle.[3] The original design called for the use of a lightweight alloy of magnesium and aluminum but wind tunnel tests indicated that from an altitude of 43 nautical miles, the operational maximum altitude, reentry into the lower atmosphere at 3,345 miles per hour would result in a warhead compartment skin temperature of 1,250 degrees Fahrenheit. Therefore the decision was made to use 1/4 inch sheet steel resulting in the need to decrease the explosive payload to hold the total warhead weight to 2,200 pounds (the steel casing weighing 550 pounds). The explosive chosen for the warhead was Amatol, a mixture

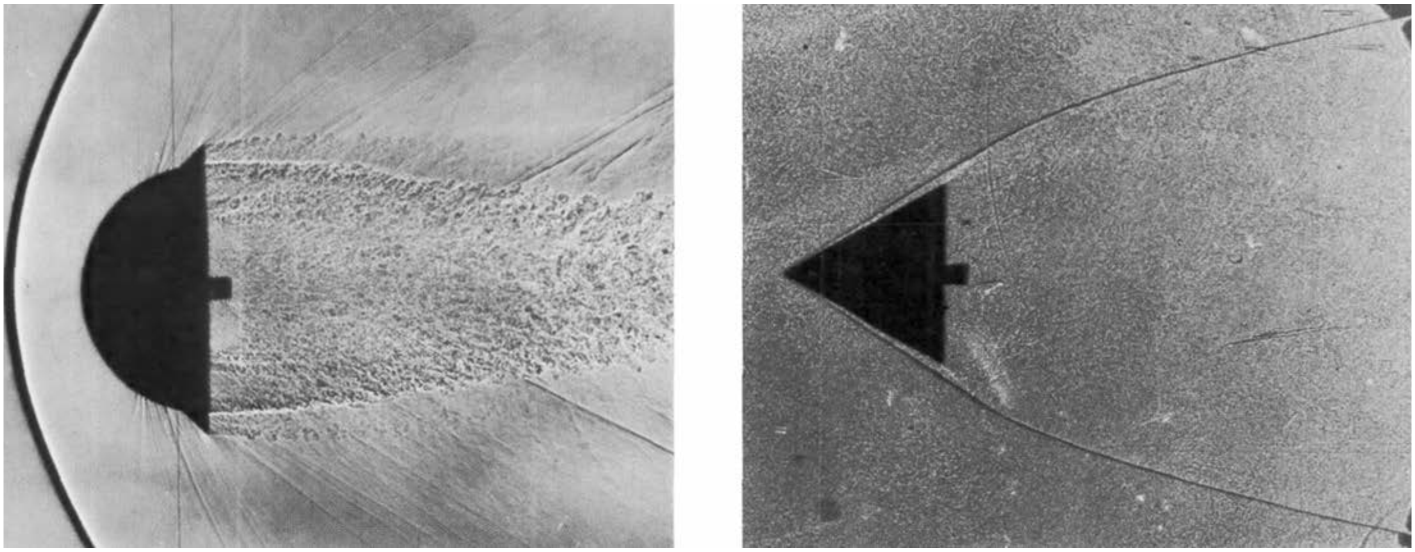


Figure 1: Atmosphere Entry Simulator Schlieren photographs illustrating the detached bow shock wave generate by a blunt reentry body compared to the attached shock wave with a pointed reentry body. The detached bow wave dissipates heat well away from reentry body (D. D. Baals and W.R. Corliss, Wind Tunnels of NASA,(Washington, D.C., 1981), SP-440, 76).

of sixty percent TNT and forty percent ammonium nitrate, which was insensitive to heat and shock. There was no warhead compartment insulation.[4]

Arming a guided missile derived from the V-2 with an atomic warhead was an obvious next step in strategic warfare since it was only a matter of time for atomic bomb design to catch up with guided missile delivery capability. Concerned with the vulnerability of the eastern United States to long range missiles from the Soviet Union, in 1945 the National Advisory Committee for Aeronautics (NACA) realized an urgent need to begin studying the problems of hypersonic flight (defined as greater than five times the speed of sound which is the speed at which aerodynamic heating begins to be significant). By the late 1940s, two major NACA facilities, Ames Aeronautical Laboratory (Ames), Moffett Field, California, and Langley Aeronautical Laboratory (Langley), Hampton, Virginia, responded by expanding their aeronautical work to study aerodynamic issues involved in ballistic missile flight.[5]

Theoretical research into the problem of aerodynamic heating of ballistic missiles upon reentry into the atmosphere at high speeds was first published in 1949 by Carl Wagner.[6] The first comprehensive theoretical work was begun in 1951 by H. Julian Allen and A.J. Eggers, Jr., engineers at Ames. They studied the problem of reentry heating for ballistic, glide and skip-entry trajectories. Their investigation of the three types of trajectories was driven by the need to find a flight path that could best utilize the thermal protection materials then available. Allen and Eggers dismissed the pointed nose shape, a carry over from rifle bullet design, at the start, instead focusing their calculations on a blunt, hemispherical shape, recommending that "not only should pointed bodies be avoided, but that the rounded nose should have the largest radius possible." (**Figure 1**)

It is important to note that these calculations were made with "light" and "heavy" missile options and no mention was made of a reentry vehicle as such. The "light" missile optimum nose shape from a heat transfer standpoint was a blunt shape; for the "heavy" missile a more slender shape was optimum. Their calculations showed that the high drag caused a detached shock wave thus the majority of the heat generated was dissipated back into the atmosphere leaving only radiated heat to contend with, unlike a sharply pointed body where the shock wave was attached to the tip, causing heat transfer and destruction of the body. Additionally the heat reaching the blunt body would be more evenly distributed, preventing hot spots more prone to burn through.

Allen and Eggers demonstrated that the maximum deceleration encountered by a reentry vehicle was a function of the angle of reentry as well as velocity and independent of the shape, size and mass or drag coefficient. The importance of shape was the amount of heat that was absorbed by the reentry vehicle. A team of Ames researchers led by Eggers and including Fred Hansen and Bernard Cunningham published a method

David K. Stumpf, Ph.D., is retired plant biochemist living with his wife, Susan, in Tucson, Arizona. He has written two nuclear weapon histories, Regulus the Forgotten Weapon, a history of the Navy's Regulus I and II cruise missiles *and* Titan II: A History of a Cold War Missile System*, as well as contributing to the Air Force Missileers history. He is currently working on a comprehensive history of the Minuteman ICBM program endorsed by the Office of the Secretary of the Air Force. He volunteered at the Titan Missile Museum, Sahuarita, Arizona, as museum historian and as a tour guide for 15 years. He was instrumental in the effort to gain National Historic Landmark status for the museum.*

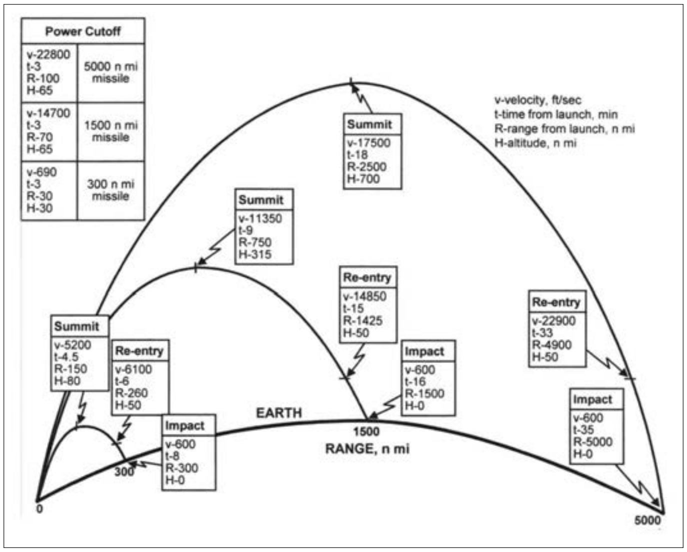


Figure 2: Short, Medium and Long Range Ballistic Missile Trajectories (adapted from Figure 1-1, Ordinance Engineering Design Handbook, Ballistic Missile Series: Trajectories, 1967. *Drawing by Mitch Cannon*).

for predicting heat transfer to blunt bodies in 1958 though the work was done and in use much earlier but not published for six years due to classification issues.[7]

In order to reach targets 4,000 to 6,000 nautical miles away, ballistic missiles would need to be accelerated to speeds of up to approximately Mach 20 (15,223 miles per hour, just short of orbital velocity), 10 times the speed of a high-powered rifle bullet.[8] Reentry into the atmosphere at these speeds would generate a shock wave in which the atmosphere is heated to many thousands of degrees, even approaching 12,000 F, which exceeded the melting point of tungsten, the metallic element with the highest known melting point, 6,116 degrees Fahrenheit.[9] At this temperature the air plasma is also highly chemically reactive. There is a transport of heat by mass conduction from the air plasma to the vehicle surface which is dependent on both the temperature and density of the air in the plasma. At high altitudes where the air density is low, the mass transport of heat is low, in spite of the very high shock wave temperature. Conversely, at lower altitudes, the higher density plasma results in a higher heat flux for equal reentry vehicle velocities(**Figure 2**).[10]

Before discussing individual test and operational reentry vehicles, a brief discussion of testing methods, both for ground and flight is necessary.

Reentry Research Tools

Hypersonic Wind Tunnels

While the history of the military use of ballistic missiles rightly starts with the development of the A-4 (V-2) missile, perhaps just as important was the discovery by Allied troops of two highly advanced wind tunnel facilities at Peenemünde in the summer of 1945. One had apparently been in operation, a small diameter (1.2 foot) super-supersonic wind tunnel for intermittent use up to Mach 5 and a larger diameter (3.3 foot) continuous flow super-supersonic wind tunnel designed for speeds up to Mach 10.

In 1945 the first hypersonic wind tunnel in the United States was proposed by John Becker at Langley. Design difficulties and a perceived lack of urgency by NACA and Langley administrators delayed the construction for over a year but on November 26, 1947, the first tests were successfully run at Mach 6.9.[11] Eggers at Ames, proposed a continuous flow hypersonic tunnel and it was completed in 1950. Between these two facilities, hypersonic research began in earnest, mainly focusing on aerodynamic issues directed towards supersonic aircraft research.

By 1955, the three major ballistic missile programs, the Air Force Thor (IRBM) and Atlas (ICBM) and the Army Jupiter (IRBM), made reentry vehicle research a high national priority. Two flight regimes required detailed study. The 1,500 nautical-mile IRBM Thor and Jupiter warhead reentry speed would be nearly 15,000 feet per second while the 5,000 nautical mile range ICBM would be nearly 25,000 feet per second.[12] Basic ballistic shapes, along the lines suggested by Allen and Eggers were tested up to the Mach 7-10 capabilities of the early hypersonic wind tunnels, confirming their theoretical results. However, the limitations in run times and temperatures, as well as atmospheric densities, soon illustrated the need for additional testing facilities.

Shock Tubes

The first shock tube was built in France in 1899 by Vielle to study flame fronts and propagation speeds resulting from explosions.[13] The concept languished until 1946 when Payman and Shepard in Britain published a thorough description of the design and use of shock tubes in studying explosions in mines.[14]

There are many variations of shock tube design but all share a basic two chamber concept. The first chamber is separated from the second with a burst diaphragm calculated to burst when the gas in the first chamber is compressed to a predetermined value. Since 1949, shock tubes have been used to augment aerodynamic studies using hypersonic wind tunnels, in particular the use by the mid-1950's was focused on reentry vehicle design and material selection since speeds greater than Mach 10 could easily be achieved, as well as much higher temperatures. The major drawback was the limited duration of test conditions.[15] Both Ames and Langley's Wallops Island Flight Test Range utilized shock tubes for reentry vehicle research.[16]

Avco Corporation learned of the shock tube work of Arthur Kantrowitz at Cornell University's School of Aeronautical Engineering funded by the Naval Ordnance Laboratory. Kantrowitz ran test models of the Mark 4 reentry vehicle that Avco was developing as a back-up for the General Electric Mark 3 for Atlas and for use as the primary reentry vehicle for the Titan I. In 1956 he left Cornell to

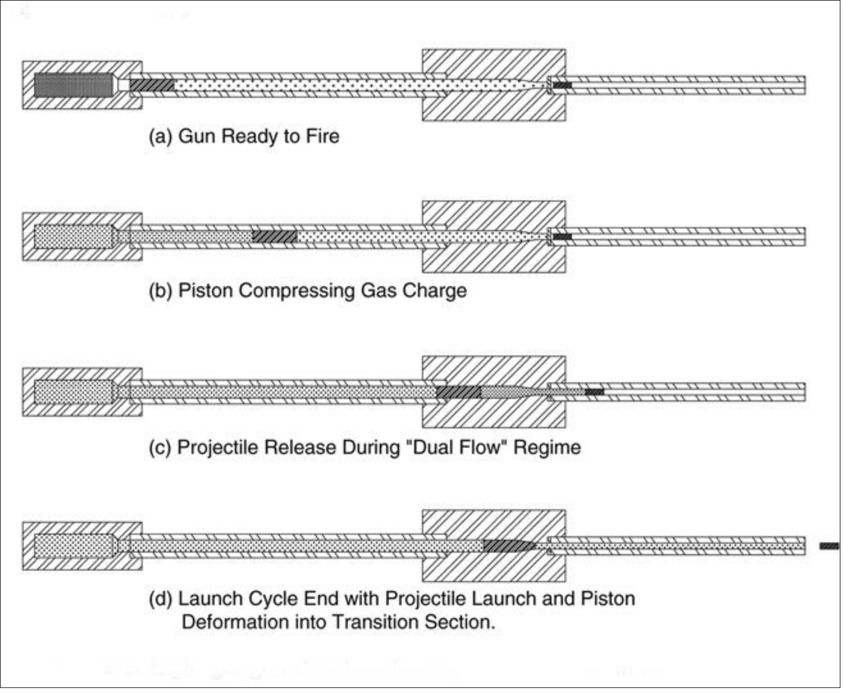


Figure 3: Light Gas Gun Schematic *(H.F. Swift, Light– Gas Gun Technology: A Historical Perspective, in "High-Pressure Compression of Solids VIII," with permission from the publisher.)*

head up the Avco Everett Research Laboratory where he led development of the ablative materials for the final Mark 4 design as well as for the Minuteman Mark 5 and Mark 11 reentry vehicles.[17]

Light-Gas Gun

The two stage light-gas gun was invented in 1948 by E.J. Workman at the New Mexico Institute of Mining as a method to dramatically increase projectile velocity. Despite the impressive German and Russian developments in artillery during World War II, perhaps the most famous of which was the German Tiger Tank 88 mm gun, projectile velocities remained at an upper limit of 9,000 feet/second.

The basic concept of the light-gas gun was to replace the gaseous byproducts of conventional gun powders which propelled the projectile, with a column of hydrogen or helium. A standard gunpowder cartridge was used to fire a plug down a barrel filled with helium or hydrogen (hence the term light-gas) which would compress to the bursting point a diaphragm immediately behind the actual test projectile. When the diaphragm burst, compressed light gas would propel the projectile down a second barreling allowing far greater velocities to be achieved since the molecular weight of the propellant gas would now be approximately 1/8th of that of the water, carbon dioxide and nitrogen byproducts of gunpowder combustion (4 g/mole for helium versus approximately 30 g/mole) (**Figure 3**).

Workman's research group received funding from the Army Ballistic Research Laboratory (BRL) and proved the concept, reaching a velocity of 9,800 feet per second and quickly extending it to nearly 14,000 feet per second. The results caught the attention of the BRL managers, the device declared classified and removed, with all of the associated equipment, to the BRL facilities. Work did not continue at BRL for reasons that are not clear.

With the need for a relatively inexpensive method to "flight" test small models of proposed Atlas and Thor reentry vehicles, in the mid-1950's the light-gas gun concept was given new life via contractors and universities as well as researchers at both Langley and Ames. Velocities were soon extended beyond 25,000 feet per second.[18]

Atmospheric Entry Simulator

In early 1955, Eggers at Ames pondered the idea of simulating reentry through the varying densities of the upper and lower atmosphere. Could a method be found for launching a test article at reentry speeds into a test chamber that could simulate the gradual increase in atmospheric density which was the most problematic for the thermal stress of reentry? A light-gas gun could be used for launching the test article as their development had progressed to provide reentry velocities but how to simulate the atmosphere at 100,000 feet where most of the aerodynamic heating takes place? The necessary 100-fold variation in atmospheric density in this part of the reentry envelope might be achieved using components of a supersonic wind tunnel, the settling chamber and the exit portion of a Mach 5 supersonic nozzle. Eggers reasoned that the light-gas gun could be used to fire a small scale reentry vehicle model into the Mach 5 supersonic nozzle and then caught for detailed examination. The result was a small prototype Atmospheric Entry Simulator (AES) which was built in 1956, and successfully tested in 1957, evolving into a larger version in 1957.[19] This large AES was used successfully in exploratory work on blunt body copper heatsink designs meant for use on the shorter range and substantially lower heat regime IRBM missiles with reentry speeds of 15,000 feet per second.[20]

Arc Jet

Major drawbacks to the methods already addressed was still the relatively short duration of velocities, temperatures and inability to reach the higher temperatures of reentry in a continuous flow wind tunnel. After investigating several possibilities, the solution appeared to be the use of an arc-jet heater. Research at Ames began in 1956 and resulted, six years later, in the Gas Dynamics Laboratory devoted to further arc-jet development for use in stand-alone testing of ablation materials. While arc-jet wind tunnels are used to study reentry phenomena in a step-wise manner, they are unable to simulate conditions of a constantly descending reentry vehicle.[21] Several different types of arc-jet heaters, including subsonic air arc jet heaters and arc-jet radiant heaters are also used outside of a wind tunnel to study the ablative properties of materials. The arc-jet, with its more easily managed test conditions as well as longer test duration times, along with the fact that the test model was held in place, eventually replaced the AES for study of ablative materials at Ames.

Avco Corporation's Everett Research Laboratory and General Electric's Missile and Space Vehicle Division, amongst other labs, also employed variations of the arc-jet in their research and development of ablative materials for use on reentry vehicles. In 1958 James Fay, from the Massachusetts Institute of Technology and Avco's Frederick Riddell published a theory that allowed calculation of boundary layer conditions in high speed flight: [22]

The boundary-layer equations are developed in general for the case of very high speed flight where the external flow I in a dissociated state. In particular the effects of diffusion and of atom recombination in the boundary layer are included. It is shown that at the stagnation point the equations can be reduced exactly to a set of nonlinear ordinary differential equations even when the chemical reactions proceed so slowly that the boundary layer is not in thermochemical equilibrium.

P.H. Rose and W. I. Stark at Avco published a paper at the same time comparing the theory against shock tube experimental results: [23]

Simulation of flight stagnation conditions at velocities up to satellite velocity of 26,000 feet per second is shown to be possible in shock tubes and data has been obtained over a large altitude range at these velocities.

These two papers extended that of Lester Lees published in 1956 which had been found to underestimate by as much as 30 percent heat transfer rates at the reentry vehicle tip.[24] Now reentry vehicle researchers had both experimental and theoretical methods for evaluating ICBM reentry vehicle materials and possible designs.

Rocket Motor Exhaust

Development of the Jupiter IRBM reentry vehicle took place at the Army Ballistic Missile Agency (ABMA) facilities at the Redstone Arsenal, Huntsville, Alabama. Researchers there used the exhaust from a number of different liquid rocket engines to test candidate jet vane materials to replace the troublesome graphite vanes used in the V-2.[25]

Solutions to the "Reentry Problem"

Theodore von Kármán, perhaps the leading aerodynamics expert of his time, described what he called "the reentry problem" at a symposium in Berkeley, California, June 1956. Reentering the atmosphere at speeds of Mach 12-20 was "perhaps one of the most difficult problems one can imagine. . . a challenge to the best brains working in these domains of modern astrophysics." [26] While the workers at Ames, Langley and other facilities had partially met the challenge via theoretical calculations about vehicle shape which led to the design of testing facilities, what was the solution to the remaining aspect, taming the thermal load encountered at these high speeds?

Four categories of cooling were considered: a) radiant cooling via emittance from the vehicle surface, b) solid heatsinks which would have sufficient mass to absorb the heat and protect the payload, c) transpiration and film cooling which would cause heat removal by material phase change, d) ablation which would allow heat dissipation via the many protective processes associated with surface removal.

Each of the four options had specific environments where they were most effective. Radiant cooling was best for long duration reentry environments where heat load was relatively low and constant and in practice worked best at temperatures below 2,000 F. Solid heatsinks could accommodate higher temperatures as long as the heating rate was not so rapid as to melt the material. Additional large structural mass was necessary to store the heat and protect the payload. Transpiration and film cooling would be able to work over a wide thermal environment but were mechanically complicated which might reveal hidden reliability issues. Ablation worked well for short duration, high temperature environments, the question was one of which materials to select and how to test them.[27] Only two of these concepts, heatsink and ablation, were used in research and operational reentry vehicles.

A key description of a reentry vehicle is its ballistic coefficient, beta (β). is defined as $W/(C_d \times A)$, where W is the weight of the reentry vehicle, C_d is the coefficient of drag and A is the cross-sectional area. With reentry vehicle weight being held constant, reentry vehicles with a low β (high coefficient of drag and cross-sectional area, and thus high air resistance) decelerate at a relatively high altitude, where the density of the atmosphere is low and heat fluxes are lower but reentry times are longer, facilitating radar detection while simultaneously resulting in decreased accuracy. Medium β vehicles decelerate at a medium altitude with higher heat fluxes but shorter detection times and increased accuracy. High β vehicles decelerate at much lower altitudes, encountering much denser air and hence higher heat fluxes but for a shorter time, allowing less time for radar detection and also greatest accuracy. Obviously these considerations were critical to mission requirements but were constrained by both the materials and testing facilities available at the time.

The First Generation - Heatsink

The work of Allen and Eggers had clearly shown the importance of selecting a relatively blunt nose shape for ballistic missile reentry vehicles to minimize aerodynamic heating. There was still an enormous amount of

Table 1. Air Force Reentry Vehicle Designators Through Minuteman II.		
Mark 1	Atlas D, Thor	General Electric (development, not flown)
Mark 2	Atlas D, Thor	General Electric
Mark 3	Atlas D	General Electric
Mark 4	Atlas E, F, Titan I	Avco
Mark 5	Minuteman IA	Avco
Mark 6	Titan II	General Electric
Mark 7	Skybolt	General Electric (cancelled)
Mark 8, 9, 10	not assigned	
Mark 11, 11A, 11B, 11C	Minuteman IB, Minuteman II	Avco

Miller, B., *Studies of Penetration Aids Broadens,* 20 January 1964, Aviation Week and Space Technology, 79.

heat to be dealt with and this meant selecting the best temperature-resistant and high strength materials. Allen and Eggers research showed that most of the aerodynamic heating would be outside the boundary layer and not in direct contact with the reentry vehicle provided the boundary layer remained laminar. A considerable amount of radiative heat still had to be dissipated. Since radiation varies as the fourth power of the temperature, it was likely that the reentry vehicle would not be an efficient radiator with the result that surface temperature would rise beyond either the structural stability of then currently available materials or the tolerance level of the enclosed equipment, i.e., fusing and actual warhead. Heavily influenced by Allen and Eggers seminal work in conjunction with the paucity of high temperature stable materials, the first choice for reentry vehicle heat control was the heatsink concept. Both the Navy and Air Force elected to use the heatsink concept for their first generation reentry vehicles. The Air Force program is known in greater detail but both are discussed next because the Navy had a novel approach to reentry vehicle design (**Table 1**).

Navy

Mark 1

As with Thor and Atlas, the reentry vehicle (the Navy used the term reentry body but reentry vehicle is used here for consistency) needs for Jupiter-S (progenitor to Polaris) coincided with the viability of the heatsink concept since ablative material research was still relatively new in 1955 had not progressed far enough.(**Figure 4**).

The Navy quickly moved from the Jupiter-S program to Polaris. Due to weight constraints imposed by the Polaris missile solid engine performance, the reentry vehicle/warhead combination had to be much lighter than the Jupiter payload with a goal of a nearly seventy

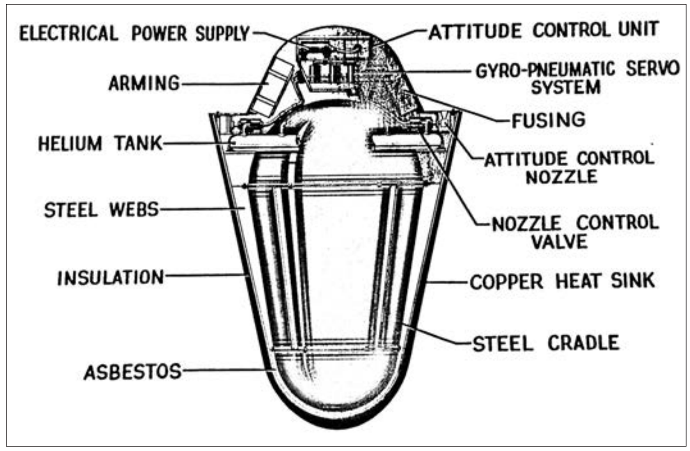
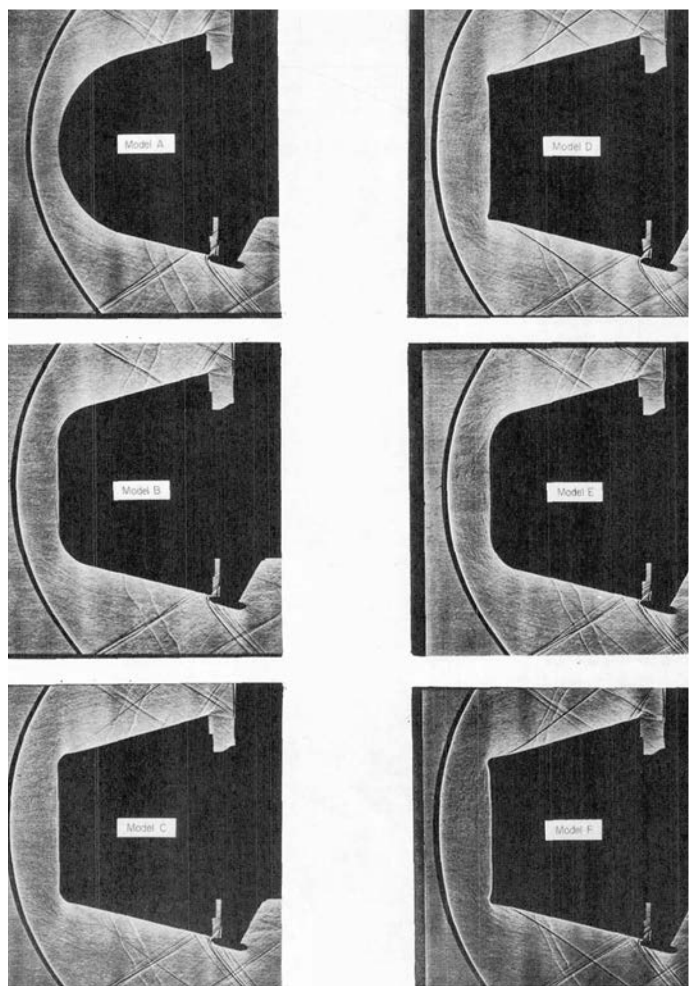


Figure 4: Early Reentry Vehicle Design for Jupiter-S missile. ***(U.S. Navy Photograph, author's collection.)***

percent reduction to 1,000 pounds, at most. Consequently, the Navy was focusing, unlike the Air Force and Army reentry vehicle designs, on a reentry vehicle that did not encase the warhead. Instead, the warhead would ideally be an integral part of the design.[28]

Figure 5: Evaluation of Flat-Faced Blunt Nose Reentry Vehicle Shapes (National Advisory Committee for Aeronautics, "Heat Transfer and Pressure Distribution on Six Blunt Noses at a Mach Number of 2," H.S. Carter and W.E. Bressette, NACA Research Memorandum L57C18, (18 April 1957), 10.



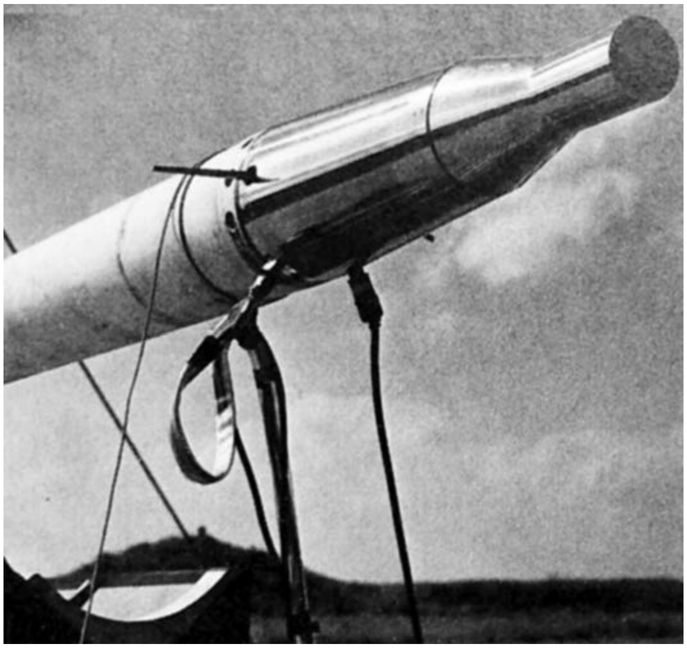


Figure 6: Free Flight Flat-Faced Blunt Nose Reentry Vehicle Sub-scale Model (J.A. Shortal, A New Dimension, Wallops Island Fight Test Range: The First Fifteen Years,), 518.

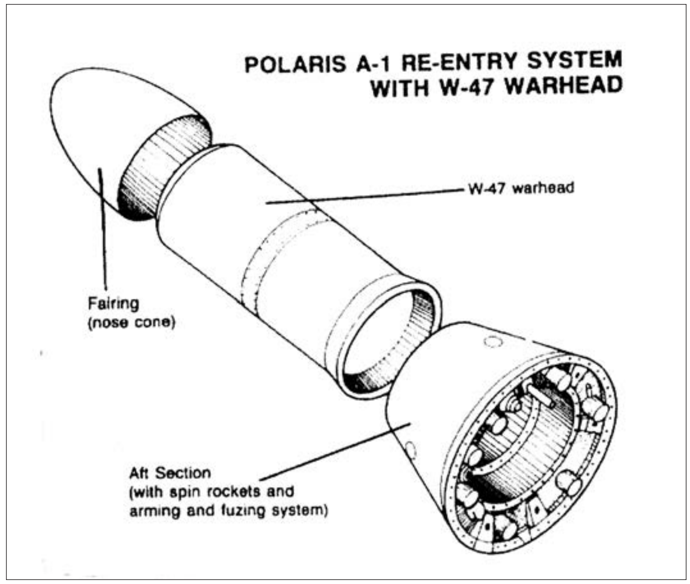


Figure 7: Polaris A-1 reentry vehicle major components *(U.S. Navy photograph).*

On December 21, 1956, the Navy Bureau of Ordnance asked the NACA to study reentry body shapes for use in the new Polaris IRBM program. Just one day earlier a flight test at Wallops Island had shown that using a flat-faced cylinder sub-scale model made of copper, the design could survive reentry speeds of Mach 13.9. Additionally the superiority of copper over Inconel-X was also proven.[29] Earlier work in 1956 with five flat-face and one hemispherical shape at Mach 2 illustrated the potential for blunt nose shapes with the flat-face shapes showing substantially reduced heat transfer (**Figure 5**).[30] In mid-1958, a feasibility study was published by James R. Hall and Benjamin J. Garland of Wallops Island Pilotless Aircraft Research Division. Two possible flat-faced cylindrical shapes with flared ends were evaluated. Their calculations showed that a flat-faced cylindrical shape with a flared afterbody was possible and if made of beryllium (the cylindrical part was assume to be the outer casing of the warhead) the resultant vehicle would be 134 pounds lighter than if composed of copper (**Figure 6**). Soon backed up by additional ground and flight testing, the Polaris reentry vehicle shape was close at hand.[31]

The Navy used flight test systems at Cape Canaveral and Wallops Island. At Cape Canaveral a modified Air Force X-17 rocket was used in a four flight FTV-3 series to evaluate reentry vehicle shapes and materials. These flights took place from July 17, 1957 to October 1, 1957 and all were successful. Three flight test programs were conducted at Wallops Island in support of the Polaris reentry vehicle development, with fifteen flights between March 1958 and August 1959.[32]

The addition of a hydrodynamic faring which covered the flat nose shape and was ejected once the missile began flight was all that was left to complete the shape of the Mark 1. At the September 26, 1957 meeting of the Special Projects Office Steering Task Group, evaluation of heatsink materials had narrowed down the W47 nose cap material to beryllium or copper. Knemeyer at China Lake had read a RAND study on reentry heat shield materials and noticed that beryllium was an excellent candidate from a heat shield standpoint as well as the fact that the warhead casing was also made of beryllium.[33] The decision to use beryllium, at the time not a commonly used metal or readily available in the United States and which had only been used in alloy with copper, was somewhat controversial. The controversy stemmed from the issue that the Atomic Energy Commission (AEC) was being told by the Navy which material should be used for the casing of the warhead. The AEC resisted the suggestion at first but armed with the results of the Hall and Garland study, the Navy persisted and prevailed. (**Figure 7**).[34]

Air Force

On January 24, 1955, the Air Force and Lockheed Aircraft Corporation (Lockheed) signed a letter of intent authorizing Lockheed to develop and conduct a program into the design of reentry vehicles. At this time none of the currently available aerodynamic research facilities in the country could simulate the high thermal and velocity conditions of long range ballistic missiles. New techniques were becoming available but the conclusions reached from them needed to be confirmed with actual flight test data.

The result was the X-17, designed to achieve a reentry speed of Mach 15 and achieve a Reynolds number of 24 million (the Reynolds number is an indication of viscosity with a high value indicating viscosity is negligible) while measuring boundary layer conditions and the transition from laminar (desired) to turbulent (unde-

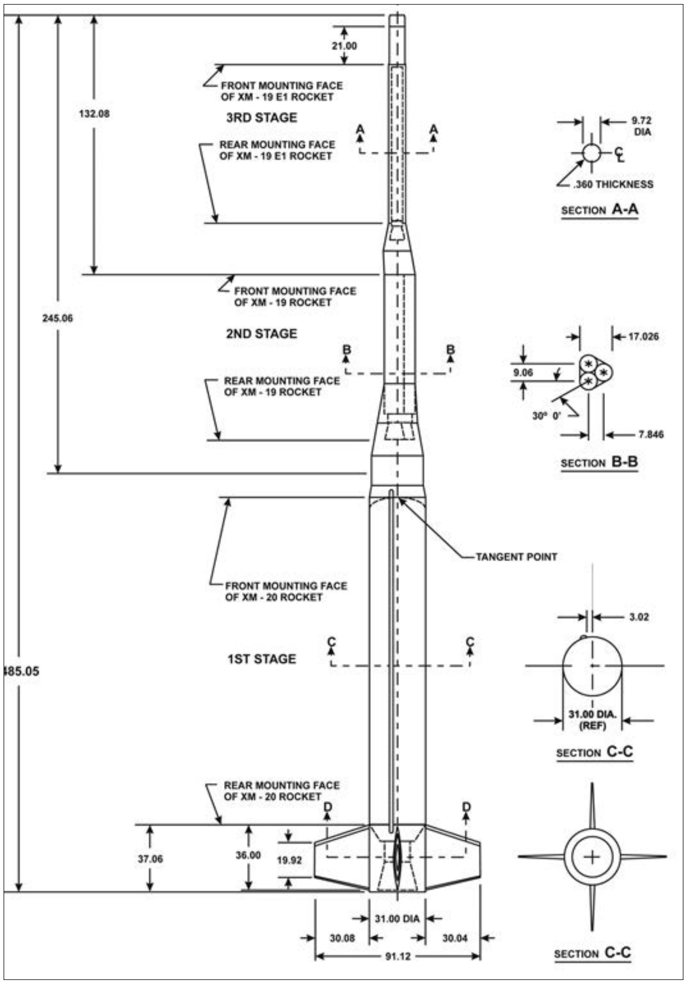


Figure 8: X-17 Full Scale Configuration (adapted from R.W.Roy and R.A Foster, "Final Report: Re-Entry Test Vehicle X-17, 10 May 1957", History Air Force Missile Test Center 1 July - 31 December 1957, Vol IV Supporting Documents Appendix F, AFHRA and (R.Smelt, "Lockheed X-17 Rocket Test Vehicle and Its Applications," American Rocket Society Vol 29, No. 8, (1959), 565-567. (*Drawing by Mitch Cannon.*)

sired) flow around the reentry vehicle. The Air Force reasoned that the X-17 would be able to provide the required data without waiting years for full-scale Atlas or Titan missiles to be ready while also being much less expensive. Sub-scale reentry vehicle shapes and material could be screened quickly and appropriate conversion of the data to full-scale models could be made.[35]

On February 17, 1955, representatives from the Western Development Division, Ramo-Wooldrigde and Lockheed visited the Langley facilities at Wallops Island where a few months earlier the first Mach 10 flight of the Langley Pilotless Aircraft Research Division (PARD) had taken place using a four stage solid propellant vehicle. Unlike the proposed X-17 flight profile which focused on high speed reentry, the PARD program Mach 10 speed had been reached at 86,000 feet with a coast up to 219 statute miles and a down range distance of 400 nautical miles. The X-17 program was described with the hope that the PARD program could be expanded to include the X-17 program. The Air Force schedule of a dozen flights at Mach 15 within a year was incompatible with the existing PARD programs but the Air Force decide to support the ongoing PARD programs by transferring some of the Sergeant rocket motors assigned to the X-17 program to Langley for use at Wallops Island.[36]

The X-17 was a three stage solid propellant missile designed to expose sub-scale re-entry shapes and materials to conditions of Mach 15 and a Reynolds number of 24 million. The program had four phases, using quarter- and half-scale rockets for development purposes and full-scale airframes for the research phase. For the full-scale rocket, 40.5 feet in length and weighing 12,000 pounds (8,500 pounds of propellant), the first stage was a single 31 inch diameter Sergeant motor, the second stage was a cluster of three Recruit motors 18.4 inches in diameter and, and the third stage a single Recruit motor, 9.72 inches in diameter.[37] The X-17 flight program began on May 23, 1955 using quarter-scale models, moving to half-scale on June 23, 1955 and the full-scale rocket on August 26, 1955, ending with the seventh full-scale flight on June 26, 1956. The fourth phase began on July 17, 1956 and ended on March 21, 1957 with only two failures out of thirty-six test flights. The two failures were caused by airframe problems and not propellant or staging issues, thus demonstrating the reliability, of multistage a solid propellant system.[38]

The flight profile emphasized the type of reentry conditions foreseen for ICBM reentry vehicles. The first stage propelled the airframe to 90,000 feet at burnout (**Figure 8,9**). The missile then coasted to an altitude of 300,000 to 517,000 feet depending on the launch angle and vehicle weight. As the missile fell back to earth, the four fins on the first stage assured that the missile orientation was nose down. At an altitude of 90,000 to 70,000 feet, depending on the test objectives, a pressure probe initiated stage separation and ignition of the second stage along with activating a delayed signal for third stage ignition. At third stage burnout, speeds of Mach 11.2 to 14.5 were reached at 55,000 feet, again depending on launch angle. No effort was made to recover the reentry vehicle models, they lasted only long enough for telemetry on heating rates to be transmitted and often completely consumed. Of the 24 research phase flights, 18 were completely successful, one partial successful and five were failures. Blunt, hemisphere and cubic paraboloid reentry vehicle nose shapes were flown with six flights each for the General Electric and Avco blunt heatsink shapes being developed for the Atlas and Thor programs.[39]

Mark 2

The smaller the radius of the nose cone, the higher the temperature generated by atmospheric friction. By 1955, the scientists at the Army Ballistic Missile Agency (ABMA) had demonstrated to their satisfaction that the ablation method was the obvious direction to pursue, but the Air Force had opted for the more conservative approach of the heatsink method. If an ICBM was to be developed in a timely manner, to the Air Force way of thinking there was no other option but to go to a large

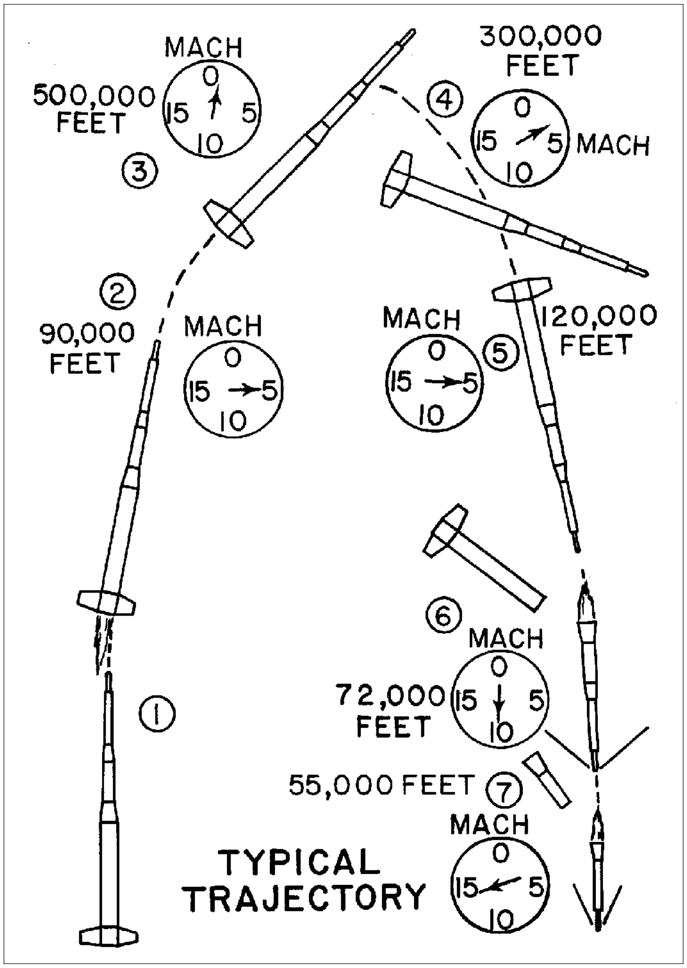


Figure 9: Typical X-17 Trajectory (R.W.Roy and R.A Foster, "Final Report: Re-Entry Test Vehicle X-17, 10 May 1957", History Air Force Missile Test Center 1 July - 31 December 1957, Vol IV Supporting Documents Appendix F, AFHRA.

radius, low β reentry vehicle, the heatsink approach.

Much earlier work by Convair, the Atlas prime contractor, had pointed towards transpiration cooling for the reentry vehicle. The resultant weight, approximately 7,000 to 8,000 pounds, necessitated the original five engine design. Convair wanted to use a ceramic reentry vehicle, possibly due to the Army's work on Jupiter but at the time fabrication techniques for this large a vehicle were not available. When Ramo-Wooldridge (R-W) became the systems engineering contractor for the Western Development Division in 1954, they took a systems approach to reentry vehicle development. A blunt heatsink reentry vehicle design was well within the laboratory investigation abilities at that time. On December 22, 1954, R-W, Sandia Corporation and the Atomic Energy Commission agreed that the proposed Convair reentry vehicle weight could be cut in half and still provide space for the one megaton yield warhead the Air Force required. The decrease in reentry vehicle weight, combined with a new 2,000 pound warhead, meant that the overall weight of the missile could decrease from 460,000 pounds to 260,000 pounds and the propulsion unit reduced from five to three engines.[40]

General Electric (primary contractor) and Avco (backup contractor) were awarded an Air Force contract in 1955, to design, develop and manufacture a heatsink reentry vehicle for use on the Atlas ICBM. In this design, the heat of reentry was conducted from the surface to a mass of high heat capacity material rapidly enough to keep the surface temperature below the melting point of the shield material. Additionally, the mass of the heatsink absorbed the heat and prevented the payload from suffering thermal stress. The Air Force's scientific advisors concurred with the heatsink decision and the General Electric "froze" the design in terms of the warhead dimensions and heatsink method on 5 September 1956.[41] When the Air Force was assigned the Thor IRBM program, the Atlas reentry vehicle design was shifted to accommodate both missiles, saving development costs since an reentry vehicle designed for ICBM conditions would easily withstand the less strenuous conditions of IRBM reentry.[42]

Work by Jackson Stadler at Ames in 1957, evaluated copper, Inconel-X, graphite and beryllium for use in heatsink reentry vehicles. Copper represented an example of an easily machined material with high thermal conductivity but relatively low melting point, 1,984 F. Inconel-X was an example of refractory metal (resistant to heat and wear), but had low thermal conductivity and a 1,200 F melting point as well as being difficult to machine. Beryllium was an example of a lightweight metal with high strength, excellent thermal conductivity, a melting point of 2,348 F, but was difficult to machine as well as being hard to supply in quantity at the time. Additionally the dust generated by machining was highly toxic. Graphite was an example of a semi-metal with high thermal conductivity and highest melting point, 6,442 F, and high sublimation temperature. Stadler's evaluation included: a) thickness of material to prevent melting or sublimation at the surface, b) weight of material thick enough to meet (a), and c) determining thermal stress due to temperature gradients in the material.

Stadler concluded copper was a likely candidate due to the mass of material being resistant to thermal shock (weight was a drawback) and protection from oxidation would be needed. Inconel-X was "completely unsatisfactory" due to the low thermal conductivity causing melting to occur early in reentry and little heat was transferred to the interior. Graphite was superior to copper from the standpoint of weight, requiring 1/24 the weight of copper for equivalent protection. Unfortunately it would require to be coated which would inhibit exploitation of the high sublimation temperature. Beryllium was attractive due to a higher melting point then copper and being much lighter, 1/6th the equivalent weight of copper, but it was brittle and difficult to form in large pieces at that time.[43]

For the General Electric Mark 2 design copper was selected due to its ease of machining, high heat capacity and high thermal conductivity which meant the heat generated would be rapidly absorbed into the mass of copper and not cause melting at the surface. Avco scien-

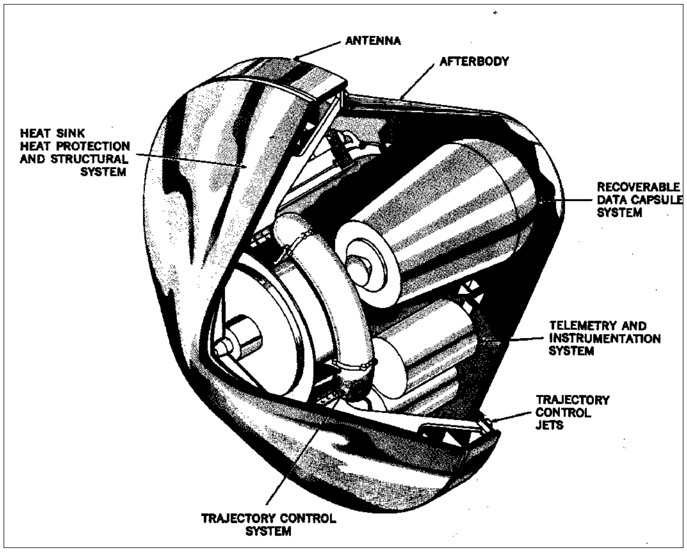


Figure 10: General arrangement of the General Electric Mark 2 heatsink reentry vehicle (M.Morton, Progress in Reentry Recovery Vehicle Development, Philadelphia, PA: General Electric, Missile and Space Vehicle Division, 1961, 6.)

tists pursued the use of beryllium and were successful in creating a Mark 2 reentry vehicle but it was too late as ablation took over as the method of choice. The techniques developed were used to fabricate early research and development beryllium heat shields for Project Mercury.[44]

Work by Katherine C. Speegle at Wallops Island's preflight jet test facility in 1957, investigated the best shape for the nose and the compartment that would contain the warhead. Six blunt nose shapes with identical afterbodies were tested at Mach 2.0 velocities. The results showed that the selected truncated cone afterbody was completely surrounded by the separated flow region, meaning heating would be acceptable.[45] The final design was known as a blunt conic sphere. The Mark 2 had a maximum diameter of 63.6 inches and was 60 inches in length, weighing nearly 2,000 pounds (**Figure 10**).[46] The blunt conic-sphere was inherently unstable and prone to oscillations causing turbulent flow to develop on the nose of the vehicle so a trajectory control system was incorporated to provide rate damping of the oscillations as well as impart spin to increase accuracy. A Mark 1 reentry vehicle was initially developed as a flight article but due to changes in missile flight schedules was not flown and instead used for development fit testing and as a flight reserve article.[47] The surface of the Mark 2 was coated with a thin layer of nickel to decrease radiative heating and was highly polished to prevent localized hot spots.[48]

The X-17 program had demonstrated that an ionized air layer surrounding the vehicle during the highest temperature period of reentry caused a telemetry black-out. For full-scale flight testing of the Mark 2, General Electric engineers developed a buoyant data capsule. The capsules were 18-inch spheres made from two hollow hemispheres of polyurethane foam which housed a tape recorder, radio beacon, battery pack, dye pack and SOFAR (sound fixing and ranging) device for locating the capsule. The bottom half of the capsule was coated with shark repellent after a test capsule was recovered with a shark bite mark. The capsule was attached to a small rocket to boost it free of the reentry vehicle. The urethane sphere was encapsulated in an ablative shell which shattered on impact (40,000 g's), releasing the buoyant capsule. Contact with salt water triggered the release of dye, the SOFAR device and the radio beacon.[49]

The Atlas Mark 2 flight test program began on July 19, 1958 and ended on December 19, 1959, a total of seventeen flights; seven Atlas B, four Atlas C and six Atlas D, nine were successful flights. The Thor Mark 2 flight test program began on November 5, 1958 and ended on December 17, 1959, a total of twenty-eight flights, with twenty-four successful. Details on Mark 2 reentry vehicle performance on these flights remains classified. The Mark 2 Mod 4 operational warhead weighed 3,500 pounds of which 1,600 pounds was warhead weight and was only deployed on Atlas D gantry sites at Vandenberg AFB from 1959 to 1964 and on Thor missiles in England from 1959 to 1963.[50] (**Figure 11**).

The Second Generation - Ablative

The first to actually describe ablation was Dr. Robert H. Goddard in 1920:[51]

In the case of meteors, which enter the atmosphere with speeds as high as 30 miles per second, the interior of the meteors remains cold, and the erosion is due, to a large extent, to chipping or cracking of the suddenly heated surface. For this reason, if the outer surface of the apparatus were to consist of layers of a very infusible hard substance with layers of a poor heat conductor between, the surface would not be eroded to any considerable extent, especially as the velocity of the apparatus would not be nearly so great as that of the average meteor.

The process of ablation during reentry is described as follows:[52]

As heating progresses, the outer layer of polymer may become viscous and then begins to degrade, producing a foaming carbonaceous mass and ultimately a porous carbon char. The char is a thermal insulation; the interior is cooled by volatile material percolating through it from the decomposing polymer. During the percolation process, the volatile materials are heated to very high temperatures with decomposition to low molecular weight species, which are injected into the boundary layer of air. This mass injection creates a blocking action, which reduces the heat transfer in the material. Thus, a char-forming resin acts as a self-regulating ablation radiator, providing thermal protection through transpirational cooling and insulation. The efficiency, in terms of heat absorbed per weight of material lost, is about 40 times that of the earlier copper heatsink design.

Figure 11: Mark 2 reentry vehicle (shown upside down) being inspected prior to loading on a Thor missile in England. ***(Courtesy of Jim Causby.)***

Army

Jupiter

Ablation provided thermal protection for the Jupiter reentry vehicle. Earlier work had shown the transpirational cooling approach, while it worked, required complicated plumbing that would likely be hard to support in the field. The heatsink concept would work but was determined to be too heavy. The ablative approach came from a fortuitous result of research begun in 1953, investigating materials to replace graphite for jet vane application during the development of the Redstone missile (jet vanes were used for directional control instead of gimbaling the engine). The trouble was one of quality control because while a source of the right grade of material was found, the manufacturer's poor quality control meant that only twenty-five percent of the jet vanes were acceptable. In an attempt to find a replacement, researchers tested several materials including a jet vane made of commercial grade fiberglass-reinforced melamine. Exposure to the Redstone rocket motor exhaust eroded the vane as expected but much to the surprise of the researchers, one-quarter inch beneath the surface the material was not only undisturbed but the embedded thermocouples revealed no heating had taken place. While the tested material was not used as a jet vane, the ABMA researchers skipped past the heatsink concept and went straight to ablative reentry vehicle materials.[53] Ceramic material was also carefully evaluated and found to be too sensitive to thermal shock at that time though sufficient work was done with a method of ceramic manufacture called slip forming to successfully fabricate the necessary shape.

Scientists at ABMA estimated the weight of five candidate materials: Refrasil-phenolic, fiberglgass-melamine, unfired ceramic, beryllium and copper to provide thermal protection for a proposed heat shield design. Refrasil, fiberglass-melamine and ceramic were found to be the materials of choice. An expedient method for evaluating candidate materials was to expose flat plates of the material to rocket exhaust at a heat flux of 100 BTU/ft^2-sec and a velocity of 6,700 feet per second. The plates were four inches square and tilted at a 45 degree angle in the exhaust stream. Further research in resin based ablative materials revealed that asbestos reinforced phenolic resin would be the best overall material for the Jupiter reentry vehicle environment. After initial evaluation of the plate material, reentry vehicle shapes were tested both with the rocket exhaust technique and via shock tube studies by Arthur Kantrowitz at Cornell University.[54] Using a variety of rocket motors, researchers were able to simulate heating rates up to 2,500 BTU/ft^2-sec. Transonic wind tunnel tests of a half-scale model Jupiter reentry vehicle were

Figure 12: Jupiter-C sub-scale reentry vehicle attached to the spinning "tub." This vehicle was an early fiberglass-melamine ablative material flown on 15 May 1957. While not recovered, the telemetry showed that the ablative concept worked well on an IRBM trajectory. ***(NASA photograph courtesy of Joel Powell.)***

conducted at the Air Force's Arnold Engineering Development Center, Arnold Air Force Base in June 1957 and at the hypersonic test facilities of the Naval Ordnance Laboratory, White Oak, Maryland in September 1957, confirming the full-scale nose cone design.[55]

For flight testing of the one-third scale Jupiter reentry vehicle designs, the Army's Redstone tactical ballistic missile was modified into a three stage booster. The first stage had an elongated fuel tank and used a more powerful fuel called Hydne (unsymmetrical dimethyl hydrazine). The forward section of the first stage was strengthened to support the new upper stages. The second stage was made up of a cluster of eleven scaled-down Sergeant solid propellant missiles, six inches in diameter, housed in a cylindrical fairing called the "tub." The third stage was located in the center of the second stage and made up of three additional scaled down Sergeant missiles. Atop the third stage was a 300-pound, 1/3rd-scale ablative (1/10th surface area) reentry vehicle composed of a welded steel shell supporting the heat shield. While fabrication techniques were being perfected for the resin-asbestos material, a heat shield made of layered disks of melamine, a commercially available laminated fiberglass-resin was flown first. The tub was spun up by electric motors at launch to provide ballistic stability. The resulting vehicle was called Jupiter-C (Jupiter Composite) and now had a range of over 1,500 nautical miles with an apogee of over 175 nautical miles.[56] (**Figure 12**)

Only three of a scheduled of thirteen flights were necessary for the Jupiter-C program. The first launch was on September 20, 1956, Jupiter C Missile RS-27, with the missile reaching 600 nautical miles in altitude and a speed of Mach 18. This was a test of the modified propulsion and staging system and was successful. The second flight, Jupiter C Missile RS-34, was launched on May 15, 1957. The missile pitched up at 134 seconds into flight so while the planned range was not reached and the reentry vehicle was not recovered, telemetry indicated that the fiberglass melamine ablative material had functioned as expected. The first sub-scale operational Jupiter reentry using a phenolic resin asbestos ablative material was flown on Jupiter C Missile RS-40, August 8, 1957. The booster and high-speed upper stages worked well. Failure of the reentry vehicle to separate from the third stage changed the reentry trajectory, reducing the angle of attack at the point of maximum heating. Nonetheless, the reentry vehicle traveled 1,168 nautical miles, achieving a velocity of 13,000 feet per second and withstanding a temperature of over 2,000 degrees F, conditions similar to those expected for an IRBM reentry vehicle. While the reentry vehicle did not separate as planned, the heat of reentry melted the magnesium ring of the separation system and the recovery system deployed successfully. Analysis of the ablative covering showed only a one and a half percent loss (the reentry vehicle was displayed in President Eisenhower's office and is in storage at the National Air and Space Museum in Washington, D.C.) Ablation technology had been proven with the ultimate test, full IRBM range and velocity.[57]

Full-scale Jupiter reentry vehicles were successfully recovered on three flights; Jupiter Missile AM-5, launched on May 18, 1958, the first recovery of an IRBM reentry vehicle; Jupiter Missile AM-6, July 17, 1958, which also carried a lightweight high explosive warhead; and Jupiter Missile AM-18, May 28, 1959, which carried two monkeys, Able and Baker, which survived unharmed. While the reentry vehicle flown on AM-5 showed an ablation depth of three-eighths inch at the greatest point of loss, the remaining flights showed considerably less, validating the ablative concepts of the sub-scale model flown and recovered earlier (**Figure 12**).[58]

The deployed reentry vehicle, built by Goodyear Aircraft Corporation, was an hermetically sealed conical aluminum shell with a twelve and a half-inch radius spherical tip attached to a cone frustrum with a base 65 inches in diameter and an overall length of nine feet. The molded nose cap was composed of thirty percent, by weight, phenolic resin with seventy percent Type E glass; the frustrum material was a layer of a mixture of forty-five percent phenolic resin and fifty-five percent Chrysotile asbestos.[59] A key design feature, also found in other reentry vehicle designs, was a convex dish shaped aft cover which conferred the ability to recover from any attitude to the correct reentry alignment. The ablative material was much thinner than the sub-scale fiberglass melamine heatshield. (**Figure 13**). The complete reentry vehicle with warhead, weighed 2,617 pounds, the W49 weapon weighed 1,600 pounds.[60]

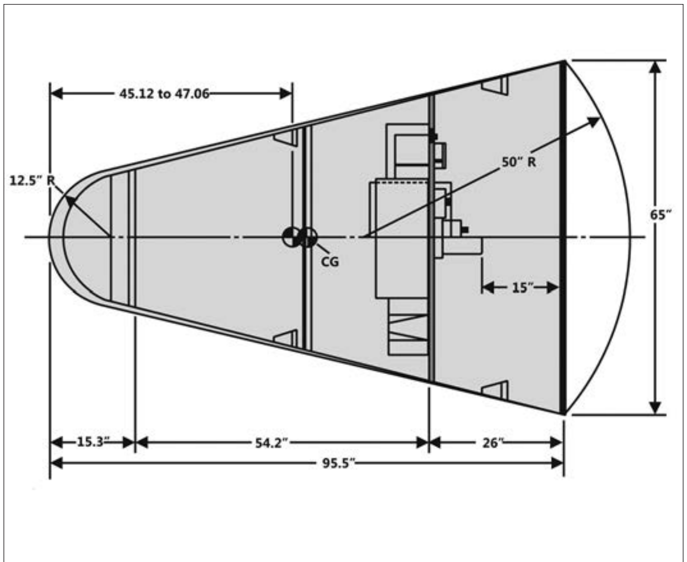


Figure 13: Operational Jupiter reentry vehicle dimensions (adapted from National Aeronautics and Space Administration, NASA History Office, "Facing the Heat Barrier: A History of Hypersonics," by T.A. Heppenheimer, NASA History Series, SP-2007-4232 (2007), 46. ***Drawing by Mitch Cannon*****).**

Air Force

Atlas and Titan I

The Air Force was not new to the concept of ablation. Indeed the two contractors selected in 1955, to develop the Atlas reentry vehicle, General Electric and Avco Corporation, were directed to look at all methods for solving the reentry problem. Wright-Patterson's Air Research and Development Command were also evaluating ablation materials as was Langley Aeronautical Laboratory and Ames Research Center. The decision to work with the heatsink concept had stemmed from recommendations of a number of scientific advisory committees and panels. On June 16, 1953, the Department of Defense Study Group on Guided Missiles, better known as the Teapot Committee, had been created to evaluate the status of guided missile development by the Air Force. On February 16, 1954, the committee submitted its report. It recommended that the reentry problem be reinvestigated as Convair's approach (transpirational cooling) was insufficiently broad.[61]

On August 31, 1957, in the 21st Monthly Report on Progress of ICBM and IRBM Programs, a shift in reentry vehicle design was noted. While the heatsink design for Atlas and Thor was sufficient, developments in materials and testing capability indicated that ablation reentry vehicles could have ballistic coefficients five to eight times greater than the Mark 2 heatsink which would lead to greater accuracy and decreased vulnerability. Dispersion caused by wind would also be greatly decreased, the error due to wind was calculated to be approximately 500 feet in CEP (circular error probable, a circle within which fifty percent of the reentry vehicles impacted) at a 5,500 nautical mile range.[62]

On August 28, 1958, after only two Atlas B flights with the Mark 2 and just before the start of the Thor Mark 2 flight testing, almost exactly one year after the highly successful conclusion of the Army's Jupiter-C reentry test vehicle program, Brigadier General O.J. Ritland, Vice Commander of the Ballistic Missile Division, notified the Air Research and Development Command of the decision to reorient the ICBM reentry vehicle program from heatsink to ablative technology. The decision was based "recent developments aimed toward improving the solution to the ICBM reentry problem." The Mark 2 heatsink reentry vehicles would be supplied for all WS-315A (Thor) and early operational WS-107A-1 Atlas missiles at the two operational sites at Cooke Air Force Base (Cooke had not been renamed Vandenberg yet). All Avco work on heatsink development was to be discontinued. General Electric was now assigned development responsibility for a light weight second generation reentry vehicle capable of carrying a 1,600 pound warhead, and to be flight tested on the Series D Atlas missiles with deployment starting at Warren Air Force Base. This was the Mark 3. Avco was assigned responsibility for a heavy weight second generation reentry vehicle capable of carrying a 3,000 pound warhead to be flight tested on lot J Titan I missiles. This was the Mark 4.[63]

As early as 1956, plastics had been examined for use in the high temperature environment of ramjet engines. Researchers at the Marquardt Aircraft Company exposed model ramjet inlet cones made from three fiberglass reinforced plastics, Conolon 505 (phenolic), DC 2106 (silicone) and Vibrin 135 (polyester) for twenty minutes at temperatures up to 500 to 600 F at a speed of Mach 2. They found that all three materials showed little or no detrimental effects, concluding that reinforce plastics might have a role in missile development.[64]

Researchers at General Electric's Missile and Ordnance Systems Division in Philadelphia expanded on the Marquardt work by estimating a candidate ablative material's ability to absorb heat up to 8000 F under equilibrium conditions. The results showed that plastic materials had the highest theoretical heat absorbing capacities, more than twice that of beryllium. The more gas a material generated upon heating, again under equilibrium conditions, the better the material. Heat capacity and gas generation values were useful indicators but could not be used as guides in selection of materials because of the non-equilibrium conditions of the operational environment. When the material melted, the liquid would be swept away in the air stream, upsetting the thermal equilibrium. The higher the melting point and the more viscous the resulting liquid, the more optimal the thermal effect. Phenolic resin plastics were found to decompose slowly at high temperature and did not liquefy, instead forming gaseous byproducts and a char layer that protected to the base material. Exposure of phenolic-glass cloth with sixty-five percent resin to 12,000 F in a high temperature arc showed only 1.4 percent erosion; phenolic-Refrasil (Refrasil is the trade

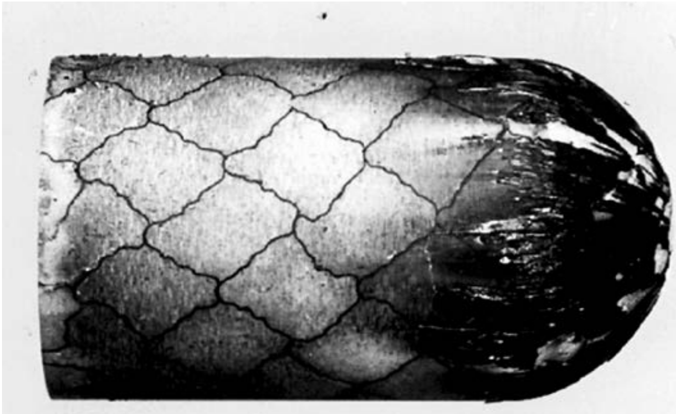


Figure 14: Shock tube development sample of Avcoite. Avcoite was a ceramic material contained in a magnesium honeycomb matrix and was used on the Avco Mark 4 and Mark 5 reentry vehicle nose cap *(author's collection).*

name for a high silica content glass) with forty-one percent resin only 2.1 percent erosion and phenolic-nylon cloth with fifty-seven percent resin only 1.0 percent. The organic reinforcement's lower erosion rate was due the organic fiber's lower thermal conductivity. Key variables were type of resin, orientation of the fibers, type of fiber and ratio of resin to fiber. Phenolic resins gave a higher yield of carbon char. Large variations in performance were found amongst the various suppliers. Orientation of the fibers had a significant effect on performance with random orientation giving the best results. At temperatures above 5,000 F amorphous silica fibers were superior to ordinary glass and organic fibers were found superior to glass fibers. Resin to fiber ratio optimization had somewhat counter intuitive results. Higher glass fiber content gave better mechanical properties but was slightly detrimental to thermal erosion above 5,000 F. At plasma jet temperatures, 12,000 F, higher resin content gave greatly improved performance. Clearly ablative materials had come of age for use in ICBM reentry vehicle heat shields.[65] The result was the General Electric's Mark 3 reentry vehicle deployed on Atlas D.

Avco Corporation began defense contract work in 1955, with the creation of the Avco Everett Research Laboratory. Victor Emanuel, president of Avco Corporation, knew of the work of Dr. Arthur Kantrowitz, a physicist working at Cornell University with shock tube experiments in the study of the hypersonic flight. Emanuel approached Kantrowitz with a proposal to come work at Avco and apply his theories towards the solution of the "reentry problem." Enticed by the prospect of a new, modern facility to be built for him, Kantrowitz agreed and the Avco Everett Research Laboratory was built. At the same time and undoubtedly due to Kantrowitz's presence, the lab's Research and Advanced Development Division won the backup contract for the Mark 2 heatsink reentry vehicle and was the primary contractor for a similar design for Titan I. Like General Electric, Avco was also studying and developing ablative as well as heatsink material. Unlike the engineers at General Electric who had studied ceramics and dismissed them as too difficult to work with compared to reinforced plastic resins, Avco engineers decided to pursue the use of ceramics for the nose section of the reentry vehicle where the heating was the most severe.

Expanding on the ceramics research by Georgia Institute of Technology and Battelle Memorial Institute for the Jupiter program, Avco researchers focused on solving the brittle fracture problem which was preventing the fabrication of the large and complicated reentry vehicle shapes light enough to be practical. The weight issue was the result of the amount of material needed to be structurally sound and not one of thermal protection efficacy. The decision was made not to search for new materials but rather to focus on new fabrication techniques. One solution investigated was the use of small ceramic tiles. This was rejected due to the thinness of the tiles and difficulty in assembling them on the curved nose section. The eventual solution was to use a metal honeycomb structure to hold small "pencils" of ceramic which did not easily fracture. By orienting the pieces in honeycomb cells at ninety degrees to the surface, optimum thermal protection and structural strength was obtained. In 1959, Avco's Research and Advanced Development Division announced the development of Avcoite, a magnesium honeycomb reinforced ceramic for use on the nose of the Mark 4 reentry vehicle originally destined for Titan I but which was also deployed on Atlas E and F (**Figure 14**).[66]

Flight Testing

Once the feasibility of ablative material had been experimentally determined, flight testing of sub-scale reentry vehicles began. The primary research and development flight testing for evaluating the early Air Force sub-scale and full-scale ablative ICBM reentry vehicles were the Thor-Able 0 and II, Atlas D and Titan I Lot J programs.

Thor-Able

The first in a series of ballistic missiles used for Air Force reentry vehicle development was the Thor-Able launch vehicle. Use of research and development flights of the Atlas ICBM was considered and rejected at this point as integration of reentry vehicle testing would interfere with the early development objectives. In October 1957, the Ballistic Missile Division and Space Technologies Laboratory began the design of the Advanced Reentry Test Vehicle (ARTV) that could be ready for use within six to eight months using existing hardware. The critical capability of the ARTV would be to reach ICBM reentry speeds of approximately 24,000 feet per second carrying a one-half scale reentry vehicle. A variety of possible test vehicle combinations were examined but only one that met the requirements of availability and performance; a Thor first stage and Vanguard second stage modified with eight spin rockets was configured

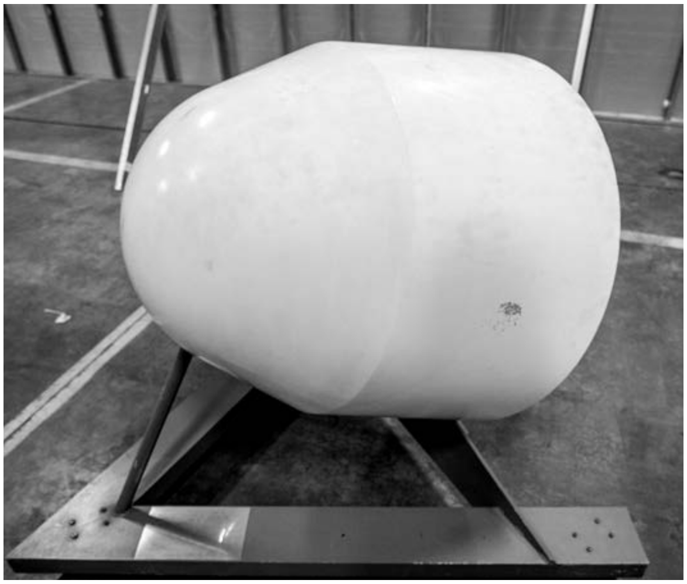


Figure 15: Thor-Able 0 RTV. *Courtesy Northrup Grumman.*

by STL with autopilot and cutoff controls assembled from available Thor and Atlas components.[67]

Able RTV

The Thor-Able 0 program flight tested three General Electric reentry vehicle development models, designated Able RTV's. The RTV's were biconic-spheres 34 inches long and a base 38 inches in diameter, weighing 620 pounds and (**Figure 15**) fabricated with ablative material and flown from Cape Canaveral from April 23, 1958 to July 23, 1958. There was one failure due to booster malfunction and two partial successes. All three flights carried biomedical experiments with mice and while the two successes clearly demonstrated the efficacy of ablation at ICBM ranges and speeds, the reentry vehicles were not recovered as planned. The data provided by these tests helped determine how much the heat shield weight could be decreased and still be effective as well as verifying the superior performance of ablative materials compared to the heatsink materials. A description of the RTV series vehicle's ablative materials has proven elusive.[68]

Able RVX-1

For the Thor-Able II program, a modified Thor booster was used with its guidance package removed and the radio-inertial guidance system for the Titan I ICBM installed in the RVX-1 reentry vehicle. These six flights were designated as Precisely Guided Reentry Test Vehicle launches with two goals; evaluating the new guidance system which would also indicate the exact point of impact as well as continue to evaluate new ablative materials.[69]

Instead of using the recovery system from the Jupiter reentry vehicle test program which had been proven unsuccessful with the Thor-Able 0 flights, General Electric developed a more robust system to handle the much heavier RVX-1 vehicles. Additionally, the data capsule concept used in the Mark 2 program was used to record the telemetry during the flight and reentry phase when ionization phenomena prevented telemetry transmission.

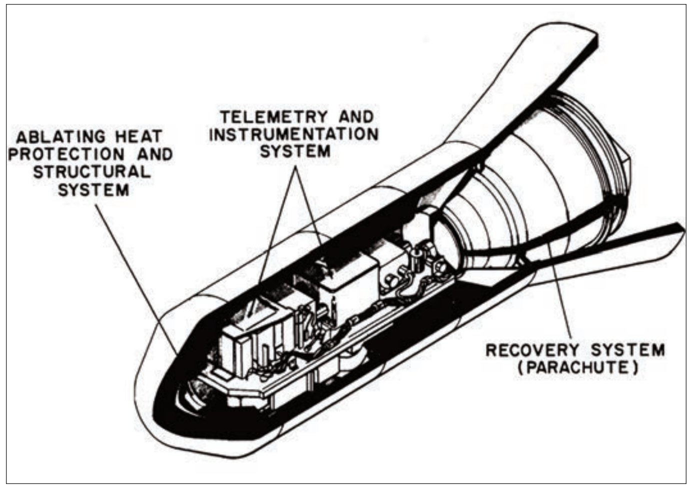


Figure 16: General arrangement of the RVX – 1 experimental reentry vehicles. The maximum diameter was 28 inches at the base of the flare, length was 68 inches. (M.Morton, Progress in Reentry Recovery Vehicle Development, Philadelphia, PA: General Electric, Missile and Space Vehicle Division, 1961, 6. *Measurements courtesy of Craig Brunetti, National Air and Space Museum*).

General Electric provided the RVX-1 internal frame used to test both the General Electric and Avco Corporation ablative materials. The RVX-1 was a conic sphere flared-cylinder configuration (**Figure 16**), sixty-seven inches long with a cylinder diameter of fifteen inches and a flare diameter of twenty inches, and weighed 645 pounds. The flights began on January 23, 1959, starting with the RVX-1 carrying General Electric materials and alternating flights with Avco materials, and ended on June 11, 1959 with one failure, three partial successes and two complete successes. The General Electric RVX-1 tested three types of phenolic nylon ablative materials (phenolic nylon, phenolic glass and phenolic Refrasil) in sixty degree segments repeating every 180 degrees on the cylinder and flare. The nose was made of a thick layer of molded phenolic resin with one- inch squares of nylon cloth.[70]

The Avco RVX-1 vehicles (sixty-eight inches in length with a nose cap of eleven inches, a cylinder diameter of seventeen inches, cylinder length of thirty-nine inches, a flare length of eighteen inches and a flare base diameter of twenty-eight inches) had Avcoite on the nose and phenolic Refrasil tape covering the mid-section and flare.[71] On the April 8, 1959, the Avco RVX-1-5 was successfully flown 5,000 nautical miles down range with a maximum altitude of 764 miles and a reentry speed of 15,000 miles per hour (**Figure 17**). The nose cap easily withstood the heat of reentry as had the Refrasil material coating the cylinder and flare sections. The Avcoite ceramic had melted and flowed back asymmetrically a short distance down the cylindrical body as expected.

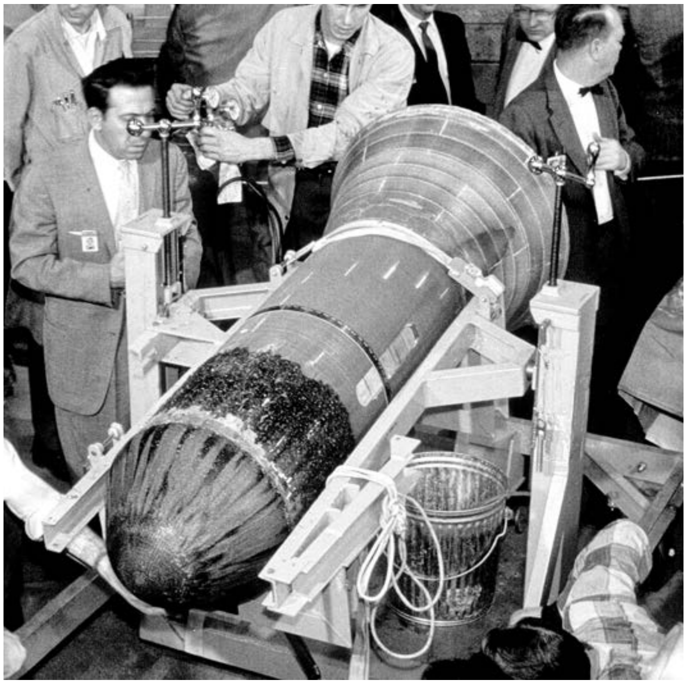


Figure 17: The Avco RVX – 1, launched on 8 April 1959 on Thor missile 133, was the first recovered reentry vehicle flown on an ICBM trajectory. Before being put on display to the press the original nose cap was removed and replaced with a mockup for security reasons. This artifact was given to the Smithsonian Institute and is in storage at the National Air and Space Museum(*photograph courtesy of Phil Fote*).

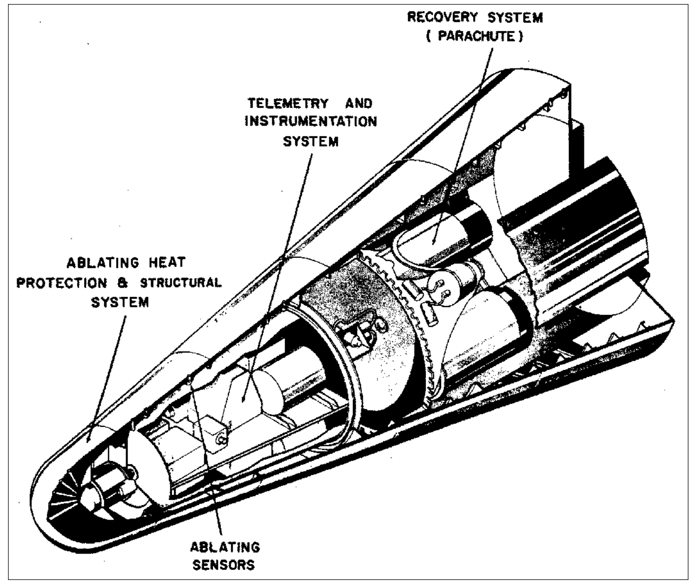


Figure 18: General arrangement of the RVX – 2 and RVX – 2A experimental reentry vehicles. The RVX – 2 had maximum diameter of 5 feet and was approximately 12 feet long. (M.Morton, Progress in Reentry Recovery Vehicle Development, Philadelphia, PA: General Electric, Missile and Space Vehicle Division, 1961, 8).

Telemetry results indicated no effect on aerodynamic stability. Soon after recovery the nose cap was removed for further inspection and replaced with a mock-up due to security concerns. The RTV-1-5 is now in storage along with the removed nose cone at the National Air and Space Museum's Garber facility.

On May 21, 1959, the second General Electric RVX-1 flown was also successfully recovered, looking much the same as the Avco vehicle except that the reinforced phenolic-chopped nylon nose cap simply ablated and did not flow back along the cylinder.[72]

The RVX-1 flight program, even with the failures due to not recovering all of the vehicles (complete telemetry was obtained via the data capsules), further confirmed the maturity of ablative materials for use in high speed reentry as the RVX-1 vehicles were exposed to temperatures exceeding 12,000 F. The RVX-1 test vehicles were the direct progenitors of the General Electric Mark 3 (Atlas D) and Avco Mark 4 (Atlas E, F and Titan I) reentry vehicles.[73]

RVX-2 Series

By mid-1960 Atlas D missiles were available for use in the final phase of ablative material testing, flights of full-scale reentry vehicles at operational ranges and reentry speeds. The RVX-2 series involved tests of newer plastic ablative materials. Ranges flown varied from 4,400 nautical miles to the Ascension Island impact area to 6,400 nautical miles off the coast of Capetown, South Africa and further yet, 7,900 nautical miles to the Southern Atlantic off of the Prince Edward Islands. The reentry evaluation portion of the program commenced on March 8, 1960, and ended on January 23, 1961.[74]

RVX-2

Three General Electric RVX-2 reentry vehicles were flown to test a new type of ablative material, unreinforced phenolic resin, General Electric Series 100, for the proposed Titan II Mark 6 reentry vehicle.[75] The RVX-2 was a conic-sphere configuration, twelve feet tall and five feet in diameter, weighing over 2,000 pounds, the largest reentry vehicle yet flown with what appears to a phenolic resin-chopped nylon nose cap and unreinforced phenolic resin side frustrum panels. The first two flights suffered guidance and booster failures; March 17, 1959 and March 18, 1959 respectively, but the last flight, on July 21, 1959, was successful and the reentry vehicle was recovered intact after a flight of 5,000 nautical miles.(**Figure 18**). Photographs of the recovered vehicle show a close resemblance to the General Electric Titan II Mark 6 reentry vehicle which also used these materials.[76]

RVX-2A

The RVX-2A program had three flights during the Atlas D test flight program, August 12, 1960, September 16, 1960 and October 13, 1960. The RVX-2A vehicle had the same dimensions as the RVX-2 and weighed slightly more than 2,700 pounds. The main difference between the two was the instrumentation, the RVX-2A was used for extensive scientific experiments beyond reentry. The eighteen experiments included black and white and

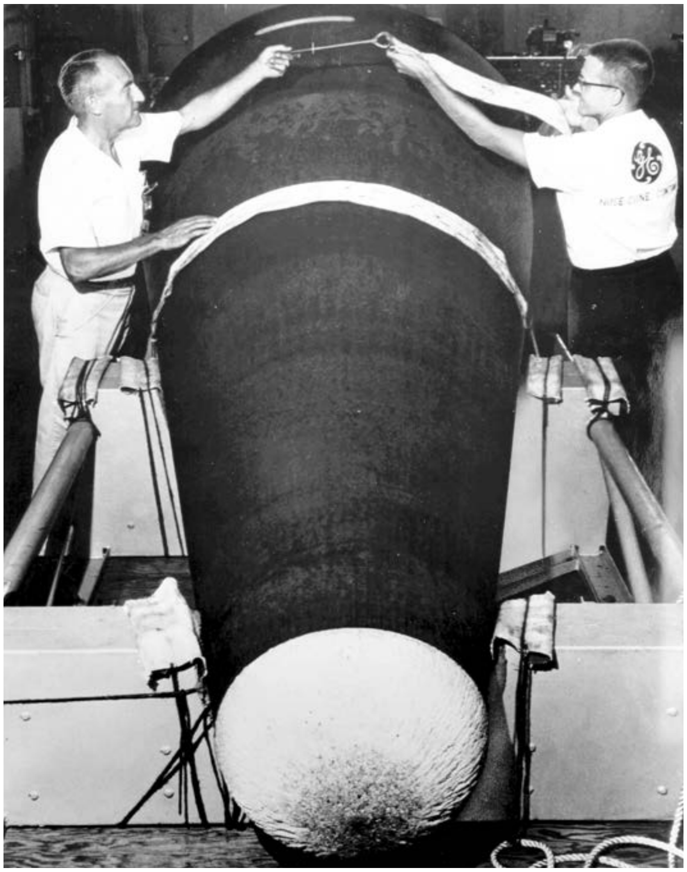


Figure 19: General Electric RVX-2 reentry vehicle being prepared for transport after successful recovery on 21 July, 1959 (*photograph courtesy of Donald Schmidt*).

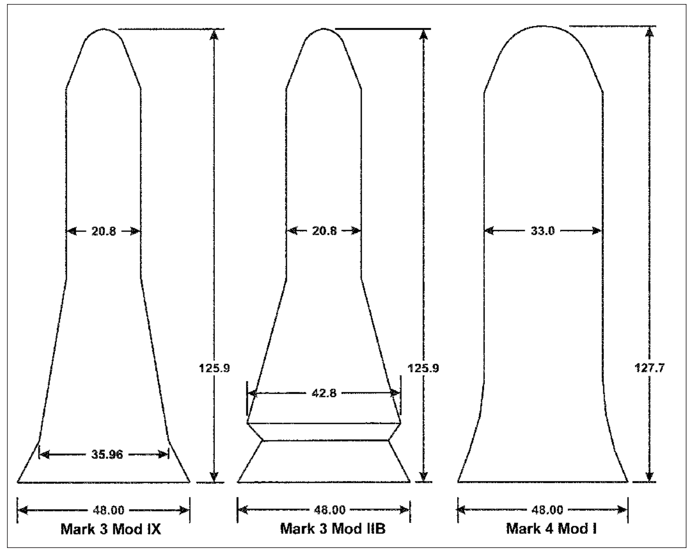


Figure 20: Comparison of Mark 3 Mod I, Mark 3 Mod IIB, and Mark 4 Mod I (adapted from Flight Summary Report Series D Atlas Missiles, (San Diego, CA: General Dynamics/Astronautics, DTIC AD0833337, 21 June 1961), 8–6, 8–7 and 8-33. *Drawings courtesy of Mitch Cannon*).

color photography, live mice, radiation phenomena, reentry physics including transpirational cooling, electromagnetic propagation and fuel cell prototypes. A recovery system similar to that of the RVX-1 program was used on all of the flights with successful recovery on only the final flight.[77]

The General Electric portion of the RVX-2A program were the first and third flights, testing the General Science Century Series of unreinforced phenolic resin for use on the conic frustrum part of the conic sphere design for the Titan II Mark 6 reentry vehicle. Four formulations, GE Type 123,124 and 135 as well as GE Type 525 were used. General Electric researchers had discovered a radical departure from previous ablation research. Under laboratory test conditions simulating reentry, unreinforced phenolic resin formed several porous char layers one to two millimeters thick were formed in sequence. The first one quickly plugged up, was sloughed off by aerodynamic forces and was replaced instantly by the formation of a new char layer. Large amounts of pyrolysis gases that formed as the material degraded served to inhibit heat transfer from the very hot boundary layer to the ablating surface, greatly reducing the actual heating at the vehicle surface. These results greatly simplified the design of the large Mark 6 reentry vehicle and saved considerable weight.[78] The maximum internal temperatures reached in the two flights were 90 and 100 F, well below the 350 F expected. Nose cap ablation was greater than expected. Degradation of the Series100 phenolic resin was comparable to that of nylon reinforced phenolic resin and was in agreement with computer modeling(**Figure 19**). [79]

Avco flew one RVX-2A flight on September 16. The nose cap was RaD 58D followed by a twenty-six-inch frustrum section of RaD 58B and 100 inches of tape wound Refrasil. Test plugs of Avocoat x3007 and RaD 58E were inserted at alternating ninety-degree intervals in the forward portion of the tape wound Refrasil section. The RaD 58E was a candidate material for the Minuteman missile reentry vehicle and the Avocoat was a proposed low temperature ablation for the boost phase of the Minuteman trajectory. Telemetry problems prevented transmission of thermal and ablation data.[80]

Mark 3

The Mark 3 reentry vehicle was designed for the Atlas F missile, as mentioned earlier, but deployed only on Atlas D. The Mark 3 was a direct descendant of the General Electric RVX-1 program. Measuring 114.8 inches in overall length, there were two Mark 3 shapes (see **Figure 20**). Both had the sphere-conical nose shape, 29.22 inches in length and a cylindrical mid-section 20.7 inches in diameter and 40.6 inches in length. The Mark 3 Mods I, IX and IA had a single biconic frustrum flare, 35.9 inches in diameter, that blended smoothly with the reentry vehicle adapter spacer atop the missile. The Mark 3 (Mods IB and IIB) had a biconic-2 shape with an second, wider flare at the base, 42.8 inches in diameter, resulting in a characteristic "skirt" conical ring slightly outwards above the spacer which was not modified to affect a more streamline appearance. The second flare aided in reentry stability by mov-

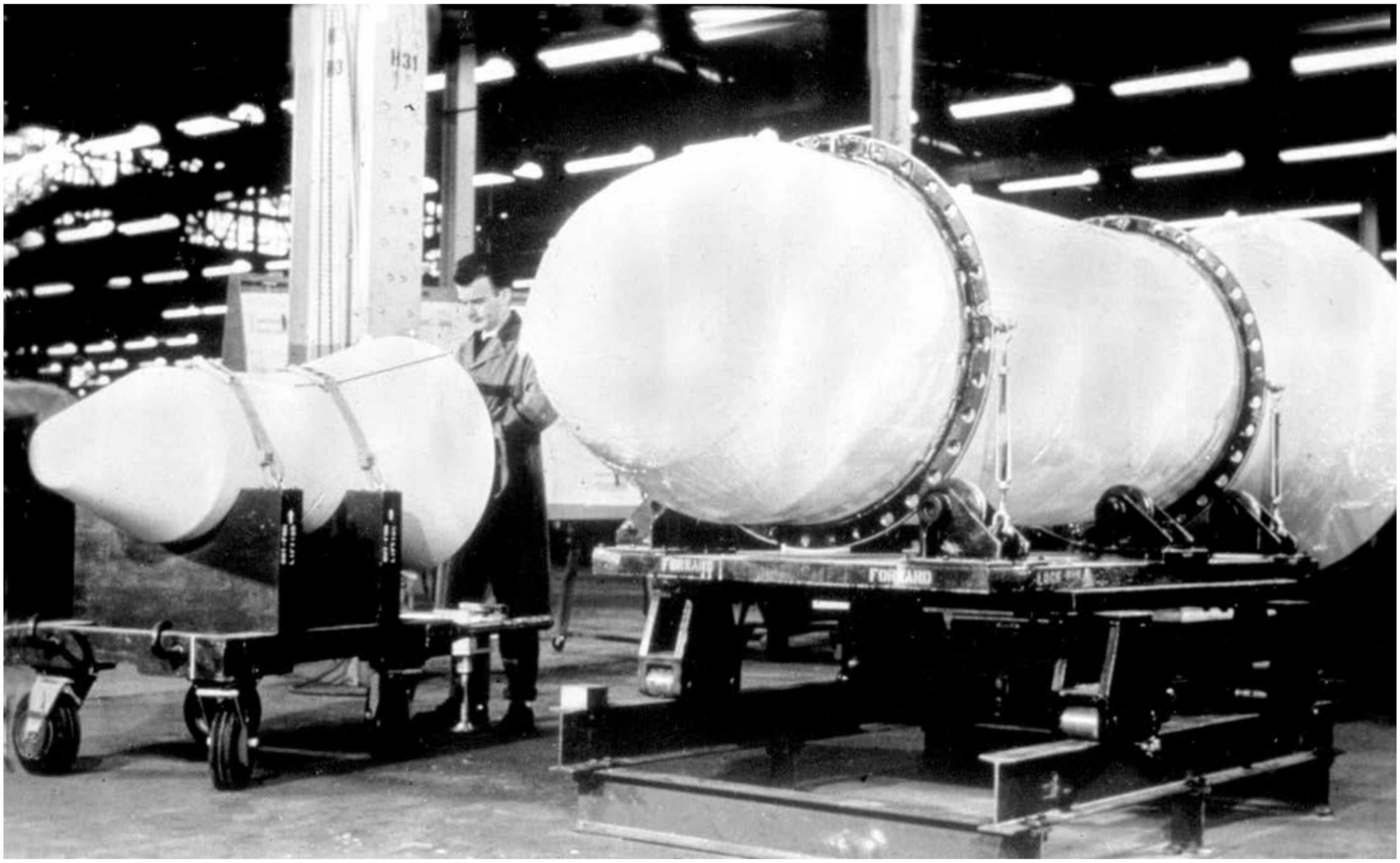


Figure 21: Mark 5 (left) and Mark 4 (right) operational reentry vehicles on factory floor at Avco facility. (*Photograph courtesy of Phil Fote.*)

ing the aerodynamic center of pressure toward the rear of the vehicle.(**Figure 20**). Available photographic evidence indicates that the biconic-2 modification was the deployed version. The nose section was thermally protected by molded phenolic nylon, the mid-section and flare by tape wrapped phenolic nylon.[81]

Eleven full scale Mark 3 reentry vehicles were flight tested as part of the Atlas D research and development program from March 8, 1960 to January 23, 1961, with ten successful and one failure due to booster failure prior to launch.[82] The Mark 3 was deployed on Atlas D missiles from 1960-1965.[83] Mark 3 Mod 3 operational RV weighed 2,200 pounds of which 1,600 was the warhead.[84]

Mark 4

Unlike the General Electric Mark 3, the Avco Mark 4 design required additional experimental flights designated RVX-3, a 0.72 scale model and the 0.94 scale model RVX-4 due to modified Air Force requirements. The RVX-3 was flight tested on 5 Titan I C missile flights from December 12, 1959 to April 28, 1960. The RVX-4 was to have been the full-scale model but the diameter of the warhead was changed slightly, leading to the actual full-scale Mark 4. The RVX-4 was flight tested on one Atlas D and seven Titan I Lot G missiles.[85]

The Mark 4 was a sphere-cone-cylinder-biconic flare shape, 126.7 inches long, 33 inches in diameter at the cylindrical mid-section and 48 inches in diameter at the base of the flare. The Mark 4 flare varied from 7 to 22 degrees with two very small spin fins at the base of the flare. The nose cap was made of Avocite varying from 1.32 to 0.82 inches thick, the cylindrical body and flare protected by oblique tape wound Refrasil at 0.61 to 0.32 and 0.44 to 0.66 inches respectively; and the afterbody was protected with fiberglass. The Mark 4 with warhead weighed 3,800 pounds.[86] A second reference gives the operational Mark 4 as weighing 4,100 pounds of which 3,100 pounds was the warhead.[87]

The Mark 4 was flight tested on one Atlas D, seven Atlas E, seven Atlas F and twenty-eight Titan I Lot J and M missiles from October 11, 1960 to May 1, 1963. The Mark 4 was deployed on Atlas E and F and Titan I from 1962 to 196.[88] One Mark 4 was flown on Titan II during the Titan II research and development program.[89]

Mark 5

On January 13, 1958, in discussions within the Nose Cone Division of Space Systems, Ballistic Missile Division, a decision was made that initial design responsibility for the advance reentry vehicle for Minuteman would be Avco Corporation due to the heavy technical load already assigned to General Electric. On February 5, 1958, a letter was issued to Avco confirming the request for an advanced reentry vehicle design study which included design specifications. This was not a sole source contract for the reentry vehicle production, as

Figure 22 The effect of reentry on the Avcoite nose cap material of a Mark 5 reentry vehicle, left and right, before and after respectively. The modified Avcoite ceramic material did not melt and flow as much as on the Mark 4 (*photographs by author of artifacts at the National Atomic Museum*).

with other reentry vehicles the contract would be a competitive one.[90]

With contractor bid proposals to be evaluated in late June, on May 28, 1958, the Nose Cone Division clarified the desire, previously discussed in the proposed preliminary operational concept of Minuteman dated April 8, 1958, for two reentry vehicle designs and two warheads.[91] One vehicle would have a weight of 790 pounds, including a 600 pound warhead for a range of 5,500 nautical miles; the second vehicle would have a weight of 550 pounds including a 350 pound warhead for a range of 6,500 nautical miles. The two designs would permit the preliminary operational plan target coverage from bases located in the southwest portion of the United States. The designs would be optimized for maximum range target coverage permitting each missile to fly to the maximum range estimated for the payload, negating the need for lesser range targeting for a given missile. Phase I and Phase II warhead feasibility studies had already been completed, permitting reentry vehicle dimensions to be established. Requests for proposals were issued to ten contractors for the reentry vehicle studies covering either or both of the reentry vehicles.

The Nose Cone Division explained the need for two reentry vehicles: [92]

There are several reasons which in our opinion make it imperative that we continue with development of both vehicles. These relate primarily to the warhead development itself. At the present time this country is considering a moratorium on testing, the duration of this being somewhat indeterminate. For this reason, AEC laboratories are endeavoring to carry out during Hardtack all tests which appear to them of importance in development of weapons for which requirements have been stated. At the same time the AEC is attempting to get acceptance by DOD of the concept of multi-use warheads. Under this concept which has been favorable reception a weapon system requiring a warhead of a particular weight will be forced to use an already available or planned weapon which in some instances will have been developed for quite different requirements. In our case for example the smaller warhead will be that now under development for Nike-Zeus. Provided that the Minuteman requirements are incorporated in the weapon design initially which can be done if we establish our need for this weapon, there will be no difficulty in obtaining maximum performance of the system (the same is not true for the 600 pound Polaris warhead which must be modified to a considerable degree to meet Minuteman requirements.) If on the other hand we do not today establish a firm requirement for a second, lighter warhead, it will be designed on the basis of Nike-Zeus requirements and will be completely incompatible with the Minuteman system in the event that we choose to use the second reentry vehicle at some later date.

We feel emphatically that development must continue on both warheads and hence both reentry vehicles since a requirement for one can not be established without the other.

On July 20, 1958, AFBMD announced that Avco Corporation had been selected from a group of seven proposals (Aerophysics Allison, Avco Corporation, Ford Aeroneutronics, General Electrical, McDonnell, Republic Aviation and Douglas/Goodyear) to develop the two Minuteman reentry vehicles. Avco's role as the Mark 2 alternate source, as well as its research and development expertise with the new ablative materials gained from their work on alternatives to the Mark 2 were a key in their selection. The contract required development of a light and heavy reentry vehicle to accommodate two possible warheads designs weighing 350 and 600 pounds respectively, with warhead dimensions to be forthcoming.[93] The contract was formally awarded to Avco on September 19, 1958.[94]

The light version was cancelled December 4, 1958 to reduce costs (Avco was directed to continue studying the light version on a lower priority basis). The decision was based on the lower yield available for the light vehicle warhead as well as complications introduced into the missile test program by multiple combinations of reentry vehicles and the missile airframe. The result was a 790 pound reentry vehicle of which 600 pounds was due to the warhead. The larger reentry vehicle could also more easily accommodate changes in warhead dimensions.[95]

After nearly a year of indecision on the Minuteman warhead design on September 1, 1959, the Minuteman warhead was finally authorized. Avco's reentry vehicle sphere-cone-cylinder-flare design was based on the Mark 4 shape but was considerably smaller due to weight constraints. (**Figure 21**) Development work commenced on what was now called the Mark 5 reentry vehicle. Extensive wind tunnel and light gas gun evaluation of ablative material composition and thickness as well as studies of attitude control and structural design to withstand deceleration forces of twenty to fifty G's were undertaken. Flight test vehicles (Mark 5 Mod I) were in production by the end of 1960. Like the Mark 4, the Mark 5 had a nose cap of Avcoite, in this case Avcoite-1, bonded to the top of the cylindrical and flare sections which were machined out of a block of RaD-58B phenolic resin-Refrasil material. Reformulation of the ceramic material reduce the melting and flowing which occurred with the Mark 4 (**Figure 22**). The aft closure was configured to stabilize the RV during early reentry and was coated with Avcoat . The Mark 5 did not have an active attitude control system. It and the Mark 4 tumbled and upon entering the atmosphere small fins induced a stabilizing spin before the fins ablated early in reentry.[96]

The full-scale research and development flight test program began on February 1, 1961, with the successful launch and flight of FTM-401, a fully configured Minuteman IA, from the Launch Complex 31A pad, Cape Canaveral Air Force Station, Florida. Two more pad launches took place, March 19, 1961 (failed) and July 27, 1961 (successful). Silo research and development launches at Cape Canaveral began on August 30, 1960 with a spectacular failure and ended on February 20, 1963 with six failures out of twenty-one launches. Mark 5 flight tests also utilized Atlas D (1), E (4) and F(3) missiles with one failure. The Atlas flight tests commenced on May 13, 1961 with a Mark 5 Mod I flown on an Atlas E and ended on July 31, 1963 with a successful Atlas D flight (**Figure 23**).[97] The Mark 5 Mod 5B weighed 300 pounds including SOFAR bomb. The Mark 5 was deployed on 150 Minuteman IA missiles beginning in 1962 and ending in 1969.[98]

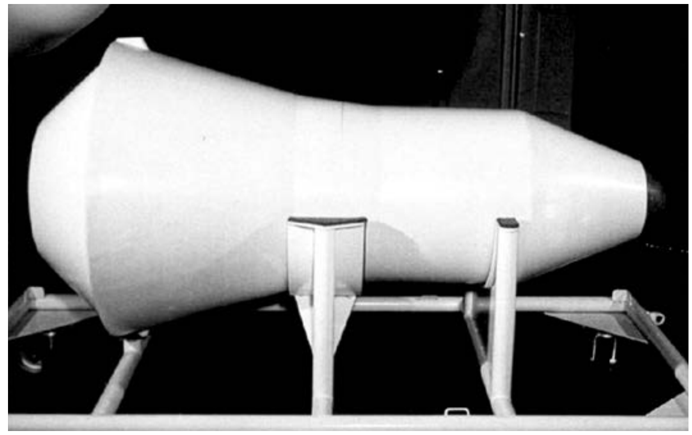


Figure 23: Mark 5 reentry vehicle on handling dolly. Note the small spin fins located at the top and bottom of the flare (*photography courtesy of the National Atomic Museum*).

Mark 11, 11A, 11B and 11C

In October 1960, the Department of Defense and the Atomic Energy Commission authorized development of an advanced version of the XW-56X1 warhead. In December 1960, the Air Force requested development of a lighter and higher yield warhead, designated the XW-59. One month later it was decided to have Avco develop a new reentry vehicle, the Mark 11, able to carry either of the new warhead designs and to be deployed starting with the second Minuteman wing, equipped with Minuteman 1B at Ellsworth Air Force Base. The Mark 11 series reentry vehicle had an operational requirement for a reduced radar cross section during the exoatmospheric portion of its trajectory.[99] (**Figure 24**)

The Mark 11series, 11, 11A, B and C, had a somewhat similar size and shape to the Mark 5 but was slightly longer. Avcoite was not used in the nose section. RaD 58B was high silica content phenolic resin which was pressed into a block, machined to shape and then bonded to the reentry vehicle forecone. For the Mark 11, the body of the vehicle was made of RaD 60, a molded silica phenolic using chopped silica fibers which was machined to fit over an airframe made of fifty magnesium ribs that were covered with a spin formed magnesium skin for both the cylindrical and flare section (formed separately). The two assemblies were bonded with epoxy, the final machining completed, a radar cross section reducing mesh applied and final layer of Avcoat 2 applied. The pointed tip, a distinguishing feature of the Mark 11 series was made of glass fiber resin impregnated cloth molded on a mandrel and epoxied to the nose. It is was used to provide protection to the nose section radar cross section material from boost-phase heating. Once the Mark 11 entered the atmosphere, the nose and base fairing as well as the radar cross section reducing mesh were removed by ablation. At this point in reentry the vehicle was producing a highly ionized and readily detectable wake which was unavoidable. Unlike the Mark 4 and 5, the Mark 11 had small spin rockets to confer spin stabilization prior to reentry.

The Mark 11A, B and C had a different fabrication process from the Mark 11. The new aluminum frame was heavier than the Mark 11 magnesium frame but was stronger, a feature required for the nuclear hardening of the vehicle, a new operational requirement due to advances in the Soviet AntiBallistic Missile (ABM) system in the process of development. The flare, cylindrical body and nose cap frames were bolted together and then the heatshield applied using Oblique Tape Wound Refrasil by a unique process developed by Avco. Afer curing, the heatshield was machined to tolerance, the radar cross section reducing material applied and covered with a final layer of Avcoat 2. The aft fairing was specifically designed to reduce the radar cross section.[100]

While the Mark 4 and 5 tumbled at first during reentry and thus provided a large radar return, the Mark 11 was spin stabilized so as to present a reduced radar return for as long as possible. The Mark 11 deployed from the third stage with only a slight increase in velocity so the third stage served almost like a radar beacon for Soviet ABM systems.

Virtually indistinguishable in outer appearance, the Mark 11 series were approximately 100 inches in height, with cylindrical section nineteen inches in diameter, a base diameter of thirty-two inches and all used the same ablative material. The Mark 11 was deployed on Minuteman IB. All four variants were deployed on Minuteman II. For the Mark 11A and 11B, Avco developed a

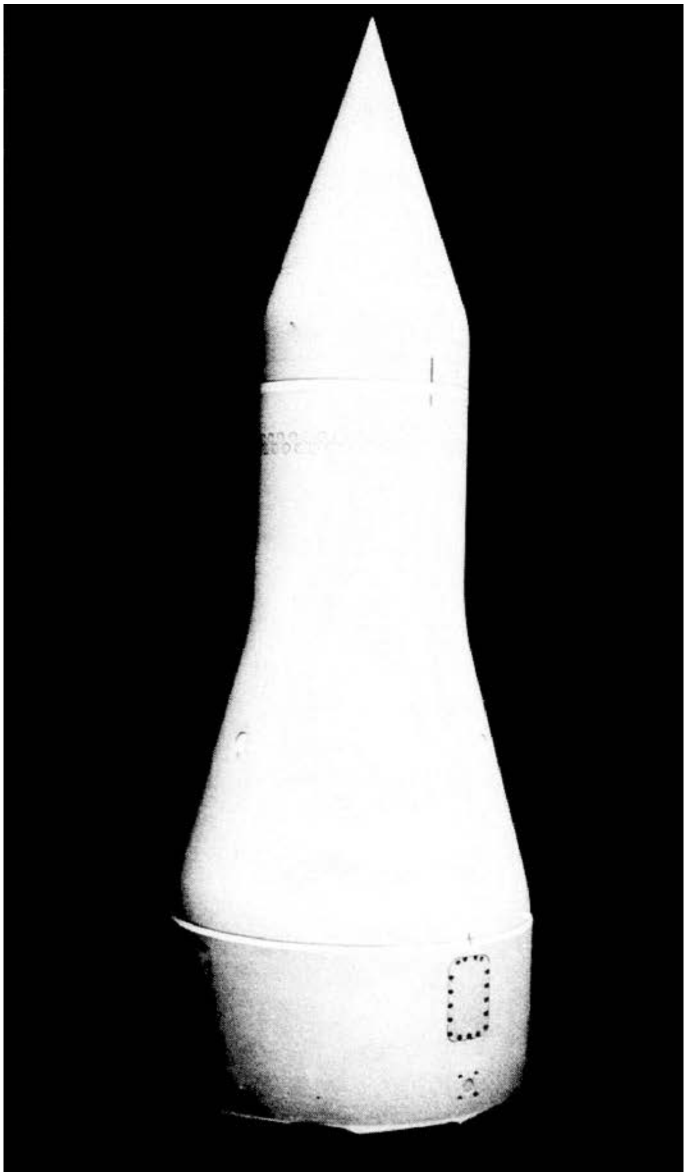


Figure 24: Mark 11C on top of chaff dispenser (*author's collection*).

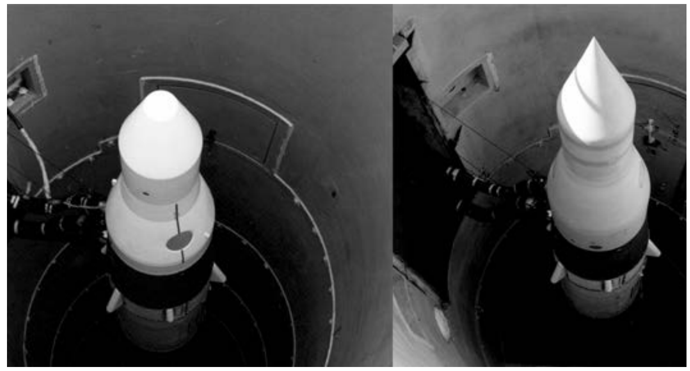


Figure 25. Mark 5 on Minuteman FTM IB 423A in LC31B, 7 January 1963 (left) and Mark 11 on Minuteman FTM IB 425 in LC-31B, 14 March 1963, Patrick Air Force Base (*courtesy of Air Force Space Museum, Cape Canaveral Air Force Station.*) The triangular fin protrusions were telemetry antennas and not flown on the operational vehicles.

retro rocket spacer that had ten small thrusters which fired in pairs to provide a random velocity to the third stage. Before firing the retro rocket thrusters, a tumbler motor fired perpendicular to the centerline of the third stage to impart a rotation rate. This combination randomized the third stage position relative to the reentry vehicle and thus reduced the problem of the third stage serving as a radar beacon.[101]

For the Mark 11C the retrorocket spacer was replaced with a chaff spacer which carried a number of Mark 1A chaff dispensers, each equipped with different level impulse thrusters. This was in response to the low frequency Soviet ABM radars. The chaff dispenser was connected to the Mark 11C via a lightweight spacer made of beryllium rather than aluminum as this configuration was up against a weight limit due to the chaff system and beryllium was thirty percent lighter than aluminum. After Mark 11C release, the chaff dispensers were fired up and down the range insensitive axis to generate a train of chaff clouds spaced far enough apart that the defensive systems would have to target each cloud.[102]

The Mark 11 research and development program included six flights on Atlas D missiles beginning on August 28, 1963 and ending February 12, 1964 with one successful flight, the failures were due to booster malfunctions. Minuteman IB flight tests began on December 7, 1962 and ended on December 8, 1967 after forty-one flights with six failures. The Mark 11C penetration aids capability was tested on the final six flights which began on April 28, 1967.[103] (**Figure 25**).

The weight of the Mark 11 was 200-250 pounds. The Mark 11A, B and C were twenty-five percent heavier than the Mark 11.[104] The Mark 11 series reentry vehicles were deployed on Minuteman IB and Minuteman II from 1963 to 1973 (Minuteman IB) and 1995 (Minuteman II).[105]

Summary

There were three key technologies that needed to be developed for the Minuteman program to succeed: large diameter solid propellant motors, lightweight inertial guidance systems and lightweight reentry vehicles. The evolution of reentry vehicle design began with the need to quickly design and field a reentry vehicle system for a relatively large warhead using readily available materials. The result was the first generation heatsink concept used with the Air Force Thor and Navy Polaris A-1 and A-2 IRBMs.

The second generation reentry vehicle system, ablation, was demonstrated first by the Army in its development of the reentry vehicle for the Jupiter IRBM. The Air Force quickly saw the advantage of ablation technology which permitted the design of lighter, more streamlined and hence more accurate, reentry vehicles. The Mark 5 and Mark 11 reentry vehicles represented the culmination of the pyrolytic or charring method of ablation with their small size and greater accuracy compared to heatsink reentry vehicle systems. ■

NOTES

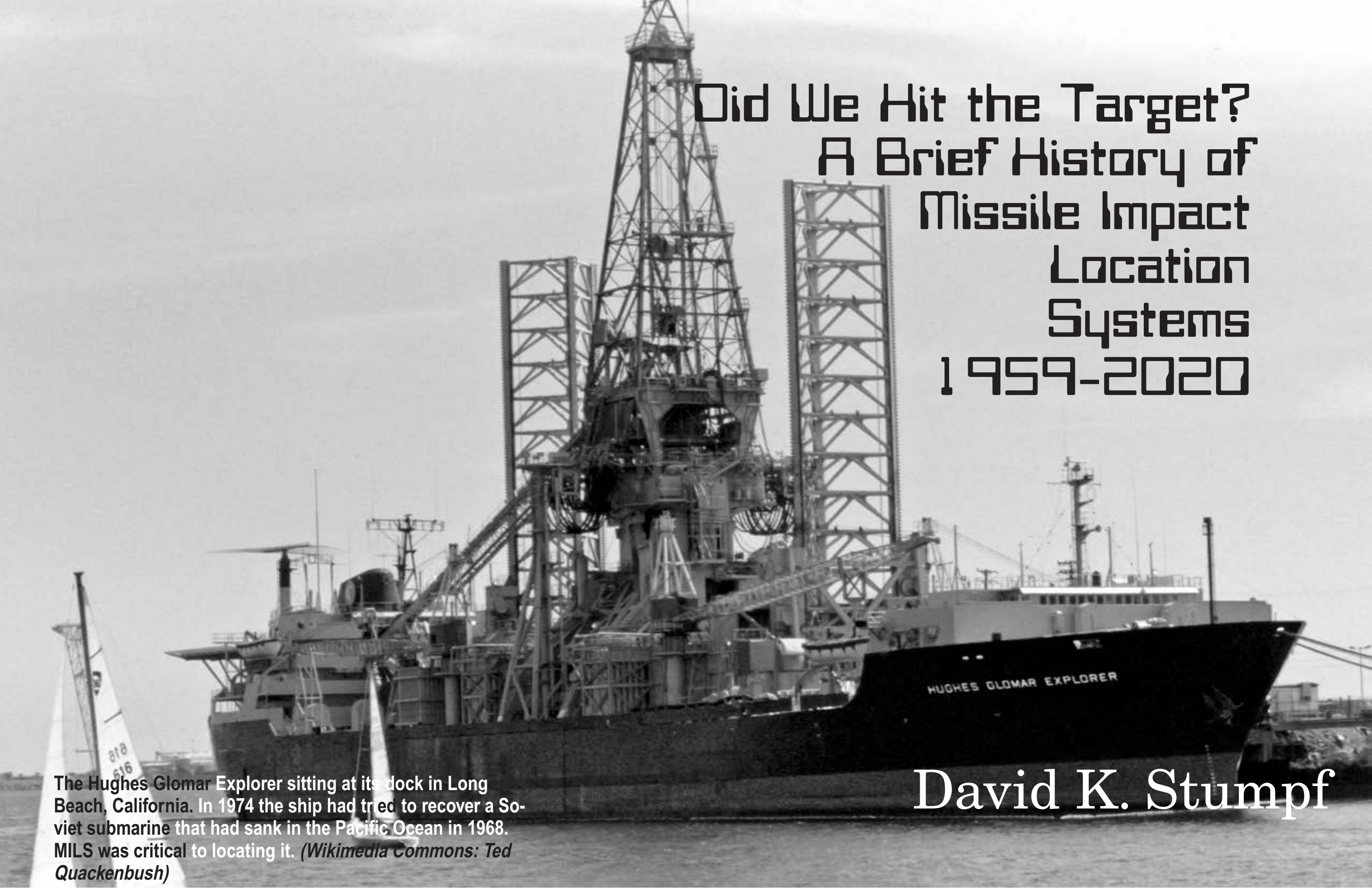
1. T.C Lin, Development of U.S. Air Force Intercontinental Ballistic Missile Weapon Systems, *Journal of Spacecraft and Rockets*, Vol. 40, No. 4, July August 2003, 503-506.
2. W. Johnson, The Rise and Fall of Early War Rockets, *International Journal of Impact Engineering*, 1994, Vol.15, No.4, 365-383; Winters, F., *The First Golden Age of Rocketry: Congreve and the Hale Rockets of the 19th Century*, (Washington, D.C.): 1990, Smithsonian Institution Press 1 9, 215 224.
3. W.E. Greene, The Development of the SM-68 Titan: Vol. I, Narrative, 1962, *AFSC Historical Publication Series 62-23-1*, footnote page 111. In March 1957, Avco proposed changing the term nose cone to reentry vehicle. Initial response was negative but the term was eventually accepted and is used throughout this text to avoid confusion.
4. W. Dornberger, *V-2*, (New York: Viking Press), 1954, 222; Gregory P. Kennedy, *Vengeance Weapon 2,* (Washington, D.C.: Smithsonian Institution Press, 1984), 68-69.
5. D.D. Baals, and W.R. Corliss *Wind Tunnels of NASA*, (National Aeronautics and Space Administration, Scientific and Technical Information Office, 1981) SP-440, 55; J.R. Hanson, *Engineer in Charge: A History of the Langley Aeronautical Laboratory, 1917-1958*, (National Aeronautics and Space Administration, Scientific and Technical Information Office,1986) SP-4305,343.
6. C. Wagner*, The Skin Temperature of Missiles Entering the Atmosphere at Hypersonic Speed,* (U.S. Department of the Army, Ordnance Research and Development Division), Technical Report No. 60 October 1949, 1.
7. H.J. Allen and A.J. Eggers, Jr., *A Study of the Motion and Aerodynamic Heating of Missiles Entering the Earths Atmosphere at High Supersonic Speeds*, National Advisory Committee on Aeronautics, 1953, RM A53D28, 17, 25 27. These two authors published several updated versions of this seminal paper. It is not clear to this author what was updated, the conclusions in each of the sequential papers appear to remain the same; E.P. Hartman, *Adventures in Research, A History of Ames Research Center 1940-1965*, (National Aeronautics and Space Administration, Scientific and Technical Information Office, 1970), NASA Center History Series, SP-4302, 216 218.
8. H.J. Allen, Hypersonic Flight and the Re-Entry Problem, *Journal of the Aeronautical Sciences*, Vol. 25, No. 4, 223, Fig. 9.
9. T. von Karman, Aerodynamic Heating - The Temperature Barrier in Aeronautics, in *Proceedings of the Symposium on High Temperature - A Tool for the Future*; Berkeley, California, June 1956, (Menlo Park, California: Stanford Research Institute, 1956), 140 142; *CRC Handbook of Chemistry and Physics, 52nd Edition*, 1971 72, (Cleveland, Ohio: The Chemical Rubber Company,1971), D-142.
10. A.J. Eggers, C.F. Hansen and B.E. Cunningham, Stagnation-Point Heat Transfer to Blunt Shapes in Hypersonic Flight, Including Effects of Yaw, National Advisory Committee for Aeronautics, 1958, Technical Note 4229, 1 2.
11. J.V. Becker, Results of Recent Hypersonic and Unsteady Flow Research at the Langley Aeronautical Laboratory, *Journal of Applied Physics*, (July 1950), 620.
12. D. Schmidt, Hypersonic Atmospheric Flight*,* in *Environmental Effects of Polymeric Materials*, (New York: Interscience Publishers, 1968), 489.
13. P. Vielle, Sur Les Discontinuities Produites par la Brusque de Gas Comprises , 1899, *Comptes Rendus* 129,(1899), 1228.
14. W. Payman and C.F. Shepard, Explosion Waves and Shock Waves. VI. The Disturbances Produced by Bursting Diaphragms with Compressed Air, 1946, *Proceedings of the Royal Science Academy*, Vol 186, (1946), 293.
15. B.D. Henshall,, On Some Aspects of the Use of Shock Tubes in Aerodynamic Research, (Aeronautical Research Council, Great Britian, 1957) Reports and Memoranda, No. 3044, 6; H.J. Davis and H.D. Curchack, Shock Tube Techniques and Instrumentation, (U.S. Army Material Command, Harry Diamond Laboratories, March 1969) TR-1429, 1 16. Available as Defense Technology Information Center AD692295.
16. Hartman, *Adventures in Research,* 241; J.A. Shortal, *A New Dimension: Wallops Island Flight Test Range, the First Fifteen Years,* National Aeronautics and Space Administration, Scientific and Technical Information Office, 1978) NASA Reference Publication 1028, 433.
17. G.H. Stine, *ICBM: The Making of the Weapon That Changed the World,* (New York: Orion Books, 1991), 187.
18. H.F. Swift, Light-Gas Gun Technology: A Historical Perspective, in *High Pressure Shock Compressions of Solids, Vol. VIII,* (Berlin Heidelberg, Germany, 2005), 1 6.
19. A.J. Eggers A Method for Simulating Atmospheric Entry of Long Range Ballistic Missiles*,* National Advisory Committee for Aeronautics, Ames Aeronautical Laboratory, 1958, TR-1378, 1009 1012.
20. Hartman, *Adventures in Research,* pp. 238, 264.
21. *Ibid*., 339.
22. J.A. Fay and F.R. Ridell, Theory of Stagnation Point Heat Transfer in Dissociated Air, , *Journal of Aeronautical Sciences*, Vol 25, No 2, (February 1958), 73-85.
23. P.H. Rose and W. I. Stark, Stagnation Point Heat-Transfer Measurements in Dissociated Air, *Journal of Aeronautical Sciences*, Vol 25, No 2, (February 1958), 86-97.
24. L. Lees, Laminar Heat Transfer Over Blunt-Nosed Bodies at Hypersonic Speeds, *Jet Propulsion*, (April 1956), 259-269.
25. W.R. Lucas and J.E. Kingsbury, A Brief Review of the ABMA Ablation Material Program, (Redstone Arsenal,AL: Army Ballistic Missile Agency,12 May 1960) ABMA DSN-TM-7-60 1, 3.
26. Von Karman, *Aerodynamic Heating*, 142.
27. D.L. Schmidt, *Ablative Plastics for Reentry Thermal Environments, (*United States Air Force, Air Research and Development Command, Wright Air Development Division,1961), Rep 60-862, 4 5.
28. R.A. Fuhrman, The Fleet Ballistic Missile System: Polaris to Trident, *Journal of Spacecraft*, Vol 15, No. 5, (Oct-Sept, 1978), 270 271.
29. J.R. Stoney and A.J. Swanson, Heat Transfer Measured on a Flat-Faced Cylinder in Free Flight at Mach Numbers Up to 13.9, NACA Research Memorandum L57ER13, 17 June 957, 1 2.
30. H.S. Carter and W.E. Bressette, Heat Transfer and Pressure Distribution on Six Blunt Noses at a Mach Number of 2, NACA Research Memorandum L57C18, 18 April 1957, 10.
31. J.R. Hall and B.J. Garland, A Feasibility Study of the Flare-Cylinder Configuration as a Reentry Body Shape for an Intermediate Range Missile, NACA Research Memorandum L58C21, 28 May 1958, 11.
32. Shortal, *A New Dimension,* 556-561; J.P. McManus, *A History of the FBM System*, (Lockheed Missiles and Space Company, Inc., 1989), A-11.
33. G.A. Hoffman, *Materials for Space Flight*, (Santa Monica, CA: RAND Corporation, P-1420, 1 July 1958), 1-26.
34. Rear Admiral Robert Wertheim, personal interview with author, May 2015; Fuhrman, The Fleet Ballistic Missile System, 272.
35. R.Smelt, Lockheed X-17 Rocket Test Vehicle and Its Applications, *American Rocket Society* Vol 29, No. 8, (1959), 565-567.
36. Shortal, *A New Dimension*, 377, 441 444.

37. Re-entry Research: The Lockheed X-17, *Flight*, 6 February 1959, 181; R.F. Piper, *The Development of the SM-80 Minuteman,*(U.S. Air Force Historical Office, Deputy Commander for Aerospace Systems, April, 1962), *Memorandum for Secretary, Ordnance Technical Committee, Office of the Chief of Ordnance, Department of the Army, Subj: JATOs, T64 and T65 Establishment of DOA Project 517-1-032 (TU2-2032), 6 April 1955,* Vol. II Supporting Documents, Document 1(1962), 2 4. The propellant weights differ slightly from other sources but this appears to be the original contract information.
38. E.S. Sutton, From Polymers to Propellants to Rockets: A History of Thiokol, in 35th AIAA/ASME/SAEA/ASEE Joint Propulsion Conference and Exhibit, (Los Angeles, California: American Institute of Aeronautics and Astronautics, June 20-24, 1999), Paper 99-2929, 13.
39. R.W.Roy and R.A Foster, Final Report: Re-Entry Test Vehicle X-17, 10 May 1957", *History Air Force Missile Test Center 1 July - 31 December 1957, Vol IV Supporting Documents Appendix F,* Air Force Historical Research Agency, IRIS NO. 484479, Reel 15345, K241.01, Vol. 4, 1 6, 30; T.A. Heppenheimer, *Facing the Heat Barrier: A History of Hypersonics,* (National Aeronautics and Space Administration, NASA History Office, 2007) NASA History Series, SP-2007-4232, 44.
40. Colonel Bogart Staff Study on R W Role, Air Force Historical Research Agency, IRIS 1040339, Reel 35267, 168.7171-191, Report No. 20, frame 211, no pagination; Recoverable Data Capsule Designed for Thor and Atlas Test Missiles, *Aviation Week*, 24 November 1958, 71 72.
41. The Scientific Advisory Committee's First Report on Ballistic Missiles to the Secretary of Defense, 11 February 1956, Digital National Security Archive, (http://www.proquest.com/products services/databases/dnsa. html), NH00553, 3; Monthly Report on Progress of ICBM and IRBM Programs (Report No. 16), 31 March 1957, U.S. Declassified Documents Online (http://www.gale.com/c/us-declassified documents online, CK234914 9174, 2 July 2016), 6.
42. M. Morton, *Progress in Reentry Recovery Vehicle Development* (Philadelphia, PA: General Electric, Missile and Space Vehicle Division, 1961), 6. The author is indebted to Donald L. Schmidt for this document.
43. J.R. Stalder, The Useful Heat Capacity of Several Materials for Ballistic Nose Cone Construction, NACA TN-4141, (November 1957), 1-8.
44. P. Fote, personnel interviews with author, July 2015, May 2017. Fote is Chief Engineer Missile Systems, Textron Systems Corporation. Fote was a reentry vehicle design engineer for Avco Corporation for the Mark 4, 5, and 11; Two Approaches Used in First Production Nose Cones, *Aviation Week*, 12 May 1958, 65.
45. K.C. Speegle, Pressure Measurement on an Afterbody Behind Various Blunt Nose Shapes at a Mach Number of 2, NACA RM L5714, 27 December 1957, 5.
46. Morton, *Progress*, 7; Ballistic Missile Program Progress Report, 15 October 1956, Eisenhower Library, Papers as Pres. of the US, 1953 61 (Ann Whitman File), Folder: Guided Missiles (5), Box 16, v.
47. Morton, *Progress*, 7; Holaday, W.M., *Monthly Report on Progress of ICBM and IRBM Programs, Report 23, 31 October 1957*, U.S. Declassified Documents Online (http://www.gale.com/c/us-declassified-documents-online, CK2349205928, 27 November 1957), 4.
48. D.J. Stewart, Nose Cones: The Case for Heat Sink, *Missiles and Rockets*, 8 June 1959, 16-17.
49. Smithsonian News Release, 14 May 1959; Recoverable Data Capsule Designed for Thor and Atlas Test Missiles, *Aviation Week*, 24 November 1958, 71 72.
50. Progress of ICBM and IRBM Programs, April, May, June 1960, United States Air Force, Office of the Director of Defense Research and Engineering, Digital National Security Archive, ttp://www.products-services/databases/dnsa.html), NH00710, 17; F.X. Ruggerio, Missileers Heritage (Air University, Maxwell AFB, 1981), Report Number 2065-81, 34-69.
51. R.H. Goddard, *Report Concerning Further Developments*, Smithsonian Institution Archive, March 1920, 4.
52. P. Juneau, Composite Materials, Ablative, *Encyclopedia of Chemical Technology*, 3rd Edition, (1978), Vol. I, 10-26. The author thanks Juneau for providing this reference, and for personal correspondence, February 1997.
53. E. Stuhlinger, Army Activities in Space, *IRE Transactions in Military Electronics*, Volume MIL, Issue 2, (April-July 1960), 65.
54. U.S. Congress, House of Representatives, *Organization and Management of Missile Programs, Eleventh Report by the Committee on Government Operations: Hearings Before a Subcommittee of the Committee on Government Operations,* 86th Congress, 1st session, 2 September 1959, 108.
55. E.J. Redman and L. Pasuk,, Pressure Distribution on an ABMA Jupiter Nose Cone (13.3 Degrees Semi-Vertex Angle) at Nominal Mach Numbers 5, 6, 7, and 8, NAVORD Report 4486, U.S. Naval Ordnance Laboratory Aeroballistic Research Report 381, 27 September 1957, 6. Available from Defense Technology Information Center, AD0158516; H.C. Dubose and R.C Bauer, Transonic Dynamic Stability Tests of a Half-Scale Model of the Jupiter W-14 Re-Entry Configuration, U.S. Air Force, Arnold Engineering Development Center, , AEDC TN-58-1, (February 1958), 3. Available from Defense Technology Information Center AD778200.
56. J.M. Grimwood and F. Strowd, *History of the Jupiter Missile System*, U.S. Army Ordnance Missile Command,(1962), Appendix 8, 8-1. Available from Defense Technology Information Center, ADA434109; Explorers in Orbit, Army Ballistic Missile Agency, 10 November 1958, National Archives and Record Administration, Record Group 156, Stack Area 290, Row 902, Compartment 9, Shelf 1, Box 10, 38-42 and 112-119; Lucas and Kingsbury, A Brief Review of the ABMA Ablation Materials Program, 6.
57. M.C. Cleary, *Army Ballistic Missile Programs at Cape Canaveral 1953-1988,* (45th Space Wing History Office,Patrick Air Force Base, Florida, 2006), 52; Grimwood and Strowd,, *History of the Jupiter Missile System*, Appendix 8, 8-1.
58. *Ibid*., Appendix 9, 9-2, 9-4.
59. W. von Braun, *Letter to D.L. Schimdt, Technical Manager for Ablative Materials, Air Force Materials Laboratory, Wright-Patterson AFB, Ohio, 14 September 1969*, National Archives and Research Administration, SE, RG 255, 01-0002, Box 24, 2; Grimwood and Strowd, *History of the Jupiter Missile System*,65. Cutting off the tip of a right circular cone generates a frustum; J.C. Brassell, Jupiter: Development Aspects and Deployment, Mobile Air Material Area, Brookley AFB, Historical Office, Office of Information,1962, Air Force Historical Research Agency, IRIS 474833, Reel 14643, K205.0504-2, Vol 1 , 30.
60. C. Hansen, *The Swords of Armageddon: U.S. Nuclear Weapons Development Since 1945,* Volume VII, (Sunnyvale, CA: Chuckelea Publications 1995), 323; M. Yaffee Two Approaches Used in First Production Nose Cones, 12 May 1958*, Aviation Week,* 61.
61. J. Neufeld, *The Development of Ballistic Missiles in the United States Air Force 1945-1960,* (Office of Air Force History 1990), Appendix 1: The Tea Pot Committee Report, 259-260; U.S. Congress, House of Representatives, *Organization and Management of Missile Programs: Hearings Before a Subcommittee of the Committee on Government Operations*, 3 March 1959, 383.
62. *Monthly Report on Progress of ICBM and IRBM Programs, Report 21, 31 August 1957*, Department of Defense, Office of the Director of Defense Research and Engineering, U.S. Declassified Documents Online (U.S. Declassified Documents Online tp://www.gale.com/c/us-declassified-documents-online, CK2349145648), 2.
63. W.E. Green, *The Development of the SM-68 Titan*, (History Office, Deputy Commander for Aerospace Systems, Air Force Systems Command, August 1962), Vol II. Supporting Docu-

ments: Letter, Brig Gen O J Ritland, V Cmdr, AFBMD, to Cmdr, ARDC,, Subject: Reorientation of Nose Cone Program, 22 Aug 1958, Air Force Historical Research Agency, IRIS 897235, Document 57, 1-2.
64. A.V. Levy, Evaluation of Reinforced Plastic Material in High Speed Guided Missile and Power Plant Application, *Plastics World*, Vol. 14, (March 1956), 10-11.
65. I.J. Gruntfest and L.H. Schenker, Behavior of Materials at Very High Temperatures, , *Industrial and Engineering Chemistry*, Vol. 50, (October 1958), 75A-76A; G.W. Sutton, Ablation of Reinforced Plastics in Supersonic Flow, , *Journal of Aero/Space Sciences*, (May 1960), 378. Refrasil is approximately 90 percent silicone oxide, made by leaching out the lower flux oxides of E glass fibers found in fiberglass.
66. M.C. Adams and E. Scala, The Interaction of High Temperature Air with Materials During Reentry, in: *Proceedings of an International Symposium on High Temperature Technology: Asilomar Conference Grounds, California, October 6 9, 1959*, (New York: McGraw-Hill, 1960) 54 60; M. Yaffee, Ablation Wins Missile Performance Gain, *Aviation Week*, (18 July 1960), 57; *Flight Summary Report Series D Atlas Missiles,* (San Diego, CA: General Dynamics/Astronautics, 21 June 1961), 8-36. Available from Defense Technical Information Center, AD0833337.
67. U.S. Air Force, Study on the Future of AFBMD/MCO/SACMIKE/STL (R-W) Co., Air Force Historical Research Agency, IRIS # 01040315, 168.7171-167, reel 35264, n.d., 74-79.
68. J.W. Powell, Thor-Able and Atlas Able, *Journal of the British Interplanetary Society*, Vol 37, (1984), 219 220, 222; Thor Able Launched in Nose Cone Test, *Aviation Week*, 28 July 1958, 27; D.L. Schmidt, Ablative Plastics for Thermal Protection, , Wright Air Development Division,U.S. Air Force, WADD Report 60-862, August 1968), 58. This report was provided to the author by Don Schmidt in June 1999; M. Morton, *Progress*, 11. The author thanks Don Schmidt for a copy of this paper.
69. W.M. Arms, Thor, the Workhorse of Space A Narrative History, (Huntington Beach, CA: McDonnell Douglas Astronautics Company, (31 July 1972), 4-1. The author thanks Joel Powell for a copy of this report.
70. Powell, Thor-Able, Atlas-Able, 220; Heppenheimer, *Facing the Heat Barrier: A History of Hypersonics,* 47; I. Clausen and E.A. Miller, Intelligence Revolution 1960: Retrieving the Corona Imagery that Helped Win the Cold War, (Washington, D.C.: U.S. Department of Defense, Center for the Study of National Reconnaissance, 26 April 2012), 46.
71. The author thanks Craig Brunetti for the Avco RVX-1 measurements.
72. Ablative Nose Cone Shows Reentry Effect, *Aviation Week*, 25 May 1959, 30.
73. Arms, *Thor: The Workhorse of Space, A Narrative History*, 4-4, 4-6; M. Morton, *Thor-Able and Atlas Reentry Recovery Programs*, (Philadelphia, PA: General Electric Defense Electronics Division, Missile and Space Vehicle Department, no date.), 1-7. The author is indebted to Don Schmidt for this document; Schmidt, Ablative Plastics for Reentry Thermal Protection, 58 59.
74. *Flight Summary Report Series D Atlas Missiles*, 2-1.
75. W.T. Barry, personal interview and correspondence with author, February 1997. Barry was a materials scientist consultant at the General Electric Space Sciences Laboratory in Philadelphia during the development of the Titan II Mark 6 reentry vehicle. The Series 100 plastic ablation process was patented by Barry, U.S. Patent 3,177,175 (1965).
76. While not explicitly described as such, the available pictures of the recovered vehicle appear to show material similar to the RVX-2A reentry vehicle which did have these materials.
77. Morton, *Thor-Able and Atlas Reentry Recovery Programs*, 22-23.
78. Barry, personal interview by author, February 1997.
79. *Ibid*.
80. *Flight Summary Report*, 8-38.
81. *Ibid*., 8-5 to 8-11.
82. *Ibid*., 8-2.
83. F.X. Ruggerio, Missileers Heritage, 34-69.
84. *Progress of ICBM and IRBM Programs, April, May, June 1960*, Department of Defense, Office of the Director of Defense Research and Engineering, Declassified Documents Online (U.S. Declassified Documents Online tp://www.gale.com/c/us-declassified-documents-online, CK2349126998), 17.
85. W. Greene, *The Development of the SM-68 Titan,* 25.
86. *Flight Test Summary,* 8-32 to 8-37.
87. *Progress of ICBM and IRBM Programs, April, May, June 1960,* 17.
88. F.X. Ruggerio, Missileers Heritage, 34-69; J. Neufeld, *Ballistic Missiles of the United State Air Force,* 234, 276.
89. J. McDowell, personal interview by the author and extracts from unpublished *History of Flight.* The data can also be found at his website, http://www.planet4589.org/space/lvdb/index.html. McDowells database is considered the gold standard of civilian missile launch records.
90. *Memos, May 1958,* Personal Collection of Gen. B.A. Schriever, AFHRA, IRIS # 01040258, K168-7171-110, Reel 35259, 1-2.
91. R.F. Piper, *The Development of the SM-80 Minuteman*, Vol 2, Supporting Documents, Proposed Preliminary Operational Concept for Minuteman, 8 April 1958, Document 76, 6.
92. *Ibid*., Letter, Col H.L. Evans, Asst D/Cmdr, Space Sys, to Col C.H. Terhune D/Cmdr, Ballistic Missiles, 28 May 1958, Subject: Minuteman Warheads and Reentry Vehicles , Air Force Historical Research Agency, IRIS 897233, K243-012-5, Document 80, 1-2.
93. Personal interview by the author with Secretary of the Air Force Thomas Reed, May 2015. The companies were listed in his personal diary entry for Monday, 23 June 1958.
94. Space and Missile Systems Organization: A Chronology, 1954-1979, U.S. Air Force, Space Division,(Chief of Staff History Office, October 1979), 57.
95. R.F. Piper, *The Development of the SM-80 Minuteman*, Vol 2, Supporting Documents, Cancellation of the Light Minuteman Reentry Vehicle, 9 December 1958, AFHRA IRIS#, 897233, K243-012-5 Document 94, 1.
96. Fote, personal interview by author, May 2017; Piper, *The Development of the SM-80 Minuteman*, Vol 1, 190 195.
97. McDowell, unpublished.
98. Operational Test Report: ELM BRANCH, Minuteman IA, LGM-30A, FTM 631, 1st Strategic Air Division, AFHRA, IRIS 918812, reel 26122, 2; J.C. Hopkins, The Development of the Strategic Air Command 1946 1981: A Chronological History, (Office of the Historian, Headquarters Strategic Air Command, 1 July 1982), 112, 157.
99. R.F. Piper, *The Development of the SM-80 Minuteman*, Vol I, 190 196.
100. Fote; M.L. Yaffee, Mark 11A Hardened Against Air Bursts, *Aviation Week and Space Technology*, 24 August 1964, 50 60.
101. Fote; M.L. Yaffee, Mark 11A Hardened Against Air Burst, 50-59.
102. Fote.
103. McDowell.
104. Operation Test Report: NICKED BLADE, Minuteman Missile IB, LGM-30B, FTM 1101, 1st Strategic Aerospace Division, AFHRA, IRIS 918790, reel 26121, 4; Fote.
105. Air Force News Service, http://www.af.mil/News/Tag/51024/air-force-news-service; Unites States Air Force Supporting Studies, *A History of Strategic Arms Competition 1945 1972*, June 1976, 362; J.C. Hopkins, *The Development of the Strategic Air Command 1946 1981: A Chronological History*, 191.

Did We Hit the Target? A Brief History of Missile Impact Location Systems 1959-2020

David K. Stumpf



The Hughes Glomar Explorer sitting at its dock in Long Beach, California. In 1974 the ship had tried to recover a Soviet submarine that had sank in the Pacific Ocean in 1968. MILS was critical to locating it. *(Wikimedia Commons: Ted Quackenbush)*

Along with the 1947 decision to locate the first U. S. long-range ballistic missile test range at Cape Canaveral, Florida, came the need to accurately determine reentry vehicle impact location in the open ocean. Tracking stations were to be located along the British West Indies Islands chain to monitor the boosted phase of missile flight for both performance and safety reasons.[1] They were, however, inadequate for determination of guidance system accuracy in the broad ocean area (BOA) targets. A similar problem arose with the decision in November 1956 to conduct the operational training and testing of IRBMs and ICBMs at Cooke Air Force Base, California. The IRBM target was a BOA 300 to 1500 nautical miles off the coast of Cooke AFB. Several of the ICBM targets were also BOAs, near Wake and Midway Islands, while others were near or within the lagoons at Eniwetok and Kwajalein Atolls (approximately 400 and 700 square statute miles respectfully).[2]

Fortunately, a solution was well into development. In 1941, a physicist at Woods Hole Oceanographic Institute, Massachusetts, Maurice Ewing, postulated the existence of what he called the deep sound channel. The confirmation of the existence of the channel in 1944 and the detailed evaluation of its properties led to the concept of the sound fixing and ranging system (SOFAR). SOFAR became a key part of the missile impact location system (MILS) for both the Eastern and Western Test Ranges. This article describes the SOFAR system and its application for the location of reentry vehicle impacts, recovery of data return capsules and locating Mercury spacecraft splashdowns. Photographic and radar systems are also briefly discussed.

The Deep Sound Channel

The long-range transmission of underwater sound was first suggested in 1934 by Karl Dyk and O. W. Swainson as a result of seismic experiments conducted by the U. S. Coast and Geodetic Survey off the coast of Southern California in 1933. Signals from the explosion of 0.5-pound charges of TNT were received at a distance of 50 nautical miles. The authors indicated that much greater ranges might be obtained.[3] The deep sound channel aspect of their research was not pursued further until 1941 when researchers Maurice Ewing, Columbus Iselin, Allyn Vine, Alfred Woodcock, and Lamar Worzel at Woods Hole Oceanographic Institute published "Sound Transmission in Seawater," a report sponsored by the National Defense Research Committee. Ewing postulated the existence of the deep sound channel, a layer of seawater approximately 4,000 feet deep in the Atlantic and similarly in the Pacific, though at a different depth, through which sound could travel remarkable distances.[4]

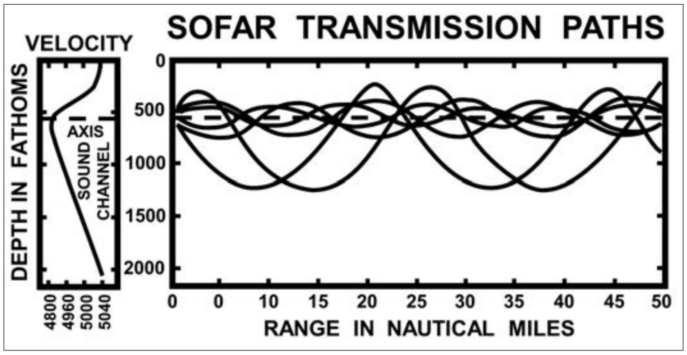


Figure 1. Left: speed of sound in seawater versus depth; Right: some of the many possible SOFAR ray paths simplified and exaggerated vertically. Counterintuitively, the longer ray paths arrive sooner at the receiver due to the higher speed of sound in the region they are traveling. ***(Long-Range Sound Transmission Interim Report 1)***

In deep ocean water the temperature normally decreases gradually with increasing depth, reaching a minimum slightly above zero at approximately 700 fathoms (4,200 feet), in the Atlantic, after which the temperature gradually rises until reaching the ocean floor. The sound speed follows a similar pattern, reaching a minimum at a depth of 4,200 feet, then increasing near the ocean floor to a greater speed than at the surface. The increase in velocity is due to a pressure effect. If an omnidirectional signal source is placed at the depth of minimal velocity, the axis of the sound channel, signals that start at an angle of 12 degrees above or 15 degrees below the axis of the channel are repeatedly reflected downward or upward, respectively, within the channel until absorbed or blocked by an obstruction (**Figure 1**).

Ewing and coworkers noted that signals in the deep sound channel had these qualities:

1. Extremely long-range transmission (probably 10,000 miles).
2. Signal was positively identifiable.
3. Abrupt termination of the signal allows the arrival time to be read with an accuracy better than 1/20th of a second. This permits location of the source to better than a mile, if the signal is received at three suitably located stations.
4. The signal duration is related in such a way to the distance that the distance may be estimated to 3 nautical miles in 1,000 from reception at a single station.

David K. Stumpf, Ph.D., is a retired plant biochemist living with his wife, Susan, in Tucson Arizona. He has written three nuclear weapon histories, Regulus the Forgotten Weapon*, a history of the Navy's Regulus I and II cruise missiles;* Titan II: A History of a Cold War Missile System *and* Minuteman: a Technical History of the Missile that defined American Nuclear Warfare*, published February 2021. Dr. Stumpf volunteered at the Titan Missile Museum, Sahuarita, Arizona, as an historian and as a tour guide for 15 years. He was instrumental in the effort to gain National Historic Landmark status for the museum.*

The limitations were:

1. It is required that the great circle path which the sound follows between source and receiver be entirely deep water (probably at least 1,000 fathoms).
2. Sound travels in water at a speed of roughly 1 mile per second so that the interval between the origin of the signal and its reception become sufficiently great to be a handicap for some uses.[5]

In July 1943, Ewing filed a report with the Navy Bureau of Ships describing the use of the deep sound channel for coded transmissions to submarines. Somewhat to his surprise, his report was met with little enthusiasm.[6] Undeterred, from March 1944 to January 1945, Ewing and coworkers undertook to more fully characterize the deep sound channel. The results clearly showed that three or more stations equipped with hydrophones located in the deep sound channel could be used to triangulate a signal from a downed aircraft, life raft or ships in distress to within 1 nautical mile. Since all of the receiving stations in the experiment had been hydrophones suspended from ships, a station with one hydrophone located on the ocean floor in the deep sound channel was established on Eleuthera Island to complete the investigation. Signals were detected out to 450 nautical miles, after which the hydrophone cable broke.[7]

To the casual observer, it would seem difficult to isolate the signal generated by a relatively small explosion from the background noise in the ocean, but this proved not to be the case. The received signal consists of a series of impulses corresponding to the possible propagation paths. Paths within the deep sound channel are the slowest and also most numerous. The first sound to arrive is weak. Though coming over the longest path, i.e., reflections from the surface and ocean floor, it arrives first by virtue of the higher velocities encountered along this path. The last, strongest, signal to arrive comes via the shortest path, along the axis of the deep sound channel, which is the path of minimum velocity. Sound from a source located on the axis will follow paths which are refracted toward the axis. Therefore, a large portion of the signal will be confined more or less to the plane of the velocity minimum and not encounter reflection off the surface and bottom. As a result, losses are relatively low and very long ranges are possible.[8]

The longer the distance from the source, the greater the time differential between the first and last arrivals (**Figure 2**).[9] The abrupt cutoff represented the signal

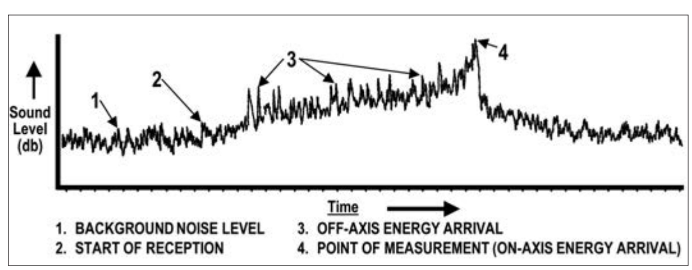


Figure 2. Typical SOFAR signal trace. Normally the SOFAR channel signal was this clearly indicated. ***(AF Western Test Range Instrumentation Handbook)***

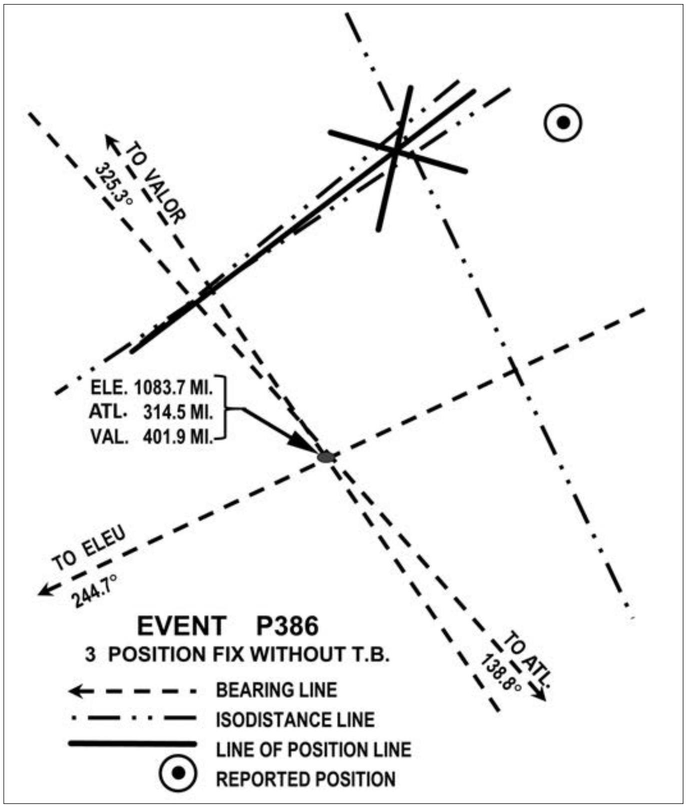


Figure 3. Example of a triangulation plot. Large cross indicates where the isodistance lines from Eleuthera, USCG Valor and USRV Atlantis coincided. *(Long-Range Sound Transmission Report Number Three)*

transmitted by the deep sound channel. This characteristic pattern made signals that originated at or near the axis of the sound channel easily recognized. The maximum signal range during the cruise was 900 nautical miles due to the limitations imposed by the Navy on the use of the *USS Buckley* (DE-51). Work completed after the cruise resulted in reception of a signal from detonation of a 6-pound TNT charge at a range of 3,100 nautical miles.[10]

In 1959, Ewing and coworkers proposed that SOFAR be used to "connect the geodetic networks of all continents and islands into a single unit." The major obstacle to establishing the many international ties required for a global geodetic system was the difficulty of making geodetic measurements at sea. Such a survey would be coupled with a gravimetric survey to determine the shape of the earth. They proposed methods for the establishment of benchmarks in the ocean, measuring the distances using the SOFAR technique with an accuracy of one part in 200,000. This work would facilitate the accurate navigation of spacecraft and targeting of ballistic missiles.[11]

SOFAR Begets MILS

Regardless of the skepticism of the Navy for the use of the deep sound channel for submarine communications, work progressed at Woods Hole on the design and production of explosive charges called SOFAR bombs. The Navy did see the potential of the SOFAR bomb concept for experimental use as air-sea rescue aids. The bombs varied in design from simple demolition blocks with detonators to cast charges of TNT, in pressure proof cases, fired by a pre-set pressure sensitive mechanism. Since the depth of the deep sound channel was variable, the charges had to have easily adjustable detonators for both experimental work and as rescue aids.[12]

In the summer of 1945, after seven months of testing the bomb design, a two-week cruise involving three ships, several aircraft and the repaired shore station at Eleuthera, successfully evaluated SOFAR triangulation techniques using bombs ranging from 1 to 48.5 pounds and one 300-pound Mark 6 depth charge (**Figure 3**). Crucial to the SOFAR concept was the use of the correct axial sound speed value. The average value for the northern Atlantic was 4,888 feet/second. In the Pacific, the value was 4,845 feet/second off California and 4,852 feet/second off Hawaii. Calculations using the appropriate average value for each ocean proved sufficiently accurate to delineate a relatively small air-sea rescue search area.[13]

The utility of the SOFAR concept was demonstrated in 1953 during a month-long experiment using two hydrophones separated by 16 miles off the southeast coast of Bermuda. The *USS San Pablo* (ADP-30) fired 234 0.5-pound TNT shots at a depth of 50 feet in an arc between 34- and 221-degrees true bearing, 120 nautical miles off of Bermuda:

The SOFAR signals received by the Bermuda instruments do not have the characteristic sharp cut off nor are the signals identical on both instruments. This is caused by the location in different depths of water, both being shallower than the sound channel. It is also caused by their location on dissimilar morphological features along the southeast Bermuda island slope. In general, their SOFAR signals start with staccato bursts and end with a confused reverberation. Relative timing between signals at both instruments is done by comparing their overall signal envelope.

The results indicated that bearing accuracies of 1.5 degrees were possible. The fact that the signals were not as clear as those found in similar experiments on the West Coast demonstrated the efficacy of the system under less-than-ideal conditions.[14]

While tracking radar could be used for visual display of booster or reentry vehicle impact prediction for range safety issues, it was insufficient at the time for determination of impact locations in the BOA targets of the Air Force Eastern Test Range (AFETR).[15] SOFAR was the solution in the form of stations with groups of hydrophones around the periphery of the North and Mid-Atlantic. These were not part of the sound surveillance system (SOSUS), which operated at a different frequency and utilized a much larger number of hydrophones. Reentry vehicles, data capsules and spacecraft would release SOFAR bombs as location aids. The system was named the Missile Impact Locating System.

Sound Channel Axis Velocity Experiments

The Polaris flight test program presented the problem of accurately locating the reentry body (the Navy term for

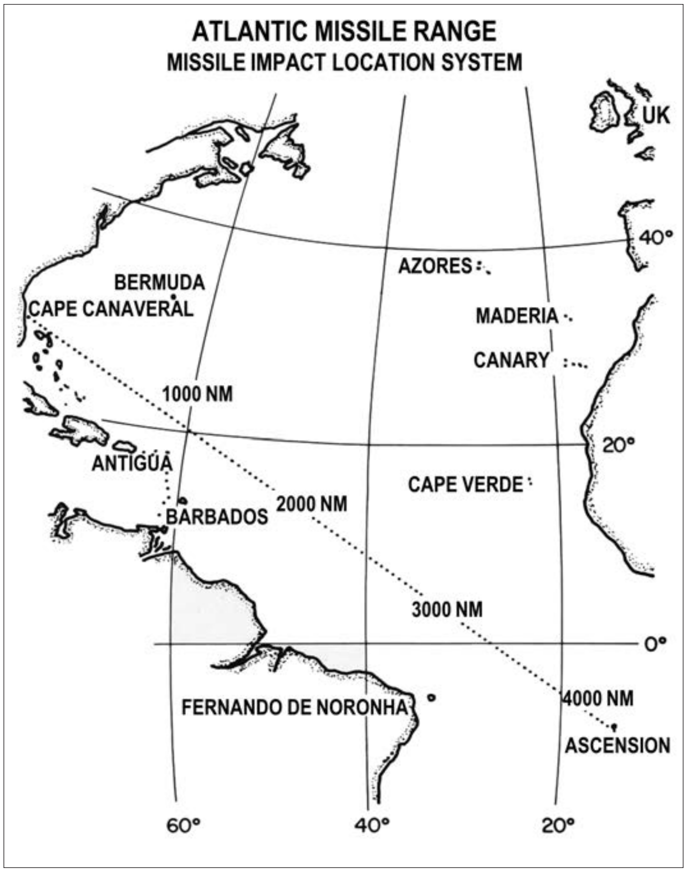


Figure 4. Portion of the Atlantic covered by the Sound Channel Axis Velocity Experiments. Signals were detected by SOFAR and MILS stations at Ascension, Barbados, Bermuda, Canary Islands, Eleuthera, Fernando de Noronha. *(Time Variations of Sound Speed over Long Paths in the Ocean)*

reentry vehicle) SOFAR detonation in the mid-Atlantic. Sound-Channel Axis Velocity Experiments (SCAVE) were conducted from 1961 to 1964 to evaluate solutions to the problem. SCAVE was a series of precisely located and timed SOFAR charges detonated off the island of Antigua and detected by the MILS and SOFAR stations at Ascension, Barbados, Bermuda, Eleuthera, Fernando de Noronha, with additional hydrophones installed at the Canary Islands to balance the unknown bias from the existing hydrophones to the south and west (**Figure 4**). The seasonal and short-term variability of the axial sound speed of the deep sound channel were evaluated as possible sources of error.[16]

The first year's experiments, utilizing two hydrophones at Bermuda and three at Eleuthera, demonstrated sound channel axial speed was not constant, although there were times when it remained steady for a month or two. The results after two and half years of experiments demonstrated it was not feasible to try to predict the axis sound speed due to time of year.

The solution was to calibrate shortly before the predicted impact and again afterwards. An eight-day test revealed that while the axial sound speed did vary, the change was small in this short a period of time. The method adopted was calibration before and after the flight test by firing 10 SOFAR charges in the vicinity of the proposed

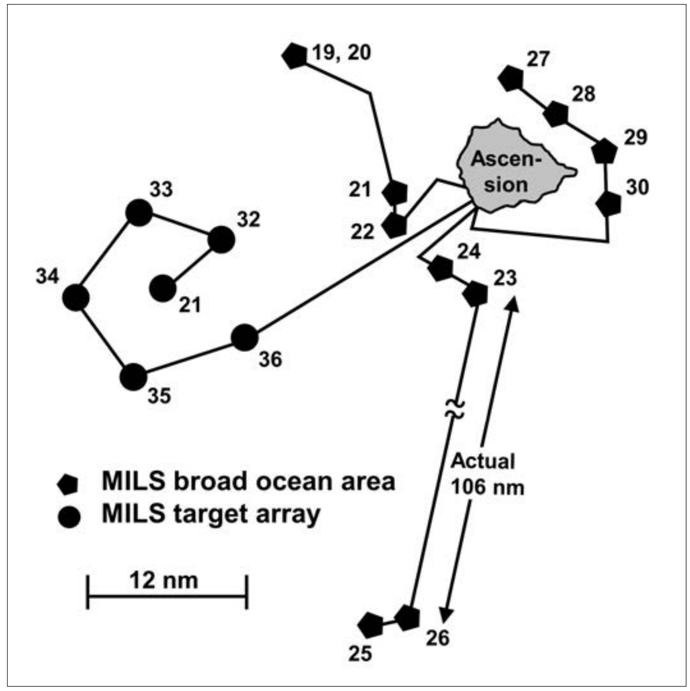


Figure 5. Approximate location of hydrophones at Ascension Island for target array and broad ocean area signal detection. *(Sonobuoy MILS)*

reentry body impact area over bottom transponders that had been geodetically located.[17]

Acoustic-Based Missile Impact Locating Systems

Initially, there were two acoustic-based systems used for impact location determination, the missile impact locating system (MILS) and the sonobuoy missile impact location system (SMILS). MILS was subdivided into the target array, also known as the splash detection system, and BOA array.[18]

Missile Impact Locating System

Target Array (Splash Detection System)

A target array consisted of six hydrophones, five of which were placed on the ocean floor in a regular pentagon configuration, 5-24 nautical miles across depending on sea floor topography, with the sixth located in the middle (**Figure 5**). The pentagonal shape was used so that at least four hydrophones were at a range less than the refraction limit, thereby enabling them to pick up the sound of impact by a direct transmission path instead of bottom and surface reflection paths. Accuracy with this design was ±30 feet when impact was within the confines of an array at least 10 nautical miles across.[19]

BOA Array

A BOA array was used when flight test requirements dictated impact locations away from established target arrays as was necessary for the later Polaris flight test program. Shore stations were connected to individual hydrophones or groups of hydrophones. The stations were

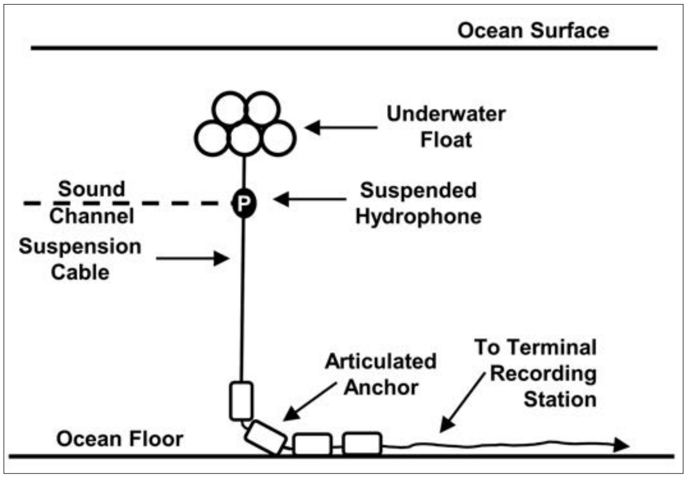


Figure 6. Typical broad ocean area hydrophone installation. It was critical to have them positioned accurately in the sound channel. *(Air Force Western Test Range Instrumentation Handbook)*

separated by several hundred to 1,000 nautical miles or more. Where the installation was a group of hydrophones, they were placed in a plane-hyperbolic array, located as close as possible to the deep sound channel axis (**Figure 6**). With at least three stations receiving the SOFAR bomb signal, the impact location was determined by triangulation. The calibration of the BOA array hydrophones consisted of a ship releasing several SOFAR bombs at the same time the ship's position was being accurately determined by the Acoustic Ship Positioning System via geodetically surveyed bottom transponders in the impact area.[20]

Sonobuoy Missile Impact Locating System

By the late 1960s, the capability of the MILS system, deployed in 1958-1960, was no longer sufficient. Accurately monitoring the impact of the 6 to 14 reentry bodies carried by the Poseidon SLBM was not feasible. Installation of additional stations was expensive and, in many cases, politically difficult. SMILS developed by adapting already existing antisubmarine warfare sonobuoy detection system equipment.

The SMILS concept was evaluated by monitoring the water impact of finned Martlet rounds fired from 5-inch, 7-inch and 16-inch smooth-bore cannon during the High-Altitude Research Project (HARP,1962-1967).[21] For SMILS, projectiles were launched from Barbados, West Indies, to altitudes approaching 300,000 to 400,000 feet, splashing down in the nearby ocean at a speed sufficient to mimic reentry vehicle impacts. The projectiles were spin-stablished by canting the fins 3 degrees, resulting in an impact dispersion of less than one mile.[22]

SMILS was deployed by aircraft just prior to the flight test. There were four basic components:

1. The Acoustic Ship Positioning System (ASPS) deep ocean transponders on the ocean floor. These were geodetically surveyed using the Navy's Transit satellites and served as reference points for the sonobuoys. The batteries for the transponders lasted between 2 to 3 years and replacement units could be located with accuracies approaching 50 feet in the 1969 timeframe. The transponders were energized by a 16 kHz interrogator signal and each responded on a different frequency at 0.5 kHz intervals from 7.5 to 12 kHz.[23]

2. Specially equipped Navy P–3 Orion Lockheed Electra antisubmarine warfare aircraft modified to receive and record up to 32 sonobuoy signals. A precision timing system was also installed as well as the ability to monitor and provide a quick-look recording capability.

3. The standard Navy aircraft-deployed AN/SSQ-41 sonobuoy was modified, extending the battery life and providing the ability to receive the ASPS transponders interrogation and reply signals.

4. Unlike the MILS system, SMILS used the well-mixed surface isothermal layer. Projectile splash signals from the HARP experiments had been received up to 20 nautical miles distance. A bathythermograph sonobuoy dropped by the aircraft was used to determine the presence and depth of the surface mixed layer prior to the flight test. Without this layer the splash signal propagation paths were by ocean bottom bounce rather than the surface duct, degrading the SMILS performance.[24] This information, combined with the expected reentry vehicle impact footprint, was used to configure the sonobuoy pattern for the particular test. The typical pattern for a single reentry vehicle impact footprint consisted of four sonobuoy rings approximately three nautical miles apart with a total outside diameter of 20 nautical miles. This involved as many as 30 sonobuoys including the interrogator sonobuoy.[25]

The transponders were energized by the interrogator sonobuoy and served to locate the pinger sonobuoys relative to the transponder. The signals from these pinger sonobuoys propagated through the surface duct and were received by the circular array sonobuoys. The splash position relative to these sonobuoys and the time at which the splash occurred could then be determined.[26] The estimated accuracy for the system was 0.1 nautical mile as originally deployed, but early improvements brought the accuracy down to 0.05 nautical miles (**Figure 7,** following page).[27]

Portable Impact Locating System 1

The Portable Impact Locating System (PILS) represented an example of the ultimate evolution of the acoustical-based impact detection system. The Navy began development in 1994, expanding on the research conducted for the Air Force in 1983-84 before cancellation in 1986.[28] The deep ocean transponders of the SMILS were replaced with sonobuoys equipped with NAVSTAR Global Positioning System receivers. This eliminated the costly positioning and upkeep of deep ocean transducers and made flight test targeting much more flexible.

Operationally, the system was a simplified version of SMILS, utilizing two concentric rings, 10 and 14 nautical miles in diameter, each with six sonobuoys. The ring dimensions were chosen to allow for sonobuoy drift during possible launch holds. The sonobuoys were deployed from the P–3 Orion aircraft approximately 90 minutes prior to

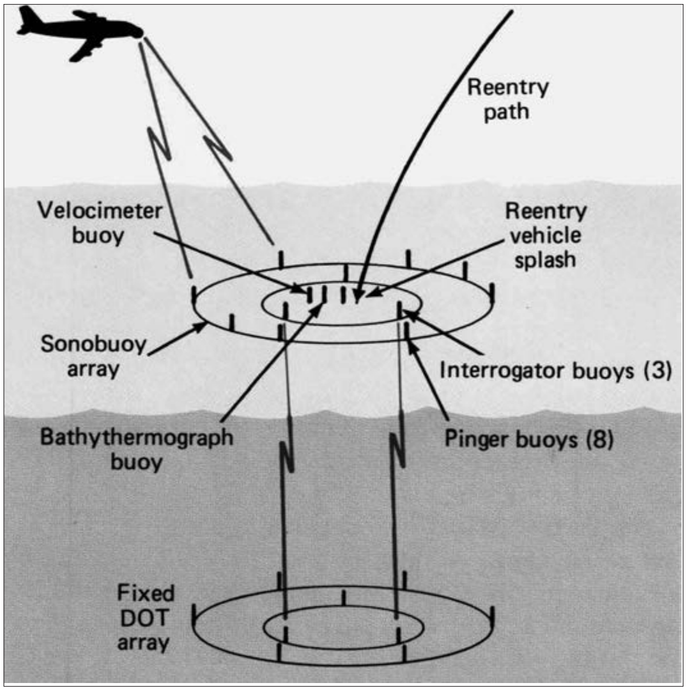


Figure 7. Overview of the DOT/SMILS. Each sonobuoy is equipped with an acoustic transmitter and receiver. The acoustic information picked up by the sonobuoys is transmitted to the aircraft via a VHF radio link. The fixed deep ocean transponder (DOT) array, previously placed on the ocean bottom, is used to determine the position of sonobuoys. The velocimeter buoy measures the velocity of sound in the water, while the bathythermograph buoy measures the temperature of the water as a function of depth. Interrogator buoys are equipped with sonic transmitters that send commands to the DOT, the DOTs respond to the interrogations by generating an acoustic signal, different for each transducer. The pinger buoys propagate the signal through the surface duct which are received by the circular array buoys. ***(Copyright 1984 John Hopkins University applied Physics Laboratory, LLC. All Rights Reserved)***

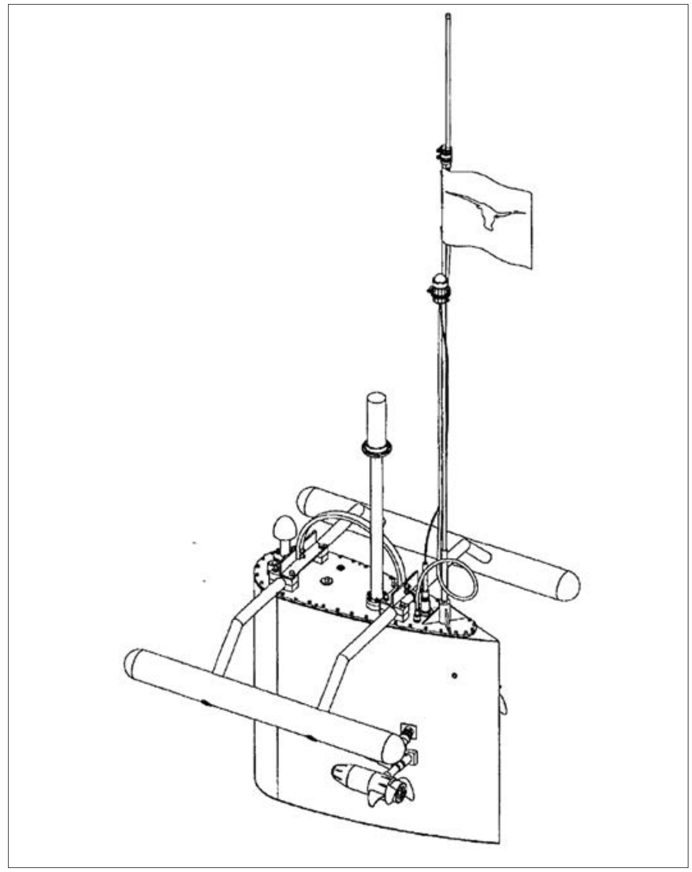


Figure 8. PILS 2 self-propelled sonobuoy. (*Adapted from United States Patent 6,854,406B2)*

programmed flight test vehicle launch. Typical impact position accuracies were 15 feet, with impact time accuracies approaching 3 milliseconds. The system was declared fully operational in October 1996.[29]

Portable Impact Locating System 2

The current PILS 2 differs from PILS 1 in three respects: the sonobuoys are deployed from a ship carrying the Navy Mobile Information System (NMIS); they are designed to maintain position after deployment and only nine sonobuoys are used, eight in a six nautical mile diameter circle with the ninth in the center (**Figure 8**).[30] The date of deployment has proven elusive.

Over-the-Horizon Buoy

Trident II flight test safety rules can require that the NMIS ship be over-the-horizon from the deployed PILS 2 sonobuoys. An over-the-horizon (OTH) buoy system was developed for the Navy by Johns Hopkins University Applied Physics Laboratory and the University of Texas, Austin, Applied Research Laboratory, to provide satellite communications capability between the ship and the buoys. The test operator onboard the ship programs the buoys with telemetry recording start and stop times. The multiple reentry body impact timing must be at least 12 seconds apart, permitting 10 seconds of data recording and two seconds to change the settings for the next reentry body impact. When the test is complete, the buoys are recovered and the data extracted. The OTH buoys are modified PILS 2 buoys.[31]

Air Force Eastern Test Range

Missile Impact Locating System

Target Arrays (Splash Detection System)

Target arrays were located at Antigua, Ascension and Grand Turk. The dimensions of the three target arrays, as of 1976, are listed in **Table 1**. Polaris A-1 and A-2 reentry body impacts in the Antigua and Grand Turk target arrays could be located within 0.05 nautical miles.[32]

Table 1. AFETR Target Array Location and Description.

Location	Description	Distance from Cape Canaveral
Antigua	150 nm northeast, at a depth of 3 miles, 5 nm across	1230 nm
Ascension Island	35 nm west-northwest, at a depth of 2 miles, 12 nm across	4370 nm
Grand Turk Island	75 nm north , at a depth of 3 miles, 24 nm across	660 nm

AFETR Range Instrumentation Handbook, September 1971

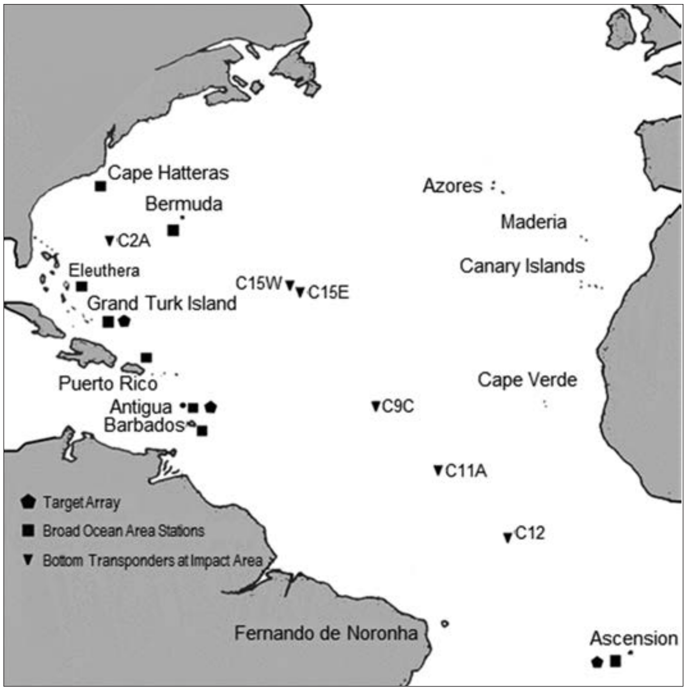


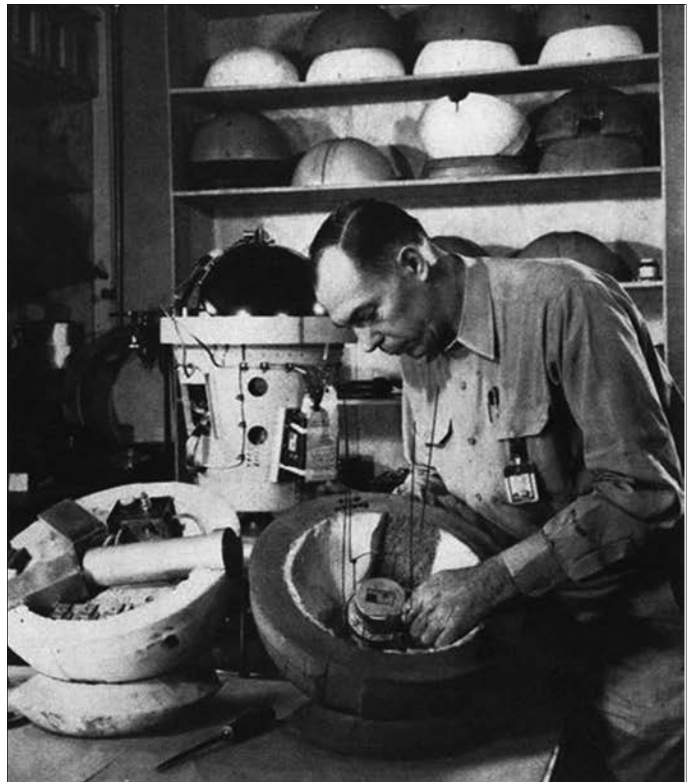
Figure 9. Location of unclassified MILS components of the AFETR, July 1, 1976. There was at least one additional MILS station in the eastern Atlantic. The Canary Island SCAVE installation was temporary. *(AFETR Range Instrumentation Handbook)*

BOA Arrays

BOA arrays and receiving stations unclassified locations, as of 1976, were: Antigua, Ascension, Barbados, Bermuda, Cape Hatteras, Grand Turk, Eleuthera, Fernando de Noronha and Puerto Rico (**Figure 9**).

In May 1958, the Thor IRBM research and development program began at Cape Canaveral with the Series III flight tests to determine the performance of the Mark 2 reentry vehicle and continue evaluation of all the missile subsystems. Earlier work with the X–17 reentry vehicle research rocket had demonstrated that telemetry transmission through the ionized air flow around the reentry vehicle during reentry was intermittent at best. General Electric, manufacturer of the Mark 2 reentry vehicle, developed a recoverable data capsule that housed a tape recorder for recording telemetry, power supply, radio antenna, dye pack and SOFAR bomb.

The capsule was an 18-inch-diameter sphere made of polyurethane foam and fabricated as two hollow hemispheres. The bottom half contained a data tape recorder, battery pack, dye packs and SOFAR bomb. The top half contained the radio beacon and antennas. There was an opening for the ejection of the SOFAR bomb as well as to detect contact with saltwater, activating the radio beacon, releasing the dye packs and ejecting the SOFAR bomb. The two hemispheres were cemented together and enclosed in an ablative outer shell that shattered on impact with the water surface. The capsule was ejected from the reentry vehicle by a small rocket motor (**Figure 10**).[33] The first successful recovery of a data capsule took place on 13 June 1958 after the flight of Thor FTM 122.[34]



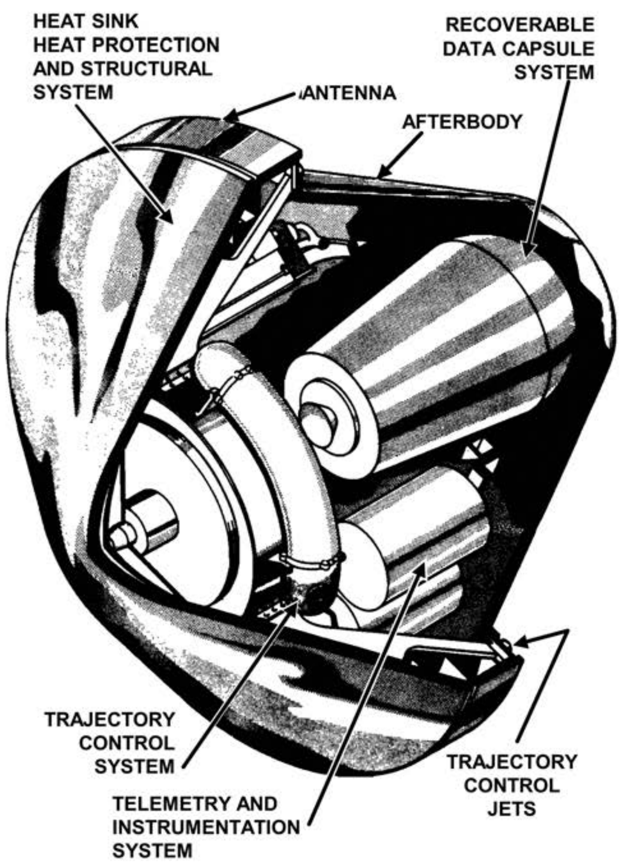


Figure 10. Top: General Electric recoverable data capsule system. The technician is assembling the two hemispheres of the recoverable capsule. The hemisphere on the left contains two dye packs and the data recorder as well as the SOFAR bomb, the large cylindrical object in the center In the background is the fully assembled system including the separation rocket. (USAF); Bottom: Mark 2 development reentry vehicle general layout. (General Electric)

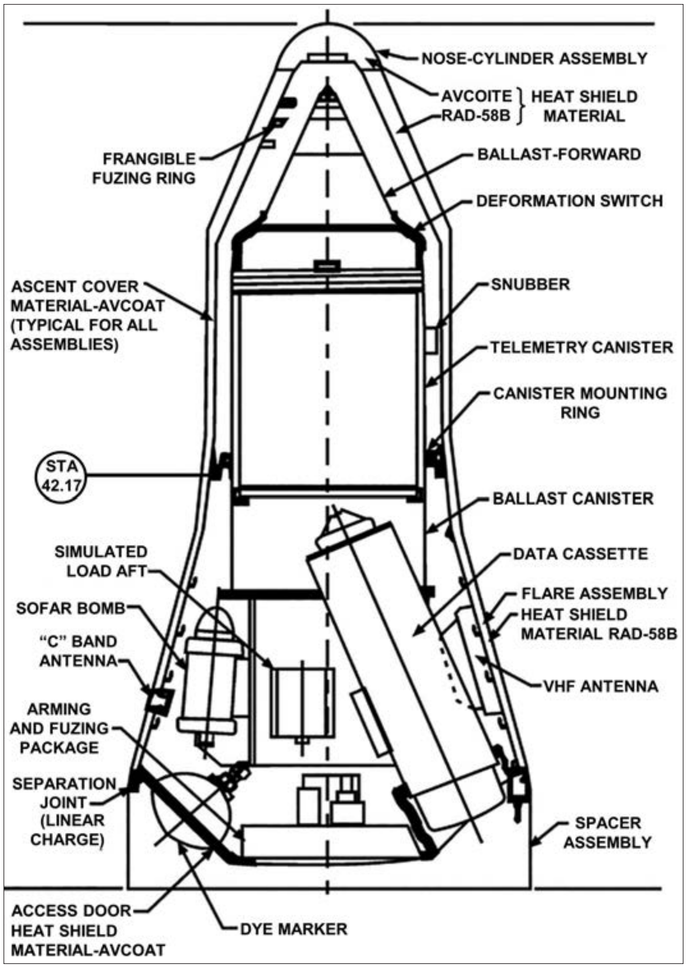


Figure 11. Minuteman Mark 5 development reentry vehicle. Telemetry was transmitted therefore there was no need for a recoverable data capsule. The SOFAR bomb is located on the left side of the illustration. ***(USAF)***

Details of the developmental flight testing of Atlas, Titan I and II reentry vehicles are scarce. The Mark 3 and 4 series reentry vehicles (Atlas E, Atlas F and Titan I respectively) could be equipped with SOFAR bombs and data capsules, but not all flights carried the systems.[35]

The Minuteman ICBM flight test program at the AFETR began in 1961. The program consisted of minimum-range flights of 3,000 nautical miles and to the target array and BOA target located at 4,300 nautical miles near Ascension Island. Both the Minuteman IA Mark 5 and Minuteman IB Mark 11 reentry vehicles could be equipped with SOFAR bombs that would explode at the pre-set depth regardless of whether they were ejected from the reentry vehicle (**Figure 11**).

Manned Spacecraft

The Mercury Program included SOFAR bombs as part of the recovery package on several of the developmental flights, beginning with a suborbital heatshield test in September 1959. Only two of the manned flights, MA-6 and MA-8, carried SOFAR recovery aids.[36] The Gemini and Apollo spacecraft did not carry SOFAR bombs.

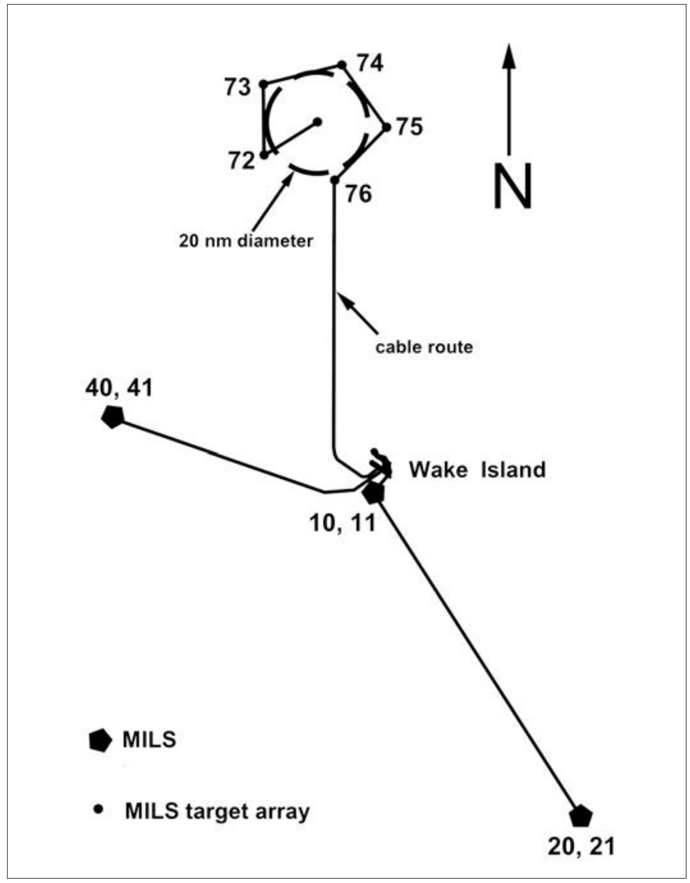


Figure 12. Wake Island MILS hydrophone installations. The target array north of the island was installed first followed several years later with the six-hydrophone broad ocean array west and south of the island.(USAF)

Sonobuoy Missile Impact Locating System

The system was used exclusively by the Navy with the Polaris A-1, A-2 and A-3 SLBM flight test programs.[37]

Portable Impact Locating System

The system was used exclusively by the Navy for the Poseidon and Trident I and II flight test programs.[38]

Pacific Missile Range/Air Force Western Test Range

Like the AFETR, the Navy's Pacific Missile Range was faced with the dilemma of accurately scoring reentry vehicle impacts in the open ocean (the name was changed to Air Force Western Test Range, AFWTR, on May 15, 1964).[39] The solution over the years was the evolution of the SOFAR/MILS techniques.

Missile Impact Locating System

Target Arrays (Splash Detection System)

One target array was approximately 60 miles northwest of Wake Island (**Figure 12**). Initially the use of the Eniwetok and Kwajalein lagoons as targets obviated the

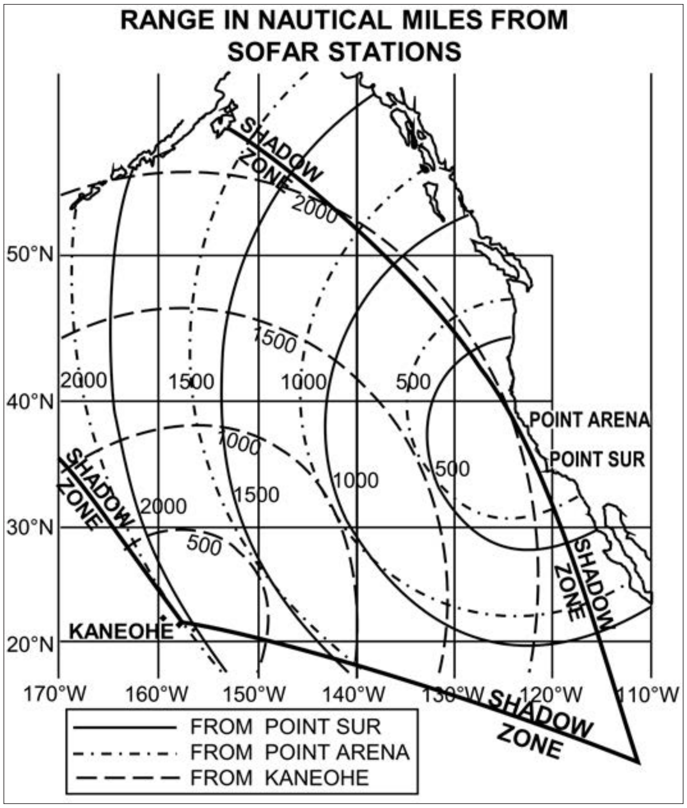


Figure 13. Northeast Pacific SOFAR network coverage 1948. The system was incorporated into the Pacific Missile Range MILS in the 1958-1960 timeframe. ***(USN)***

need for target arrays near those islands. On September 9, 1959, the Wake Island array successfully detected and scored the impact of the Mark 2 reentry vehicle carried by first Atlas ICBM (12D) launched from Vandenberg Air Force Base.[40]

BOA Arrays

In late 1945, the Navy Department decided to install a SOFAR network in the eastern North Pacific for air-sea rescue purposes. The network consisted of three stations: Kaneohe, Oahu in Hawaii and two stations on California's central coast separated by 180 nautical miles—the U.S. Coast Guard Station, Point Sur and the U.S. Coast Guard Lifeboat Station, Point Arena. The system became operational for evaluation in September 1948 (**Figure 13**).

Accuracy varied from 10 to 20 nautical miles in the southeasterly portion of the network to 20 to 100 nautical miles in the northeasterly section. Between the West Coast and the Hawaiian Islands, the accuracy was much better, on the order of 3 nautical miles. Due to the more complicated topography of the Pacific Ocean bottom, the signals were not as clear as those found in the Atlantic. Nonetheless, in the spring of 1951, signals from SOFAR charges dropped off the coast of Japan were easily detected 4,340 nautical miles away at the California stations. While the concept worked well, by 1956 budget constraints resulted in the stations being closed, but the hydrophones and equipment were left in place.[41] Reactivated in the 1958–1960-time frame, the Northeast Pacific SOFAR stations became part of the Pacific Missile Range MILS.[42]

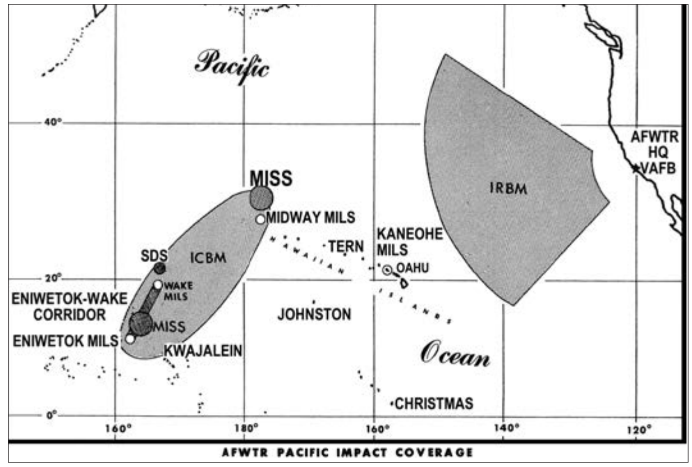


Figure 14. AFWTR Pacific Ocean MILS coverage 1966. ***(USAF)***

The Pacific Missile Range BOA array locations started with the IRBM sector between Vandenberg and Hawaii, extending 300 to 1500 nautical miles off the California coast.[43] The IRBM range became active in October 1958 with the completion of the signal receiver building at the Marine Corps Air Station, Kaneohe Bay, Oahu, Hawaii. The first use of the range took place on December 16, 1958 with the first launch of a Thor IRBM (DM-18A, 58-2262, *Tune Up*) from Vandenberg.[44]

Plans to extend the Pacific Missile Range MILS to support ICBM operations were finalized in December 1958 with expansion to include Eniwetok, Midway and Wake (in addition to the target array at Wake). The MILS system had two additional hydrophones installed between Wake Island and Eniwetok. The installation was completed in March 1961(**Figure 14**).[45]

Sonobuoy Missile Impact Locating System

Until the early 1980s, there had been no need for the SMILS capability as part of the Western Test Range. This changed with the flight test programs for the Peacekeeper (MX) ICBM and Trident SLBM scheduled to begin in 1982-1983. The range safety instantaneous impact prediction system in use at the time for the Kwajalein terminal area precluded Peacekeeper or Trident flights to the Kwajalein lagoon. Additionally, many of the flights needed to be conducted at distances beyond Kwajalein at ranges of 6,000 to 7,400 nautical miles depending on the number of reentry vehicles carried.[46] The solution was to develop BOA targets in the vicinity of Guam and north of the Mariana Islands for the long-distance flights and north and east of Kwajalein for the shorter-range tests. This involved positioning and maintaining deep ocean transponders at the new sites.[47] Already existing facilities at Wake, Phoenix and Oeno Islands were also available.

Initial SMILS support utilized Navy P–3C assets operating from the Pacific Missile Test Center, Point Mugu, California. The 4950th Test Wing, Wright-Patterson AFB, assumed management of the program in 1986. To econo-

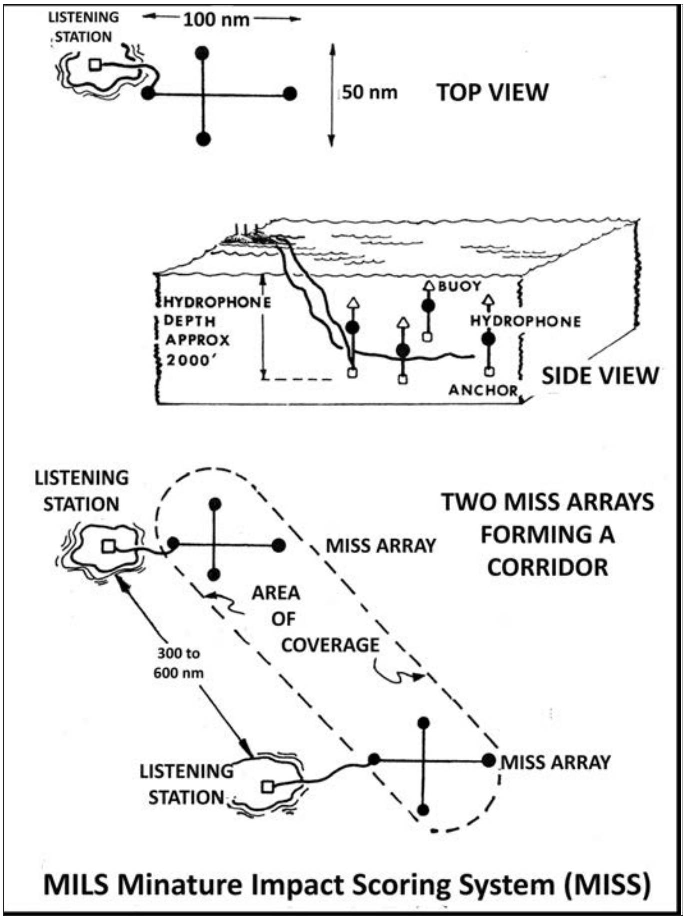


Figure 15. Miniature Impact Scoring System configuration. *(USAF)*

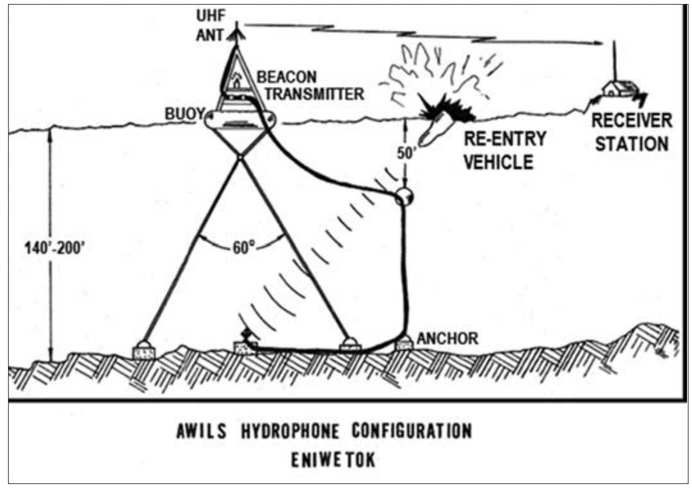


Figure 16. All Weather Impact Location System (AWILS), Eniwetok Lagoon. *(USAF)*

mize, SMILS capability was added to the EC–18 Advanced Range Instrumentation Aircraft (ARIA). Now a single aircraft could both track the reentry vehicles and record telemetry as well as deploy sonobuoys and determine the impact locations. One of the original requirements had been that Global Positioning Satellite capability be added to the sonobuoys and eliminate the need for the placement of deep ocean transponders. Research proved this to be feasible but in late 1986, the Office of the Secretary of Defense canceled the requirement due to budgetary restraints. After flying 13 ARIA missions as backup, the 4950 TW assumed the primary scoring mission in 1993.[48]

Portable Impact Locating System

The Pacific Ocean extended-range flight test program for Navy's Trident II SLBM utilizes PILS 2. The system was successfully tested on 21 November 2006 during the FCET dual launch exercise of the *USS Maryland* (SSBN-738). The NMIS ship was not located over the horizon but the capabilities of the new buoys to record the data was verified.[49]

Miniature Impact Scoring System

The miniature impact scoring system (MISS) was a special case of the BOA array installation. Four pairs of hydrophones were arranged in a crossed-dipole pattern, separated by 30 to 60 nautical miles. Two pairs of hydrophones were suspended from seamounts at depths of 450 to 520 fathoms. Two pairs were bottom mounted on the insular slope of the atoll. The first MISS array was completed at Eniwetok in March 1961, off Japtan Island, followed by an installation at Midway and eventually at Kwajalein forming a MILS corridor (the hydrophone arrangement was different at Kwajalein and referred to as the KMISS, see below).[50] Most signals originating from the North Pacific Ocean could be detected at the Eniwetok installation. Impact in the open ocean area 20 nautical miles northeast of Eniwetok was also monitored by the MISS installation.

Sand Island, part of the Midway Atoll, was the termination point for 10 hydrophones. Four pairs of hydrophones were installed north of the island in the MISS configuration (**Figure 15**). There was excellent coverage over an angle of 120 degrees on both sides of true North and indefinite coverage in other directions. The exceptions were signals blocked by the Hawaiian Archipelago. To the southeast, signals were often blocked by various island groups, and in the southwest, signals were blocked by the Eniwetok Atoll.[51]

All Weather Impact Location System

On February 1, 1965, the Air Force accepted operational control of the Pacific Missile Range facilities from the Navy. At that time there was only one reentry vehicle impact scoring system at Eniwetok Atoll for scoring impacts in the lagoon target area—the optical-photographic system which could only be used during daytime and in good weather to score surface or air burst options. The Air Force rectified this situation with completion of the installation of the all-weather impact location system (AWILS) and the splash detection radar scoring system (see below).

The Navy had studied the concept of the AWILS in 1963 and determined it was feasible. AWILS was a modification of the MILS target array. Instead of undersea cable connections to the receiving station, the seven bottom

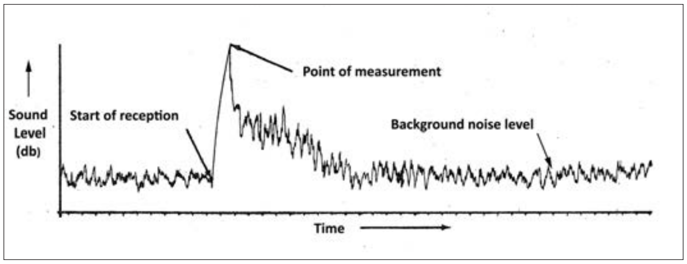


Figure 17. Reentry vehicle splash signal. The target arrays and AWILS hydrophones picked up a distinctly different signal than that detected by the broad ocean area hydrophones. The first peak was a direct signal from the impact of the reentry vehicle with the water. No SOFAR bomb was necessary. ***(USAF)***

mounted hydrophones, distributed in a hexagonal configuration with one hydrophone in the middle, were connected to surface buoys that housed a battery supply and transmitter (**Figures 16, 17**). The reentry vehicle splash signal from the hydrophones was transmitted via radio to the MILS building at Site David on Japtan Island. The prototype system was installed in April 1964. Initial operation was unsatisfactory so the diameter of the 7-hydrophone array was decreased from 10 to 6 nautical miles. The first test of the system took place on 30 July 1964 with the successful scoring of the impact of a Mark 6 reentry vehicle launched from Vandenberg on Titan II B-28.[52]

The Air Force upgraded the system in April 1965 and the system was calibrated with a series of explosions in the impact area on April 10, 1965. The system was successfully used on 14 April 1965, Eniwetok time, to score the impact of two Minuteman IB Mark 11 reentry vehicles—*Sea Point* at 2109:57.856 and *Yellow Light* at 2124:51.6—"ripple" launched from Vandenberg Air Force Base on April 13, 1965.[53] The final flight report scored the two reentry vehicle impacts using the optical-photographic system, but the AWILS was in close agreement.[54] The accuracy of the optical photographic system was ± 100 feet and, with AWILS, ±150 feet.[55]

Bottom Mounted Impact Location System

In 1968, the bottom mounted impact location system (BMILS) replaced the AWILS buoys with hardwired, bottom-mounted hydrophones in the same hexagonal configuration. In 1969, the BMILS system at Eniwetok was dismantled due to the decision to fly to Kwajalein (see below).[56]

Kwajalein Missile Impact Scoring System

Kwajalein did not have a MILS-type scoring system installation until the addition of the overlapping hexagonal, 10-hydrophone Kwajalein Missile Impact Scoring System (KMISS) in 1996 off Gagan Island (**Figure 18**). Upgraded in 2014, as presently deployed the refurbished KMISS covers 39.5 square nautical miles (approximately 1/8 the area of metropolitan Tucson, Arizona) providing an accuracy of ±18 feet within the boundary of the array. The relatively small target area exemplifies the accuracy of the Minuteman III guidance system.[57]

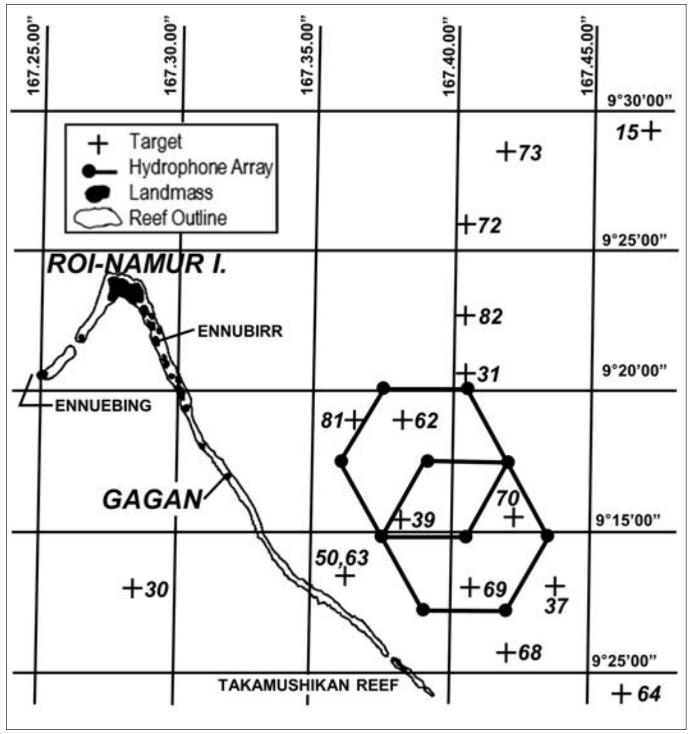


Figure 18. Original Kwajalein Missile Impact Scoring System (KMISS) configuration east of Gagan Island. The 49 mi.² system was installed in 1996 and upgraded in 2014. ***(USN)***

Minuteman III reentry vehicles are now targeted to either the KMISS or Illeginni Islet impact zones. If targeting the KMISS, the reentry vehicles land at least 3 nautical miles to the east of Gagan Islet where the ocean waters are between 6,900 to 12,000 feet deep. Those targeting the ocean area off of Illeginni Islet impact about 0.4 nautical miles southwest of the island in water about 1,000 feet deep. Typically, one reentry vehicle each year is used for conducting an airburst test above either zone though the majority of the tests are done southwest of Illeginni Islet.[58]

Flights on October 30, 2017 (FE-1) and March 20, 2020 (FE-2), tests of the Navy's Intermediate Range Glide Body (IRGB) concept for the Conventional Prompt Strike system used both the KMISS and a deep-water ocean area approximately 18 nautical miles southwest of Illeginni Islet as target options (**Figure 19**, following page).[59]

Hydroacoustic Impact Timing System

The splash detection radar system (see below) could only determine reentry vehicle impact timing to within 1.5 seconds. Because Minuteman II and III development required accuracy to within 100 milliseconds or better, three hydrophones were installed in the Kwajalein lagoon to improve timing accuracy to within 10 to 20 milliseconds. The system is no longer operative.[60]

Livermore Independent Diagnostic Scoring System

The SMILS concept has evolved into the Livermore Independent Diagnostic Scoring System (LIDSS) developed at Lawrence Livermore National Laboratory. Similar to the

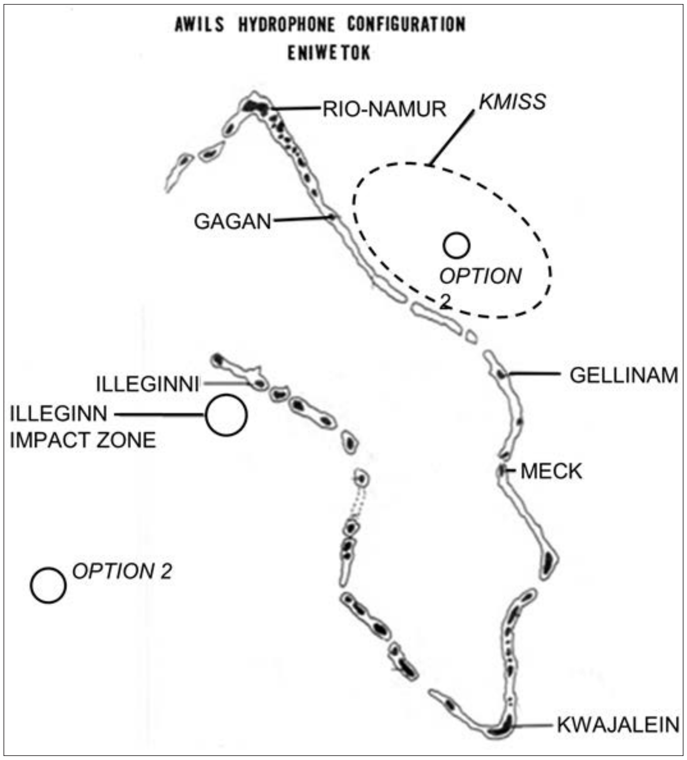


Figure 19. Target options for the Navy's Intermediate Range Glide Body concept test for the proposed Conventional Prompt Strike system. ***(USN)***

PILS 2 concept and developed in the same timeframe, LIDSS rafts are equipped with high-speed, streak, and high-definition video cameras as well as neutron detectors, hydrophones and microphones. On-board telemetry equipment records data for air burst or ocean impact missions. The rafts maintain their position in the water using GPS-based controls and trolling motors. Within two hours of reentry vehicle impact, "quick look" data can be supplied concerning reentry vehicle-warhead performance. Detailed analysis takes place back at Lawrence Livermore Laboratory. As many as 17 of these rafts can be deployed in the deep water off Illeginni Island (for example the FE-1 and 2 tests) or in BOAs such as targets near Guam or Saipan as is necessary (**Figure 20**).[61]

Other Scoring Systems

Optical

Manned Optical and Photographic Systems

In 1961, impact location in the Eniwetok lagoon, or impacts sufficiently close but outside to the east, were determined by triangulation using angular data from manned optical instruments and camera equipment platforms on three towers positioned along the eastern periphery of the atoll. Runit Island (Site Yvonne) had a 196 ft^2 cab on a tower approximately 85 feet above the lagoon. Site Yvonne was chosen because it was nearly directly underneath the reentry vehicle trajectory to the lagoon. Parry Island (Site Elmer) was the central location, with a 270 ft^2 cab atop a 300-foot tower (**Figures 21 & 22**). Eniwetok Island (Site Fred) had a 273 ft^2 cab built on top of the 50-foot water tower. Each of the tower cabs were equipped with surveyor's transits, motion picture cameras and aircraft reconnaissance cameras.[62]

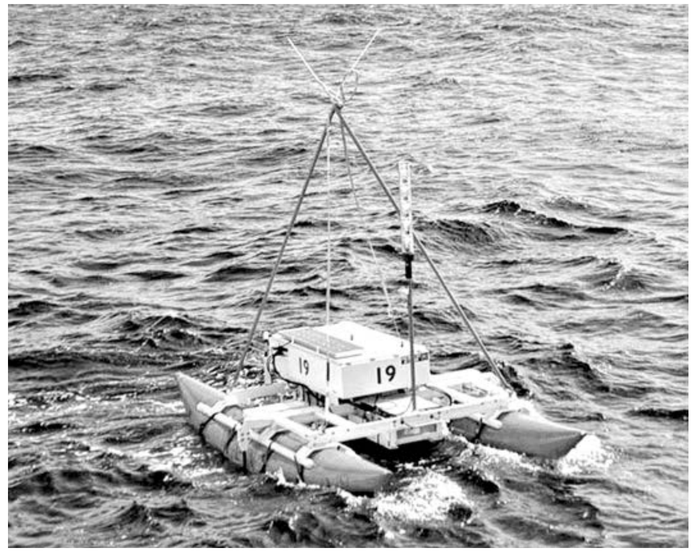


Figure 20. Livermore Independent Diagnostic Scoring System (LIDSS) instrument raft. (Courtesy Lawrence Livermore National Laboratory)

LA-24 Tracking Telescopes/Askania Cinetheodolites

The original Kwajalein tracking equipment was designed to track launches of missiles associated with development of the Nike-Zeus antiballistic missile system. There were two LA-24 Tracking Telescopes, one each on Ennylabegan and Kwajalein Islands.

In 1963, three Askania Cinetheodolites, along with three Mobile Optical Tracking Units, were added to the system, one each on Gugeegue, Ennylabegan and Kwajalein Islands, forming a triangle with a nine-mile base for point-of-impact triangulation.[63]

Recording Automatic Digital Optical Tracker (RADOT)

In the late 1960s, Kwajalein was the test site for Spartan and Sprint anti-ballistic missile developmental launches against incoming reentry vehicles from Vandenberg. RADOT cine-sextants were deployed to provide maximum coverage of the Sprint and Spartan launches from Meck Island and Spartan launches from Kwajalein Island. By December 1969, a total of eight RADOTs were deployed on Kwajalein, Gugeegue, Ennylabegan, Legan and Gellinam.[64]

Optical Scoring System

The system was established in 1966 to facilitate optical coverage of impacting reentry vehicles in the Kwajalein lagoon. Composed of stations on Legan, Gellinam and Eniwetak which were equidistant from the established target area, the result was a triangle 11 nautical miles across. Daylight optical determination of impact location was provided with an accuracy of $\pm$ 50 feet.

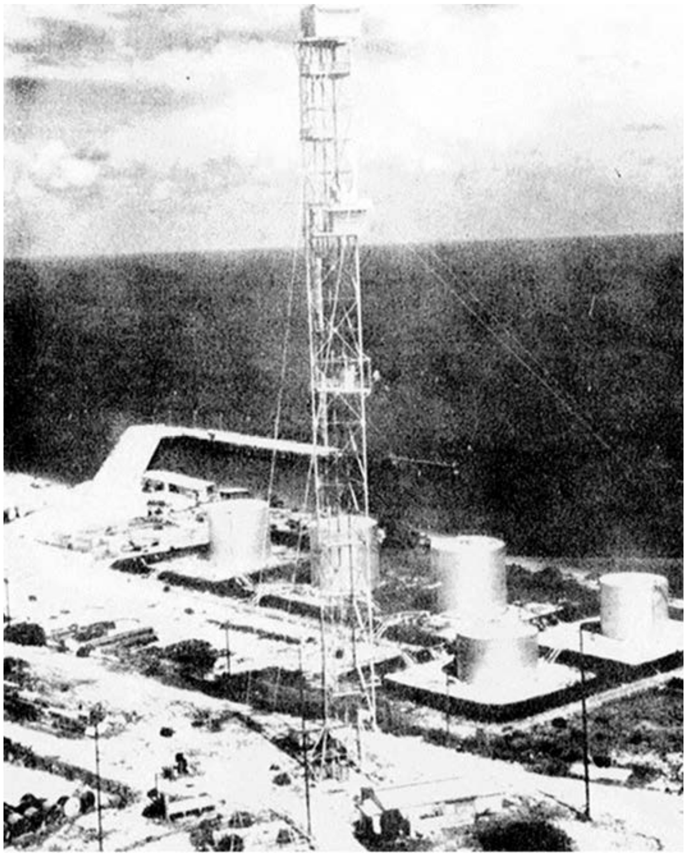


Figure 21. 300-foot instrumentation tower, Parry Island (Site Elmer) 1961. *(USAF)*

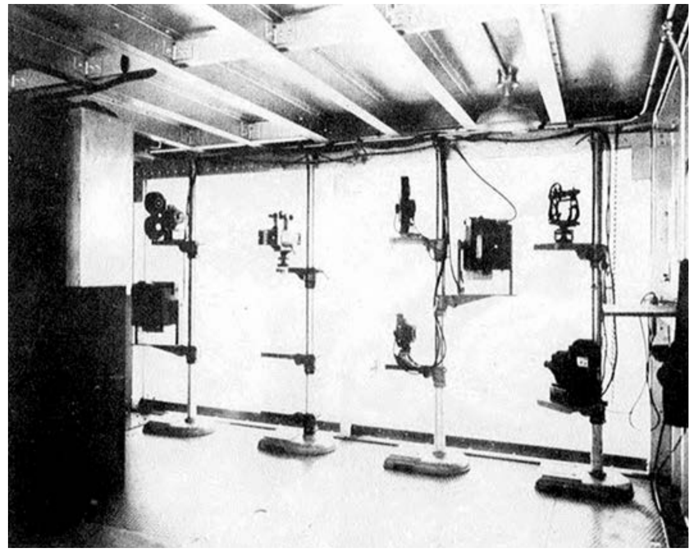


Figure 22. Optical and photographic instrumentation room, Runit Island (Site Yvonne) 1961. *(USAF)*

Ballistic Impact Locating System

The ballistic impact locating system consisted of four mobile ballistic cameras with a wide field of view. There were seven surveyed camera locations on Kwajalein Atoll. The system could be used for both air burst and surface impact missions.[65]

Radar

Splash Detection Radar

On April 1, 1965, Bendix engineers began installing the first splash detection radar system at Eniwetok. This system provided all-weather reentry vehicle splash detection, day or night. The SPN-8A radar was modified to provide a system pulse repetition frequency of 4,000 pulses per second versus the standard 2,200 pulses per second. While the SPN-8A range was reduced to 20 nautical miles, the increased pulse rate greatly enhanced the splash detection capability. The antennas were mounted on 100-foot towers and could detect a splash of 27 feet minimum height and three second minimum duration at ranges up to 20 nautical miles. The accuracy was $\pm$10 feet with a detection probability of at least 95 percent.[66]

The system was successfully evaluated against optical scoring with a series of sand-ballasted oil drums dropped from a C–54 aircraft flying a base leg from the Elmer Island tower to the Mack Island tower. The system successfully detected the two impacts of Minuteman IB Mark 11 reentry vehicles "ripple" launched from Vandenberg AFB on April 13, 1965 (see above). To further enhance system accuracy, five radar reflectors were placed at various locations in the target area to serve as calibration points.[67] The SDR system at Eniwetok was removed in 1969.

At Kwajalein, one SPN-8A splash detection radar was installed on Eniwetak Island in May 1966. The system could detect a splash of 30 feet or higher but also needed the splash to be a minimum of two seconds in duration.[68] A month later, the system was successful in determining the lagoon impact point of a Mark 11A reentry vehicle delivered by a Minuteman II, *Fox Trap*, launched on 24 June 1966 at 2310 hrs.[69] A second unit was installed on Gagan Island in Fiscal Year 1969. The system covered not only the lagoon but also BOA targets 20 nautical miles to the east and west of the atoll.[70] By late 1989 the system had exceeded its life expectancy with no source of major repair parts.[71]

The Phoenix Islands Terminal Complex Area of the Western Test Range was formed as part of the Minuteman III flight test and operational test program. Splash detection radars were deployed on Canton, Endenbury and Hull Islands in 1971.[72]

Broad Ocean Scoring System

The broad ocean scoring system (BOSS) was used to detect and locate impacts of reentry vehicles at remote island sites or in the open ocean, thereby augmenting the results of the MILS. The system was similar to that of the splash detection radar but was mounted on the Range Instrumentation Ship *USNS Huntsville* (T-AGM-7). The system operated in one of two modes: reflector or navigation. In the reflector mode, the ship and the reentry vehicle impact had to be within 20 nautical miles of an island on which there were two geodetically surveyed radar reflec-

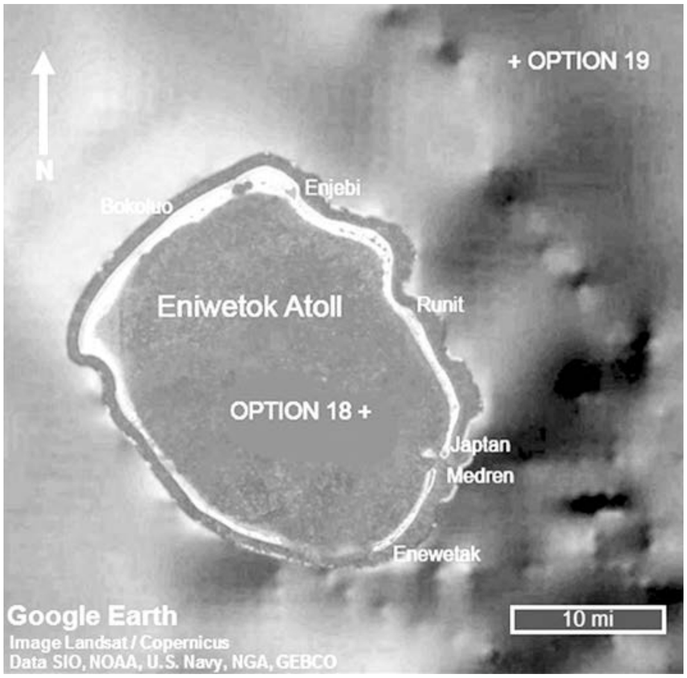


Figure 23. Minuteman I target locations, Eniwetok Atoll, 1962-1969.

tors. In the navigation mode, the ship's navigation system, such as a Ships Inertial Navigation System or Acoustical Ships Positioning System, provided the geodetic reference.[73]

Targets

The most complete information on targets is from the Minuteman I program. Between 1962-1969, the majority of the flights were to Eniwetok Target Options 18 (in the lagoon) and 19 (20 nautical miles northeast, **Figure 23**). Option 18 made use of the cine-theodolites, the most accurate (± 100 feet) scoring system which was limited to daylight. Option 19 made use of the MISS equipment (± 360 feet). The small percentage of flights against the Kwajalein anti-ballistic missile radars utilized Target Option 24, which was 68 nautical miles northeast of the lagoon and was scored by the BOA MILS network (**Figure 24**).[74]

Summary

MILS was the first-generation reentry vehicle impact detection technology. As is often the case with first-generation technology, more famous examples of its use, such as SOSUS for detection and tracking of Soviet and Chinese submarines, overshadowed details of other applications of the deep sound channel phenomenon.

The MILS BOA techniques were developed for the AFETR IRBM and ICBM test programs and further re-

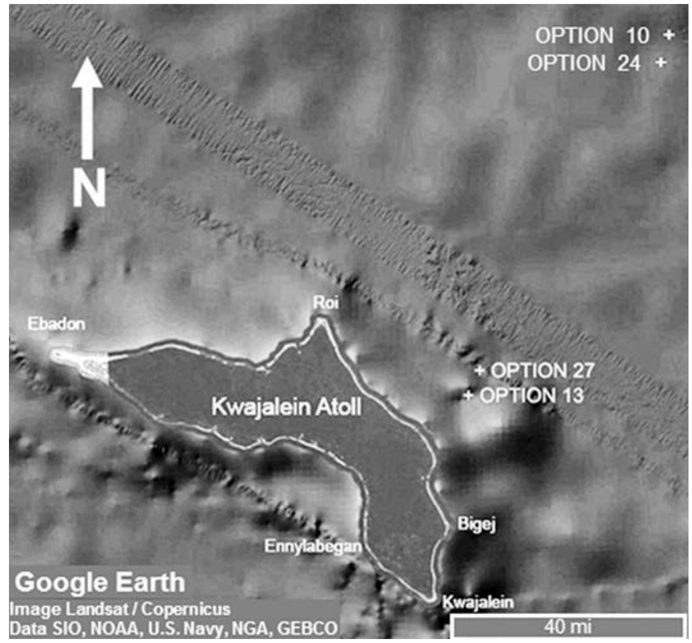


Figure 24. Minuteman I target locations, Kwajalein Atoll, 1965-1971.

fined for use in the IRBM and ICBM operational test programs at the PMR/AFWTR.

They were used in the Atlantic Ocean until 1992, presumably similarly for the Pacific Ocean.[75] The equipment was not completely abandoned and is now used for a variety of civilian marine-life and geophysical investigations.

Technology and cost savings forced the demise of the AWILS and its variant, BMILS, at the end of 1969. While the modification to the BMILS had proven highly successful, the system was expensive to maintain and impact missions were now being flown to Kwajalein or to a new target, the Phoenix Islands. The SDR equipment was removed for transfer to the Phoenix Islands group for use with Minuteman III flight testing. If scoring capability was needed at Eniwetok, a BOSS-equipped ship would be brought into the lagoon on a temporary basis. If land impact was desired, an acoustic array could be constructed specifically for land impact missions.[76]

In 1968, the MILS stations at Midway, Wake, Kanoehe, Hawaii and Eniwetok provided crucial data used to locate the position of the sunken Soviet submarine K-129. Combined with the data from the SOSUS stations at Adak, Alaska; Point Sur, Centerville Beach, California; Coos Head, Oregon and Pacific Beach, Washington, the Navy was able to locate the site of the accident within two nautical miles of 40.1 North Latitude and 179.9 degrees East Longitude.[77]

The PILS, KMISS and LIDSS technology represent the ultimate evolution of acoustic-based reentry vehicle impact detection. ■

NOTES

1. Report of the Committee on Long-Range Proving Ground, (Joint Research and Development Board War and Navy Department, Washington 25, DC, 20 June 1947), Microfilm Publication M1195, 684.0 Guided Missile Ranges, National Archives and Records Administration, i.

2. M. Gerster, "History of the 1st Missile Division and the 392nd Air Base Group, 15 April 1957-30 June 1957," (Air Force Ballistic Missile Division, Air Research and Development Command, 15 October 1957), Air Force Historical Research Agency (AFHRA), Maxwell Air Force Base, Alabama, IRIS NUM 425408, Reel 11106, Document 17, 58-65; E. Doran, *Handbook of Selected Pacific Islands,* (Pacific Missile Range, Point Mugu, California, December 1959), 61, 137. Author's collection.

3. K. Dyk and O. W. Swainson, "Velocity and Ray Paths of Sound Waves and Deep Seawater," *Geophysics: 18* (1953), 75-103.

4. "Sound Transmission in Seawater," *Woods Hole Oceanographic Institute Technical Report 41-5, 1941*, 18-21. Though not stated on the cover of the report, a handwritten note by Vine on the inside cover of the author's copy indicates that Columbus Iselin wrote the oceanography chapter, and Maurice Ewing wrote the physics chapter assisted by Allyn Vine, Lamar Worzel and Alfred Woodcock.

5. M. Ewing and L. Worzel, "Long-Range Sound Transmission: Interim Report 1, March 1, 1944-January 20, 1945," *Woods Hole Oceanographic Institute Technical Report 45-12, 1945*, 1-3.

6. Ewing and Worzel, 6.

7. Ewing and Worzel, 9.

8. G. M. Bryan, M. Truchan and J. I. Ewing, "Long-Range SOFAR Studies in the South Atlantic Ocean," *Journal of the Acoustical Society of America, Volume 35, Number 3, March 1963*, 274.

9. G. P. Woollard, "A Manual for SOFAR Observers," *Woods Hole Oceanographic Institute Technical Report 47-18, 1947*, Section 1, 5.

10. Ewing and Worzel, 27; M. Ewing, G. P. Woollard, A.C. Vine and J. L. Worzel, "Recent Results in Submarine Geophysics," *Bulletin of the Geological Society of America, 57, October 1946,* 909-934; Bryan, 273. Experiments conducted in 1963 detected signals from 4700 nautical miles with an accuracy of 160 feet per thousand nautical miles.

11. M. Ewing, J. Lamar Worzel and M. Talwani, "Some Aspects of Physical Geodesy," in *Geophysical Monograph Number 4: Contemporary Geodesy,* (National Academies Press, Washington DC, 1959), 7-21.

12. S. Cornell, "Long-Range Sound Transmission: Interim Report 2, SOFAR Bombs and Detonators," *Woods Hole Oceanographic Institute Technical Report 47-15, 1947*, 1-3.

13. L. H. Barbour, "Long-Range Sound Transmission: Interim Report 3, SOFAR Position Triangulation," *Woods Hole Oceanographic Institute Technical Report 47-17, 1947,* 8.

14. G. B. Tirey and G. R. Hamilton, "Bearing Determinations for SOFAR Type Signals Using Two Hydrophones," *Technical Report No. 8, CU-18-55-TO24-Geolog., December 1955*, (Lamont Geophysical Observatory, Palisades, New York), 1-6.

15. V.B. Kovac, "Notes on Evaluation of an Impact Prediction and Location System," *Proceedings of the Fifth Symposium on Ballistic Missile and Space Technology, Los Angeles, California, 1960*, 391.

16. G. R. Hamilton, "Time Variations of Sound Speed Over Long Paths in The Ocean," *International Workshop on Low-Frequency Propagation and Noise, Woods Hole, Massachusetts, 14-19 October, 1974*, 1.

17. Hamilton, 16-18.

18. *AFETR Instrumentation Handbook*, ETR-TR-71-5, September 1971, (Directorate of Range Engineering, Instrumentation Division, Air Force Eastern Test Range, Air Force Systems Command, Patrick Air Force Base, Florida), 45-49. Unless otherwise noted the discussion of the Atlantic missile impact location system is derived from this document.

19. Hamilton, 11. This was determined during the SCAVE work in 1961.

20. *AFETR Instrumentation Handbook,* 1 July 1976, , (Directorate of Range Engineering, Instrumentation Division, Air Force Eastern Test Range, Air Force Systems Command, Patrick Air Force Base, Florida), Defense Technology Information Center (DTIC), AD029237, Section 2-74.

21. Sabot projectiles.

22. G. R. Hamilton and M. E. Drake, "Sonobuoy MILS (SMILS)," *6th Space Conference Proceedings, Volume 2, Space, Technology and Society*, Section 16-9-Section 16-16; C. H. Murphy and G. V. Bull, "Review of High-Altitude Research Program (HARP)," Report No. 1327, July 1966, (Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland), DTIC, AD 645284, 1-37.

23. Hamilton and Drake, Section 16-9-Section 16-10.

24. *Ibid*., Section 16-10.

25. *AFETR Instrumentation Handbook*, September 1971, 48-49.

26. *Ibid*., 49.

27. Hamilton and Drake, Section 16-10.

28. *Against the Wind: 90 Years of Flight Test in the Miami Valley,* (History Office, Aeronautical Systems Center, Air Force Material Command, Wright-Patterson AFB, 1994), 76-77.

29. D. Guilford and M. A. Cardoza, "A Portable Impact Location System," *Proceedings of the 17th Annual Meeting of the Institute of Navigation, June 2001,* 824-828; R. W. Sturdevant, *NAVSTAR, The Global Positioning System: A Sampling of Its Military, Civil and Commercial Impact,* in *Societal Impact of Spaceflight*, S. J. Derek and R. D. Lanius, editors, (National Aeronautics and Space Administration, Office of External Relations, History Division, Washington, DC, 2007), 331-332; C. Alexandrow, "The Story of GPS," in *DARPA: 50 Years of Bridging the Gap,* (Faircount Media Group, Tampa, Florida, 2016), 54-55.

30. M. Coussa, "Naval Mobile Instrumentation System," *Naval Engineers Journal*, 114 (1): 71-92; M. Cardoza et al., Autonomous Surface Watercraft, United States Patent 6,854,406 B2, granted 15 February 2005.

31. C. H. Weaver, "Collecting Reentry Body GPS Translator Data near Impact Using the Over- the-Horizon Buoy," *Johns Hopkins APL Technical Digest,* Volume 29, Number 2 (2010), 141-148.

32. M. Whipple, "Air Force Eastern Test Range, Index of Missile Launchings: 1950-1967," (Air Force Base, Florida), Polaris, 20-6. This hard-to-find set of documents was courtesy of Jonathan McDowell.

33. "Recoverable Data Capsule Designed for Thor and Atlas Test Missiles," *Aviation Week,* November 24, 1958, 73-74; "Progress in Reentry – Recovery Vehicle Development," (Missiles and Space Vehicle Department, General Electric, Philadelphia, Pennsylvania, 2 January 1961), 4-6.

34. Smithsonian Institution News Release, May 14, 1959. Capsule and replacement contents were donated to the Smithsonian Institute on 15 May 1959.

35. Whipple.

36. J. H. Boynton, "First U.S. Manned Six-Pass Orbital Mission (Mercury-Atlas 8, Spacecraft 16)," (Manned Spacecraft Center, Houston, Texas), NASA TN D-4807, 35; "Mercury Project Summary Including Results of the Fourth Manned Orbital Flight May 15 and 16, 1963," (Manned Spacecraft Center, Houston, Texas, 1963), 12.

37. "Data Reduction Analysis Techniques," 3-4-1.

38. Coussa.

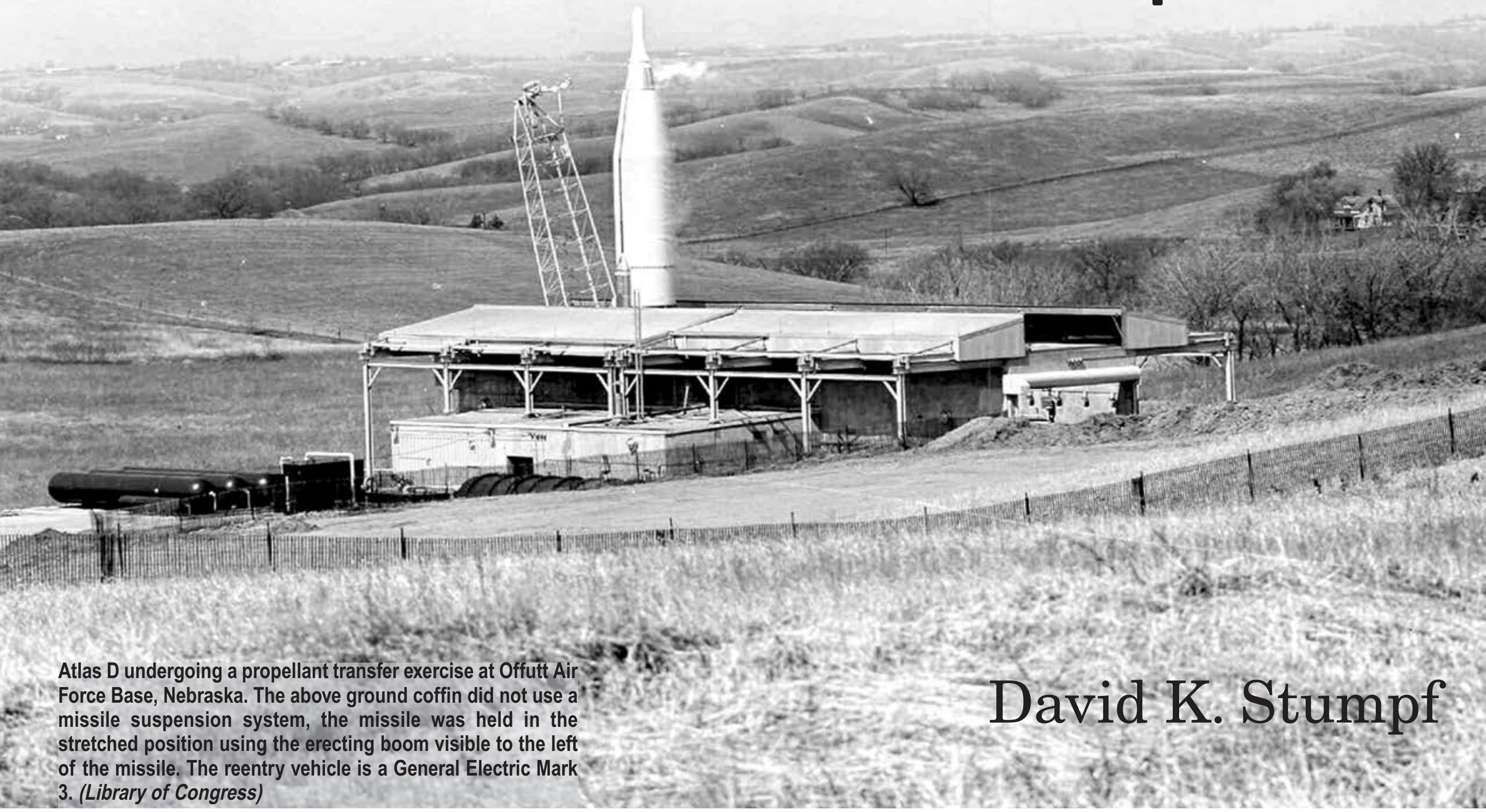
39. Chronology of Significant Events-1964, "History of the 1st Strategic Air Division and Vandenberg Air Force Base," (History Office, Vandenberg Air Force Base), 5.

40. A. Menken, History of the Pacific Missile Range: Historical Report Covering the Period 1 July 1959 to 30 June 1960, (Naval Historical Center, Washington, DC), Call Number VA68.P16 H6, 129.

41. M. J. Sheehy, "SOFAR in the Pacific," *Office of Naval Re-*

search Reviews 6 (1953):15-22.
42. R. D. Bickett, History of the Air Force Western Test Range, 15 May-31 December 1964, Volume III Supporting Documents 16-34, AFHRA IRIS NUM 00484563, Document 30, Section 6-13.
43. W. Vinzant, Air Force Western Test Range Instrumentation Handbook, 1 January 1966, (History Office, Vandenberg Air Force Base), 109. The author thanks Scott Bailey, Vandenberg historian, for access to the unclassified portions of this document.
44. W. M. Arms, Thor: The Work Horse of Space, 31 July 1972, (McDonnell Douglas, MDC G3 770), A-5.
45. Bickett, History of the Air Force Western Test Range, 1 January-31 December 1965, Volume I, 56-57; "Operational Test Instrumentation Guide," (U.S. Army Operational Test and Evaluation Agency, Falls Church, Virginia, 1981), DTIC, A113775, AA-10.
46. J. E. Medalia, "MX Intercontinental Ballistic Missile Program: Issue Brief Number IB 77080, (Congressional Research Service, 12 December 1981), 5-6; "Smart Weapons: Intercontinental Ballistic Missiles," *In Combat Magazine 1991,* no pages given. This is an obscure British publication; T. B. Cochran, W. M. Arkin, M. M. Hoenig, Nuclear Weapons Data Book: Volume 1 US Nuclear Forces and Capabilities," (Ballenger Publishing Company, Cambridge, Massachusetts 1984), 121, 142-145; Department of Defense Authorization for Appropriations for Fiscal Year 1981 Part 2, Senate Armed Services Committee, 509; Department of Defense Authorization for Appropriations for Fiscal Year 1982 Part 7, Senate Armed Services Committee, 4004.
47. S. J. Woodbury and R. G. Gorman, "Program Overview of Peace keeper Flight Test Plan," AAIA/AHS/IES/SETP/SFTE/ DGLR Second Flight Testing Conference, November 16-18, 1983, 5-6.
48. *Against the Wind,* 76-77; J. W. McIntyre, "The Advanced Range Instrumentation Aircraft/Sonobuoy Missile Impact Locating System," *Johns Hopkins APL Technical Digest, Volume* 12, *Number* 4 (1991), 330-338; D. A. Artis and H. Malcolm, "The Post-Mission Processor for the Sonobuoy Missile Impact Locating System," *Johns Hopkins APL Technical Digest, Volume 12, Number 4 (1991),* 339-346.
49. C. H. Weaver, 146; McDowell, http://www.planet4589.org/space/lvdb/launch/Trident2.
50. *Data Reduction and Analysis Techniques for Miss-Distance Determination (MDD) and Scoring Systems*, (Data Reduction Computing Group, Range Commanders Council, White Sands Missile Range, September 1980), 3-3-1; R. D. Bickett, History of the Air Force Western Test Range, 1 January-31 December 1965, Volume I, AFHRA, IRIS NUM 00484566, 56-57; Air Force Western Test Range Instrumentation Book, 113-115.
51. *Operational Test Instrumentation Guide*, AA 9-10.
52. A. Menken, History of the Pacific Missile Range: Historical Report Covering the Period 1 January 1964 to 31 December 1964, (Naval Historical Center, Washington, DC), Call Number VA68.P16 H6, 92-93, 268-269; History of the Pacific Missile Range: Report Covering the Period 1 January 1963 to 31 December 1963, 156.
53. J. McDowell, JSR Launch Vehicle Database, August 9, 2020 Edition; accessed on 31 October 2020. https://www.planet 4589.org/space/lvdb/index.html.
54. J. T. Donahue and D. J. Stevens, History of the First Strategic Aerospace Division July-December 1965, AFHRA, IRIS NUM 00425451, Document 8, "1 STRAD LGM-30B OT final report, 20 August 1965, 23-28, 38, 44; Bickett, 1 January-31 December 1965, Volume II, Document 24, AWILS History-Installation to Date, 1.
55. J. T. Donahue and D. J. Stevens, History of the 1st Strategic Aerospace Division, Strategic Air Command, 1 January-30 June 1966, Vol. I, Narrative*,* AFHRA, IRIS NUM 00425453, K-DIV-1-HI, Reel 11114, 53. This document is classified; the extract used is declassified IAW EO 13526.
56. Bickett, 1 January-31 December 1965, 90; R. D. Bickett, History of the Air Force Western Test Range/Space and Missile Test Center, 1 July 1969-30 June 1970, Volume III, AFHRA IRIS NUM 00919454, Document 41, 19.
57. "Surface Impact Detection and Scoring," Range Commanders Council, document 406-96, April 1993, DTIC, ADA 317897, 2; "Kwajalein Missile Impact Scoring System Refurbishment: Biological Assessment Final, February 2014," (U.S. Army Space and Missile Defense Command, Huntsville, AL), 1.
58. Supplemental Environmental Assessment for Minuteman III Modification and Fuze Modernization, June 2019, (U.S. Army Space and Missile Defense Command Huntsville, Alabama), Appendices C, 14.
59. Final Environmental Assessment/Overseas Environmental Assessment for Flight Experiment 1 (FE-1), August 2017, 2-4; US Navy Flight Experiment-2 (FE-2), August 2019, 1; https://planet4589.org/space/gcat/data/launch/Polaris.html.
60. Historical Summary Kwajalein Missile Range, July 1970-June 1972, (Redstone Scientific Information Center, Huntsville, Alabama), 19; "Existing System Modifications Report, USAKA Long-Range Planning Study, November 1989," (U.S. Army Strategic Defense Command, Huntsville Alabama, 1989), 2.
61. A. R. Chen, "Testing Missile Technology on the High Seas," Science and Technology Review June 2019, (Lawrence Livermore National laboratory, California), 20-23; D. Johnston, https://www.llnl.gov/news/despite-heavy-storms-and-rough-seas-laboratory-team-captures-missile-flight-data.
62. Bickett, History of the Air Force Western Test Range, 1 January-31 December 1965, Volume I, 61-65.
63. Historical Summary Kwajalein Missile Range, July 1964-June 1960, Chapter 6, 3.
64. *Ibid*., Chapter 6, 3-4.
65. *Ibid*., Chapter 6, 4-5.
66. Data Reduction and Analysis Techniques, 3-2-1, 3-2-3.
67. *Ibid*., Volume II, Document 25, SPN-8A Radar History-Installation to Date, 1-2.
68. Space and Missile Test Center Capability Summary Handbook, November 1972, (History Office Vandenberg Air Force Base, California), Section 6-5.3.
69. McDowell.
70. Historical Summary Kwajalein Missile Range, July 1964-June 1970, Chapter 6, 7.
71. R. Sampson and D. Strietzel, "Existing System Modifications Report," USAKA Long-Range Planning Study, (U.S. Army Strategic Defense Command, Hutsell, Alabama, 1989), DTIC AD-8215957, 3-4.
72. Space and Missile Test Center Capability Summary Handbook, November 1972, Section 6-5.1.
73. Space and Missile Test Center Capability Summary Handbook, November 1972, Section 6-5.2.
74. J. T. Donahue and D. J. Stevens, "Minuteman IA Demonstration and Shakedown Operation Final Report, 2 January 1964," History of the 1st Strategic Aerospace Division, 1 January 1964-30 June 1964, Volume II, AFHRA, IRIS Number 425441, Reel 11114, K-DIV-1- HI V.2, 6; J. T. Donahue and D. J. Stevens, History of the First Strategic Aerospace Division July-December 1965, AFHRA, IRIS Number 425451, Document 8, "1 STRAD LGM-30B OT Final Report, 220 August 1965, 37, 38.
75. Guilford and Cardoza, 824.
76. Bickett, History of the Air Force Western Test Range, 1 January-31 December 1965, Volume III, Document 41, "Study on Phase down of AFWTR Eniwetok Facility Including RV Scoring and Recovery Options," 1-20.
77. https://en.wikipedia.org/wiki/Naval_Facility_Point_Sur, retrieved 27 October 2021; https://en.wikipedia.org/wiki/Naval_Air_Facility_Adak; "Sub Pirates World Submarines, www.cliffhangershideout.com. Retrieved 27 October 2021; N. Polmar and M. White, *Project Azorian: The CIA and the Raising of the K-129*, (Naval Institute Press, Annapolis, Maryland, 2010), 45-46.

Ballistic Missile Shock Isolation Systems



Atlas D undergoing a propellant transfer exercise at Offutt Air Force Base, Nebraska. The above ground coffin did not use a missile suspension system, the missile was held in the stretched position using the erecting boom visible to the left of the missile. The reentry vehicle is a General Electric Mark 3. *(Library of Congress)*

David K. Stumpf

In late 1950s, designers of intercontinental ballistic missile launch facilities had to juggle hardening the facilities against nuclear weapon blast effects while maximizing reaction time and rapid force expenditure without excessive exposure time. First and foremost, however, was the need for the earliest operational capability.

The resulting designs progressed from: (1) the three Atlas D gantry launch facilities (no protection) at Vandenberg Air Force Base; (2) the above ground coffin system used with Atlas D (2 psi overpressure); (3) the buried coffin system used with Atlas E (25 psi); (4), in-silo storage combined with above-ground launch, as deployed with Atlas F and Titan I (100 psi); and ultimately in-silo storage and launch with Titan II (300 psi), Minuteman (300 psi, launch facility as-built) and Peacekeeper (1000 psi, launch facility).[1]

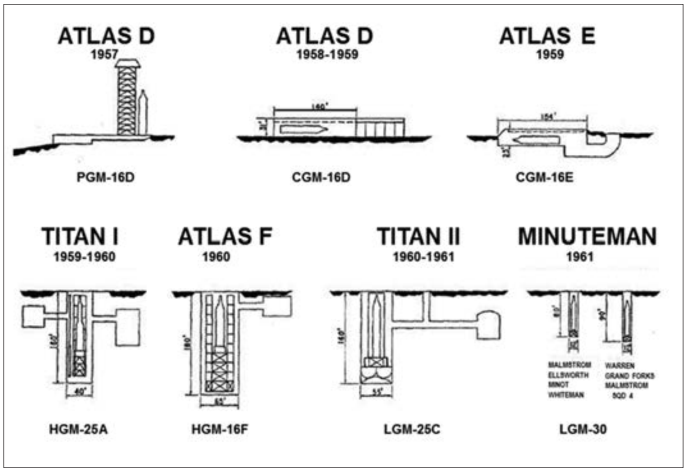
The Atlas F and Titan I launch facilities did not utilize missile suspension systems per se, as the missiles were stored on their rigid launch platform within the silo crib structure and the entire structure shock isolated. This article describes the design evolution of ballistic missile shock isolation systems used with Atlas F, Titan I, Titan II, Minuteman, and Peacekeeper .

Decisions, Decisions

On April 30, 1958, the Office of the Secretary of Defense requested the Air Force to report on the operational, logistical, engineering, construction, and cost factors anticipated for protecting ballistic missiles by hardening and dispersal of the launch facilities. After two months of study, the Ballistic Missile Hardening Committee Report concluded:

1. Hardening is required in combination with dispersal, low exposure time, fast reaction, and rapid force expenditure.
2. Methods of hardening with quick response are known and are feasible.
  a. Now – to 25 psi above ground
  b. Now – to 100 psi underground
  c. After R&D – to higher psi underground
  d. After R&D – to survive direct hits with slow response (superhard)
3. Hardening to 200 psi. appears feasible and attractive.
4. The construction costs of hardening can be estimated with reasonable accuracy.

The committee recommended that the Atlas E program be continued at the 25-psi level to obtain operational capability at an early date. Atlas F and Titan I could be hardened to 100 psi and studied for hardening beyond 100 psi. As Soviet accuracy improved, resistance to blast effects above 25 psi overpressure meant the missile sites needed to be located under-



Evolution of ICBM Basing Modes: Launch Environment Symbol: C – coffin stored for ground launch; H – silo stored, launch from surface; L – silo stored and launched; P – soft pad, surface launch. Mission Symbol: G – surface attack. Type Symbol: M – guided missile. *(Missileer's Heritage)*

ground. Ground shock and ground motion studies from the nuclear weapons tests at the National Test Site indicated the design of the underground facilities was relatively straightforward.[2]

A follow-up report, the Air Force's Missile Site Separation study of 1959, took two approaches to determine the required level of hardening. The basis was a general Soviet threat with: (1) a warhead yield of 5 to 30 Mt; (2) a CEP of 1 to 2 nautical miles; (3) 80 percent reliability; and (4) an enemy-to-US missile ratio of from 1 to 10.

The first approach was if the attack was completed before missiles were launched, i.e., still protected in their silos. Site separation distance in this case was a matter of cratering and crater ejecta dispersal; cratering resulting in physical disruption of the silo and ejecta dispersal preventing the opening of the silo closure door.

The second approach concerned exposure time, defined as "that time during a missile's launch sequence and initial flight trajectory that is soft, herein considered to be vulnerable to 2 psi over pressure." An additional consideration in determining vulnerability during the exposure period was the sensitivity of the guidance system to thermal energy. The study found that exposure time for 2 psi overpressure or a thermal pulse of 100 calories/per centimeter[2] was about the same. This became more of an issue in the case of Atlas F and Titan I during elevation to the surface

David K. Stumpf, Ph.D., is a retired plant biochemist living with his wife, Susan, in Tucson Arizona. He has written three nuclear weapon histories, Regulus the Forgotten Weapon*, a history of the Navy's Regulus I and II cruise missiles;* Titan II: A History of a Cold War Missile System *and* Minuteman: a Technical History of the Missile that defined American Nuclear Warfare*, published February 2021. Dr. Stumpf volunteered at the Titan Missile Museum, Sahuarita, Arizona, as an historian and as a tour guide for 15 years. He was instrumental in the effort to gain National Historic Landmark status for the museum.*

Table I. Characteristics of Basing Systems With Recommended Separation Distances[a]

System	Site Hardness (psi)	Missiles/Site	Sites/Squadron	Exposure Time (minutes)	Separation Distance (nautical miles)
Atlas-Titan Silo Lift	100	1	9	5 to 7	14 to18
Titan-In Silo[b]	100	1	9	2 to 3	7 to 10
Minuteman[b]	100	1	50-100	0.5 to 1.5	5

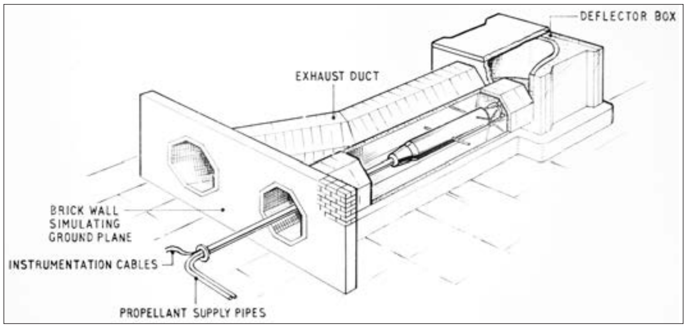
a) Adapted from "Missile Site Separation, October 1959," (Air Force Materiel Center History Office, Wright-Patterson AFB, Ohio) page vi; b) Original estimate was 100 psi, actual construction was to 300 psi hardening

and the subsequent pause until launch. Titan II and Minuteman would be only briefly exposed when the silo closure door was open prior to liftoff. In any case, once launched, missiles were still vulnerable during the early part of their trajectory (Table I).

The report concluded the survival potential of a hardened missile system was independent of site separation distance, if that separation distance was at least 4 to 5 nautical miles, as long as no limitations were placed on force expenditure time.[3] Implicit within the report was that underground basing offered the best and most cost-effective protection against air blast and ground shock. Silo-lift, surface launch, was the interim solution for Atlas F and Titan I, since neither airframe had been designed to withstand the severe acoustical energy environment of in-silo launch. Was in-silo launch even feasible?

In May 1956, a preliminary study by Aerojet General Corporation engineers determined that underground basing combined with in-silo launch was theoretically possible, but further investigation was dropped due to costs. Parallel research as part of the Blue Streak IRBM program in Great Britain confirmed, in a September 1958 report, the

Construction of the 1/6th scale Titan II in-silo launch test facilities at Aerojet, Azusa, California. The facility was built and the testing completed in a 60 day period. Aerojet opted for a W-shaped deflector with cascade vanes to direct exhaust away from the silo opening, preventing entrainment of exhaust products. *(Courtesy of Rollo Pickford)*



British in-silo launch test facility, circa 1958, which validated the feasibility of basing the Royal Air Force Blue Streak intermediate range ballistic missile in underground silos. The British opted for a J-shaped deflector. Blue Streak was not deployed. ***(British National Archives)***

validity of Aerojet's theory. Both the British scientists and the Aerojet engineers used 1/6th scale models to demonstrate the feasibility of in-silo launch. Work resumed on the Aerojet study with the first test firing conducted on June 6, 1959. Thirty-six tests later, on March 7, 1961, a modified Titan I missile, VS-1, strengthened to withstand the acoustical energy environment of in-silo launch, completed a fully successful captive fire test at Vandenberg Air Force Base. The same missile, VS-1, flew successfully on May 3, 1961, verifying the in-silo launch concept.[4]

Ballistic Missile Shock Isolation Systems

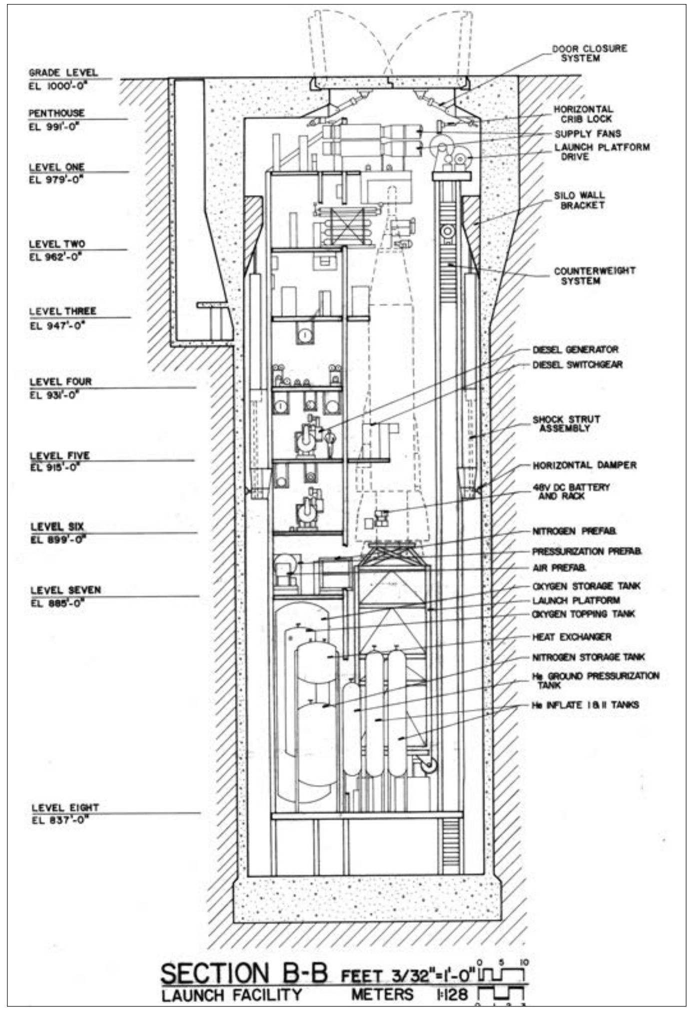
While the Atlas F and Titan I shock isolation systems did not directly support the missile airframe, the lessons learned in the silo-lift design contributed to the true missile shock isolation systems used with Titan II, Minuteman, and Peacekeeper.

Silo-Lift: Atlas F (1962-1965)

The Atlas F silo, measuring 52 feet in diameter and 173.5 feet deep, housed an octagonal steel structure called the crib, which measured 150 feet tall, 49 feet point-to-point, with eight floor levels. The crib housed the missile lift system, the liquid oxygen plant, propellant storage tanks, environmental control systems, guidance alignment, generators, and hydraulic systems. The crib also stored missile test, checkout, countdown, and launch equipment. The missile itself rested vertically on the silo launcher platform housed in the 21-foot square missile enclosure.

The shock isolation system protected the entire crib structure, which weighed approximately 900 tons.[5] Shock isolation of individual pieces of equipment was considered but discarded because of the large amount of rattle space required between the pieces of equipment. Isolating the entire crib structure facilitated use of standard equipment. Developing new equipment that could be hard mounted and withstand the anticipated shock was deemed too costly and time-consuming.

The crib was supported, and shock isolated, by four pairs of pendulous, 64-foot-long springs, known as shock isolation struts, equally spaced on the periphery of the octagonal crib.[6] The lower end of each strut was attached to the crib at Level 6, a few feet below the crib's center of grav-

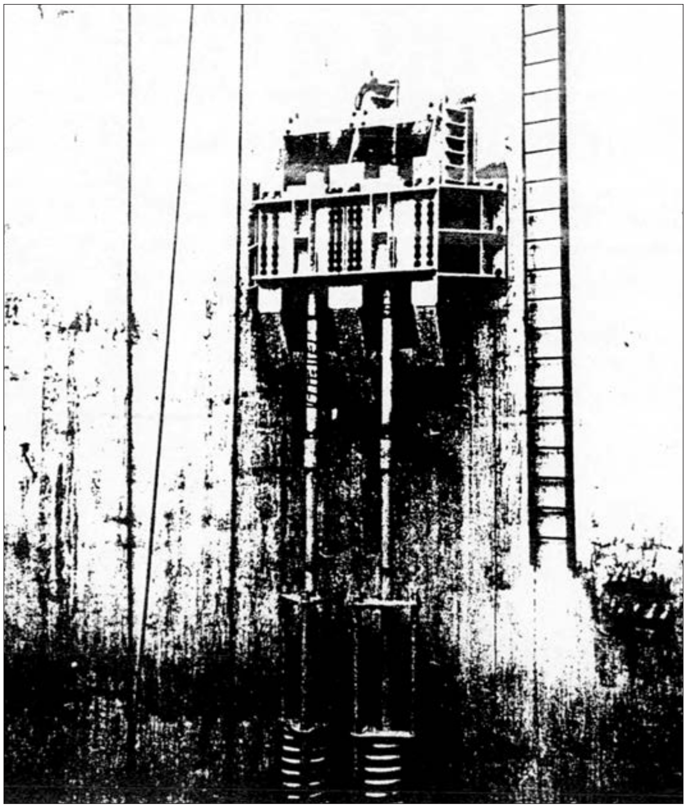


Atlas F silo cross-section. The shock isolation system was installed upon completion of fabrication of Level 6 structural steel. ***(Historical American Engineering Record)***

ity. The upper end was attached to the silo wall at Level 2, approximately 15 feet below the silo roof. Each strut spring element was composed of seven decks of springs, three sets of springs per deck, mounted in series around a common compression rod. The outer spring, approximately 2 feet in diameter, was made from 3 ½ inch diameter chrome molybdenum spring steel stock.

The spring element provided vertical shock attenuation of approximately 6 inches in response to a peak vertical acceleration of 0.4g, as dictated by the missile structure. Horizontal attenuation of a peak horizontal acceleration of 0.4g was provided by the pendulum action of the shock struts. Vertical dampers were located on each strut near the top coil spring, and horizontal dampers were located between the silo crib and silo wall at the lower point of attachment for the shock struts. Although the RP-1 fuel was stored on board the missile, a horizontal rattle space of 18 inches allowed for the anticipated pitch motion and shift of the center of gravity when loading the oxidizer. Hydraulically operated positioning and locking mechanisms enabled alignment of the crib prior to elevating the missile to the surface for launch.

This design made it difficult to increase the system weight or shift the center of gravity, because the load ca-

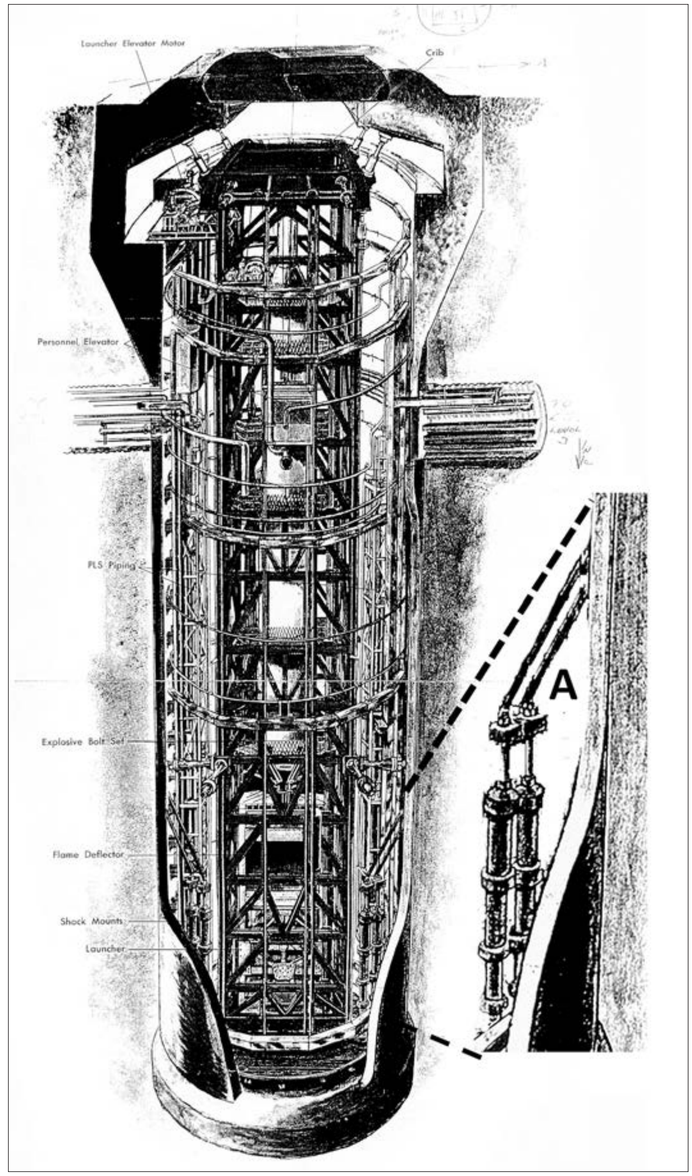


(Above) Atlas F: Upper wall bracket for crib shock isolation system. The point of attachment was at Level 2. The bracket was over 6 feet tall *(Atlas-missilesilo.com)* (Below) Atlas F: Lower crib shock isolation system bracket attachment to crib structure at Level 6. Note the workers on the beam below the leftmost spring set. *(Defense Visual Information Distribution Service)*

pacity of the springs was fully utilized. Seemingly minor changes, such as a lighter weight alloy for fuel storage tanks, necessitated the addition of ballast to maintain the crib's center-of-gravity position. Spring failures occurred in some of the first installations due to poor quality control during manufacture.[7]

Silo-Lift: Titan I (1962-1965)

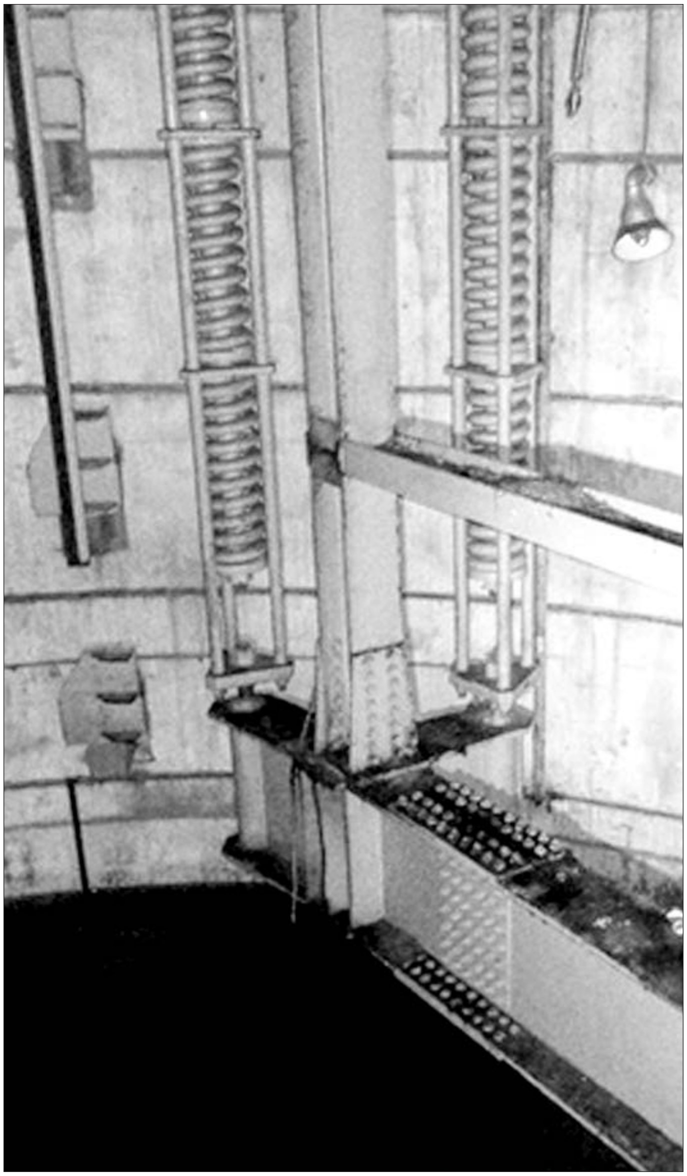
The Titan I silo was 161 feet deep, including a 6-foot-thick foundation, with an interior diameter of 40 feet. Like



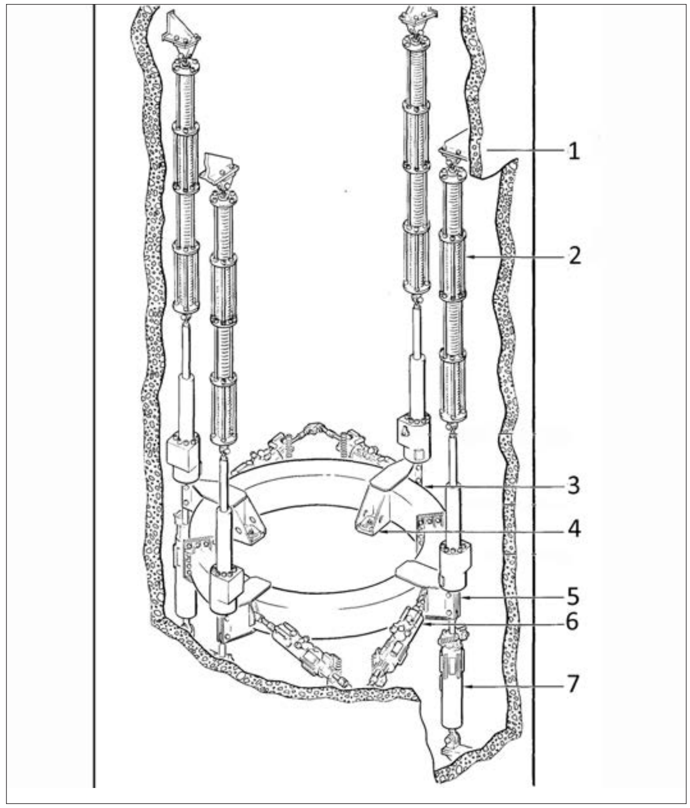
Isometric illustration of a Titan I silo. Unlike Atlas F, the shock isolation system was located in the lower half of the silo and connected to the base of the crib structure. The illustration is somewhat misleading, the brackets (A) are also attached to the silo wall. *(Courtesy of Lee O'Connor)*

Atlas F, the silo housed a crib structure, 132 feet tall and 21 feet wide, weighing 490 tons including the missile on the elevator launch platform. Like Atlas F, the crib structure housed the support equipment for the missile and the silo. Engineers evaluated several shock isolation systems for the crib, such as base- or side-mounted spring assemblies for improved pitch stability. Both systems had the drawback of requiring a re-leveling system to compensate for any permanent tilt of the silo following a ground shock.

A pendulous spring system was again used. It consisted of eight 16-foot springs (four 49-inch-long, 22-inch-diameter subassemblies) attached at the corners of the crib base and to a silo wall bracket 32 feet off the silo floor. The vertical center of gravity was above the spring attachment level on the crib but well below the missile center of gravity because of the elevator weight. When the vertical center of gravity of the missile and crib structure is higher than the shock isolation system's point of attachment on the crib, pitch sta-



Shock isolation springs attached to the base of Titan 1 crib structure. The rest of the platform has been salvaged. *(Courtesy of Groundskeeper Pete at www.chromehooves.net)*



Titan II shock isolation system components: 1) attachment to the launch duct wall at silo Level 4, 4 places; 2) spring suspension strut assembly, 4 places; 3) thrust mount, 4) missile support arm and attachment point, 4 places; 5) thrust mount suspension arm, 4 places; 6) horizontal damper assembly, 4 places; 7) vertical damper assembly, 4 places. *(Courtesy of Titan Missile Museum)*

bility is more often difficult to attain. Initial studies indicated it would be necessary to cross-couple the vertical springs to manage pitch stability. When the ground shock criteria were reduced, the spring elements were made stiffer which eliminated the need for a coupling mechanism. Coil spring elements were chosen over pneumatic springs because of their high reliability. Hydraulically operated crib locking mechanisms at the top of the crib securely positioned the crib prior to raising the missile to the surface.[8]

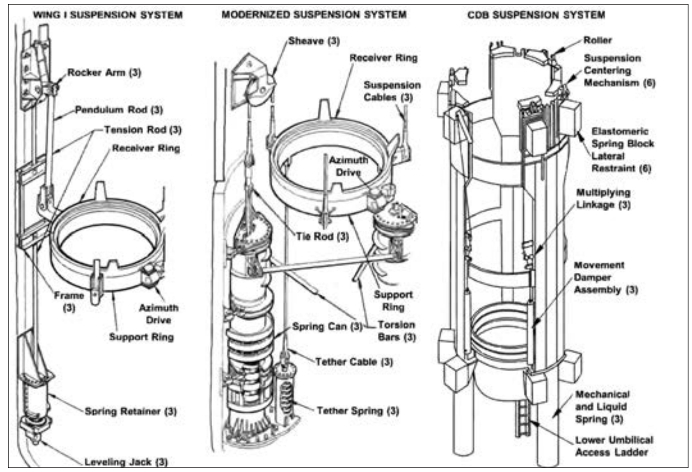
In-Silo Launch: Titan II (1963-1987)

The Titan II launch concept differed significantly from Atlas F and Titan I in that the missile was launched from inside the silo. This eliminated the need for the silo crib and its shock isolation system. The silo, 55 feet in diameter and 145 feet deep, housed the equipment area between the silo wall and the launch duct, which was a cylinder 26.5 feet in diameter. The missile rested inside the launch duct on the 11.5-ton thrust mount which was shock isolated using four 35-foot pendulous springs. Each spring assembly consisted of four coil springs, 20 inches in diameter, mounted in series. The top of the spring assemblies attached to the launch duct wall at the midpoint of the Stage I airframe and, at the bottom, to the thrust mount.

The fully fueled missile's center of gravity was 10 feet above the shock isolation system's point of attachment to the launch duct wall.[9] Use of the horizontal dampers at the thrust mount eliminated the potential for pitch instability. Vertical and horizontal dampers were attached to the launch duct wall and the thrust mount, respectively, and also locked the thrust mount into the launch position.

The peak acceleration limits were 0.8 g vertically and 0.1 g horizontally. Predicted vertical motion was 12 inches maximum and 4 inches horizontally. Oscillations due to a nearby blast were damped within 60 seconds to allow for thrust mount lockup and launch. The shock isolation system design was such that the missile was returned to within plus or minus 0.25 inch of vertical neutral position, plus or minus 0.4 inch of neutral horizontal position, and 0.25 degree of verticality for the missile axis.[10] Requirements of the optical azimuth alignment system for aligning the missile guidance inertial platform necessitated those exacting specifications.

The Titan II first stage engine took approximately one second to reach 77 percent thrust at which time two 1.8-second timers started. When they timed out, four explosive



Comparison of the general features of the three Minuteman MSS. ***(Courtesy of Boeing Corporation)***

hold-down bolts fired, and the missile lifted off of the thrust mount. Aerojet engineers knew from extensive testing that if the first stage engines reached 77 percent thrust, they would go on to reach full thrust. To provide a stable platform for launch, the shock isolation system was locked prior to engine ignition. In the locked condition it was considered "soft" because it no longer provided protection against nearby blast.

One of the more interesting tests involving a complete Titan II airframe was the "twang" test conducted on February 11, 1963 at Launch Complex 395-D, Vandenberg Air Force Base. Airframe N-3 (60-6810) had been installed in the silo on November 29, 1962. After completion of full-scale propellant transfer system design verification tests, which lasted from December 12 to December 27, 1962, the missile propellant tanks were purged and filled with water. On February 11, a series of tests, nicknamed "twang" tests, began evaluating the missile shock isolation system under dynamic conditions. The missile shock isolation system thrust mount, with the water-filled missile in place as if ready to launch, was pulled down or to the side of the silo with chains held by explosive bolts. The bolts were fired, quickly releasing the missile, simulating ground shock conditions from a nearby explosion being mitigated by the missile shock isolation system.

Elmer Dunn, the Martin Marietta Company engineer in charge of the "twang" tests, found that while the tests verified the ability of the missile shock isolation system to dampen thrust mount movement and then lock up for launch, a mechanical means of spring centering was needed. In addition, the spreader jack for unlocking the dampers—the mechanisms that locked the thrust mount into a rigid configuration to support actual launch—proved to be structurally insufficient. Dunn reported that adjustments to permit load equalization were difficult and that refurbishment after launch, at the Vandenberg sites, would be time consuming and costly unless components were better protected from the effects of the engine exhaust.

The "twang" testing resulted in major system changes to all sites, including spring centering devices and new spreader jacks for unlocking the dampers. Engineers designed ratchet-type positive shuttle lock mechanisms to prevent the dampers from unlocking due to vibration during the time between engine ignition and lift-off. A special lubricant was found to facilitate damper unlocking and inhibit corrosion. Since the original protective devices for the thrust mount shock suppression system springs were inadequate, Dunn's team built reusable fiberglass cocoons that proved to require little maintenance. These cocoons were only used at the three Vandenberg sites.[11]

In-Silo Launch: Minuteman IA 1961-1969

Minuteman IA was only deployed the at Malmstrom Air Force Base, Montana. The Minuteman IA suspension system (MSS, also referred to as Figure A 1204) used the pendulum system but in a significantly different design. The original design had 50-inch-long pendulum rods with the launch tube wall attachment point below the missile's center of gravity. Tests showed coupling of horizontal and vertical movement, which was largely negated by moving the point of attachment nearer to the missile center of gravity. Three 100-inch-long pendulum rods connected the missile support ring to three rocker arms. The other ends of the rocker arms were connected by tension rods to three vertical coil springs housed in cans anchored to the launch duct wall 300 inches below the rocker arms. The three pendulous rods had universal joints at each end and were spaced at 120-degree intervals around the missile.

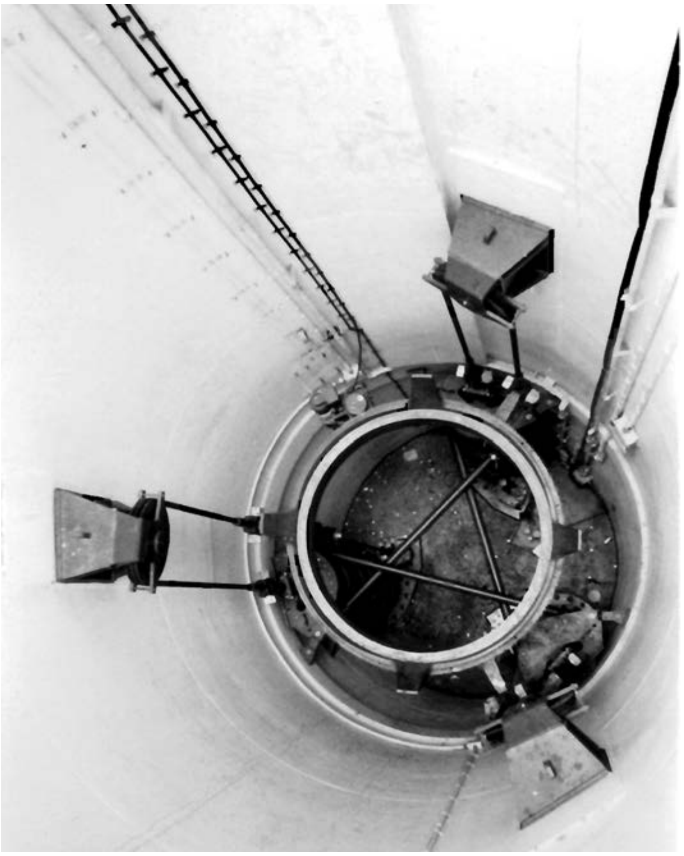
Unlike Titan II, the Minuteman IA MSS did not have horizontal or vertical dampers nor hold down bolts. Vertical oscillations were damped out in approximately six seconds while lateral oscillations took considerably longer, but within the five-minute limit requirement, limiting the ability to launch immediately after an attack. Hold down bolts were not needed because the missile literally leapt off the support ring at 0.34 seconds after ignition due to the much more rapid acceleration found in solid propellant motors compared to liquid propellant engines.[12]

The peak acceleration limits were 0.8g vertically and 0.1g horizontally, with a vertical displacement limited to 4.3 inches below the rocker arm and snubber block assembly. Horizontal motion was limited to 6 inches by the rattlespace. Snubbers were added to prevent the base support ring lofting after missile liftoff and contacting the first stage motor nozzles.[13]

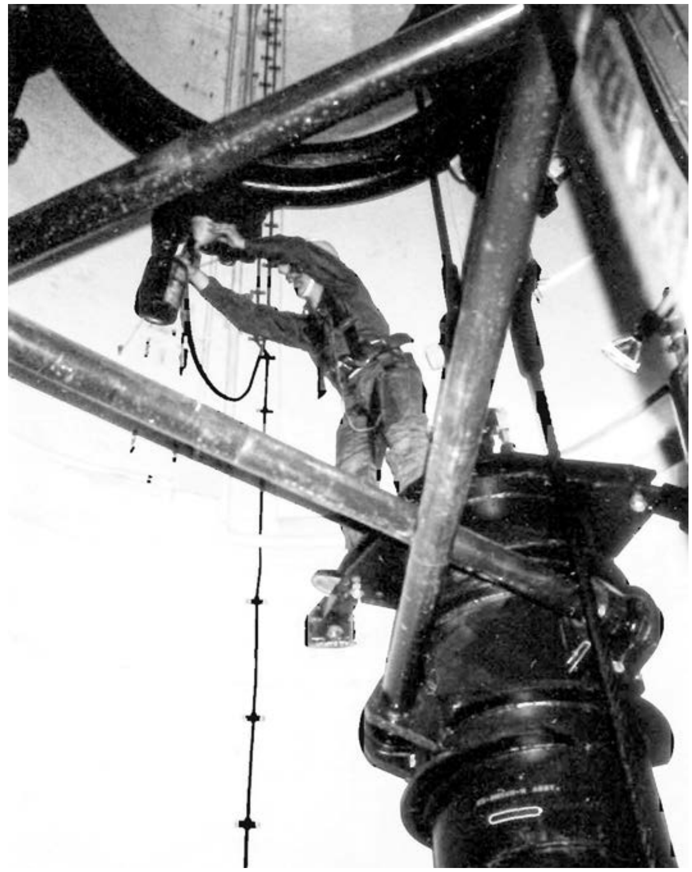
The MSS was designed to return the missile, after a ground shock, to within a 15-minute angle from the vertical—within 0.5 inches of the launch tube centerline in the plane of the missile base—and the missile elevation was to be maintained within plus or minus 0.25 inches. As with Titan II, these impressive specifications were required to keep the light beam from the optical azimuth alignment system, located in the Launcher Equipment Room Level 1, centered on the alignment window in the missile guidance system section.

In-Silo Launch: Minuteman IB, II and III (1963-1975)

The original hardening specification of October 1959 for the Minuteman launch facility was 100 psi. In April



Overhead view of Wing II-VI and 564th Strategic Missile Squadron MSS. Note the crisscrossing torsion bars. *(Library of Congress)*



The torsion bars and spring cans for the Wing II MSS. The airman is servicing the Azimuth Alignment Drive motor. The spring cans were 2 feet in diameter and 12.5 feet tall. The crisscrossing torsion bars were 3.86 inches in diameter. *(Library of Congress)*

1960, the Air Force changed the hardening specification to 300 psi. The launcher closure thickness was increased from 24 to 40 inches and a shock mounted floor added in part of Level 1 of the Launcher Equipment Room while still maintaining the deployment schedule for Wing I but the MSS was not modified. Evaluation of the geological formations in the Malmstrom area indicated the original MSS was sufficient, but the design for the remaining wings was modified and identified as Figure A 1322.[14]

A cable and pulley system, while retaining the same vertical dimension, replaced the pendulous rods, rocker arms, and snubbers (see **left** and **above**). The vertical spring stiffness was reduced to 4,500 pounds per inch to meet the new hardness specifications. Torsion bars were added between the vertical compression spring cans to increase pitch stability. The bars were mounted on the suspension spring cans and joined to tie-rod connecting assemblies in such a way that the bars furnished no resistance to vertical motion if the three suspension cans were moving in unison. Ground movement, which would tilt the base ring and thus the missile, would also exert a twisting moment on the torsion bars (**above right**). The bars resisted that force, providing pitch stiffness and stability.

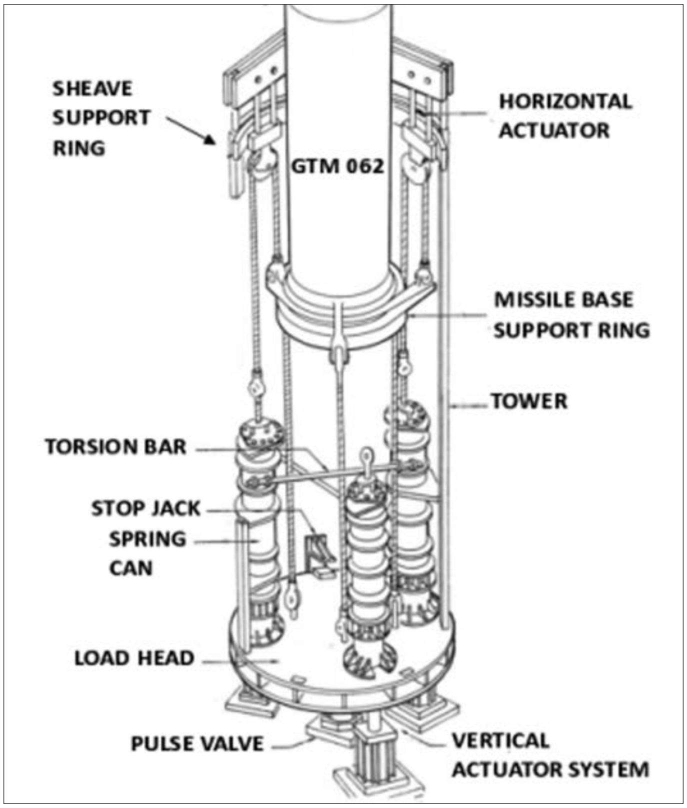
The vertical displacement was limited to 12.5 inches and the horizontal rattle space was limited to 6 inches. The change in the vertical spring stiffness also required addition of three tether cables and springs to prevent lofting of the base support ring at launch.[15]

Although the dynamic responses of the MSS had been determined mathematically, physical verification was needed. From June to August 1967, the development of equipment for the tests took place using a Wing VI Figure A 1322 MSS, minimally modified to fit in the confines of the Boeing Engineering Development Laboratory in Seattle. Three 12-inch-bore hydraulic actuators were used at the base of the simulated launch tube to generate vertical ground shock motion. Horizontal side shock was similarly applied at the top of the launch tube. Once the techniques were worked out, testing moved to the full-scale launch tube facilities at the Seattle Test Program III test building, where testing was completed, and performance verified in May 1968.[16]

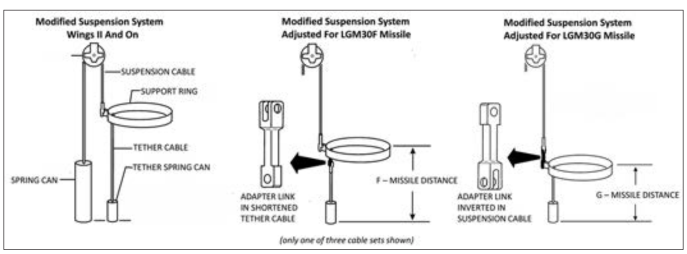
To accommodate the longer Minuteman III missiles (LGM30G) using the launchers built for the earlier and shorter Minuteman IA, IB and II airframes, the MSS had to be lowered from its original position. Rather than use new, longer suspension cables and shorter tether cables, a forged steel link was used to either extend suspension cable length for Minuteman III installations or extend the tether cable for Minuteman II (LGM30F) emplacement. [17]

In-Silo Launch: Minuteman II, III Upgrade Silo Program (1973-Present)

On April 21, 1967, the Minuteman program reached its 1,000-missile force level when the 564th Strategic Missile Squadron achieved combat readiness. Six months later,



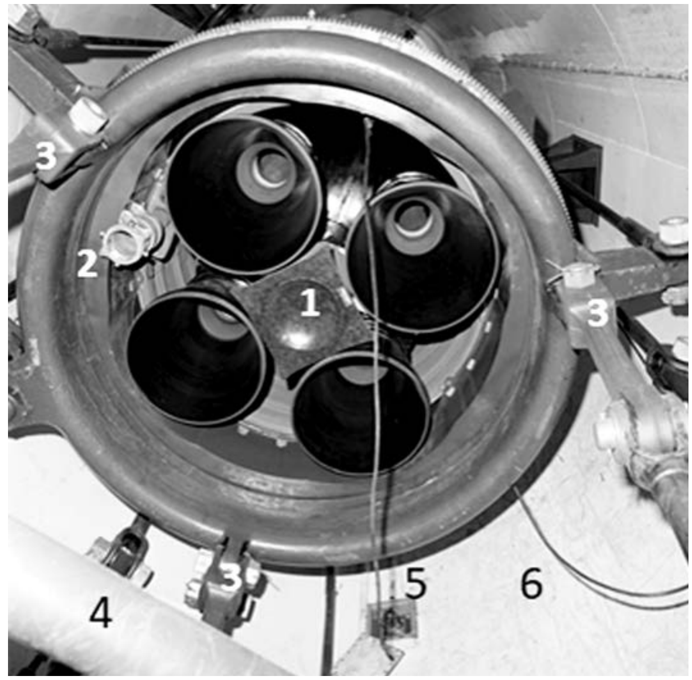
(Above) Dynamic response equipment arrangement for testing the Wing II MSS in 1968. *(Courtesy of Boeing Corp.)* (Below) The simple solution for accommodating Minuteman II and Minuteman III in the Wing II MSS. The use of the link meant that only the tether cable had to be exchanged to accommodate either missile. *(Courtesy of Boeing Corp.)*



on October 4, Secretary of Defense Robert McNamara, concerned with the threat posed by the new Soviet SS-9 ICBM, directed the Air Force to explore development of a Hard Rock Silo system for Minuteman III. On October 30, the Hard Rock Silo development program was approved.[18]

The Air Force wanted a launch facility that could withstand a 3,000-psi ground shock as well as protect against higher levels of radiation and electromagnetic interference. The new facilities would be designed to accommodate both Minuteman III and its eventual replacement, initially designated as WS-120A. In June 1970, after three years of debate within both the Pentagon and Congress, the Hard Rock Silo concept, which had reached the subscale and full-scale test stage with favorable results, was abandoned due to escalating costs and resulting delays. Instead, the Upgrade Silo program would improve the hardness of the existing "soil silo" facilities.[19]

Boeing, Strategic Air Command, and other Air Force records from that period conflict on the actual genesis of the current MSS. On June 22, 1971, Boeing was notified of its selection to provide the new MSS as part of Upgrade



Details of Wing II missile suspension system and Minuteman II Stage I: 1) base heat deflector, 2) lower umbilical connection, 3) forged cable adapter links, 4) torsion bar, 5) grounding cable, 6) work cage control cable. The presence of the forged steel links in the tether cable visible on the left and right indicates that this is a Minuteman II installation. *(Library of Congress)*

Silo.[20] Whether the design was from the Hard Rock Silo experiments is unclear because Boeing had been given a contract for the Hard Rock Silo MSS a year earlier.

The new system, commonly referred to as the Command Data Buffer (CDB) MSS and still in use today, has the missile installed in the Missile Support suspended in the launch facility. The Missile Support consists of five major components:

1. Three attachment bracket assemblies suspend the isolator and missile support structure's assemblies from the launch tube wall.

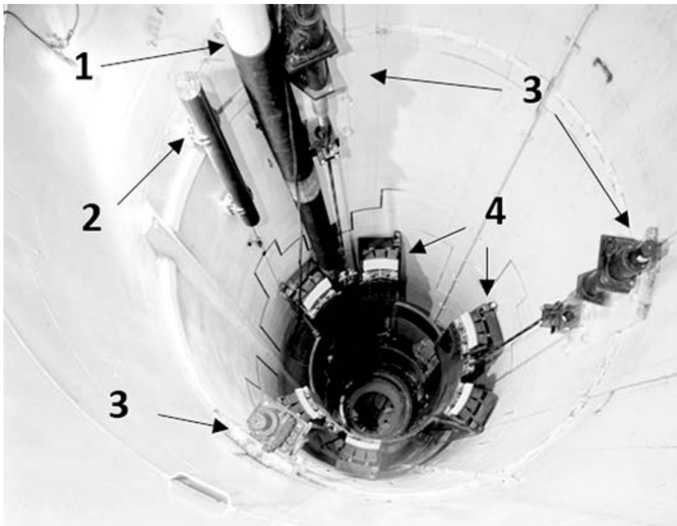
2. Three isolator assemblies support the missile support structure assembly and provide attenuation during attack induced ground shock environment.

3. The missile support structure assembly supports the missile assembly at the missile skirt through the Adapter Ring, Missile Support (ARMS)[also known as the missile base adapter ring], and with lateral restraint devices at the forward "Y" joint of the Stage I motor.

4. The lateral restraint devices are released prior to launch using explosive devices and position the missile for fly out. Missile support structure assembly to launch tube restraints are provided to attenuate the horizontal ground shock environment.

5. A tether assembly is attached between the launch tube floor and the bottom of the missile support structure assembly to prevent interference of the missile support with the missile fly out.

The MSS, a steel cage structure, weighs approximately 40,000 pounds, supports a load of between 74,000 to 79,600 pounds, and measures 8 feet in diameter and 38 feet in length, exclusive of the suspension and tether cables.[21]



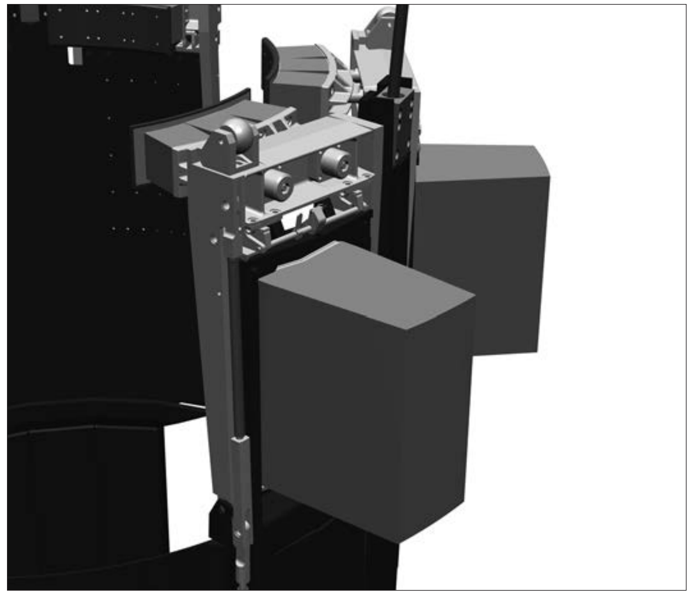
CDB MSS: 1) NCU lower umbilical snubber, 2) launch tube heater conduit, 3) MSS attachment points to launch tube wall, 4) upper lateral restraints, six places. *(Library of Congress)*

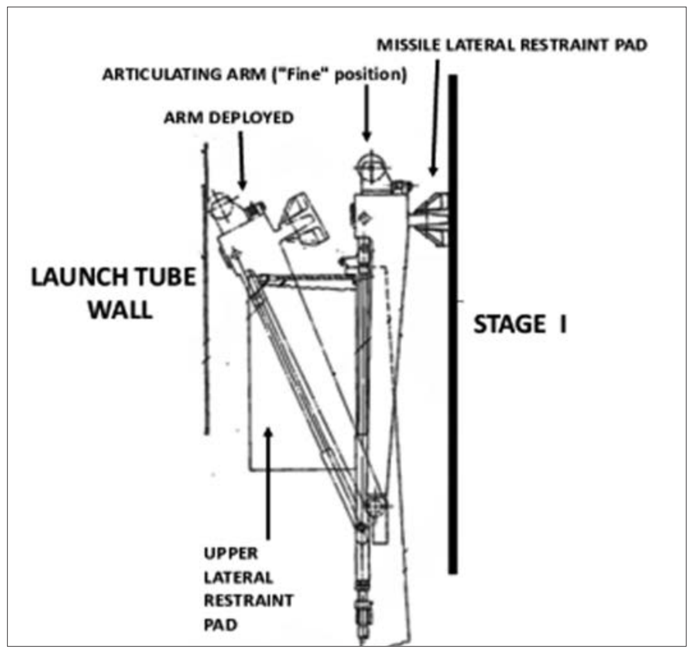
Three vertical legs spaced 120 degrees apart are connected at the top and middle by ring elements. The legs are bolted at the bottom to the base support assembly, which retained the receiver ring and azimuth alignment drive from earlier MSS designs. At the top of each vertical leg, the suspension cable slides through a cable guide. The upper end of the 1.5-inch-diameter steel cable attaches to the launch tube wall at the level of the lower Launcher Equipment Room floor. The lower end of the cable attaches to a shock isolator consisting of an actuator connected to a mechanical spring in series with a liquid spring. The isolators are attached to the base of the cage.

Under nuclear attack or seismic disturbance conditions, the liquid spring responds much more quickly to downward ground motion than the mechanical spring. When the system experiences a vertical downward shock, such as the vertical air induced shock from a nuclear blast, the suspension cables tend to become slack. The liquid spring exerts immediate downward force on the suspension cable to prevent any slack from developing. The mechanical spring recovers and again places its force on the suspension cable.[22] Tether cables are also attached to the base of the cage to prevent lofting of the MSS and uses a crushable honeycomb material to reduce shock as the tether cables come under tension during missile launch.

The missile is emplaced within the steel cage structure, resting on the ARMS, like the base support ring used in the earlier system.[23] Six polyurethane foam blocks attach circumferentially to the outside of the structure at the upper and lower ring levels to control lateral movement of the MSS during ground shock response and missile launch. These blocks do not fit tightly; a nominal launch tube clearance of 1.5 inches exists between the outer face of the upper blocks and the launch tube wall, and 2.25 inches between the lower blocks and the wall. The outer surface of the block have a Teflon face to reduce friction upon contact with the launch tube wall.

Hinged at the top of the cage structure are six articulating arms, also known as the lateral restraint system. In the non-deployed position, the polyurethane foam blocks on the inner side of the articulating arms provide lateral restraint to the missile within the cage. The arms are deployed just prior to a missile launch to reposition the MSS in the center of the launch tube. In the deployed position, the articulating arms also provide lateral restraint to the MSS during launch.

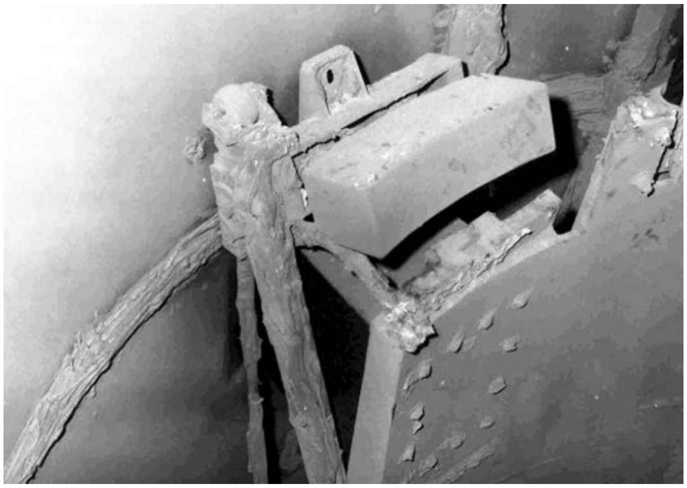


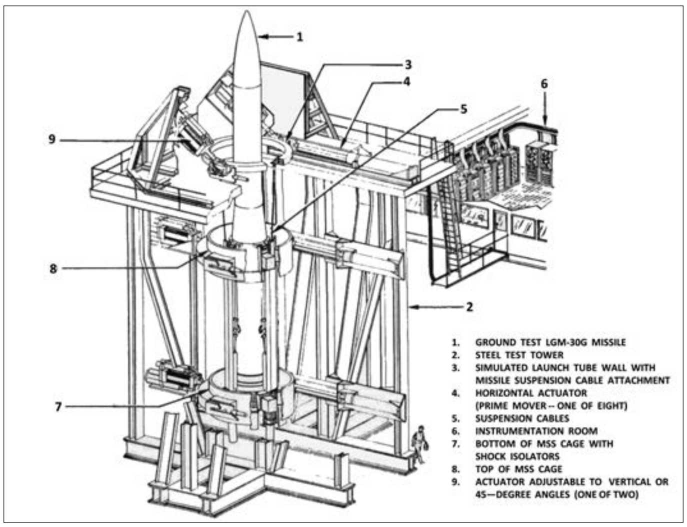


(Top) Upper lateral restraint pads and articulating arm mechanism. The upper lateral restraint pads would only be in this position if a missile was emplaced. *(Courtesy of Harold Klingensmith)* (Above) Detail of articulating arm mode of action. *(Courtesy Harold Klingensmith)*

The frustum below the base support ring reduces pressure in the base region of the missile during launch.[24]

Dynamic testing of the full-scale CDB MSS began at the Boeing Developmental Center in Seattle in 1971, with completion in 1972. The 62.5-feet-tall test structure weighed 1.8 million pounds. A 2-million-pound concrete slab on top of 45 pilings supported it. The structure included three drive rings: the top ring located at the height of the MSS support cable attachment point in the launch





(Top) Upper lateral restraint in deployed position against launch tube wall after a successful launch. The pads are replaced after each launch. *(Boeing Corporation)* (Above) Wing V MSS Dynamic Response Facility. Extensive testing was done prior to the first launch from the new MSS in January 1973. *(Courtesy of Boeing Corporation)*

tube wall; the middle ring at the point of the top of the articulating arms which restrain the missile at the forward "Y" joint of the Stage I motor; and the lower ring at the point of the lower restraint blocks. The upper ring had two hydraulic actuators that could be set at 0, 45, or 90 degrees to the horizontal. The middle and lower rings each had one actuator. Acceleration at the top ring could be as high as 160 Gs and a velocity as high as 450 in/sec. Shock pulses could be positive or negative or cyclic.[25]

Prior to ignition, the missile is supported by the MSS. The missile is held to the MSS by gravitational forces (vertical) only, and lateral relative motion is inhibited by skirt index pins (effectively about 2.67 inches long). Clearance is about 2.25 inches between the lower foam blocks and the launch tube (LT) wall.

At ignition, the missile starts to rise as thrust builds. The first and consequent motion are essentially vertical. Missile exhaust gases are turned by the LT bottom and flow back up alongside the missile, generating lateral forces and tilt moments on the missile mount. An upward gas flow is also applied to the mount. The thrust buildup transient causes a pressure wave that is reflected by the LT bottom and continues up the LT. The frustum was added to the MSS to prevent a large pressure transient at the nozzle exit plane (thereby preventing catastrophic asymmetric flow separation in the nozzle).

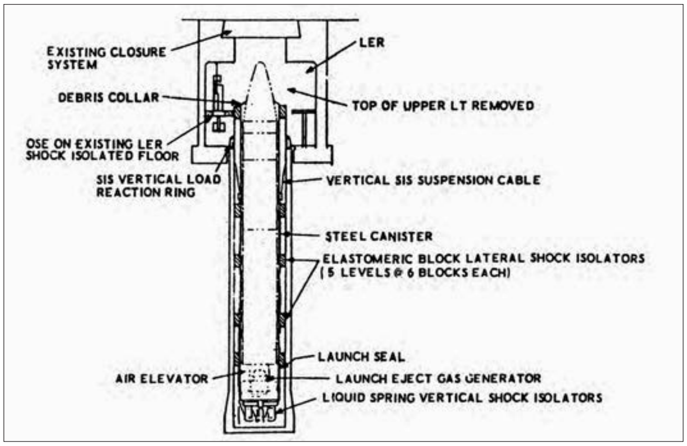
As thrust continues to develop, the missile in the MSS continues to gain vertical velocity. At about 0.34 seconds after ignition, the missile skirt lifts off the mount, but the vertical separation rate is quite small (and lateral motion is inhibited by the pins) until about 0.43 seconds after ignition (vertical travel 23.5 inches) when the tether system comes into play. The tether system imparts an essentially vertical (downward) impulse to the MSS, causing its velocity to decrease rapidly. The nozzles exit the base support ring at about 0.57 seconds after ignition. The effective dwell time, from the time the skirt lifts off the pins until the nozzles exit the ring, is about 0.12 seconds.

The missile continues to accelerate upward while the MSS is held at a nearly constant elevation by the tether system. Gas dynamic forces and moments, plus the structural forces arising when the lower foam blocks impact the LT wall and/or when the upper centering arms contact the LT wall, cause significant lateral motions of the MSS. After the nozzles exit the MSS, the missile continues to accelerate upward. The nozzles will rise above all LT hardware at about 1.85 seconds after ignition.[26]

In-Silo Launch: Peacekeeper (1985-2005)

Peacekeeper missile development began in 1971 as the MX follow-on missile to replace Minuteman III. Concerns about the vulnerability of Minuteman launch facilities to increasingly accurate Soviet ICBMs led to investigation of a multitude of basing options during MX development. On November 22, 1982, the Reagan administration announced selection of the "dense pack" deployment mode and formal naming of the program as Peacekeeper. The administration asked for deployment of 100 missiles. Facing strong congressional resistance, President Reagan formed the President's Commission on Strategic Forces, known as the Scowcroft Commission, to review the US strategic modernization program. Focusing on possible alternatives for the future of ICBM forces, the commission published its findings on April 6. 1983. It recommended basing 100 Peacekeepers in modified Minuteman launch facilities at F. E. Warren Air Force Base, Wyoming. Warren AFB was selected for two reasons: (1) the soil structure was the best of all the wings and (2) the launch tubes at Warren were 10 feet deeper than at Wings I-IV, as was the case at Grand Forks (Wing VI) and the 564th Strategic Missile Squadron at Malmstrom AFB, and able to accommodate the longer missile. Congress, still unsatisfied about the need for Peacekeeper, authorized deployment of just 50 missiles at F. E. Warren AFB.[27]

The Peacekeeper missile measured 70.9 feet long, 92 inches in diameter, and weighed 196,000 pounds. Given the Minuteman launch tube diameter of 144 inches, that left an annulus of 26 inches, compared to 39 inches with Minuteman, which was insufficient for hot launch. The solution was a technique called cold launch, where the missile was



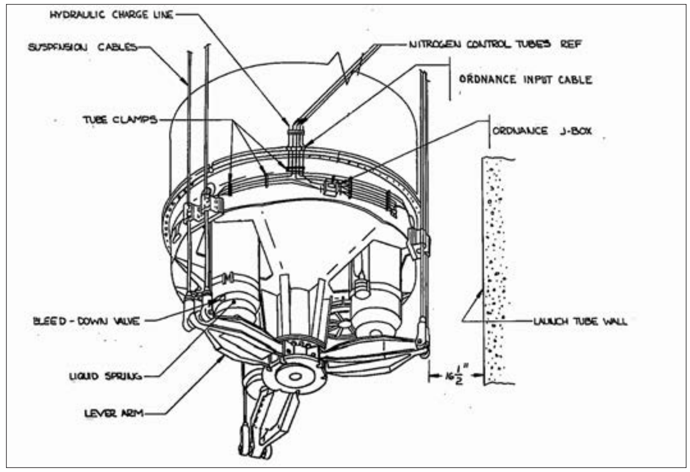
Cutaway view of a Peacekeeper Launch Facility at F. E. Warren Air Force Base, Wyoming. ***(Courtesy Westinghouse Electric Corporation)***

ejected from a steel canister suspended in the launch tube and ignited approximately 100 feet above the ground. The canister system supported the missile in the launcher, provided environmental protection, lateral and vertical shock protection, provided a means of launching the missile, guided it during launch, and enabled lowering or raising the missile for maintenance. The canister had an outer diameter of 108 inches and length of 68.2 feet.

The vertical shock isolation system design for Peacekeeper was on the surface quite similar to the current Minuteman III MSS with the canister replacing the cage structure. However, in the decade since the design of the latest Minuteman III MSS, Soviet advances in accuracy and throw-weight meant a more severe ground shock environment coupled with probable multiple attacks. The ground shock that the system is protected against consists of two components, the vertical air induced (AI) component and a horizontal ground induced (DI) seismic component. For close detonations, the AI will arrive first, for distant detonations the DI will outrun AI. The AI is the most severe of the two. The heavy steel canister and much heavier missile (196,000 pounds versus the 79,000 pound Minuteman III) coupled with the constraint of installing this system in the existing Minuteman launch tube further complicated the issue.[28]

The early studies showed that optimizing MSS response around a single set of ground motion parameters, as in past practice, would provide insufficient protection. The current state-of-the-art liquid spring/damper systems were not designed for multiple ground shock protection. What was needed was a liquid spring/damper that could produce a constant damping force, regardless of ground shock velocity, above the selected velocity threshold. Fortunately, engineers at Boeing were able to develop a liquid spring passive load control damper and full-scale drop load testing verified the design.[29]

Unlike the complex crib structure used with Atlas F and Titan I, the MSS for Peacekeeper was simply the canister and its vertical shock isolation system (VSIS). The MSS was not a pendulous system. The VSIS had two external components, one vertical and the other lateral. The vertical component protected both the canister and missile from vertical shock. The canister was supported inside the modified Minuteman launch tube at the base of the lower level of the



Details of the liquid spring actuators at the external base of the canister. ***(Author's Collection.)***

Launcher Equipment Room (LER) by six 1 7/8th-inch-diameter suspension cables (the upper launch tube was removed as part of the modifications). These cables, mounted in pairs at 120° intervals, were secured through the launch tube wall at the lower-level LER floor. Cable guides on the outside of the canister routed the cable pairs to three lever arms located at the base of the canister, two cables per lever arm. These lever arms were hinged at a center plate at the base of the canister and rested beneath three liquid spring isolators for vertical shock isolation of the canister. Prior to launch, a bleed down initiator triggered by squibs opened a valve in the liquid springs, lowering the canister to the launch tube floor to provide a massive base to support lofting the 196,000 pound missile during launch.

The second external system, the lateral shock isolation system, consisted of five levels of concentric ring's s of elastomeric foam blocks, six blocks per level. These isolators also stabilized the canister during missile launch ejection. A low-friction surface was affixed to the blocks at the launch tube wall interface to minimize resistance to sliding.

The Peacekeeper missile was further shock isolated within the canister by a longitudinal support assembly (LSA) and a lateral support group (LSG). The LSA supported and held the missile at the required axial position relative to the canister tube center line. Consisting of two mechanical structures—an axial load structure containing a gimbaled-torsion subassembly—the LSA provided lateral translation of the missile in any radial direction relative to the canister. The axial load structure was the load path for tension and compression loads during axial shock loading. The gimbaled-torsion subassembly provided torsion stability of the LSA.[30]

The second internal shock isolation system, the lateral support group (LSG), consisted of nine rows of 12 pads per row on the first (5) and second stage (4) and nine pads in a single row on the deployment module. The pads served as shock isolation devices to prevent missile contact with the canister wall but were used primarily to stabilize the missile during launch as well as guides during the assembly of the missile at the launch facility. Cable assemblies secured the pads in position as the missile was assembled in the canister and served to keep the pads in place during ground shock. The LSG cable assemblies were fitted with two delayed-release mechanisms to automatically release the pad rows in a predetermined sequence after the missile emerged from the launcher and before first stage ignition.[31]

Summary

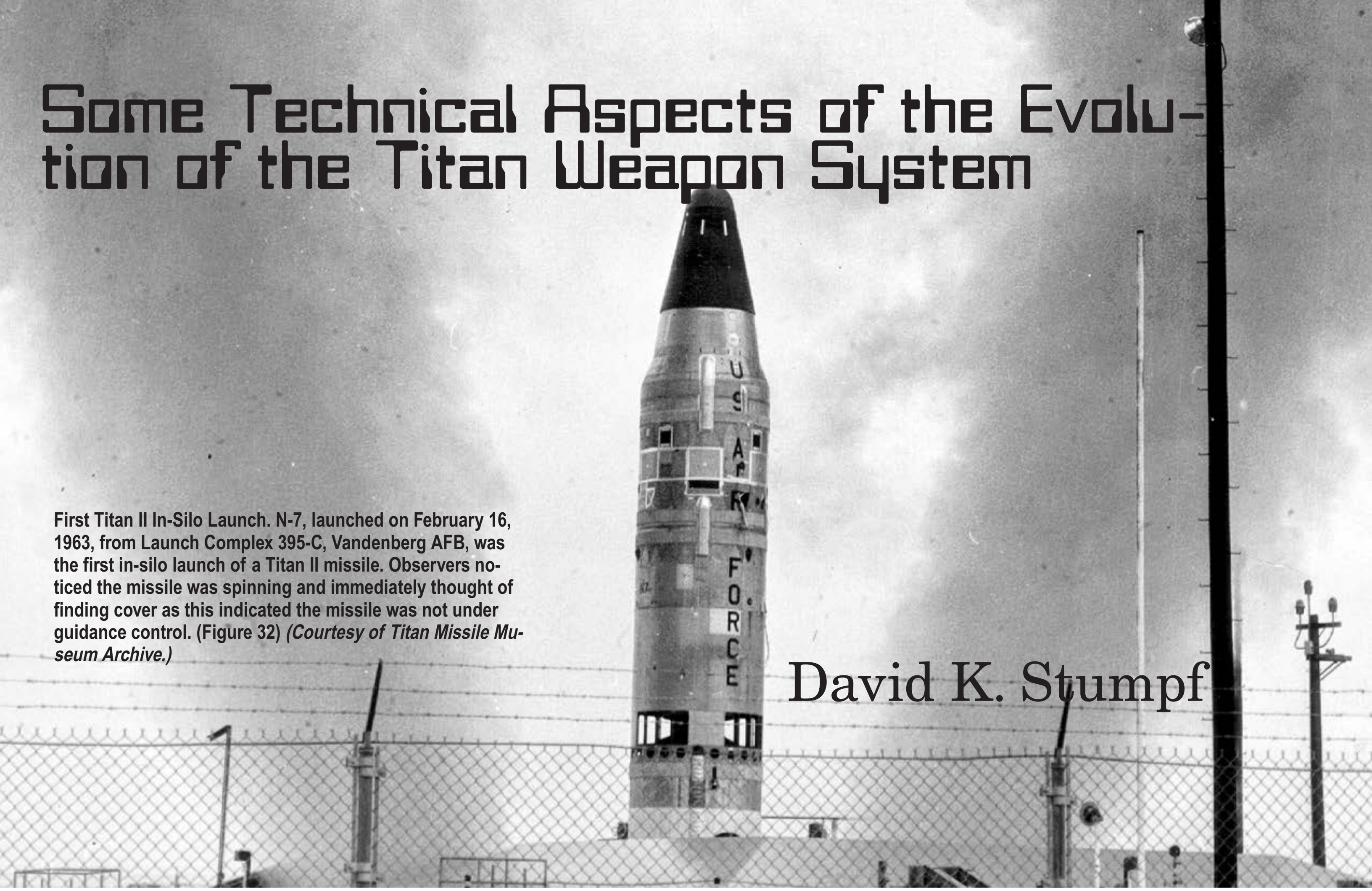
The urgent need for initial operational capacity led to the highly vulnerable above-ground options for ICBM basing. Next best was underground storage and surface launch, but the missile exposure time for loading the liquid oxygen on the surface caused concern. The ultimate solution was underground storage and silo launch.

Missile suspension system design came full circle, starting with the massive spring sets supporting the crib structure and missile launch platform for Atlas F and Titan I, to a high-tech version of the crib structure with the Peacekeeper canister system. ■

NOTES

1. Nalty, B., United States Air Force Ballistic Missile Programs 1964–1966, (Office of Air Force History, April 1966), redacted copy, Declassified Documents Research Service (DDRS), CK23496 54796, 4; Holm, R., Chronology of the Ballistic Missile Organization: 1945-1990, Vol. I, Narrative,(History Office Ballistic Missile Organization, August 1993), 76; Large , W., Ballistic Missile Hardening Study, 10 July 1958 (Air Force Materiel Center History Office, Wright-Patterson AFB, OH), 7-15.
2. The decision to move forward with Titan II was not made until May 1960 but consideration of launch site design had begun a year earlier.
3. Missile Site Separation, October 1959, (Advanced Planning Office, Deputy Cmdr. Ballistic Missiles, Air Force Ballistic Missile Division), 2-3, 9, 54-56.
4. Ricketson, B. W. A. and Smith, E.T. B., Work Supporting the Development of an Underground Launching System for Blue Streak, October 1958, Rocket Propulsion Establishment, Technical Note: 170, Air 2107 67, British Archives. The author thanks C. N. Hill for a copy of this document.
5. Wood, S. C., History the Office Area Office, US Army Corps of Engineers Ballistic Missile Construction Office, Altus, Oklahoma, 14 March 1962 - 28 April 1962, 58.
6. Operational Readiness Training, Atlas F, Task 200, Silo Familiarization, September 1962, 579th Strategic Missile Squadron, 6th Strategic Aerospace Wing, Strategic Air Command, 93.
7. Study of Shock Isolation for Hardened Structures, (Aghabian-Jacobsen Associates, Los Angeles, California, June 17, 1966), 543-549, Defense Technology Information Center, AD 639303; Technical Manual, Missile Weapon System Operation, USAF Model HGM16F, Technical Order 21M-HGM16F-1, (15 April 1964), I-9 to I-11. Author's collection.
8. Study of Shock Isolation for Hardened Structures, 552-553; Kudroff, M. J., Titan ICBM Hardened Facilities, Journal of the Construction Division, Proceedings of the American Society of Civil Engineers, January 1962, 48. Kudroff, M. J., Titan ICBM Hardened Facilities, Journal of the Construction Division, Proceedings of the American Society of Civil Engineers, January 1962, 47-48.
9. Author's calculation.
10. Study of Shock Isolation for Hardened Structures, 560-563; Technical Manual, Missile Weapons System Operation, USAF Model LGM-25C, (T.O. 21M-LGM25C-1, 18 December 1986), 1-76.
11. Personal correspondence, Elmer Dunn, April 1997.
12. Study of Shock Isolation for Hardened Structures, 574.
13. Study of Shock Isolation for Hardened Structures, 568-574; Suspension System Comparison, Minuteman Service News, March-April 1960, (Boeing Aircraft Company, Seattle, Washington), 12-13.
14. Piper, R. F., Development of the SM-80 Minuteman, Vol. II, (Historical Office, Deputy Cmdr. for Aerospace Systems, Air Force Systems Command, April 1962), Air Force Historical Research Agency, IRISNUM 897232, K243-012-05. TWX, WDF-29–8-43, Hq AFBMD, to Hq ARDC, 29 August 1960, Supporting Document 145, 2.
15. Study of Shock Isolation for Hardened Structures, 574-577; Suspension System Comparison, Minuteman Service News, March-April 1960, (Boeing Aircraft Company, Seattle, Washington), 12-13.
16. Missile Suspension System Shock Test, Minuteman Service News, May-June 1968, 10-11
17. MM III Suspension Cable Links, Minuteman Service News, March-April 1970, 11-12.
18. SAC Missile Chronology 1939-1988, (Office of the Historian, Headquarters Strategic Air Command, Offutt Air Force Base, Nebraska), 53.
19. Nalty, USAF Ballistic Missile Programs 1967-1968, (Office of Air Force History, September 1969), 60; Neufeld, J., USAF Ballistic Missile Programs, 1969-1970, 30.
20. Minuteman Historical Summary, 1970-1971, (Boeing Aircraft Company, 1976), IV-127.
21. Qualification Report-Support, Missile Shock Isolation and Alignment (CI 10764AA), 1971, 44; Minuteman Upgrade Missile Suspension System, Ground Shock Dynamic Model, (the Boeing Company, 1982), Sheets 21-22.
22. MSS Shock Isolator-Wing V, Minuteman Service News 72, January-February 1974, 6-7.
23. The ARMS is the same as the missile base adapter ring which secures the missile to the transport vehicle and supports the missile during emplacement and removal.
24. Minuteman Upgrade Missile Suspension System, Ground Shock Dynamic Model, Document Number D2-26743-1, (Boeing Aircraft Company, Seattle, Washington, 23 February 1982), 21-23.
25. Testing Wing V MSS, Minuteman Service News, November-December 1972, 6-7; Shock Test Device Helps Hardened ICBMs, Aviation Week and Space Technology, 19 February 1973, 52-53.
26. Qualification Report-Support, Missile Shock Isolation and Alignment (CI 10764 AA), Boeing Company, 1974, Sheet 77-78.
27. Text of Reagan and Pentagon Statement on MX Missile Basing Proposal, 23 November 1982, New York Times, A-14; Report of the President's Commission on Strategic Forces, 6 April 1983, 17-18; Department of Defense Authorization Act, 1984, Public Law 98-94, 98th Congress, 621, 693.
28. Glasstone, S. and P. J. Dolan, The Effects of Nuclear Weapons, Third Edition (United States Department of Defense and the United States Department of Energy, 1977), 237.
29. Eckblad, D. M. and P. J. Schirmer, Passive Load Control Dampers, The Shock and Vibration Bulletin, Part 1, June 1985, 131-137; 50 Years of Shock and Vibration Technology, edited by Henry C. Pusey, 1996 (Shock and Vibration Information Analysis Center, Booz-Allen and Hamilton, Arlington, Virginia), 334.
30. Gassler, R.D. and D. L. Hahn, Missile Longitudinal Support Assembly, US Patent 4665792, May 19, 1987, 1-9.
31. Peacekeeper Weapon System: Baseline Configuration Description, March 1985, (Westinghouse Electric Corporation, Sunnyvale, California), Section 4-1 to 4-12; Peacekeeper Canister Subsystem Preliminary Design Review Executive Summary, March 1984, (Westinghouse Electric Corporation, Sunnyvale, California), 8, 11.

Some Technical Aspects of the Evolution of the Titan Weapon System



First Titan II In-Silo Launch. N-7, launched on February 16, 1963, from Launch Complex 395-C, Vandenberg AFB, was the first in-silo launch of a Titan II missile. Observers noticed the missile was spinning and immediately thought of finding cover as this indicated the missile was not under guidance control. (Figure 32) *(Courtesy of Titan Missile Museum Archive.)*

David K. Stumpf

The Titan Weapon System origin reaches back to February 8, 1954 with the publication of a report by B. W. Augenstein, a mathematician at the RAND Corporation. Augenstein pointed out that the reliability of liquid propellant rocket engine ignition at high-altitude had increased sufficiently that a two-stage design was now feasible. In the early 1950s, reliably starting liquid propellant engines at a high altitude and achieving smooth combustion was still an unknown.[1]

On July 21, 1954, the Atlas Scientific Advisory Committee recommended a second propulsion contractor for the nascent Atlas ICBM project. On October 25, 1954, Brigadier General Bernard A. Schriever, Commander, Western Development Division, responsible for the development of the ICBM program, went further and recommended development of an alternative configuration to the Convair design for Atlas. Schriever wanted to introduce an element of competition as well as possibly provide a substantially superior design. On January 4, 1955, the ICBM Scientific Advisory Committee agreed with Schriever and recommended development of an alternative to Atlas as a backup.[2]

On May 2, 1955, the Air Force authorized the Air Research and Development Command to issue a request for proposals from Bell Aircraft, Douglas Aircraft Company, General Electric, Lockheed Aircraft and Glenn L. Martin Company (the Martin Company) for the alternate design ICBM. On October 27, 1955, a letter contract, AF 04(645)-56, was issued to Martin Company to build a two-stage alternate ICBM, Titan, using the same propellant combination as Atlas.[3]

Encouraged by advances in the development of hypergolic storable propellants, on January 15, 1958, the Air Force Ballistic Missile Committee, recommended the conversion of Titan I to storable propellants. On December 1, 1959, the Air Force announced the Titan II program. On 1 April 1961, Titan I and Titan II became separate programs.[4]

The short life of the Titan I ICBM program obscures its importance in the development of the Titan II ICBM program. This article describes several key aspects of the Titan I program and evolution into the highly successful Titan II program.

From Atlas to Titan I

Atlas

The precursor to Atlas was the Convair MX–774. The MX–774 pioneered the concept of gimbal engines, replacing the jet vanes that had been used with the V–2. In an effort to minimize airframe weight, the MX–774 design replaced the traditional airframe fuel tanks, which used skin/stringer construction, with a pure monocoque design. Due to funding difficulties, only three flight test missiles were built before the program was canceled in July, 1947. The three flight tests

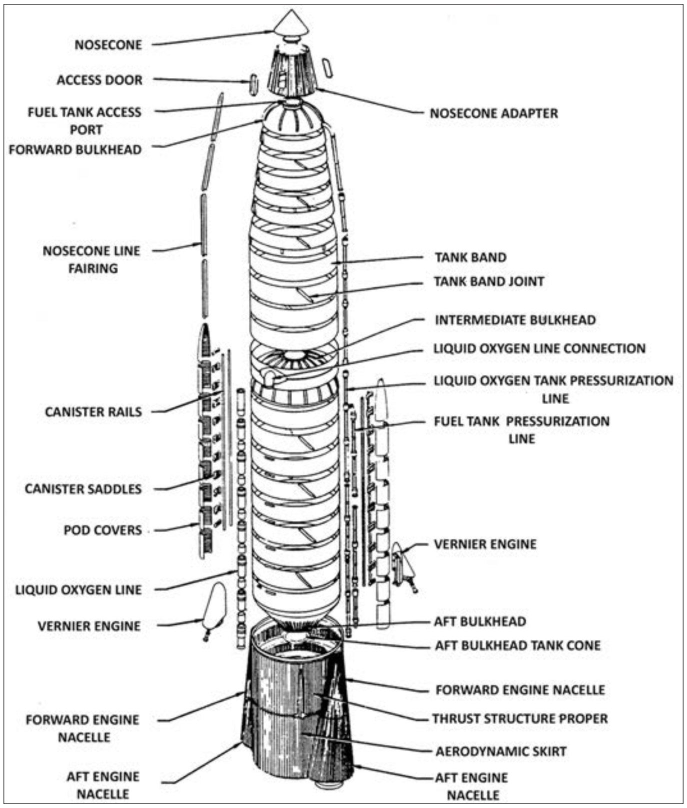


Figure 1: Atlas Series A Missile-1957. An expanded view showing the unique barrel hoop construction technique. The propellant tanks, when empty, had to be inflated with helium, or in a stretched configuration, to keep the airframe from collapsing. ***Courtesy R.E. Martin.***

Table 1. Comparison of Airframe Design: V-2, Atlas, and Titan

Missile[1]	PMF Launch[2]	PMF Staging	Airframe(lbs)[3]	Propellant (lbs)[4]	%Airframe/Propellant[5]
V-2	0.78	----	8,818	19,640	33
Atlas F	0.93	----	18,900	254,886	2.2
Sustainer	----	0.82	11,101	63,663	13
Titan I	0.95	----	15,000	209,000	3.5
Stage II	----	0.89	8,219	40,800	4.5
Titan II	0.95	----	22,758	301,000	3.1
Stage II	----	0.91	13,175	57,000	4.1

1. Data: V-2 , "V-2"; Atlas F, "Atlas: The Ultimate Weapon;" Titan I, II "Titan II: A History of a Cold War Missile Program."
2. PMF = 1-((weight of airframe + reentry vehicle)/(airframe + propellants+ reentry vehicle))
3. Airframe includes engines and reentry vehicle: V-2, 2,205; Atlas F and Titan I, Mark 4, 3,797; Titan II, Mark 6, 7,500.
4. Propellant remaining at BECO, 63,663.
5. % A/P = ((gross wt- engine-propellant)/propellant wt)*100

validated the gimbaled engine concept as well as the feasibility of the monocoque propellant tanks. All three flights suffered engine failures subsequent to launch. For the next four years Convair engineers worked on various aspects of the MX–774 program. In January, 1951, the Air Force Research and Development Command awarded Convair a new contract designated Project MX–1593, Atlas.[5]

Due to concerns with the MX–774 engine operation at altitude, the decision was made to design Atlas as a stage-and-one-half missile. The two booster engines and one sustainer engine were ignited at sea level. At 250,000 feet altitude the booster engines would drop away and the sustainer, the one-half stage, continue powered flight. The sustainer engine exhaust nozzle expansion ratio, the ratio of the area of the nozzle throat to the exit diameter, was built for operation at altitude and was therefore inefficient at sea level. The aluminum monocoque propellant tanks used in MX–774 were replaced with stainless-steel "balloon" tanks that were unique to the Atlas missile family (Figure 1). While this saved airframe weight, the need for continuous pressurization of the tanks introduced additional complexity to missile operations. As is shown in Table 1, at liftoff, Atlas F had a propellant mass fraction (PMF) of 0.93, a significant improvement over the V–2 at 0.78. At booster engine cut off (BECO), the PMF was now 0.82. A PMF of 0.94 means that 6 percent of the mass is airframe and engine. Atlas at liftoff had a value of 7 percent and at BECO, 18 percent. The higher value at BECO was the weight penalty due to the partially empty propellant tank which could not be discarded during the sustainer phase of flight (18 percent of the propellant remained after BECO).[6] Comparison of percent airframe/propellant where the ratio of the weight of the structural elements of the airframe to the weight of propellant gives a value of 33 percent with V–2 and 2.2 percent for Atlas. While this is a significant achievement for the boost phase of Atlas F flight, at BECO, the sustainer ratio is 13 a nearly sixfold decrease, reflecting carrying the entire tankage during sustainer flight.

Titan I

Martin Company engineers realized that the solution for a lightweight but self-supporting airframe was to include the structural members in the missile skin propellant tank walls. This idea had been dismissed by the Convair engineers in their desire to eliminate extraneous weight. Semi-monocoque construction uses lightweight stringers to carry the airframe load. The result was that Titan I had a PMF of 0.95 at liftoff, essentially the same as Atlas but without the complication of keeping the propellant tanks inflated. At staging, the Stage I tankage and engine was discarded, leaving Stage II with a PMF propellant mass fraction of 0.89, or a 11 percent airframe/propellant ratio but in this case there was a full load of propellant. When the percent airframe/propellant ratio is examined, Titan I at liftoff was quite close to Atlas and at staging was considerably more efficient 4.5 percent versus 13 percent. The Titan I airframe design achieved the weight performance of Atlas at boost phase, improved by a factor of nearly 3 the sustainer phase while eliminating the operational complexity of the stainless-steel "balloon."[7]

David K. Stumpf, Ph.D., is a retired plant biochemist living with his wife, Susan, in Tucson Arizona. He has written three nuclear weapon histories, Regulus the Forgotten Weapon*, a history of the Navy's Regulus I and II cruise missiles;* Titan II: A History of a Cold War Missile System *and* Minuteman: a Technical History of the Missile that defined American Nuclear Warfare*. His latest book,* The Last 30 Seconds*, a book about the evolution of hit-to-kill technology, will be available in September 2024. He is hard at work on what will be his last book,* Peacekeeper: A Technical History of LGM-118*. Dr. Stumpf volunteered at the Titan Missile Museum, as an historian and as a tour guide for 15 years.*

Table 2. Titan I Specifications (Lot M)[1,2]

Fully Assembled Airframe (feet)	Length	Maximum Diameter
Stage I (including stage transition)	56.6	10
Stage II	25.5	8
Reentry Vehicle Adapter	4.62	8
Mark 4 Mod I Reentry Vehicle	10.79	2.75
Nominal Missile Weight (lbs)	**Stage I**	**Stage II**
Airframe Empty (including engine)	7,741	4,484
Oxidizer	118,044	28,468
Fuel	51,682	12,441
Mark 4 reentry vehicle and warhead	4,100	
Total Weight (including reentry vehicle)	222,860	
Engine	**Thrust (lbs)**	
Stage I LR87-AJ-3 (sea level)	300,000	
Stage II LR91-AJ-3 (vacuum)	80,000	
Range (nautical miles)		
Mark 4 reentry vehicle and warhead	5, 500	
Circular Error Probable (nautical miles)	0.65[3]	

1. "Structural Description, SM-68," February 1961, Martin Company.
2. "General Arrangement, Lot M, Sheet 327-1000501" 18 July 1960.
3. *Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance.*

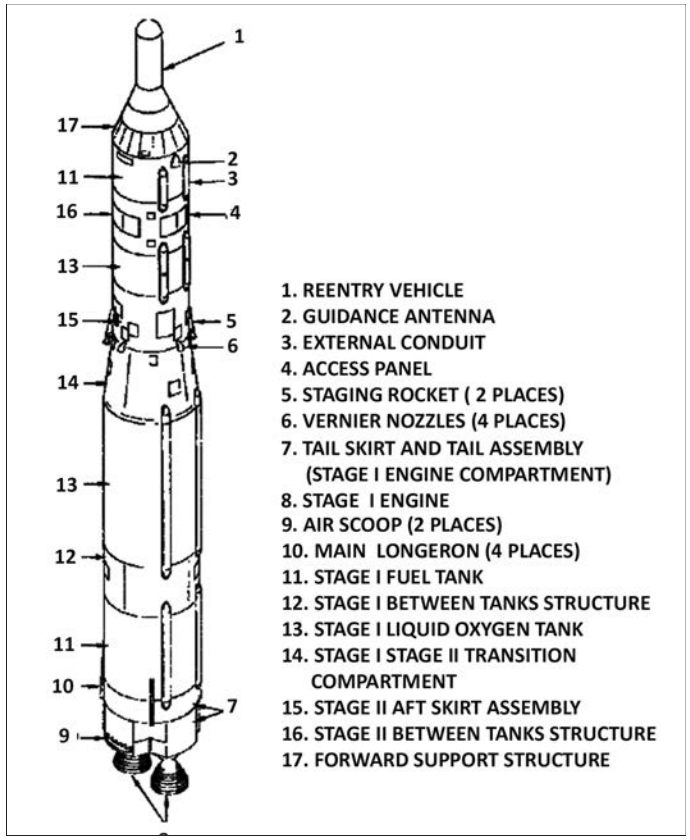


Figure 2: Titan I Missile Configuration. ***Courtesy Titan Missile Museum Archive.***

Airframe

The Titan I airframe was fabricated from 2014-T6 aluminum, a high-strength alloy with a high copper content (3.9 to 5 percent) and smaller quantities of iron, magnesium, manganese, silicon, titanium, and zinc. Because these materials were known to be difficult to work with, the Baltimore Division of Martin Company had developed a tungsten inert gas welding process for use with the 2014 alloy.[8]

Manufacture of the Titan I airframe began with the chemical milling of the aluminum tank panels. Chemical milling permitted the propellant tanks to be fabricated for maximum strength yet minimum weight by the removal of aluminum in a complex pattern in specified areas. The process required that each component be masked with chemically resistant, asphalt-like material in the desired pattern. Immersed in a sodium hydroxide bath, aluminum was removed at a rate of approximately 0.003-inches thickness per minute of exposure. Those areas that had to be etched the most had no masking at the start of the process; those that were to be etched the least were masked until the last exposure process. Typically, three or four thicknesses had to be etched on each tank panel.

Once the flat panels had been etched and rinsed, they were moved to the horizontal weld fixture. The Stage I tank barrels consisted of 12 panels that were welded to form the tank cylinder, first into quarter panels, then the four quarter panels were welded to form the cylinder or barrel. The weld was made using a machine welding process, and was performed by the weld torch traveling longitudinally over the weld joint. The tank barrels had to be supported by rings in the horizontal position until the domes were placed and welded. Each weld was x-rayed and hydro-tested (the tanks were pressurized with water). Weld repairs were usually small and done manually. No Titan I or Titan II missile was lost during flight due to tank weld failure (Table 2).[9]

A feature unique to the Titan missile family airframes was a slight discoloring of the exterior skin surface. This was the result of the application of Iridite, a chromium chemical conversion coating which was applied to the surface to prevent corrosion. The distinct coloring on the different panels was due to how that particular batch of 2014-T6 aluminum reacted with the Iridite process (Figure 2).

Guidance

In April 1955, the ARMA Bosch Corporation received the contract to develop the inertial guidance system for Titan as well as Atlas. However, delays developed due to reliability and weight issues. Rather than delay the Titan program any further, on October 18, 1955, Bell Laboratories received the contract for a radio-inertial guidance system for Titan. On May 26, 1958, a contract change was made to transfer the ARMA inertial guidance system from Titan I to Atlas.[10]

Engines

Engines for Titan I were fabricated by Aerojet-General Corporation (Aerojet), Folsom, California. On January 14,

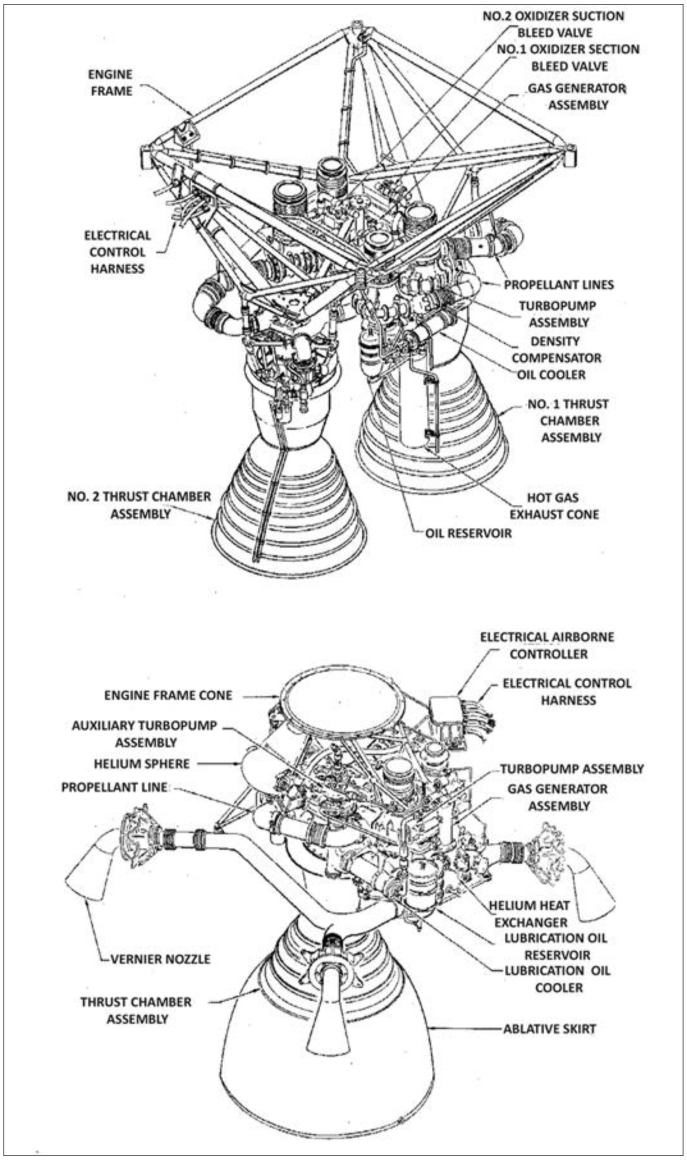


Figure 3: Titan I Engines. Upper: Titan I Stage I Engine. Lower: Titan I Stage II Engine. ***Courtesy Titan Missile Museum Archive.***

1955, Aerojet had begun research and development work on rocket engines for an as yet unnamed two stage missile. Stage I would be powered by two identical engines while the second stage would be powered by a single engine of similar design, optimized for vacuum start. Aerojet's design and development of these engines would serve as a backup to the North American Aviation team working on the Atlas engines, with the possible result of a better engine for use in Atlas.

Both the Stage I and Stage II engines had two design configurations, the LR87-AJ-1 and LR87-AJ-3 (300,000 pounds thrust at sea level) and the LR91-AJ-1 and LR91-AJ-3 (80,000 pounds thrust, vacuum). Design changes from the -1 to -3 configurations included reduction in weight and reducing the total number of parts. While the LR87 engine used regenerative cooling for the thrust chamber, the LR91 engine thrust chamber required a larger expansion ratio due to ignition taking place at an altitude of 250,000 feet. The increased expansion ratio required a larger thrust chamber bell which was difficult to effectively regeneratively cool using fuel as in Stage I. Replacing part of the cooled chamber jacket with an asbestos-based ablative skirt greatly simplified engine operation, as well as saved weight. Constant turbine speed, and thus constant propellant flow, was accomplished by metering main engine propellants to the gas generator which powered the propellant turbopumps. Stage I used a gaseous nitrogen turbopump start that was then taken over by the propellant-supplied gas generator. Gaseous helium was used for the Stage II engine turbopump start (Figure 3).[11]

Propellants

Titan I used RP-1 and liquid oxygen as fuel and oxidizer respectively. As with Atlas, the fuel was stored onboard the missile, while the cryogenic liquid oxygen had to be stored on site and quickly loaded during the countdown but before raising the missile to the surface. This was a problem with the first-generation ICBMs and was a major component of the approximately 14-minute response time for Titan I between launch key turn and missile away (see Response Time).

Staging

Staging with Titan I took place upon depletion of Stage I propellants which triggered a sensor that cut off propellant flow to the Stage I engines. A short delay allowed for thrust tail-off, then explosive nuts were triggered and two small solid propellant separation rockets moved Stage II, along short guide rails, clear of Stage I. At the same time, the acceleration forced the propellants to the Stage II engine inlet to assure engine start once clear of Stage I. Stage II roll control was provided by four vernier thrusters.

Reentry Vehicle

The Mark 4 was a sphere-cone-cylinder-biconic flare shape, 126.7 inches long, 33 inches in diameter at the cylindrical mid-section and 48 inches in diameter at the base of the flare. The Mark 4 flare varied from 7 to 22 degrees with two very small spin fins at the base of the flare. The nose cap was made of Avcoite, a ceramic material contained in a magnesium honeycomb matrix, varying from 0.82 to 2.332 inches thick; the cylindrical body and flare were protected by oblique tape-wound Refrasil at thicknesses of 0.32 to 0.61 and 0.44 to 0.86 inches, respectively. The afterbody was protected with fiberglass. The Mark 4 with warhead weighed 3,800 pounds. A second reference gives the operational Mark 4 as weighing 4,100 pounds of which 3,100 pounds was the warhead. The Mark 4 was deployed on Atlas E and F and Titan I from 1962 to 1965. The Mark 4 was flown once on Titan II during the Titan II research and development program (Figure 4).[12]

Launch Facilities

Titan I was deployed in the HGM-25A configuration (H = silo stored, surface launched; G = ground attack; M =

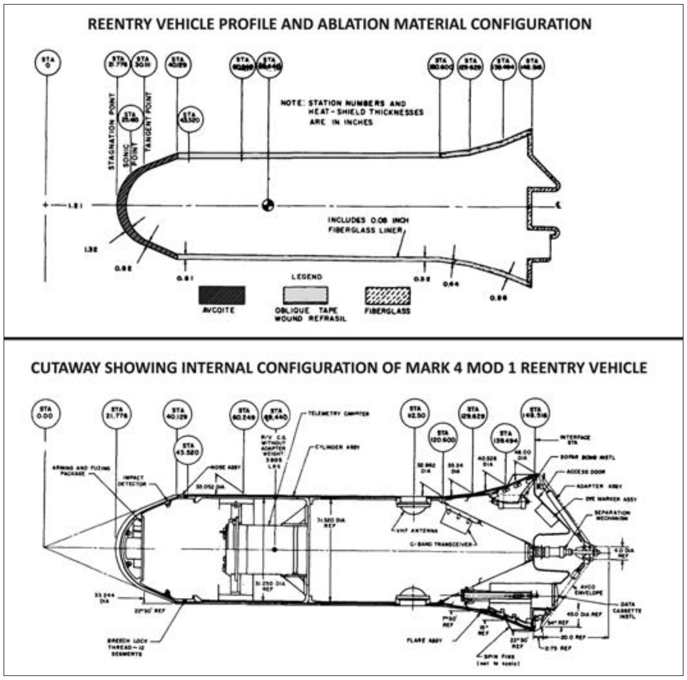


Figure 4: Mark 4 Reentry Vehicle. Upper: location of ablative materials on the Mark 4 reentry vehicle. Lower: inboard profile of the Mark 4 Mod 1-11 reentry vehicle. ***Courtesy Titan Missile Museum Archive.***

guided missile; 25 = twenty-fifth major design; A = model). At least eighteen nautical miles separated Titan I launch complexes of three missiles per launch control center, three launch control centers per squadron, hardened to withstand 100 psi overpressure.[13]

Silo/Crib

The Titan I silo was 161 feet deep, including a 6-foot-thick foundation, with an interior diameter of 40 feet. The Titan I silo door was a bi-parting, hinged design: each half weighed 102 tons, was 12-feet wide, 19-feet long and 4-feet thick. It took approximately one minute for both doors to fully open. The doors were designed to withstand 100 psi overpressure.[14]

The silo housed a crib structure,132 feet tall and 21 feet wide, weighing 490 tons, including the missile. The crib structure housed the support equipment for the missile and the silo as well as the launch platform elevator. Engineers evaluated several shock isolation systems for the crib, such as base- or side-mounted spring assemblies for improved pitch stability. Both systems had the drawback of requiring a re-leveling system to compensate for any permanent tilt of the silo following a ground shock.

Titan I used a pendulous spring system which consisted of four pairs of 16-foot springs (four 48-inch-long, 22-inch-diameter subassemblies) attached at the corners of the crib base and to a silo wall bracket 32 feet off the silo floor. The vertical center of gravity was above the spring attachment level on the crib but well below the missile center of gravity because of the elevator weight. When the vertical center of gravity of the missile and crib structure is higher than the shock isolation systems point of attachment on the crib, pitch stability is often difficult to attain.

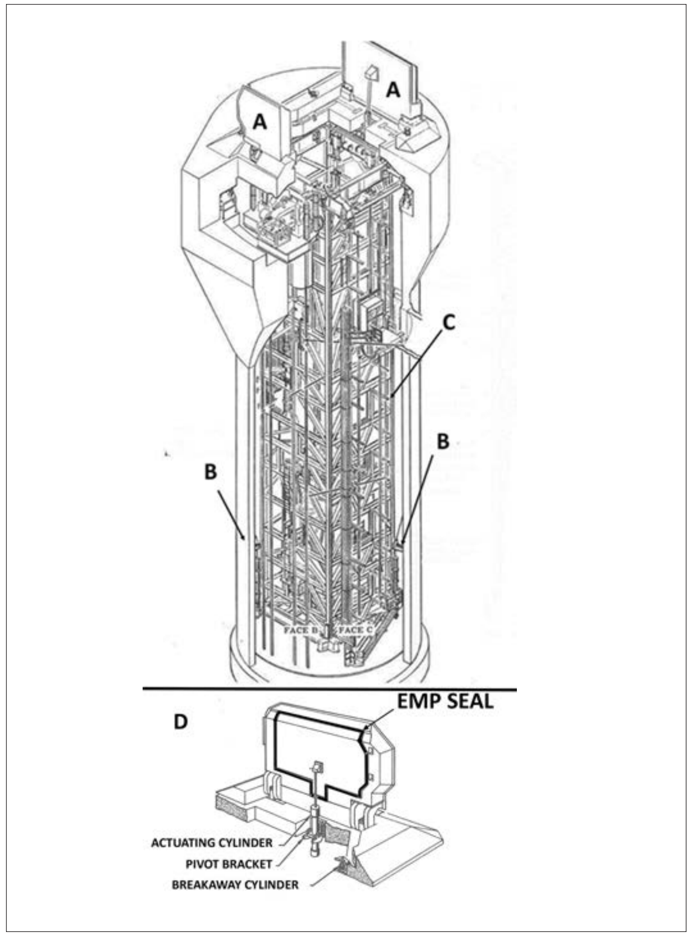


Figure 5: Titan I Silo Crib Detail. (A) The silo closure doors weighed 115 tons each. Structural isolation of the door foundation minimized transmission of surface shock to the missile silo. (B) Four pairs of springs were attached at the corners of crib platform for shock isolation. (C) There were five levels of maintenance platforms on the crib which provided a continuous walkway and working area completely encircling the missile except on the fifth level. (D) Silo closure door mechanism detail. It took 50 seconds to open both doors. ***Author's Collection.***

Initial studies indicated it would be necessary to cross-couple the vertical springs to manage pitch stability. When the ground shock criteria were revised, the spring elements were made stiffer which eliminated the need for a coupling mechanism. Coil spring elements were chosen over pneumatic springs because of their higher reliability. Hydraulically operated crib locking mechanisms at the top of the crib securely positioned the crib prior to raising the missile to the surface (Figure 5).[15]

Response Time

The Titan I countdown took 14.2 minutes from the start of loading liquid oxygen, T-850 seconds, to lift off at T+4 seconds. The shelter (silo) doors began opening at T-235 seconds and were fully open at T-185 seconds. This meant the silo was exposed to the environment, or "soft," for nearly 4 minutes (239 seconds from door opening to launch). The launch platform began elevating at T-185 seconds and was up and locked on the surface at T-55 seconds (2.25 minutes). Once the missile reached the surface, the countdown continued for another 55 seconds (Figure 6).[16]

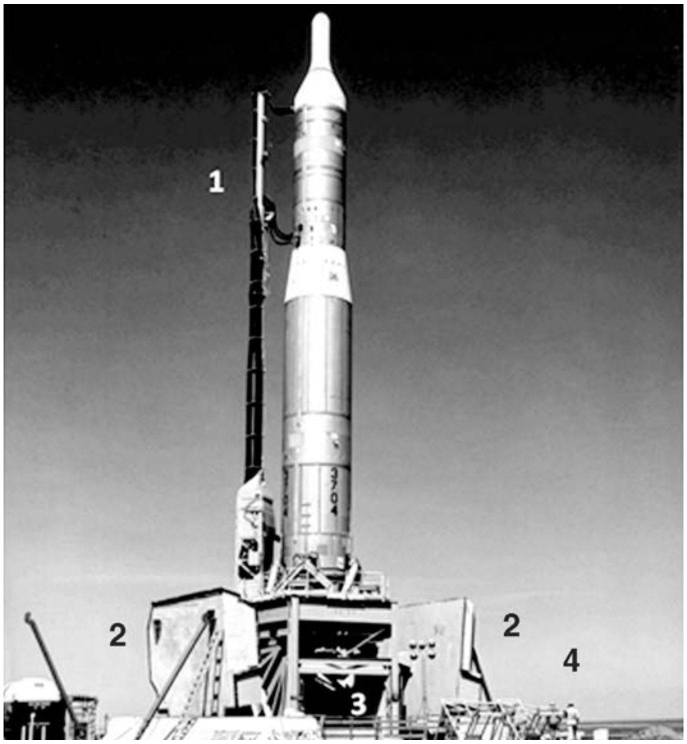


Figure 6: Titan I Ready for Launch. Titan I (60-3704) in launch position during a training exercise at Silo 3, Site-C Royal City, 568 SMS, Larson AFB, Washington. The service tower, (1), provided power, guidance and liquid oxygen to top off the oxidizer tanks. The "closure" doors (2) each weighed 115 tons. The flame bucket (3) deployed an extension to cover the gap between the launch platform and the silo wall. Note the construction worker (4). *Courtesy Titan Missile Museum Archive.*

Research and Development Flight Test

A total of 163 missiles were fabricated in eight lots of which 62 were research and development (R&D) airframes (Table 3). There were 67 launches in the program; 47 R&D

Table 3. Titan I Missile Fabrication Lots[1]

Designator	Lot	Description
XSM-68	A (6, 4)[2]	Simplified first stage; dummy second stage, limited range.
	B (7, 2)	Complete first and second stages with reduced second stage engine duration; open closed-loop radio guidance.
	C (6, 4)	Complete first and second stages with reduced second stage duration; radio guidance; separable scale model reentry vehicle.
	D, E, F	Eliminated from test program.
	G (10, 7)	Complete two-stage missile; closed-loop radio guidance, separable reentry vehicle; range up to 4,000 nautical miles.
	H, I	Eliminated from the test program.
	J (22, 22)	Complete missile capable of flights up to 5,000 nautical miles; later missiles to carry operable reentry vehicle and warhead without reactive material.
	K, L, S, T	Eliminated from the test program.
	V (3, 3)	Same as Lot J exception of instrumentation range safety equipment to be used as part of operational system testing at Vandenberg AFB and the Pacific Missile Test Range.
	VS (1, 1)	Same as Lot V except for an inert second stage; to be used in conjunction with the in-silo launch test facility at Vandenberg AFB.
XSM-68A	M (7, 7)	Same as Lot J except equipped with inertial guidance system to serve as test bed for SM-68B (Titan II) guidance system.
SM-68A	101	Operational missiles
Total	163	

1. Titan Master Schedule, 31 July 1963, AFHRA, Maxwell AFB, AL.
2. number built, number launched

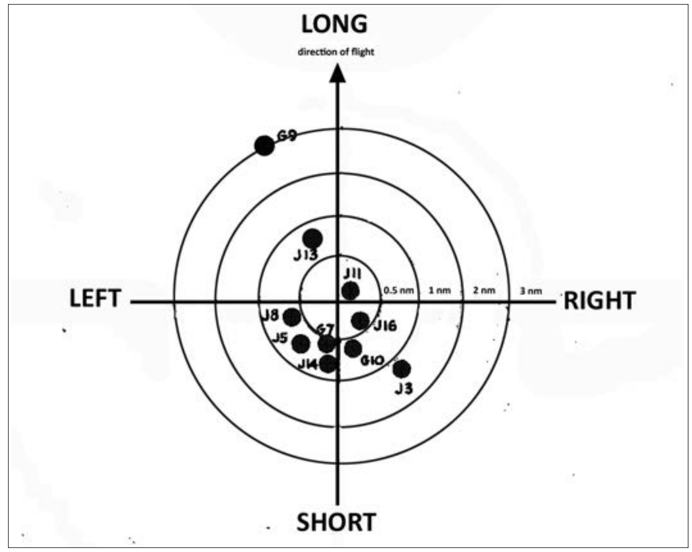


Figure 7: Titan I Ascension Island Splash Net Impact Points. Target accuracy as of June 1961. Ten missiles had been flown to Ascension Island with accuracy as an objective. Eight landed within one nautical mile of the target. *Author's Collection.*

at Cape Canaveral, Florida (four failures and nine partial successes); and 20 conducted at Vandenberg AFB (VAFB), California (one failure and seven partial successes) including five operational launches.[17]

Lot A missiles had a dummy second stage and were flown to demonstrate Stage I operation. Lot B demonstrated Stage II operation with a range of 2,020 nautical miles. Lot G tests demonstrated both Stage I and II performance to a range of 3,200 nautical miles. Lot J was the operational prototype and demonstrated range performance and reproducible accuracy at ranges from 4,385 to 5,337 nautical miles (Figure 7). Lot M missiles enabled early evaluation of the prototype Titan II inertial guidance system with seven launches and six successful flights. One Lot VS missile was used to successfully establish the feasibility of in-silo launch. There were 48 fully successful flights out of 67 launches, including the operational missile test program, for an overall flight reliability of 72 percent (Tables 4 and 5).[18]

Titan I was deployed in six strategic missile squadrons. Titan I was first placed on alert at the 724th Strategic Missile Squadron, 451st Strategic Missile Wing, Lowry Air Force Base, Colorado on April 20, 1962. Titan I (and Atlas) quickly became obsolete because of much faster response time with Titan II and Minuteman. On May 24, 1963, less than one year after deployment, the Air Force announced the phaseout of the Atlas and Titan 1 programs starting in 1965, to be completed by 1968. On May 16, 1964, Secretary of Defense Robert McNamara directed that all Titan I missile squadrons be deactivated by the end of 1965.[19] The last Titan I was removed from alert at the 569th Strategic Missile Squadron, Mountain Home Air Force Base, Idaho on April 1, 1965.[20]

Titan II

Unlike the Atlas program where major program changes were implemented as they became available, the

Table 4. Patrick AFB Titan I R&D Flight Record[1]

Key:
Lot A - booster flight, dummy second stage
Lot B - two-stage separation, second stage ignition
Lot C - two-stage performance over limited range
Lot G - two stage performance over extended range
Lot J - operational prototype - Titan I
Lot M - test bed for Titan II inertial guidance system
Lot V - assembled for OSTF/SLTF
Lot SM - operational configuration - Titan I

No.	Missile	Date	Pad	Outcome	Remarks
1.	A-3	2/6/59	15	Successful	Stage I operation only, the second stage was filled with water and not equipped with an engine. All objectives were met, structural integrity was demonstrated and Titan I became the first missile program to have a successful flight on its first launch.
2.	A-5	2/25/59	15	Successful	Dummy Stage II
3.	A-4	4/4/59	15	Successful	Dummy Stage II
4.	A-6	5/4/59	15	Successful	Stage I separation test was completed successfully with a water-filled second stage without an engine.
5.	B-5	8/14/59	19	Failure	Premature lift off, automatic destruct
6.	C-3	12/11/59	16	Failure	Accidentally destroyed on pad by destruct system
7.	B-7A	2/2/60	19	Successful	First attempt at complete staging at high altitude was successful. Guidance system was fully operational on this medium range flight.
8.	C-4	2/5/60	16	Partial Success	Nose cone fairing fell away due to structural failure 50 seconds into flight.
9.	G-4	2/24/60	15	Successful	First attempt to separate the Mark IV nose cone was successful. This was the first long range flight, reaching nearly 5,000 nautical miles.
10.	C-1	3/8/60	16	Partial Success	Stage II ignition failure
11.	G-5	3/22/60	15	Successful	Capsule recovered
12.	C-5	4/8/60	16	Partial Success	Stage II premature shutdown
13.	G-6	4/21/60	15	Successful	Capsule recovered
14.	C-6	4/28/60	16	Successful	Final limited range shot
15.	G-7	5/13/60	15	Successful	Capsule recovered
16.	G-9	5/27/60	16	Successful	Capsule not recovered due to high seas
17.	G-10	6/24/60	15	Successful	Capsule recovered
18.	J-2	7/1/60	20	Failure	Lost hydraulic power in Stage I, destroyed 11 seconds into flight
19.	J-4	7/28/60	20	Partial Success	Stage I premature shutdown
20.	J-7	8/10/60	19	Successful	Capsule not recovered, 5,000 nautical mile flight
21.	J-5	8/30/60	20	Successful	Capsule not recovered, 5,000 nautical mile flight
22.	J-8	9/28/60	19	Successful	Capsule recovered
23.	G-8	9/28/60	15	Successful	Flew 6,000 nautical miles
24.	J-3	10/7/60	20	Successful	Capsule recovered
25.	J-6	10/24/60	19	Successful	Capsule recovered, flew 6,100 nautical miles
26.	J-9	12/20/60	20	Partial Success	No ignition Stage II
27.	J-10	1/20/61	19	Partial Success	No ignition Stage II
28.	J-11	2/9/61	20	Successful	5,000 nautical mile flight
29.	J-13	2/9/61	19	Successful	5,000 nautical mile flight
30.	J-12	3/2/61	20	Partial Success	Premature shutdown Stage II
31.	J-14	3/28/61	19	Successful	5,000 nautical mile flight
32.	J-15	3/31/61	20	Partial Success	Premature shutdown Stage II
33.	J-16	5/23/61	20	Successful	5,000 nautical miles
34.	M-1	6/23/61	19	Partial Success	Premature shutdown Stage II, inertial guidance systetm worked well
35.	J-18	6/20/61	20	Successful	5,000 nautical mile flight
36.	M-2	6/25/61	19	Successful	5,000 nautical mile flight
37.	J-19	8/3/61	20	Successful	5,000 nautical mile flight
38.	J-17	9/5/61	20	Successful	6,100 nautical mile flight, data capsule recovered
39.	M-3	9/7/61	19	Successful	4,500 nautical mile flight
40.	J-20	9/28/61	20	Successful	4,500 nautical mile flight
41.	M-4	10/6/61	19	Successful	5,000 nautical mile flight
42.	J-21	10/24/61	20	Successful	6,100 nautical mile flight
43.	J-22	11/22/61	20	Successful	6,000 nautical mile flight
44.	M-5	11/29/61	19	Successful	5,000 nautical mile flight
45.	J-23	12/13/61	20	Successful	5,000 nautical mile flight
46.	M-6	12/15/61	19	Successful	5,000 nautical mile flight
47.	M-7	1/29/62	19	Successful	5,000 nautical mile flight

1. "Titan I Airframe Disposition."

Table 5. Vandenberg AFB Titan I R&D Flight Record[1]

No.	Missile	Date	Outcome	Remarks[2]
48.	SM-2	9/23/61	Successful	5,300 nautical mile flight, launched from VAFB, 395A-1
49.	SM-4	1/20/62	Partial success	No Stage II ignition, launched from VAFB, 395A-3
50.	M-7	1/29/62	Successful	5,000 nautical mile flight
51.	SM-18	2/23/62	Partial success	No Stage II ignition, launched from VAFB, 395A-1
52.	SM-34	5/4/62	Successful	Guidance tape error
53.	SM-35	10/6/62	Successful	"Pickle-Barrel" launched from VAFB, 395A-1
54.	SM-11	12/5/62	Successful	Launched from VAFB, 395A-1
55.	SM-8	1/29/63	Successful[2]	"Pickle-Barrel" launched from VAFB 395A-1
56.	SM-3	3/30/63	Successful	"Pickle-Barrel" launched from VAFB 395A-2, SAC-DASO
57.	V-1	4/4/63	Successful	"Pickel-Barrel" launched from VAFB 395A-1
58.	SM-1	4/13/63	Successful	"Pickel-Barrel" launched from VAFB 395A-3, SAC-DASO
59.	V-4	5/1/63	Failure	5 seconds of flight, launched from VAFB, 395A-1
60.	SM-24	7/16/63	Partial success	No Stage II ignition, launched from VAFB, 395A-2
61.	SM-7	8/15/63	Successful	"Pickle-Barrel", launched from VAFB, 395A-1
62.	SM-56	8/30/63	Partial success	gas generator shutdown, launched from VAFB, 395A-3
63.	SM-83	9/17/63	Successful	"Pickel-Barrel", launched from VAFB, 395A-2, SAC
64.	SM-68	11/14/63	Successful	"Pickel-Barrel", launched from VAFB, 395A-1, SAC
65.	SM-85	12/8/64	Partial success	Premature shutdown Stage I, launched from VAFB, 395A-1, SAC
66.	SM-33	1/14/65	Partial success	No Stage II ignition, launched from VAFB, 395A-3, SAC
67.	SM-80	3/5/65	Partial success	Propellant depletion, launched from VAFB, 395A-2, SAC

1. "Titan Ballistic Missle Development Plan, 30 April 1960.
2. Pickle-Barrel refers to the launch being used in determining the impact accuracy of the reentry vehicle.

Titan program combined all the technical developments into one advanced model, Titan II. Titan II PMFs and percent airframe/propellant values were nearly identical to Titan I (Table 6). Among the major design advances found in Titan II were: increase in second stage diameter; inertial guidance; storable propellants; propellant tank pressurization; the staging concept; advanced reentry vehicle; and in-silo launch (Figure 8).[21]

Airframe Design Changes

There were three major changes made with the Titan II airframe design. The first and most obvious was the second stage diameter was increased to ten feet to provide

Table 6. Titan II ICBM Specifications[1]

Fully Assembled Airframe (feet)	Length	
Stage I including interstage structure, Stage I engines	70.17	
Stage II	19.54	
Reentry Vehicle Adapter	3.74	
Mark 6 Reentry Vehicle	10.17	
Diameter (excluding conduits, air scoops)	10	
Total	103.4	
Nominal Missile Weight (lbs)	**Stage I**	**Stage II**
Airframe, empty (ncludes engine)	9,583	5979
Oxidizer	160,637	37,206
Fuel	83,232	20,696
Total	317,333	
Engine	**Thrust (lbs)**	
Stage I LR87-AJ-5 (sea level)	430,000	
Stage II LR91-AJ-5 (vacuum)	100,000	
Range (nautical miles)		
Mark 6 Reentry Vehicle	5,800	
Circular Error Probable (nautical miles)	0.78	

1. " Detailed Design Specifications for Model SM-68B Missile (Including Addendum for XSM-68B).
2. *Titan II: A History of a Cold War Missile Program.*

greater range and payload capability. The second difference was the overall missile length was increased from 98 to 103.4 feet (including reentry vehicle), mostly in the Stage I tankage. Some structural modifications, mainly increasing skin thickness and adding ring frames, were necessary due to the in-silo launch environment as well as the increased density of the propellants. One source of problems in the Titan I airframe had been the Stage I fuel tank longeron structures. The longerons served as the point of attachment of the missile to the launch mount. These were bolted onto the Stage I fuel tank skin and then sealed. Leakage had been a recurring problem in this area in the Titan I program. With Titan II, the longeron panel was

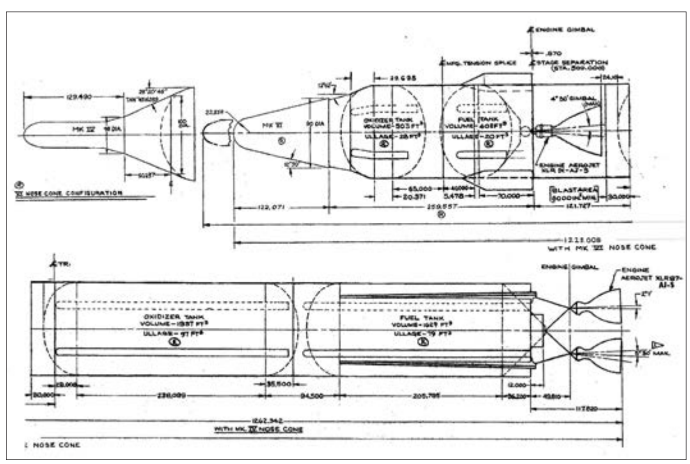


Figure 8: Titan II Stage I and II Inboard Profile Conceptual Drawing 6 June 1960. Note the inclusion of the Mark IV reentry vehicle profile. The total airframe length, including the Mark 6 reentry vehicle, was 101.91 feet. The as-built length of the missile was 103.39 feet. The difference is in the length of the reentry vehicle adaptor section. *Courtesy of Lockheed Martin Astronautics, Denver.*

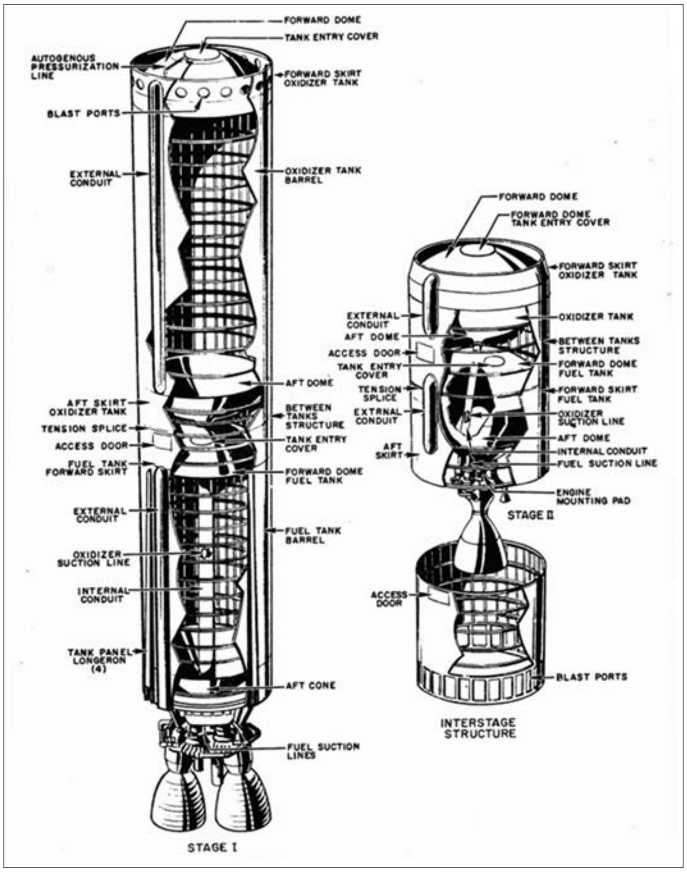


Figure 9: Titan II Airframe Configuration. The semi-monocoque airframe made the airframe self-standing without propellant load. The thickness of the metal skin ranged from approximately 0.050 inches to 0.170 inch depending on location. For comparison a U.S. dime is 0.053 inch thick, while a quarter is 0.068 inch. ***Courtesy of the Titan Missile Museum Archive.***

welded directly to each quarter panel. After the quarter panels were welded together to form the fuel tank, a machined fitting was then riveted to the longeron panel, eliminating tank skin penetration (Figure 9).[22] The third major difference was the "fire-in-the-hole" staging technique which is discussed below under Staging.

Guidance

The original contract for the Titan II guidance system was awarded to AC Spark Plug on April 14, 1959.[23] AC Spark Plug contracted with IBM for the design, development, fabrication and production of a rotating drum memory digital computer that interfaced with the inertial measurement unit (IMU). AC Spark Plug designers worked with Davidson Corporation and Perkin-Elmer Corporation in the development of the ground optical alignment system used to provide a precision pre-launch azimuth alignment reference. AC Spark Plug also designed, tested and produced the associated aerospace ground equipment and operating ground equipment that was required to test, operate and maintain the airborne components. The inertial measurement unit used three 2FBG-2C floated beryllium stabilization gyroscopes and a 25 PIGA (pendulous integrating gyroscopic accelerometer) accelerometer. The IMU was nicknamed the "Gold Ball" due to the coat of a gold-colored resin-based paint for protection from oxidizer leaks. The IMU weighed 184 pounds, Missile Guidance Computer weighed 100 pounds. Over the next 16 years this first guidance system required only eight modifications, all of which were completed by May 15, 1965.[24]

In the mid-1970s, the Air Force faced a dilemma with the original guidance system for the Titan II program. Nearly two decades after the design of the original guidance system, advances in the electronics industry made the system difficult to support. Major suppliers were not interested in maintaining the capability of building obsolete equipment in small lot sizes. In some cases, the older components simply did not exist as suppliers had phased them out of their product line. Headquarters Strategic Air Command realized that at predicted failure rates, critical parts would no longer be procurable by December 1977.[25]

Fortunately, an existing state-of-the-art replacement was available: a modified Delco Electronics Carousel inertial guidance system called the Universal Space Guidance System (USGS). The USGS had been in use with the Titan IIIC program on 13 December 1973; six launches with one failure in the guidance system at the time of the decision to modify it for use with Titan II. The Carousel IV inertial navigation system was standard equipment for the Boeing 747 and had been retrofitted into the Boeing 707 and McDonnell-Douglas DC-8.

The USGS hardware was composed of the Carousel IV IMU and the Magic 352 computer: each weighed 80 pounds (the commercial aircraft computer was the Magic III series). Modification of the basic Carousel IV inertial reference unit for space applications had been relatively simple, repackaging the instrumentation for the thermal environment as well as vibrational stresses of a missile launch. The Titan II autopilot was used with minor modifications, as was most of the airborne wiring. The umbilicals to the missile did not need to be replaced (Figure 10).[26]

While the missile silo environment, as well as the missile flight profile, were obviously significantly different than that seen by the commercial aircraft Carousel IV and Magic III systems, the missile installation had a major advantage: the guidance system would be turned on after installation, advanced to the "READY" mode and, except for maintenance or repair requirements, remain in this steady-state operating environment for months or even years. In the aircraft installation, the Carousel IV system was turned on and off several times a day depending on aircraft operations. This caused degradation in system accuracy and reliability due to the short-term operating times and the effect of heating and cooling. Once up and running, the USGS system self-calibration procedures continually fine-tuned the system and was most stable if simply left on.

Between October 15, 1975 and June 27, 1976, Delco engineers and technicians were able to modify two sets of flight systems from the already flight-proven USGS of Titan III. Included within this eight-month time frame was the design and fabrication of a new telemetry system for use during the qualifying flight(s) since the original teleme-

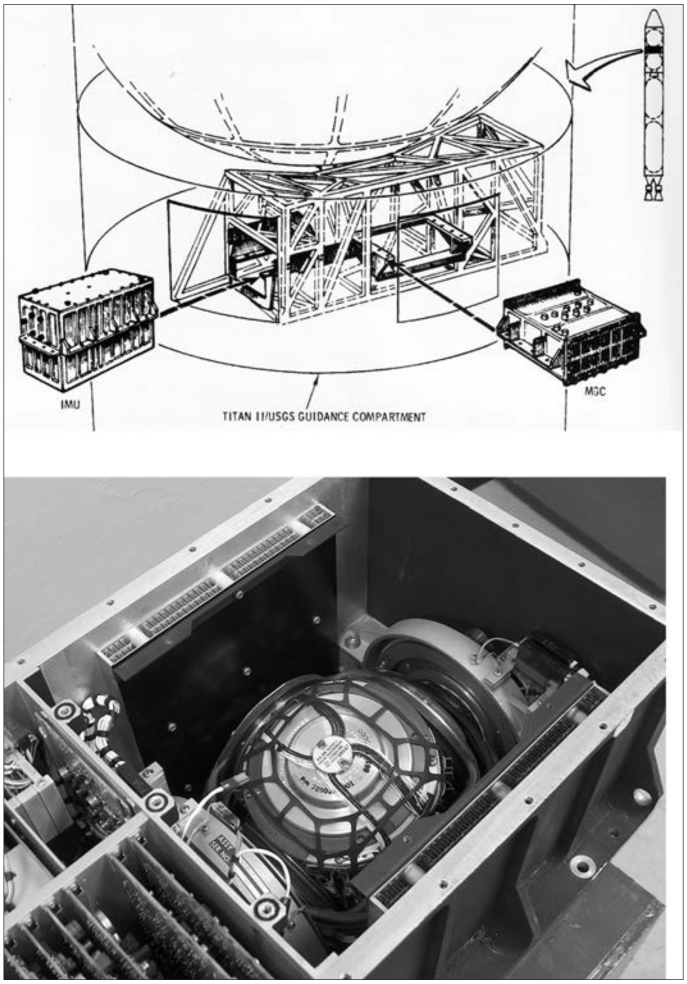


Figure 10: USGS. Upper: Location of the USGS inertial measurement unit and missile guidance computer between the Stage II propellant tanks. Lower: The cover is off the new IMU, revealing a much more compact inertial measurement unit. *Courtesy of Titan Missile Museum Archive.*

try system sets had been used up during the previous flight test program.[27]

The fourteenth launch operation for the 308 SMW, and the last launch in the Titan II ICBM program was given the name Project "Rivet Hawk." At 0213 (Z), June 28, 1976, the missile combat crew composed of: Capt. Roger B. Graves, MCCC; 1st Lt. Gregory M. Gillum, DMCCC; Staff Sergeant David W. Boehm, BMAT; and Staff Sergeant Kenneth R. Savage, MFT, began the launch procedure. Keyturn took place at 0214 (Z) and within seconds a GUIDANCE HOLD occurred due to an INERTIAL GUIDANCE SYSTEM NO-GO signal. The shock produced during pre-valve opening had been sensed by the inertial measurement unit, triggering the hold. The new software had retained both MEMORY and BLAST DETECT modes so the launch team returned the guidance system to the READY mode, the countdown recycled and after downrange checks, the countdown resumed 18 minutes later. Since the pre-valves were now already open, the second launch attempt, at 0240 (Z), encountered no problems. Liftoff occurred at 0240:53 (Z). The flight to target was successful but the reentry vehicle impacted approximately 1.46 nautical miles long and 0.36 nautical miles cross range.[28]

As one might imagine, this was more than a little disconcerting. Review of the telemetry from the guidance system, as well as extensive computer modeling, revealed an error in the software. The unique feature of the USGS inertial measurement unit was the rotating X-Y platform. This feature mitigated a source of error in the X-Y plane that had to be accounted for in a non-rotating system. The newer computer in the system allowed the continuously changing X-Y instrument outputs to be monitored for updating the platform alignment. In the USGS equipment used on Titan III, the platform rotated at one revolution per minute. For deployment in the operational Titan II fleet, the decision was made to slow the platform down to one-quarter revolution-per-minute due to a failure rate with the one-revolution-per-minute system that was unacceptable for the Titan II program. With Titan III the guidance system was on for perhaps 24-48 hours before launch. With Titan II, the guidance system would be on for weeks and months, perhaps years between required maintenance.

It seems that Titan II USGS programmers failed to provide a program path for the updating of the instrument coefficients after one minute; rather, it was after one revolution or four minutes. The resulting uncompensated instrument errors actually grew exponentially and after four minutes were unacceptably large. This was not known at the time but, by a quirk of fate, the instrument error compensation values at the time of launch were four minutes old, causing the resulting impact error. Post-launch review of the guidance software clearly revealed the cause of the error. The fix, which did not require another launch, was to refresh the instrument compensation factors after 90 degrees of rotation, or with a one-quarter revolution per minute system, once a minute as before. With only four spare Titan II missiles remaining in the inventory, including one each at the three operational Titan II wings, and Pacific Missile Range support equipment unavailable in time for a second launch before the USGS purchase decision date of October 1, 1976, the decision was made to proceed with the USGS modification.[29]

Engines

Titan II engine development began in January 1960. Valves, pumps and cooling jackets for the thrust chamber were not seen as major hurdles. Workhorse steel injector patterns were fabricated, in sub-scale first and then full scale, to see how the propellants interacted in order to achieve maximum performance. These were hot-fire tested for limited duration using uncooled steel thrust chambers to determine design parameters such as combustion stability and chamber wall thermal loads, flow rate combinations, mixture ratios and propellant temperatures. With determination of mixture ratios complete and initial injector plate patterns finalized, the timing of propellant movement through the engine cavities could be evaluated. Subsystems were being worked on simultaneously; e.g., the turbopump team was designing the turbines, gearboxes and impellers to move the propellants that the thrust

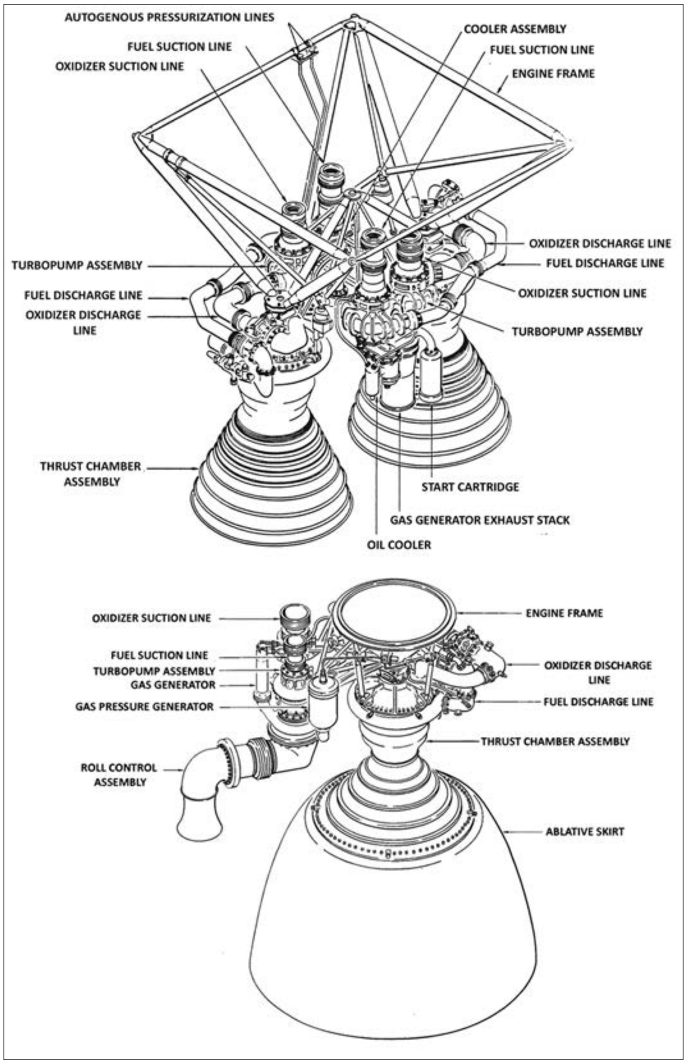


Figure 11: Titan II Engines. Upper: Titan II Stage I Engine; Lower: Titan II Stage II Engine. At first glance, the Titan II Stage I looks identical to the Titan I Stage I engine. The most obvious difference was a shorter turbopump exhaust stack. For Stage II, the vernier nozzles were replaced by one nozzle which used the exhaust from the Stage II gas generator for roll control. The Titan II vernier final velocity adjustment was provided by two solid propellant motors located in the Stage II engine compartment. ***Courtesy Titan Missile Museum Archive.***

chamber team needed for optimum operation; likewise, the gas generator team was developing the cavitating venturis concept; the autogenous pressurization team was working on the sonic nozzles, etc. Finally, the systems were placed together and system integration began.[30] Preliminary testing using Titan I engine hardware began in May 1960. The first Titan II engine prototypes were available for testing in September 1960. After approximately 80 engine tests, the engine configuration was frozen in December 1960. Delivery of the Stage I research and development engines began in January 1961. Hundreds of tests were run around the clock to get the correct hydraulic balance or mass flow rate for the most efficient operation. In March 1961 the first full duration firing of a Stage I engine was successfully accomplished and in July 1961 the first production Stage I engines were accepted by the Air Force.[31] Because of the experience gained in developing the Titan I engines, the task of developing Titan II engines took little more than two years from design inception to first flight in February 1962 (Figure 11).[32]

Along with the change to storable propellants came the opportunity to greatly simplify the engine control system. Titan I engines had 125 active control components, this was reduced to 30 for Titan II.[33] These changes were reflected in a similar decrease in power control operations, 107 to 21 respectively. Examples of the important changes: (1) elimination of the ignition system since Titan II propellants were hypergolic; (2) an autogenous pressurization system that used cooled gases from turbine exhaust to maintain propellant tank pressure; (3) use of solid propellant start cartridges instead of stored pressurized gas to start turbopump operation; (4) use of the Stage II turbopump exhaust stream as the power source for the Stage II roll nozzle, eliminating the need for an auxiliary power drive assembly for the vernier rockets, greatly increasing reliability; (5) use of cavitating venturis and sonic nozzles to provide passive control to the gas generator and autogenous pressurization system; and, (6) propellant supply lines from pump to thrust chamber designed to have the ability to articulate, allowing motion of the thrust chamber for thrust vector control, eliminating rotary seals that were possible leak paths.[34]

Two key manufacturing differences were also important. In Titan I, the thrust chamber injector assemblies were milled from solid forgings, a time consuming and costly process. With Titan II, the injector was formed from plates that were welded together. Titan I used both a fuel and oxidizer manifold whereas Titan II used a fuel manifold and an oxidizer dome feed system.[35]

Stage II Combustion Instability

The Titan II Stage II engine development was another matter. While reliable rocket engine ignition at high altitude had been successfully demonstrated with Titan I, such was not to be the case with Stage II engine development for Titan II. Roy Jones, a development engineer for Stage II, recalled the first time he witnessed a Stage II ignition combustion instability. He was watching the television monitor of a Stage II engine test, when much to his surprise, he saw the thrust chamber drop away from the injector dome as if someone had taken a sharp knife and sliced it off. After several engines failed in this manner, review of the test data indicated that a combustion instability with a period of 25,000 cycles per second had swept around the injector face, cutting through the combustion chamber wall like an ultrasonic saw 1.5 inches below the attachment point. Thrust chamber pressure was cycling through $\pm$ 200 pounds per square inch at 25,000 cycles per second.[36] This was unexpected since it had not happened with Titan I Stage II engines. This did not happen each time an engine was tested and was in fact statistically almost insignificant for use in the ICBM program, occurring in just two percent of the ground tests. However, since Titan II had been selected by NASA as the Gemini Manned Spacecraft Program launch vehicle, even two percent was too much of a risk and a solution had to be found.[37]

In September 1963, Aerojet General began work on the Gemini Stability Improvement Program, also known as GEMSIP, to resolve the Stage II combustion instability. The direct cause of the problem was known. In Stage I, the propellants flowed into the engine cavities against sea level air pressure and engine bleed-in timing could be monitored and adjusted for. At the high-altitude present for Stage II bleed-in prior to engine start, this process was very different from that at sea level since there was no air pressure to act as a barrier. The first real resistance encountered by the fuel or oxidizer was the injector plate itself. This resistance was due to the small orifices that the fuel and oxidizer had to flow through to develop the spray pattern needed for efficient combustion. The physical shock was not a problem. The engine was robust enough, as was the airframe mounting, to take the impact. The problem was the resultant combustion instability at the injector plate face.

Aerojet went through 20-30 Stage II thrust chambers trying to resolve the problem. The simple test of high-altitude bleed-in theory was to fill the thrust chamber wall tubes of the regenerative cooling system with water. When tested at 70,000 feet equivalent air pressure at the Aerojet facilities, the water provided enough hydraulic resistance to mimic that of the sea level condition. Combustion stabilized significantly as the hydraulic shock was reduced to that found at sea level. However, the use of water was not an operational fix for an engine sitting in a launch duct for years, nor was it truly feasible for the Gemini Program. The water-filled thrust chamber tubes did, however, allow for continued engine system integration. The primary solution, and the only one truly considered by both Aerojet and the Air Force, was a stable injector and a dry thrust chamber jacket start. Baffles were a logical control mechanism to break up the instability long enough for initiation of smooth combustion. The design evolved into a baffle that had oxidizer injection for thin film cooling. The final design was altitude tested in the Air Force Arnold Research Center Facilities at Tullahoma, Tennessee, and proved sound. The GEMSIP program took 18 months to complete and cost $13 million. The changes were incorporated into the ICBM program engines. Ironically, none of the R&D missile failures were attributable to a Stage II hard start, and perhaps even more ironic, NASA launched the first six Gemini flights with the old-style injector plate (Figure 12).[38]

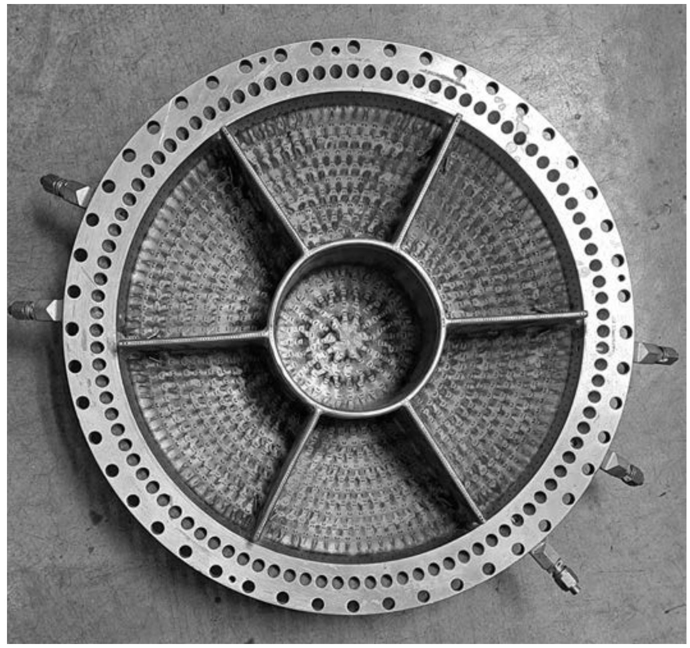


Figure 12: Titan II Stage II Injector Plate. The center baffle prevented formation of the combustion instability shockwave. The injector was 17.5 inches in diameter. *Courtesy Titan Missile Museum Archive.*

Stage II Gas Generator

A second problem, and one that proved more troublesome, was that of Stage II gas generator failures in flight during high altitude start-up. The gas generators utilized fuel and oxidizer to generate high pressure gas for powering the turbopumps during flight. Solid-propellant start cartridges provided the initial high-pressure gas for spinning the turbines and then the gas generators took over. The problem first occurred in the flight of N-1, the second launch of a Titan II. Telemetry indicated that the Stage II engine had reached only fifty percent thrust immediately after ignition and the vehicle was destroyed by the range safety officer. Unfortunately, the limited flight telemetry data provided insufficient information to the Stage II design team to solve this critical problem. The flight program continued with two partial failures in the next seven flights. Review of the accumulated telemetry data indicated that the small orifices at the injector plate for the gas generator were being partially plugged by particles on all the flights.

Careful review of the flight data indicated that backpressure was being developed due to the clogged orifices, decreasing propellant flow to the gas generator with subsequent loss of power. After trying to super-clean the gas generator components in a clean room prior to assembly, transporting the assembly to Cape Canaveral separately from the engine and conducting a preflight nitrogen blowdown before each flight to verify the flight item cleanliness, the actual solution to the problem was found to be very simple and cost effective.[39]

At sea level the air trapped in the gas generator interior served as a cushion, preventing combustion gases and solid fuel particles produced by start cartridge ignition from reaching the injector plate of the gas generator on the Stage I engine. Due to the problems of vacuum testing large liquid-fueled rocket engines, the Aerojet facilities could only reach the equivalent of 70,000-foot altitude. This was assumed to be close enough to the Stage II start altitude vacuum at 250,000 feet and the Stage II system was tested successfully.[40] However, even at 70,000 feet altitude, sufficient air was present to provide a barrier to the start cartridge combustion product particles. At 250,000 feet, the higher vacuum meant no such barrier existed and particles were being blown into the gas generator, clogging the oxidizer orifices. On many of the flights the result was not of sufficient magnitude to cause a problem, but on three of the first 20 flights it was significant. The solution to this problem was simple. A rupture disc was placed on the roll

Figure 13: Operation Wrap up. Streaks of corrosion on the top of the Stage II oxidizer tank in the between tanks area of Titan II B-23. Missiles returned during Operation Wrap Up were segregated in a separate factory area where work was conducted around the clock to get the missile tanks and valve joints repaired and the missiles returned to the operational bases. *Courtesy Lockheed Martin Astronautics, Denver.*

nozzle, the endpoint of the Stage II gas generator exhaust, entrapping the sea level atmosphere (i.e., pressure) until start cartridge ignition took place. The cushion of air was retained at altitude, preventing combustion products from reaching and plugging the orifices.

Storable Propellants

The use of storable propellants was an attractive option to eliminate the long response time. At the beginning of 1951, the Navy's Rocket Branch of the Bureau of Aeronautics contracted with the Metallectro Company and Aerojet to synthesize hydrazine derivatives and investigate their usefulness as rocket propellants. If used as the fuel half of a hypergolic propellant pair in tactical rockets, the hydrazine or mixtures of hydrazine derivatives had to have a freezing point no higher than -65°F. By 1955, researchers at Aerojet had selected a 50:50 mixture of unsymmetrical dimethylhydrazine and hydrazine (Aerozine 50) which met that specification. The freezing point specification was of no consequence for Titan II as the missile was located in a launch duct held at a temperature of 60±2°F. Nitrogen tetroxide was selected as the oxidizer. Both of the propellants were highly toxic and special protective suits were necessary when propellant transfer operations took place.[41]

Oxidizer Tank Leaks

Contract AF04(647)-213, May 15, 1962, stated ". . . it shall be a design requirement that the allowable pressure decay with the propellant tanks loaded at flight pressures, shall be less than 2.0 psi in 30 days, except for Stage II fuel tank, which shall be less than 3.0 psi in 30 days. There shall be no visible leakage... ."[42] However, by mid-1963, early in the deployment of Titan II missiles in operational silos, leaks began to appear in the oxidizer tanks. Nitrogen tetroxide, leaking through holes too small to be detected by the original quality control methods, was mixing with water vapor in the humid environment of the launch duct. The result was the formation of highly corrosive nitric acid, causing small leaks to turn into larger and more problematic leaks. The problem had not been detected earlier because none of the N-series flight test operations had necessitated the prolonged storage of propellants. Tank pressurization decays in excess of these requirements were observed, oxidizer vapor leaks sufficient to trigger the vapor detection system occurred and finally, visible leaks were noted. Seventeen missiles of the 60 missiles deployed or awaiting deployment were recalled to Denver for inspection and rewelding. This recall program was given the name Operation Wrap Up. Originally the tanks were checked via x-ray of the weld, hydrostatic and nitrogen pressure tests. Now the quality control methods were to retake the weld x-rays, fix defective welds, pressurize the tank with helium and then check each weld with a helium sniffer that was extremely sensitive. This new test equipment increased the leak detection sensitivity 10,000-fold. After hydrostatic testing, the tanks were baked to dry out all the water in the system, the welds painted with sodium silicate and then pressure-checked again prior to return to the field. A total of 15 fabrication changes were made during Operation Wrap Up. Only three missiles built after October 1963 had to be returned to Denver for rewelding (Figure 13).[43]

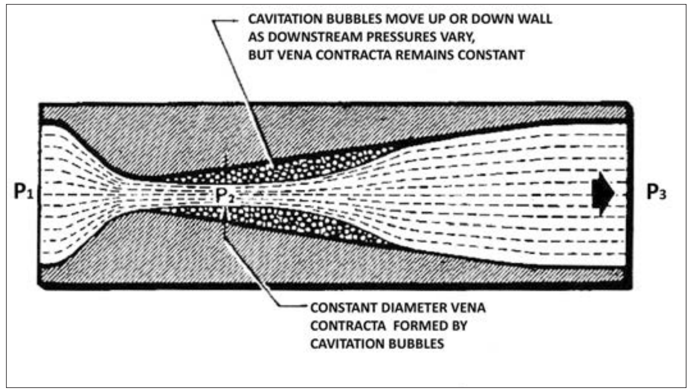


Figure 14: Cavitating Venturi. The cavitating venturi is a device used to assure a constant weight flow in liquid systems. It has no moving parts and combines the venturi principle with the fact that liquids boil when their static pressure is equal to their vapor pressure. *Author's Collection.*

Propellant Tank Pressurization

Titan I utilized pressurized helium gas to pressurize the propellant tanks. The pressure regulators and valves were a source of unreliability. Titan II used what is called an autogenous pressurization system. The oxidizer tank was pressurized with vaporized oxidizer which was bled from the main oxidizer feed line. The liquid oxidizer was vaporized in a heat exchanger that was supplied by exhaust from the turbopump gas generator. The innovation was the use of cavitating venturis to control the gas pressure. Cavitating venturis are passive devices which limit the maximum flow of fluids regardless of downstream pressure (Figure 14).[44]

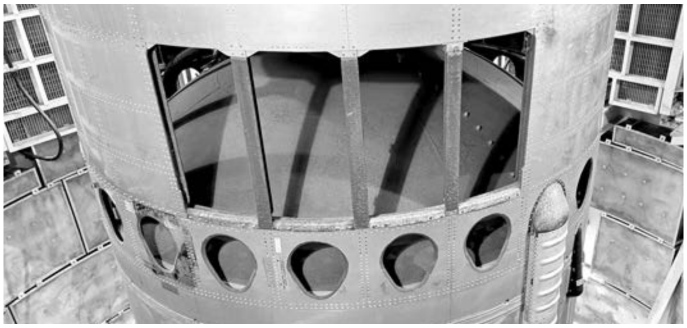
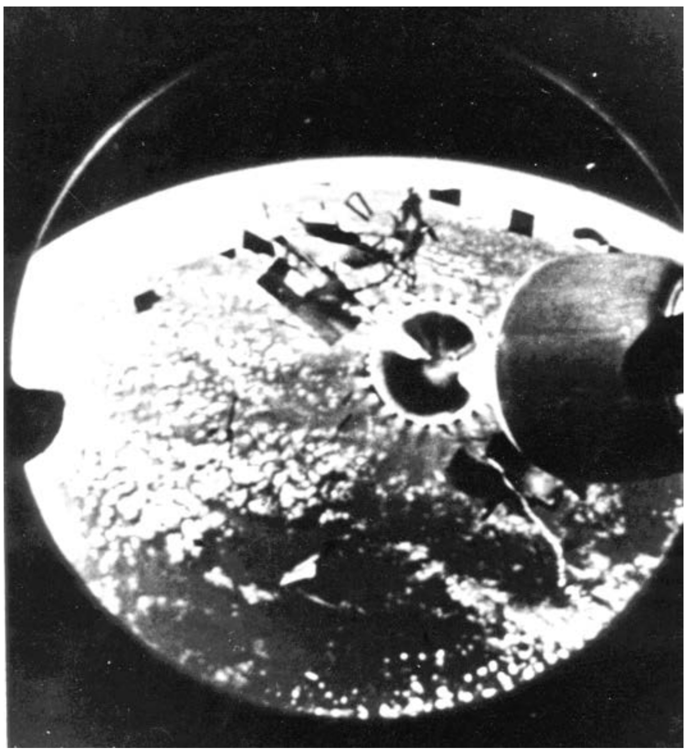


Figure 15: (Above) Titan II Stage II Exhaust Vents. The system of vents facilitated "fire-in-the-hole" staging by quickly venting the Stage II engine exhaust. *Author's Collection.*

Figure 16: (Below)Titan II Staging. A frame from an external camera showing the fragmentation of the interstage splice at Stage II ignition. Cameras on the flight of N-33, 23 March 1964, confirmed the integrity of the redesigned interstage structure. *Author's Collection.*



The fuel tank pressurization system utilized gas from the main engine turbine gas generator exhaust which was cooled in a heat exchanger similar to that of the oxidizer system. Stage I and II fuel tank pressurization was essentially the same, while the Stage II oxidizer tank relied on the tank pressure present at launch.[45] Reliability was increased tremendously with the elimination of valves and pressure regulators used in Titan I.

Staging

The third major difference was a change in the staging sequence. Nicknamed "fire-in-the-hole," Stage II was ignited during Stage I thrust tail-off while still attached to Stage I. The decaying thrust of the Stage I engines maintained sufficient acceleration to keep the Stage II propellants at the turbopump inlets prior to Stage II ignition. The forward dome of the Stage I oxidizer tank was protected from the Stage I engine exhaust by a layer of ablative material. Explosive nuts fired at Stage II thrust buildup, releasing Stage II. This eliminated the guide rails and the separation rockets used in Titan I. A swiveling secondary nozzle redirected the exhaust from the Stage II turbopump for roll control, eliminating the vernier thrusters.[46] Stage II engine exhaust was vented through large openings in the forward skirt of Stage I. Ground-based tracking cameras revealed that the "fire in the hole" was causing breakup of the Stage I interstage structure with the possibility of damage to Stage II from the debris. Camera data from most of the flights showed that the point of failure was the interstage-oxidizer tank junction. Film from the flight of N-33 verified that interstage had been successfully reinforced and the fix was applied to operational missile fabrication (Figures 15, 16). [47]

Reentry Vehicles

Detailed design documents for the Titan II ICBM list both the Mark 4 and Mark 6 reentry vehicles as possible payloads.[48] The reason for listing the Mark 4 may have been as a fallback if the development of the Mark 6 was unsuccessful. Interestingly enough, a single and successful launch of a Titan II carrying a Mark 4 did take place on December 6, 1962 from Cape Canaveral; however, the flight was not successful (Figure 17). [49]

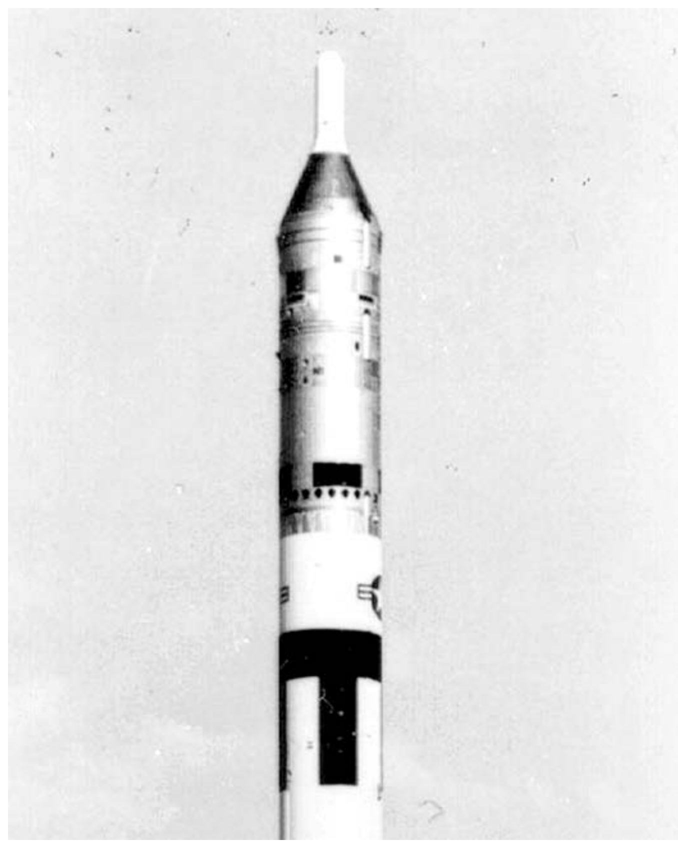


Figure 17: The Mark 4 reentry vehicle was only flown once on a Titan II. On 6 December 1962, N-11 was successfully launched from Cape Canaveral Pad-16. Carrying a Mark 4 Mod 2A reentry vehicle, the flight was normal until oscillations in Stage I were severe enough to cause a thrust chamber pressure switch in Stage II to shut down the engine with subsequent impact short of target. *Author's Collection.*

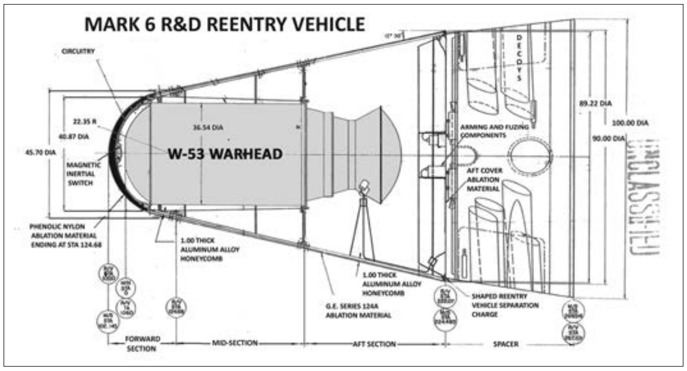
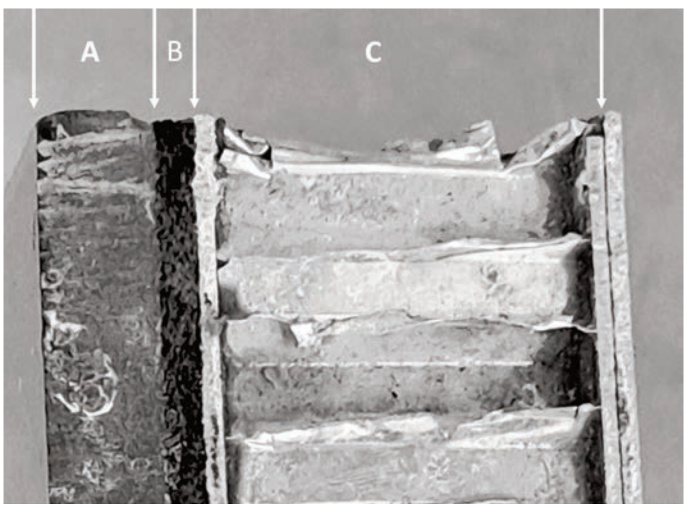


Figure 18: (Above) Outboard Profile of the Mark 6 Reentry Vehicle and Decoy Spacer. The Mark 6 carried the W-53 warhead which was an adaptation of the B-53 gravity bomb and had a yield of 8.9 Mt, the largest warhead used in the ICBM program. The Mark 6 reentry vehicle was 10.2 feet tall with a base diameter of 7.4 feet. *Author's Collection.*

Figure 19: Mark 6 Heatshield Detail. Cross-section of conical frustrum of the Mark 6 reentry vehicle heatshield. (A) The outer layer was Century Series 124A plastic, 0.295-inch thick; (B) neoprene, 0.094-inch thick; (C) aluminum alloy honeycomb, 1-inch thick. The nose cap was composed of chopped phenolic nylon, 2.33-inches thick tapering down 0.385 inch. *Author's Collection.*



The General Electric Mark 6 reentry vehicle deployed on Titan II utilized ablative materials for both the nose cap and heatshield. The nose cap was composed of phenolic nylon (66-Nylon cloth impregnated with phenolic resin), chopped into 0.5-inch squares and pressure molded to the nose cap shape. The main body of the heatshield was composed of the General Electric Century Series 124A plastic. The basic ingredients for the plastic were: Dow Epoxy—Novolac 438; methylnadic anhydride, a curing agent; polypropylene glycol to increase flexibility to make fabrication easier and N-(n-butyl) phosphoric acid as a charring agent.[50] The Series 124A plastic was easily fabricated by casting the liquid epoxy into molds having the conical frustrum shape of the heatshield and hardening in an oven without pressure. The complete heatshield was assembled from three pieces; the nose cap and two conical sections of the main body. The only machining required was to square off the top and bottom edges to the final length dimension. The Mark 6 heatshield, 0.295 inches thick, was bonded to a 0.094-inch-thick layer of neoprene rubber which was in turn bonded to a 1-inch-thick aluminum honeycomb aluminum

Okay Table 7. Developmental Mark 6 Reentry Vehicle Designations.

Mod 1:	Modified Mod 2 vehicle with GE/RSD lightweight dummy payload ballasted to duplicate Mod 3 weight, 7,400 pounds.
Mod 1B:	Modified Mod 2 vehicle with GE/RSD lightweight dummy payload, 7,200 pounds.
Mod 2:	Fully instrumented R&D vehicle with Sandia payload; weight in excess of Mod 3.
Mod 2A:	Modified Mod 4 vehicle with Sandia payload, 7,800 pounds.
Mod 2B:	Modified Mod 4 with FTU and certain other instrumentation added, 8,000 pounds.
Mod 2C:	Modified Mod 4 with FTU and certain other instrumentation added, 7,900 pounds.
Mod 3:	Operational vehicle configuration; the prime vehicle to carry an FTU or scoring kit.
Mod 4:	Partially instrumented R&D vehicle with GE/RSD dummy payload ballasted to duplicate Mod 3 weight.
Mod 4A:	Mod 4 vehicle modified to carry special experiments in support of the ARPA-sponsored vehicle instrumentation program,
Mod 4B:	Modified Mod 4 vehicle, using lightweight dummy payload, 7,000 pounds.
Block 0:	Initial R/V design with dome-shaped aft cover, a questionable tension cone to support the payload, a plane spacer assembly (i.e., not designed for decoy installation) and, in general, a one half-ampere no-fire squib requirement.
Block 1:	Block 0 design with flat aft cover, decoy spacer.
Block 2:	Operational vehicle configuration; Block 1 design with tension straps for payload support, and incorporating propellant compatibility requirements.

1. "WS 107C Titan II Weapon System Final Report, January 1965."

layer attached to the reentry vehicle airframe. The coefficient of expansion of the plastic was much higher than that of the aluminum airframe and the rubber served both as an insulator and as an elastic interface which could stretch to accommodate heatshield expansion. The nose cap had a maximum thickness of 2.33 inches (Figures 18, 19).[51]

While these dimensions seem small when the material is to be exposed to reentry temperatures of several thousand degrees, in the short time of exposure, several porous char layers 1-2 millimeters thick are formed in sequence. The first one plugged up and was sloughed off by aerodynamic forces. A new char layer formed as the process repeated itself. Large amounts of pyrolysis gases that formed as the material degraded served to inhibit heat transfer from the hot boundary layer to the ablating surface, greatly reducing the actual heating at the vehicle surface.[52]

Unlike the missiles launched at the WTR which were below ground and out of the sun, the missiles at Cape Canaveral had prolonged exposure to the sun and so the reentry vehicles were painted white to reflect the sun and help cool the reentry vehicle.[53]

Developmental Mark 6 Reentry Vehicles

Table 7 lists the developmental Mark 6 reentry vehicle designations and characteristics. The initial Mark 6 reentry vehicles were designated as Mod 2 and Mod 4. The Mod 2 vehicle was fully instrumented with sensors embedded in the heatshield for ablation measurements; motion sensors and telemetry equipment to monitor reentry vehicle functions. A Sandia National Laboratory Flight Test Unit (FTU) was installed as well as telemetry link equipment. The result was that the Mark 6 (Mod 2) weighed approximately 8,100 pounds. Mark 6 (Mod 4) had fewer instruments and weighed 7,400 pounds.

Several reports from the Operational Test and Follow-On Test Programs shed some light on details of operational Mark 6 specifications.[54] The Mark 6, including decoys, reen-

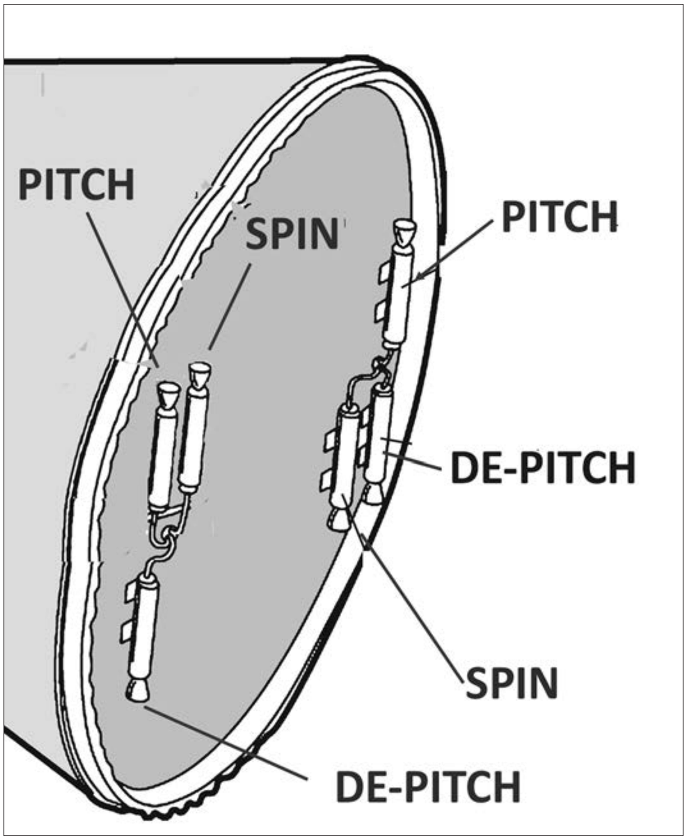


Figure 20: Mark 6 Attitude Control System. The attitude control system positions the reentry vehicle at the required entry attitude angle . Depending on the target, the reentry angle was between 19.9 and 24.98 degrees. Stage II had translation rockets which moved Stage II away from the reentry vehicle as a decoy. The flight test program developed the timing for initiating the translation procedure without affecting the reentry vehicle trajectory. *Author's Collection.*

try vehicle adaptor and W-53 warhead weighed 8,380 pounds. The W-53 warhead weighed 6,200 pounds and was the largest yield warhead used in the U.S. strategic missile forces, with a yield of 8.9 MT. When launched from VAFB, the Mark 6 carried either a denuclearized W-53 warhead that still contained the Grade II high explosive components for air burst tests, or a scoring kit utilized for surface impact flight profiles. The Mark 6 Mod 3 reentry vehicle adapter/spacer could carry up to eight terminal decoys (Optically Enhanced, Model 1037J) and six mid-course decoys (Operational, Model 1026BP).

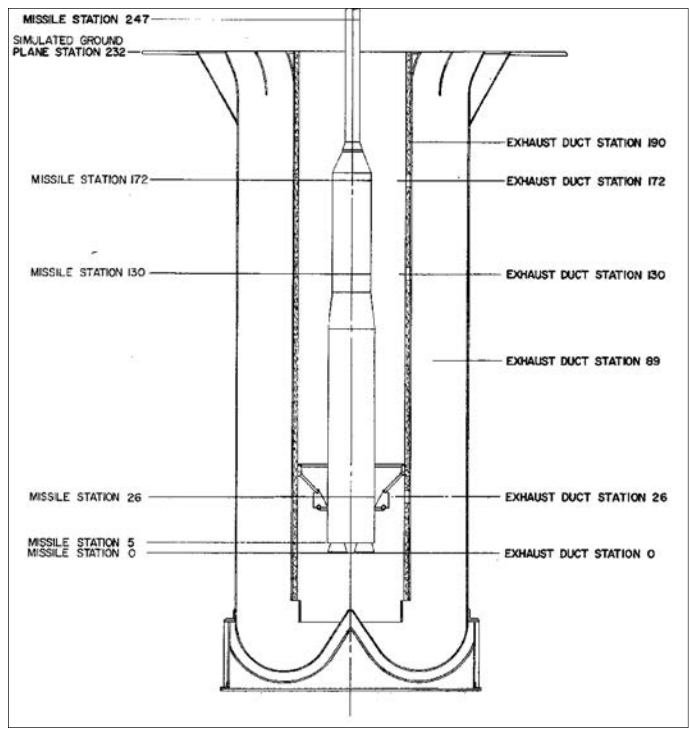
Re-orientation of the reentry vehicle immediately following separation to that required for low angle of attack was performed by an attitude control system consisting of two pitch, two de-pitch and two spin rockets. The original design of the Mark 6 included a rounded aft cover to facilitate reorientation of the reentry vehicle in the event of an initial backward reentry followed by the failure of the attitude control system. The results of the flight test program indicated a flat aft cover design permitted better attitude control and was used in all operational Mark 6 reentry vehicles (Figure 20). [55]

Launch facilities

Titan II was deployed in LGM-25C configuration (L =

Figure 21: (Above) Construction of the Silo Model. The launch duct and exhaust ducts were installed in one piece. *Courtesy R. Pickford.*

Figure 22: (Below) Schematic Drawing of the In-Silo Launch Model. The general configuration of the launch duct, flame deflectors and exhaust ducts. Previous work in Britain had used a J-shaped deflector. The W-shaped deflector demonstrated superior stability in airflow past the missile since it was symmetrical. Launch duct and exhaust duct acoustical lining position and thickness was also tested with this model. *Courtesy Aerojet General Corporation.*



silo stored and launched; G = ground attack; M = guided missile; 25 = twenty-fifth major design; C = model number). Testing of the in-silo launch concept began in April 1959. The Air Force contracted with Aerojet General at the Azusa, California facilities, to build and test a 1/6th scale model of a proposed Titan II silo.[56] The development of this ducted launcher, as it was then called, was a crash program that required only 60 days to build both the scale model silo and scale model Titan II airframe fitted with Nike-Ajax engines (Figure 21, 22).

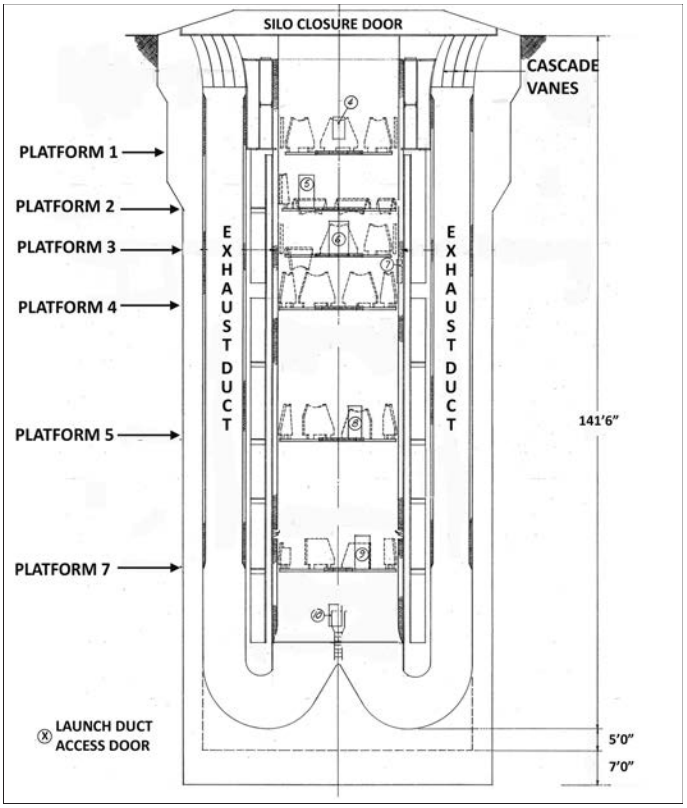


Figure 23: Titan II Silo. A sectional view of a Titan II silo. The silo was composed of two concentric cylinders; an inner cylinder called the launch duct with an inner diameter of 26 feet which housed the missile; and an outer cylinder with an inside diameter of 55 feet. The space between the two was called the silo equipment area. There were retractable work platforms on six levels in the launch duct. The upper outer wall of the silo was eight feet thick from the surface to a depth of 30 feet and then tapered to four feet thickness. The 700-ton silo closure door was supported by four massive box girders, 19 feet in height, four feet in width and 51 feet in length, filled with concrete. ***Courtesy of Titan Missile Museum Archive.***

The scale model silo was constructed completely above ground for easy access through hatches built in the silo and launch duct wall. The ground plane was simulated by a 35-foot diameter circular platform placed at the top of the silo. The entire silo, launch duct and exhaust tubes were built by a steel fabricator in San Pedro, California and trucked 40 miles to the Azusa facilities. The over-size nature of the load required careful plotting of the route to avoid underpasses. As it was, telephone and power company crews still had to proceed ahead of the truck to disconnect or raise interfering wires.[57]

The first test firing took place on June 6, 1959. By the time of the successful launch of Titan I VS-1, modified for in-silo launch from the Silo Launch Test Facility (SLTF) at VAFB on 3 May 1961, a total of 36 firings within the special silo test stand had been conducted. The first 23 were conducted using Aerojet Nike-Ajax production line engines. Originally designed for 2,500 pounds of thrust, two engines were modified to produce 4,200 pounds of thrust each.[58] These tests generated data on the general acoustic, aerodynamic and thermal environments in a 1/6th scale-model W-tube type launcher. The feasibility of the concept was shown, but in late 1959 it was clear that the Titan I airframe would have to be modified to withstand the in-silo launch environment. From February to September 1960, the test program concentrated on the specific design of the SLTF, developing and evaluating techniques for reducing potential damage to the missile systems.[59]

The last phase of the test program continued where the second phase had left off in September 1960 and was completed by February 1961. The final 13 tests were conducted using the same engine and a propellant supply package used in the first two phases, but modified for use with the Titan II propellants at a thrust of 6,000 pounds. Since engine start pressure pulse and exhaust products for the modified system were unknown, the acoustic, thermal and aerodynamic environments were again thoroughly evaluated.[60] Combining the results of these tests provided a set of pressure pulse, temperature differentials and acoustical energy profiles that permitted a launch duct acoustical liner concept to be developed.[61] The critical problem that had been addressed, modeled and solved was that of sound-induced vibrations. A sound energy of 148-decibels on the skin of the missile as it emerged from the silo had been predicted and an actual value of 158-decibels was measured.[62]

The scale model provided insight on the design of the exhaust ducts. By positioning the scale model missile sequentially higher and higher in the launch duct, engineers discovered that by the time the guidance compartment of the missile emerged from the silo, an unacceptable 163-decibel acoustical energy level was present. This was a result of not only the acoustical energy in the launch duct itself but also the sound energy coming from the twin exhaust ducts. The solution was to line the exhaust ducts with acoustical panels, reducing the resultant decibel level and providing an adequate safety margin when combined with other design features. The pressure pulse generated by ignition of the engines was also a major design constraint. The scale model again proved invaluable as a water deluge system was developed which directed high-pressure water into the engine exhaust plumes. This reduced the magnitude of the pulse to an acceptable level. The water deluge also reduced the exhaust plume temperature significantly (Figure 23).[63]

Shock Isolation System

The Titan II launch concept differed significantly from Atlas F and Titan I in that the missile was launched from inside the silo. The storable propellants eliminated the need for time-consuming propellant transfer during the countdown. The silo crib and shock isolation system where no longer needed. The silo, 55 feet in diameter and 145 feet deep, housed the equipment area between the silo wall and the launch duct, which was a cylinder 26.5 feet in diameter. The missile rested inside the launch duct on the 11.5-ton thrust mount which was shock isolated using four 35-foot pendulous springs. Each spring assembly consisted of four coil springs, 20 inches in diameter, mounted in series. The top of the spring assemblies attached to the launch duct wall at the midpoint of the Stage I airframe and, at the bottom, to the thrust mount (Figures 24, 25).

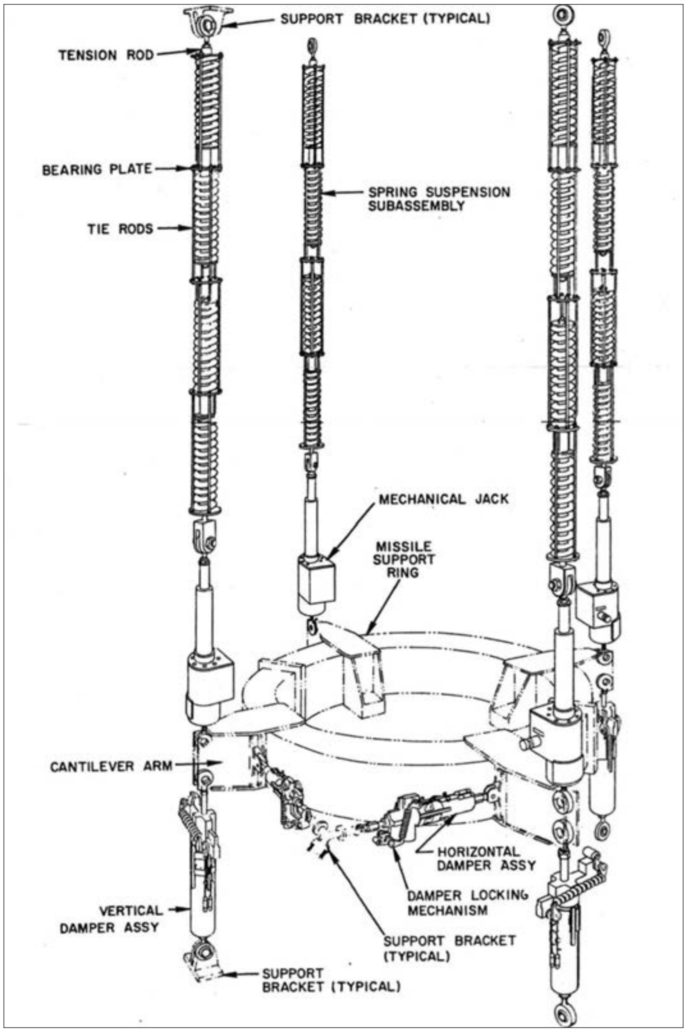


Figure 24: The Shock Isolation System. The missile was held on a thrust mount which was suspended by four 35-foot shock isolation spring assemblies attached to the launch duct wall. Lateral and vertical dampers quickly re-centered the thrust mount after a nearby blast. Prior to launch, the dampers locked the thrust mount in place to provide a stable launch platform. ***Courtesy Titan Missile Museum Archive.***

The fully fueled missiles center of gravity was 10 feet above the shock isolation systems point of attachment to the launch duct wall. Use of the horizontal dampers at the thrust mount eliminated the potential for pitch instability with this design. Vertical and horizontal dampers were attached to the launch duct wall and the thrust mount, respectively, and also locked the thrust mount into the launch position.

The peak acceleration limits were 0.8 g vertically and 0.1 g horizontally. Predicted vertical motion was 12 inches maximum and 4 inches horizontally. Oscillations due to a nearby blast were damped within 60 seconds to allow for thrust mount lockup and launch. The shock isolation system design was such that the missile was returned to within plus or minus 0.25 inch of vertical neutral position; 0.4 inch of neutral horizontal position; and 0.25 degree of verticality for the missile axis. Requirements of the optical azimuth alignment system for aligning the missile guidance inertial platform necessitated these exacting specifications. To provide a stable platform for launch, the shock isolation system was locked prior to engine ignition. In the

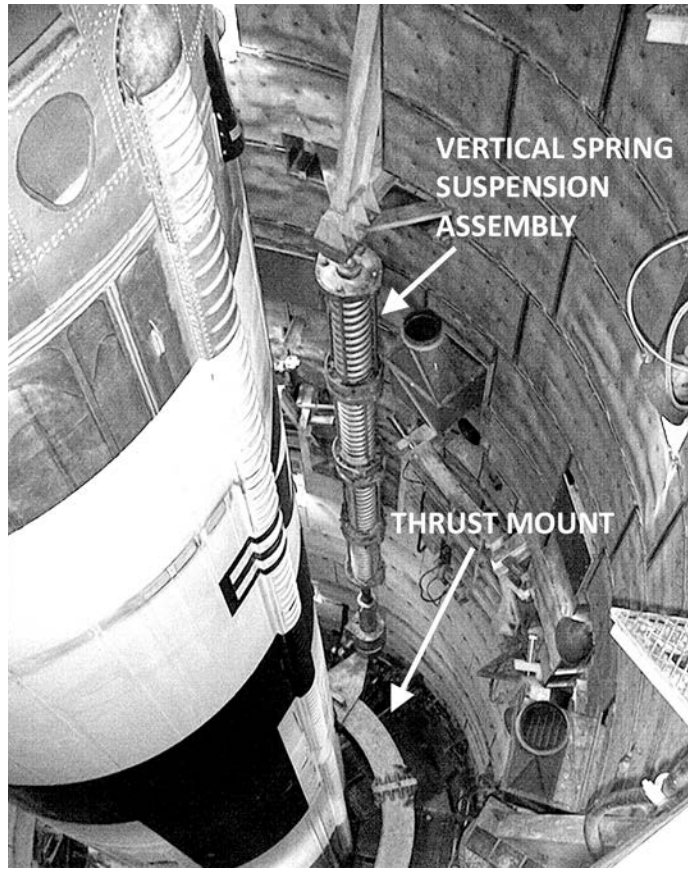


Figure 25: Vertical Spring Suspension Assembly. One of four vertical spring suspension assemblies which provided shock isolation for the missile. Each assembly weighed approximately 1000 pounds, was 14 inches in diameter and 56 inches free height. The spring load rate for each isolation system had to be matched within 1 percent. In the early 60s, they were the largest such assemblies in the Free World. ***Author's Collection.***

locked condition, it was considered soft because it no longer provided protection against nearby blast. [64]

The Titan II Stage I engine took approximately one second to reach 77 percent thrust at which time three 1.8-second timers started. Aerojet engineers knew from extensive testing that if the Stage I engines reached 77 percent thrust, they would go on to reach full thrust. When they timed out, four explosive hold-down nuts fired, and the missile lifted off of the thrust mount.[65]

One of the more interesting tests involving a complete Titan II airframe was the twang test conducted on February 11, 1963 at Launch Complex 395-D, VAFB. Airframe N-3 (60-6810) had been installed in the silo on November 29, 1962. After completion of full-scale propellant transfer system design verification tests, which lasted from December 12 to December 27, 1962, the missile propellant tanks were purged and filled with water. On February 11, a series of tests, nicknamed twang tests, began evaluating the missile shock isolation system under dynamic conditions. The missile shock isolation system thrust mount, with the water-filled missile in place as if ready to launch, was pulled down or to the side of the silo with chains held by explosive bolts. The bolts were fired, quickly releasing the missile, simulating ground shock conditions from a nearby explosion being mitigated by the missile shock isolation

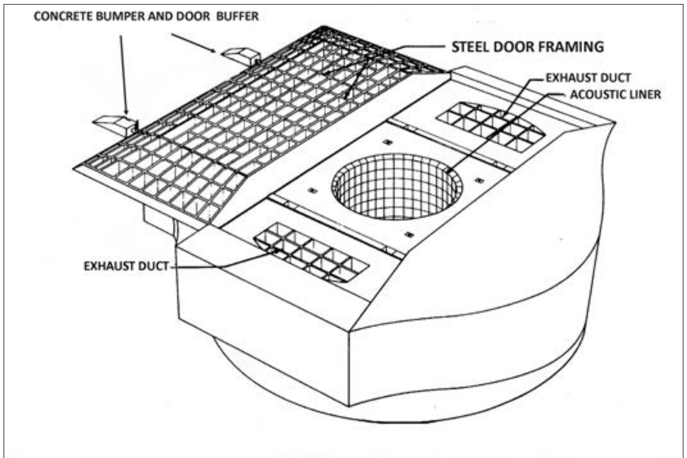


Figure 26: Silo Closure Door Detail. Upper: Diagram illustrating the "eggcrate" construction of the massive 700-ton silo closure door. The top and bottom plating was 3.5-inch battleship armor. The interior webbing supports varied from 1.375 inches to 2.5 inches in thickness. Lower: The silo closure door was prefabricated in sections and assembled on site. The pedestals will be removed and the door lowered onto temporary rails for movement onto the silo. *Courtesy Titan Missile Museum Archive.*

system. The test got its name from the sound the airframe made as it absorbed the displacement movement.

The twang testing resulted in major system changes to all sites, including spring centering devices and new spreader jacks for unlocking the dampers. Engineers designed ratchet-type positive shuttle lock mechanisms to prevent the dampers from unlocking due to vibration during the time between engine ignition and lift-off. A special lubricant was found to facilitate damper unlocking and inhibit corrosion.[66]

Silo Closure Door

The Titan II silo closure door had to cover not only the launch duct but also the two exhaust ducts. Therefore, the Titan I design was not applicable. The door was designed to withstand 300 psi overpressure:

Criteria for design of the Titan II silo closure door to resist nuclear weapons effects include ground shock, blast overpressure, thermal effects, nuclear radiation effects, and electromagnetic pulse effects. In addition, the door was designed to open/close in a matter of seconds. It was also required that the door be capable of operating, within the timescale allowed, against 6 inches of debris covering the door and 6 inches of debris in the path of its movement.[67]

Like the rest of the ICBM facilities which were built with the concurrency strategy, i.e., the launch facilities were under construction during the flight testing of the missile, the first full-scale silo closure door was built next to Launch Facility 395-B. The silo closure door originally weighed 700 tons and was 64 feet wide, 42.5 feet long with a maximum height of 5 feet.[68] The interior of the door was built with an egg crate design and the center cells were partially filled with concrete. The top and bottom surfaces were 3.5" battleship steel armor. The door opened and closed by rolling on double railroad-rail steel tracks using four double sets of railway wheel trucks.

Modifications to the original door design before testing included:

Addition of plows directly in front of the two leading wheel trucks. It was found that the wheels would otherwise ride over the debris on the rails causing the door to stall.

The drive drums were re-reeved from 3-1/2 wraps to 2-1/2 wraps to prevent the cable from wrapping around itself.

Pretension the drive cables with a tension of 20,000 to 25,000 pounds was found to be required to prevent slippage of the cable on the drive drums.

A wheel stop was added to the rails at each of the rear bridges.[69]

Testing began in April 1962 and ended in June 1962. One hundred sixty-nine maintenance runs included operating the door with 3 inches debris (an additional 26 tons of soil), without impulse actuator four operational runs with 3-inches of debris and three operational runs of 6-inches of debris (52 tons) were conducted.[70] The door traveled approximately 3 feet before uncovering the launch duct, permitting soil debris to drop onto the concrete rather than down into the launch duct and potentially damaging the reentry vehicle (Figure 26, 27).

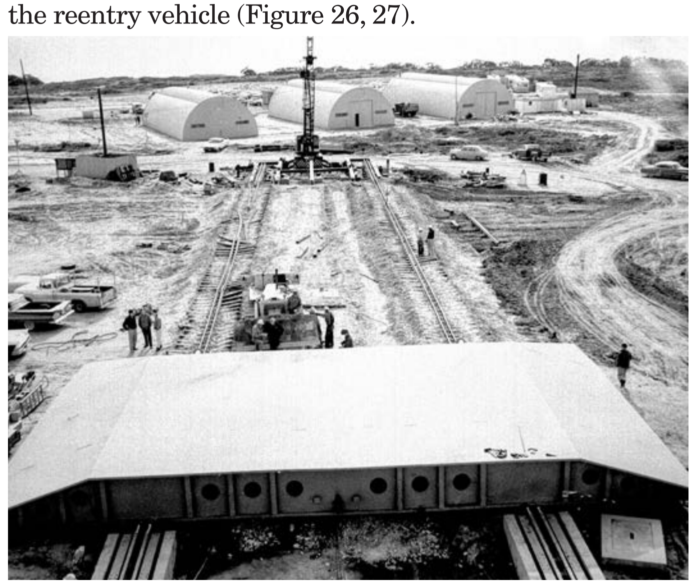


Figure 27: Silo Closure Door at Launch Facility 395-B, Vandenberg Air Force Base. The silo closure door was assembled as close to the launch duct as feasible. Here the door is being moved to Site 395-B. *Author's Collection.*

Table 8. Categories of Titan II R&D Flight Test Programs[1]

Category I Subsystems Development, Test, and Evaluation	
ETR	N-1, N-2, N-4, N-5, N-6, N-9, N-11, N-12, N-13, N-14
WTR	N-7, N-8, N-19, N-22, N-26, N-27, N-30
Category II Weapon System Development, Test and Evaluation	
ETR	N-15, N-16, N-17, N-18, N-20, N-21, N-24, N-25, N-29, N-31, N-32, N-33, N-3A
WTR	N-23, N-28, B-15
Demonstration and Shakedown Operations	
WTR	B-28, B-9, B-7, B-1, B-32

1. *Final Report.*

Response Time

The response time from key-turn to liftoff for Titan II was 58 seconds. The silo closure door started opening at approximately T-35 seconds and was completely open at approximately T-14 seconds. Exposure time was therefore approximately 35 seconds compared to 235 seconds for Titan I.

Research and Development Flight Test

The lessons learned with the Titan I flight test program translated into all Titan II flight test vehicles being flown with operable engines on both stages, operationally configured inertial guidance systems, and reentry vehicles. Thirty-three Titan II Lot N research and development airframes were built, with 32 launched. The remaining airframe, N-10, was used as a trainer at Sheppard Air Force Base, Texas and eventually donated to the Titan Missile Museum, Sahuarita, Arizona. This small sample size was insufficient to determine the variance of individual parameters. The Lot N missiles were grouped into two categories flown at the ETR and three at the WTR. Category I testing was focused on subsystem development, test and evaluation, providing for redesign at an early point in system development. Category II was focused on weapon system development test and evaluation. Category III utilized operational missiles and VAFB Launch Facilities 395-B, C and D (Table 8).[71]

Table 9 lists the specific modifications that occurred during the Lot N Titan II research and development flight test program. Several were minor modifications for installation of instrumentation. Many were changes made as the longitudinal oscillation "Pogo" problem was resolved. The only visual change took place on airframes N-1 through N-9 with the installation of exterior reinforcing bands referred to as "belly bands."[72]

Range safety requirements drove the planning of the flight test program. The instantaneous impact point (IIP) would be moving downrange at 150 nautical miles per second at Stage II engine cut-off. The flight path from the ETR launch facilities at Patrick Air Force Base did not overfly inhabited islands. The WTR had a requirement to protect the land areas of Kwajalein Atoll which meant the IIP could not cross an inhabited island. This requirement limited acceptable targets in the Kwajalein area during the research and development flights, preventing impact in the

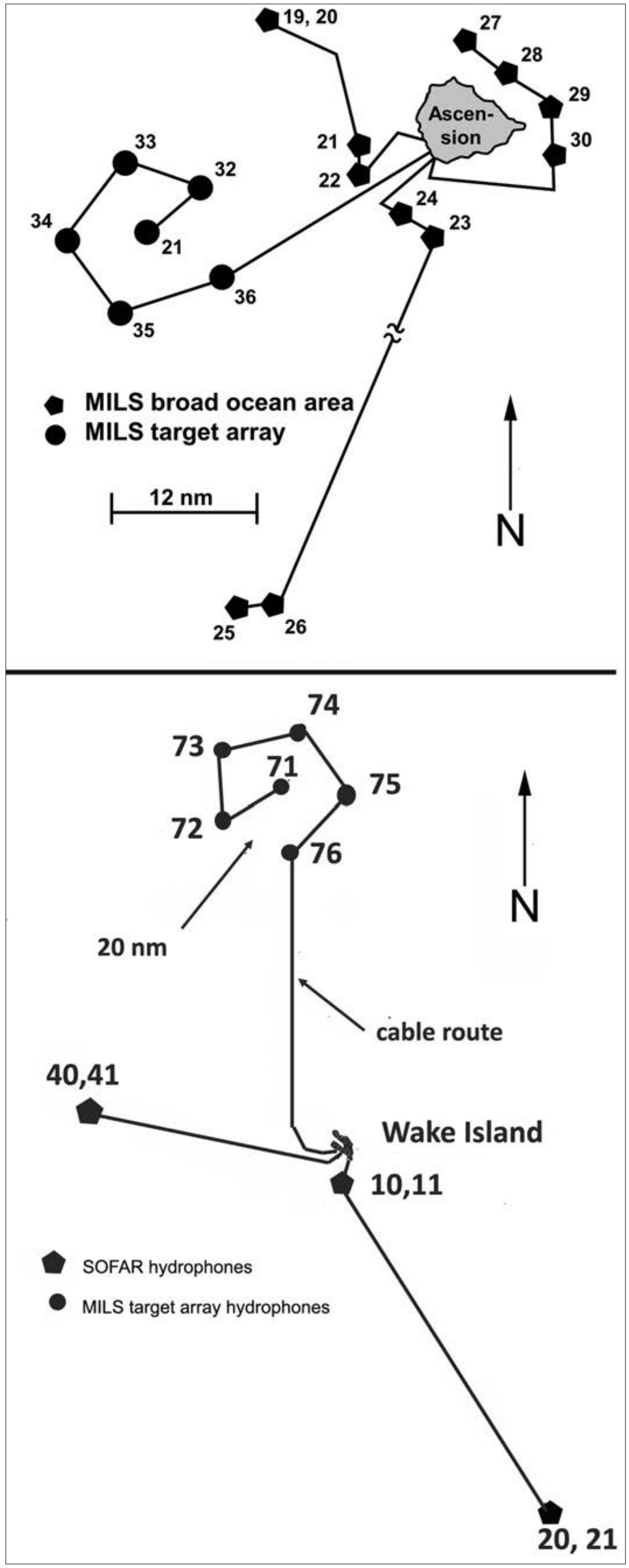


Figure 28: Missile Impact Location System. Approximate location of hydrophones at Ascension Island and Wake Island, for target array and broad ocean area signal detection. At Wake Island, the target array north of the island was installed first followed several years later with the six-hydrophone broad ocean array west and south of the island. *Author's Collection.*

Table 9. Titan II Lot N Structural Changes

Change	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	3A
1. Belly Bands	—	—	—	—	—	—	—	—	—																									A
2. Beefed Up Waffle & Skins											—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	B
3. One Piece Conduit Stage I	—	—	—	—	—	—	—	—	—																									
4. Built-Up Conduit Stage I											—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
5. Built-Up Cone Fuel Tank Stage I	—	—	—	—	—	—	—	—	—		—	—	—	—	—	—																		
6. One Piece Cone Fuel Tank Stage I																	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
7. Oxidizer Dome Support Stage I Forward	—	—	—	—	—	—	—	—	—		—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
8. Weld Land Area Increase											—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
9. Interstage Riveting														—	—	—																		
10. R/V Adapter Martin (Mk-4)											—																							
11. R/V Adapter G.E. (Mk-6)	—	—	—	—	—	—	—	—	—			—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
12. Translation Rockets											—	—									—	—	—	—	—	—	—	—	—	—	—	—	—	—
13. Spectroradiometer																								—	—	—	—	—	—		—		—	
14. Scientific Passenger Pod																								—	—				—		—		—	
15. Malfunction Detection System																								—	—				—		—	—	—	
16. 40-foot Staging Cable																									—				—		—	—	—	
17. Air Duct Stage I Engine Compartment																									—	—								
18. External Camera Pod																									—							—	—	—
19. Steel Feed Line (Suction)	—	—	—	—	—	—	—	—	—																									
20. Aluminum Feed Line (Suction)											—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	C
21. Beefed Up Transport Section																																—	—	
22. Internal Camera Pod																													—			—	—	—

N-10 was used as a trainer and is now at the Titan Missile Museum
Note A: belly bands Stage I oxidizer tanks only
Note B: Stage I fuel, Stage II fuel and oxidizer tanks
Note C: suction line modified to Gemini Launch Vehicle specifications

Kwajalein Lagoon. Later operational test flights of Minuteman and Titan II did utilize the Kwajalein Lagoon as a target. The Eniwetok Lagoon was a target as well as the Wake Island Splash Net and broad ocean areas near Kwajalein (Figure 28).[73]

Cape Kennedy, Air Force Eastern Test Range

Titan II operations at the ETR utilized much of the infrastructure from the Titan I program. All of the aboveground launch complexes, P-15, P-16, P-19, and P-20 were modified for the storable propellants and aligning the new inertial guidance system.

The east coast of Florida was ideal for tracking-camera locations for covering the early aspects of missile flight from Cape Canaveral. The staging process caused a telemetry blackout near the launch point. Tracking stations at Vero and Melbourne Beach provided excellent optical coverage of the staging process while the tracking station at Grand Bahama Island had a better angle for receiving telemetry during the staging event.

The evaluation of range and payload capability at the ETR was somewhat hampered by the relatively short range to the Ascension Island Splash Net. A key data point for the program was determination of propellant mixture ratios. The short range meant that a significant amount of residual propellant was left at powered flight termination, covering the low propellant sensors. The solution was special trajectory shaping in the later portion of the program to increase propellant usage and powered flight without materially affecting the ballistic portion.

The Caribbean Island chain provided excellent locations for a variety of tracking systems, including Azusa, GE Mod III, and MISTRAM (Missile Trajectory Measurement) systems. The Ascension Island Splash Net hydrophone system was used to determine impact points. Radar tracking with various FPS-16 installations on the island chain provided additional data.

The evaluation of system accuracy involved monitoring engine cut off, reentry vehicle separation, reentry vehicle attitude control, and Stage II translation. The instrumentation required for this included: (1) airborne telemetry of guidance functions, post-cut off velocity, and separation velocity over the missile-frame link, (2) telemetry of post-separation velocity errors over the reentry vehicle link, (3) external tracking data to provide trajectory reconstruction, and (4) accurate impact data.[74]

Many non-weapon system projects were also carried out during the Titan II R&D program at the ETR. One of the primary ancillary investigations was resolution of the POGO Stage I longitudinal oscillation problem. Titan II had been selected as the launch vehicle for the Gemini program. While the POGO effect was a minor obstacle for development of the weapon system, it needed to be resolved in order for the Gemini program to make progress.

There were two particularly dramatic flight tests at the ETR, N-4 and N-20. The first attempted launch of N-4 on June 28, 1962 was aborted when a combustion instability in the Stage I Subassembly 2 thrust chamber caused the thrust chamber to be cut off at the fuel manifold and blown out the flame deflector several hundred feet. The automatic sequencer instrumentation sensed that the Stage I engines had not come to full power and shut down the engines, saving the missile. Combustion instability had been a problem with the Stage II engine but not Stage I. Subsequent investigation found that the most probable explanation was residual alcohol left from cleaning the engine after an acceptance test firing. The "tangential combustion instability" high frequency oscillations had acted as an ultrasonic saw which cut through the thrust chamber wall. The engine was replaced and N-4 was successfully launched on July 25, 1962 (Figures 29, 30).

N-20 was successfully launched on May 29, 1963. Immediately after launch, stress corrosion of the Stage I caused a leak in the thrust chamber fuel valve which ignited and damaged the flight controls. The missile pitched

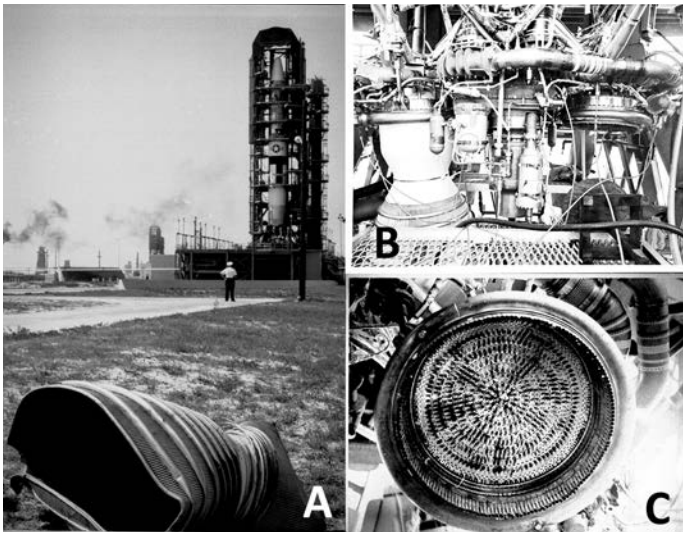


Figure 29: Titan II Ground Abort. (A) Titan II N-4 (60-6811) on Pad 16, 28 June 1962, shortly after the first and only ground abort in the Titan II ICBM research and development program. A combustion instability at the Stage I subassembly 2 injector cut the thrust chamber off. It came to rest several hundred feet from the flame deflector. (B) Stage I engine set on N-4 after the ground abort. The combustion instability worked like an ultrasonic cutoff saw, cleanly cutting off the thrust chamber bell which was expelled from the flame deflector by the exhaust gases. The airframe suffered no damage. (C) The injector face of Stage I engine subassembly 2. The thrust chamber cooling tubes can be seen at the edge of the injector plate, cleanly sheared off by the combustion instability. The engine was replaced and N-4 was successfully launched on 25 July 1962. *Courtesy R. Stahl.*

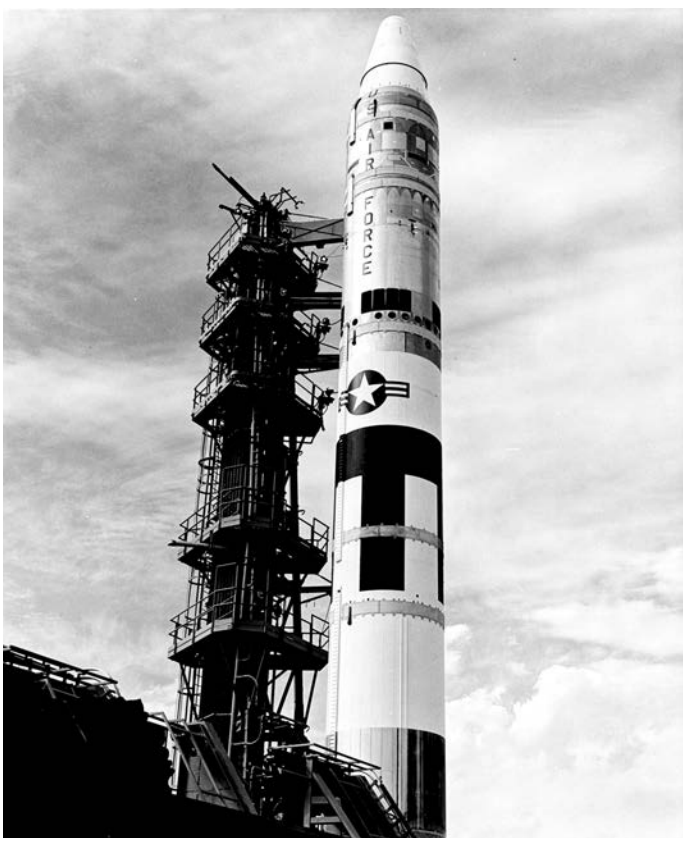


Figure 30: Belly Bands. Titan II N-2 is ready for launch on March 3, 1962 from Cape Canaveral Launch Complex 16. The arrow indicates one of six "belly band" structural reinforcements. The belly band modification was necessary for Missiles N-1 through N-9 after which it was incorporated into the airframe at the factory. *Author's Collection.*

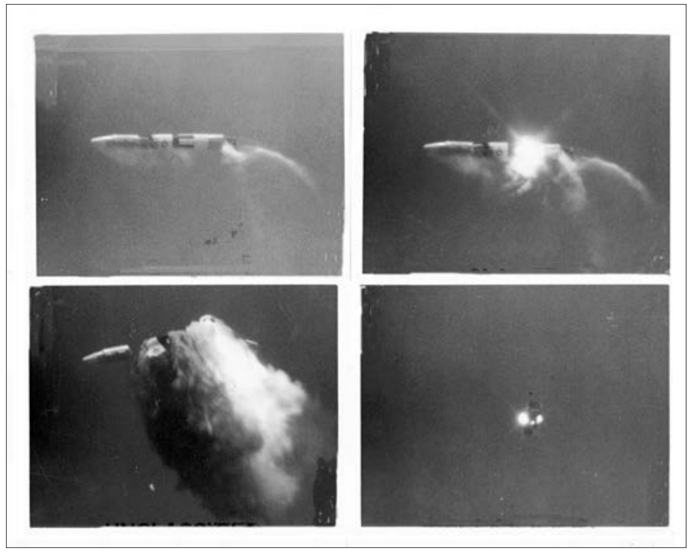


Figure 31: Titan II N-20 In-Flight Failure. N-20 was launched from Cape Canaveral on 29 May 1963. Stress corrosion in the Stage I thrust chamber fuel valve caused an engine compartment fire with resultant loss of engine control. Clockwise from upper left: rapid missile pitch over and interstage collapse prior to breakup; major airframe failure and Stage I premature separation destruct triggered; complete breakup of Stage I and separation of Stage II; command destruct of Stage II. *Courtesy D. Kemper.*

over and broke up 52 seconds into flight. Replacing the 7075T6 aluminum alloy with 7073T6 solved the problem and the modification was installed all the operational missiles and Gemini-Titan launch vehicles (Figure 31).[75]

Twenty-three Titan II Lot N missiles were launched between March 16, 1962 and April 9, 1964. 15 of the flight tests were successful (80 percent of test objectives achieved); six were partially successful (20 to 80 percent of test objectives achieved); and two were failures (less than 20 percent objectives achieved). Twenty-two missiles carried variations of the Mark 6 reentry vehicle. N-11 carried the Mark 4 reentry vehicle in a test to demonstrate the capability and interchangeability between the Mark 4 and the Titan II airframe. Successful RV separation occurred on 20 flights, 14 using the primary release circuitry with reentry vehicle impact in the target area. The remaining six were released using the backup system which allowed reentry data to be collected when full range was not achieved.[76]

Overall objectives of the Titan II R&D test program at ETR were fully achieved. Range capability of the Titan II missile was demonstrated to be in excess of 5,800 nautical miles with a Mark 6 reentry vehicle; a CEP of 0.99 nautical miles was better than the specified CEP requirements and in-flight reliability, as demonstrated by flight tests, exceeded the weapon system design goals (Table 10).[77]

Vandenberg Air Force Base, Air Force Western Test Range

The Titan II launch facilities at VAFB were prototype facilities for the three operational Titan II wings. The three launch facilities that made up Titan II Test Facility (TF-2) were 395B, 395C and 395D. They differed from the opera-

Table 10. Patrick AFB Titan II R&D Flight Record[1]

Flt. #	Date	Airframe #	Launch Site	Description
				Category I
	1962			
1	16 Mar	60-6809	Pad 16	The successful first Titan II launch operation was conducted on 16 March 1962, 28 months after the first storable propellant feasibility studies had begun. N-2 boosted the payload to the full 5,000 nautical mile range and the R/V impacted in the target area. Mark 6 Mod 4
2	7 Jun	60-6808	Pad 15	N-1 partial success, Stage II gas generator restricted, failed to develop full thrust. Mark 6 Mod 4
3	11 Jul	61-2729	Pad 15	N-6, flight test objectives achieved. Mark 6 Mod 2
4	25 Jul	60-6811	Pad 16	N-4, launch attempt #1 (27 Jun) aborted by combustion instability in Stage I engine, launch attempt #2 successful, flight was a partial success, Stage II fuel pump leak. Mark 6 Mod 4
5	12 Sep	60-6812	Pad 15	N-5, first successful launch of a Titan II ICBM with decoys took place at Cape Canaveral. Mark 6 Mod 4
6	12 Oct	61-2732	Pad 16	N-9, flight test objectives achieved. Mark 6 Mod 2
7	26 Oct	61-2735	Pad 15	N-12, flight test objectives achieved. Mark 6 Mod 4
8	6 Dec	61-2734	Pad 16	N-11, failure, Stage II bootstrap line severe vibration, thrust chamber pressure switch shut down. Mark 6 Mod 2A
9	19 Dec	61-2736	Pad 15	N-13, flight test objectives achieved Mark 6 Mod 1.
				Category II
	1963			
10	10 Jan	61-2738	Pad 16	N-15, partial success, Stage II gas generator restriction. Mark 6 Mod 1
11	6 Feb	61-2739	Pad 15	N-16, flight test objectives achieved, first attempted launch of a Titan II by a SAC crew was successful on 6 February 1963 at Cape Canaveral. The missile traveled 5,800 miles and the reentry vehicle impacted in the target area. Mark 6 Mod 1
13	21 Mar	61-2741	Pad 15	N-18, flight test objectives achieved. Mark 6 Mod 1
14	19 Apr	61-2744	Pad 15	N-21, partial success, Stage II bootstrap, premature engine shutdown. Mark 6 Mod 2A
16	9 May	61-2737	Pad 16	N-14, partial success, Stage II oxidizer leak, premature shutdown. Mark 6 Mod 1
18	24 May	61-2740	Pad 15	N-17, successful, flight test objectives achieved. Mark 6 Mod 2A
19	29 May	61-2743	Pad 16	N-20, failure, thrust chamber fuel valve failure, leak and fire in Stage I engine compartment. Mark 6 Mod 2A
21	21 Aug	61-2747	Pad 15	N-24, successful, flight test objectives achieved. Mark 6 Mod 2A
23	1 Nov	61-2748	Pad 15	N-25, successful, flight test objectives achieved. Mark 6 Mod 4A
25	12 Dec	61-2752	Pad 15	N-29, successful, flight test objectives achieved. Mark 6 Mod 2A
				Category III
	1964			
27	15 Jan	61-2754	Pad 15	N-31, successful, flight test objectives achieved. Mark 6 Mod 1
30	26 Feb	62-1867	Pad 15	N-32, successful, flight test objectives achieved. Mark 6 Mod 2C
32	23 Mar	62-1868	Pad 15	N-33, successful, flight test objectives achieved. Mark 6 Mod 4A
33	9 Apr	60-6810	Pad 15	N-3A, successful, flight test objectives achieved, last Titan II ICBM launch from Cape , Mark 6 Mod 2C

1. N-3 was used in the "twang" test. Often listed as N-34, N-3 was modified after the test: Stage I oxidizer belly band, beefed up waffle and skins all other tanks; aluminum feed line (suction) Gemini Launch Vehicle flanged joint replacing the Alfin Joint configuration; Stage I oxidizer tank salvaged from N-3 and updated to N-28 configuration; transportation section salvaged from N-3 and updated to N-28 configuration; Stage II fuel tank is scrapped Gemini Launch Vehicle 2 tank; Stage II oxidizer, forward and aft domes are operational domes chem-milled to R&D configuration, skirts were operational configuration. The modified airframe was designated as N-3A.

tional bases in lacking the inter-complex radio communication system equipment. Launch facilities 395-C and 395-D also had the extensive range safety and support equipment for the flight testing. Upon completion of the Category I and II flight tests, 395-C and 395-D were refurbished to duplicate the instrumentation system used at 395-B during the Functional Demonstration Launch (Table 11).

Category I testing at TF-2 consisted of four separate groups of test operations: verify conformance of individual subsystems with basic design specifications; demonstrate performance of specified functions under normal operating conditions. Principal subsystems development testing involved the propellant transfer system; silo closure door; missile thrust mount shock isolation and the CMG-4 simulation control chassis.

Category II included testing and evaluation of integrated subsystems through the mating process that evolved into a complete system. The program was accomplished in a realistic operational environment beginning with missile receipt and continuing to preparation, inspection and maintenance for several days before launch. The Category II series included an exercise designated as Functional Demonstration Launch.

The Category I and II test objectives at VAFB were designed to complete developmental testing of the Titan II Weapon System in an operational environment. In addition to verify demonstrate the capability of the Titan II weapon system to meet established operational requirements. One LG-25C (operational series) and the nine Lot-N missiles

Table 11. Vandenberg AFB Titan II R&D Flight Record[1]

Flt. #	Date	Airframe #	Launch Site	Description
				Category I
	1963			
12	16 Feb	61-2730	Complex 395-C	N-7, first Titan II silo launch successful. Stage II umbilicals failed to disconnect properly, missile self-destructed at 18,800 feet. Successful in that missile cleared silo intact. Mark 6 Mod 2A
15	27 Apr	61-2731	Complex 395-C	N-8, flight test objectives met. Mark 6 Mod 2A
17	13 May	61-2742	Complex 395-D	N-19, successful, flight test objectives achieved . Mark 6 Mod 2A
20	20 Jun	61-2745	Complex 395-C	N-22, partial success, Stage II gas generator failure. Mark 6 Mod 4B
24	9 Nov	61-2750	Complex 395-C	N-27, successful, flight test objectives achieved. Mark 6 Mod 2B
	1964			
28	23 Jan	61-2749	Complex 395-C	N-26, successful flight test objectives achieved. Mark 6 Mod 2B
31	13 Mar	61-2753	Complex 395-C	N-30, successful, flight test objectives achieved, last flight of N-series missiles from VAFB
				Category II
	1963			
22	23 Sep	61-2746	Complex 395-D	N-23, successful, flight test objectives achieved. Mark 6 Mod 1B
26	16 Dec	61-2751	Complex 395-D	N-28, successful, flight test objectives achieved. Mark 6 Mod 1B
				Category III
	1964			
29	17 Feb	61-2769	Complex 395-B	B-15, successful, flight test objectives achieved, first technical data launch, first launch of operationally configured missile. Mark 6 Mod 3.

1. *Final Report.*

were allocated to the VAFB flight test series. Seven Category I and three Category II flight tests were programmed for TF-2.

Category I Flight Tests

The first launch of a Titan II ICBM from a silo environment was scheduled to take place on 15 February 1963. About midnight, two days before the launch, Don Kundich, a Martin Marietta Company engineer who was the "missile mother," the engineer responsible for expediting and ensuring that all changes to the missile were completed, George Teft, Martin Marietta Company engineer and John Adamoli, the Martin Marietta Company Flight Test Conductor, along with several other engineers, were finishing the preflight inspection of N-7 (61-2730). The group walked around the missile at all six levels where there were work platforms. This inspection was the last chance to look for the unusual connection or situation that might have passed the earlier walk-throughs.

The group looked at the way the umbilical lanyards were attached to the launch duct wall. These umbilicals were "flyaway" in that they were pulled free of the missile as it rose off the thrust mount, rather than being mechanically ejected. The umbilical lanyards were stainless steel cables attached to the wall at one end and to the umbilical connector at the other. When the missile lifted off the thrust mount, the lanyards were pulled taut, activating the connector release and then pulling the connector and cable free of the missile. The lanyard attachment points on the launch duct wall were just D-rings of metal on galvanized pipe, mounted directly on the wall. Kundich and Adamoli recall that the entire group commented that they just did not look strong enough. The only other silo launch, that of Titan I VS-1, May 3, 1961, had a completely different umbilical release mechanism. The Titan II launches at Cape Canaveral used booms to support the umbilicals and were not a valid comparison. They decided to re-analyze the rise rates of the vehicle to see if the lanyard would tighten and snap the D ring. The concern was that the lanyard had to pull tight to activate the plug release mechanism, fingers of metal that pulled up and allowed the connector to be

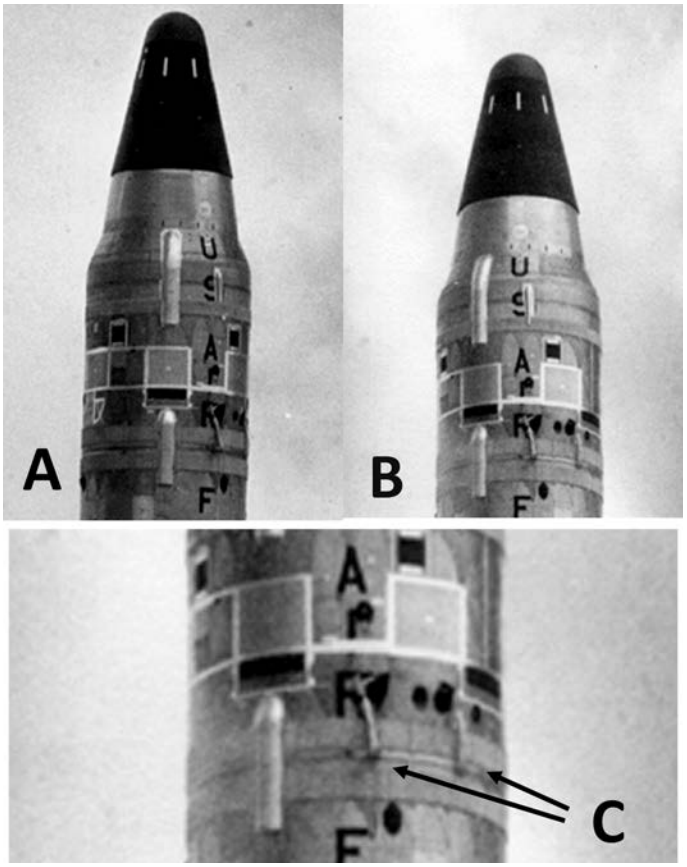


Figure 33: Detail of N-7 Launch. (A) N-7 has just cleared the launch duct, note the location of the U.S. Air Force lettering. (B) N-7 is now approximately 100 feet above the launch duct, rotating to the left, as can be seen by the shift to the left of the U.S. Air Force lettering. (C) Arrows point to the dangling umbilical connectors. *Author's Collection.*

pulled free. A phone call to Denver the next day resulted in a recalculation and reassurance that the installation was strong enough.

At 2144 (Z), February 16, 1963, the first in-silo launch took place (Figure 32, on first page). Robert Popp, an engineer at Delco Electronics, the supplier of the inertial guidance system, had driven to the official viewing area to watch this inaugural Titan II launch. He had remained in his car, filming the launch through the long sloping windshield of his Buick. As the missile emerged from the silo, he noticed an unusual spinning motion. As the missile cleared the silo, the programmed roll and pitch maneuver did not take place. Popp panned up until the roof blocked his view. He started to get out of the car with his camera and then thought better of it when he realized a lot of top Air Force brass was nearby and might not like the idea of his amateur cinematography. Nearly simultaneous with this decision on his part was the breakup of N-7 at 18,000 feet. Popp dove back into the car realizing that while he was a good two miles from the launch site, debris was starting to spread from the explosion of Stage I.[78]

Kundich and Adamoli were among the Martin Marietta Company employees watching the launch from the engineering compound. They noticed that the missile was spinning as it left the silo and immediately knew something was very wrong. Both Kundich and Adamoli clearly recalled seeing the Stage II electrical umbilical connectors,

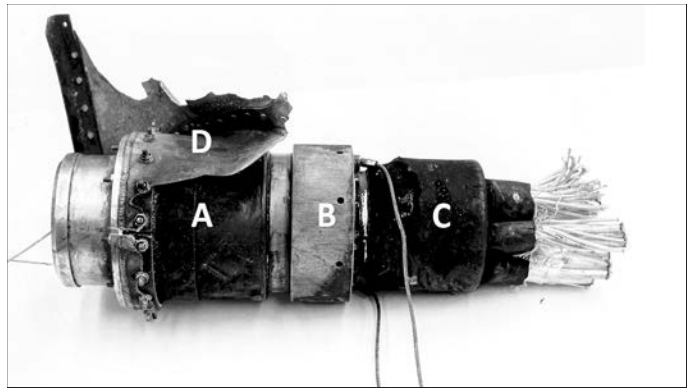


Figure 34: Umbilical 2B1E. The (A) airborne; (B) release mechanism, (C) ground umbilical connectors prior failure analysis. (D) missile skin. *Courtesy of F.C. Radaz .*

normally flush to the surface of the missile, dangling out at the end of about three feet of wiring (Figure 33).

At 18,000 feet the missile leaned over and the stages separated due to the weight of Stage II. Stage I's inadvertent separation activated the destruct system and destroyed Stage I. The range safety officer had tried to destroy the missile but the system did not work since the missile logic still sensed it was on ground power due to the electrical umbilical connector problem. Stage II fell into the water more or less intact and the expanding cloud of propellant vapor was luckily blown out to sea. The primary objective of the test had been accomplished, that of a Titan II successfully clearing the silo environment intact, but all involved were hardly celebrating.[79]

Later that night, Kundich and Adamoli returned to the silo to find that the Stage I electrical umbilicals had pulled properly but that electrical umbilicals 2B1E, 2B2E and 3B1E of Stage II had not. The airborne half of the connector and a piece of the missile skin was dangling from each umbilical. The missile had been spinning, or more correctly, rolling, because with the umbilicals not physically disconnected, the logic circuitry had sensed that the missile had not lifted off, returned the missile to ground power and left the range safety system disarmed. The missile had left the silo without any airborne electrical power or guidance. The force of the umbilicals not releasing properly had started the spinning motion and without electrical power to the missile components, the guidance system could not stop the spin. This spin was fortunate, in a sense, because it imparted some stability to the missile and might have helped it clear the silo intact (Figure 34).

Further investigation showed that the lanyards became taut too quickly and snapped before they could activate the release mechanism in the umbilical connectors. The interim fix was a spring mechanism that cushioned the shock of the umbilical becoming taut. The final fix was to make the D-ring fixture into a J-bar shape that gave enough by bending to absorb the shock and permit the lanyard to pull tight and release the umbilical properly (Figure 35).[80]

Damage to the launch duct equipment and components was extensive, including: air conditioning; communication and camera cables; propellant transfer fill and

Figure 35: New Umbilical Release System. The solution to the lanyard failure was to replace the rigid D-ring attachment point on the launch dock wall with a flexible, J-shaped bar. The J-shape allowed it to flex slightly when the release lanyard pulled taut, permitting the mechanism to release. The umbilical pull problem did not reoccur. *Courtesy of F.C. Radaz.*

drain lines and valves; vapor detection system components; and umbilicals. While the thrust mount received only superficial damage, the flame deflector was damaged, and 55 acoustic modules in the launch duct and a further 209 in the exhaust ducts needed replacement or repair.[81]

On March 31, 1963, the first Titan II ICBM was placed on alert that Launch Complex 570-2, 570th Strategic Missile Squadron, 390th Strategic Missile Wing, Davis-Monthan AFB, Arizona. After 24 years, one month and 6 days of strategic alert, on May 6, 1987, the last Titan II ICBM was taken off alert at Launch Complex 373-8, 373rd Strategic Missile Squadron, 308th Strategic Missile Wing SMW, Little Rock Air Force Base, Arkansas.[82]

Operational test and evaluation launches took place from 1964 to 1976 with 51 launch attempts, 48 launched with 40 successful flights for a launch reliability of 94 percent and 83 percent successful flights. While the accuracy of the Titan II Mark 6 has not been officially released, calculation of available test data gives a circular error probable of 0.78 nautical miles (Figure 36) .[83]

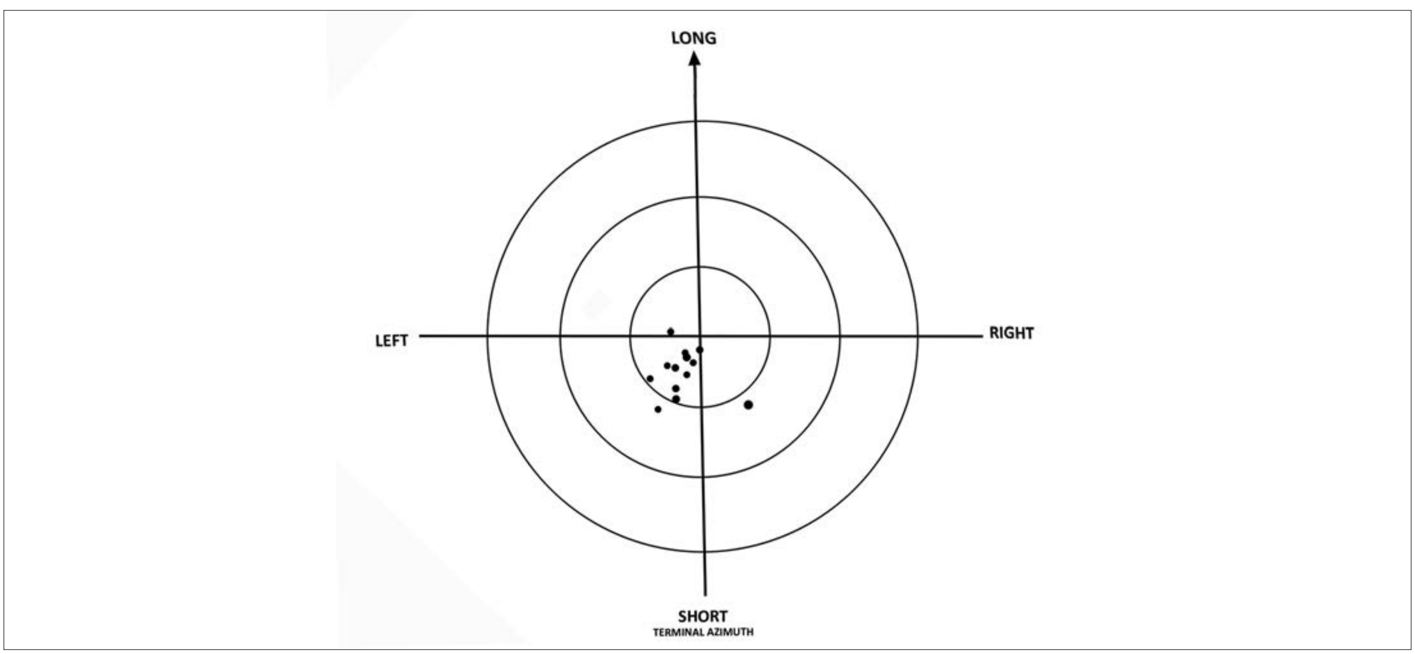


Figure 36: Titan II Operational Test Impact Points. The Titan II Operational Test Program was successfully completed on 20 April 1966. Nineteen missiles were launched, of these, 14 successfully impacted in the designated target area and five experienced in-flight failures. The result in-flight success ratio was 74 percent. Four of the missions were airburst missions ranging in altitude between 13,000 and 14,000 feet. *Courtesy of Titan Missile Museum Archive.*

Summary

The short operational life of the Titan I ICBM program has tended to obscure the relationship between the Titan I and Titan II programs. This brief comparison of aspects of the two programs reveals that the lessons learned with Titan I, both in the missile itself and the deployment mode, led to the highly successful Titan II ICBM program. The Titan II design became the basis for the equally successful Titan family of space launch vehicles, Titan IIIA-E, Titan IIIM, Titan 34D and Titan IV. All because of the decision to provide a backup for Atlas! ■

NOTES

1. B.W. Augenstein, A Revised Development Program for Ballistic Missiles of Intercontinental Range, 8 February 1954, Special Memorandum Number 21, U.S. Air Force Project RAND; C. Walker and J. Powell, *Atlas: The Ultimate Weapon by Those Who Built It,* (Apogee Books Publication, 1971), pages 24-25.
2.. Warren Greene, *The Development of SM 68 Titan*, AFSC Historical Publication Series 62-23-1, 1962, page 11. The Western Development Division (WDD) was headquartered in Inglewood, California. WDD was a development management group whose sole responsibility was to oversee the research and development, testing, and production leading to creation of a successful ICBM. This document is available from the Homeland Security Digital Library, https://www.hsdl.org/.
3.. Technically, the Titan I designation was not used until the programs were separated. The term Titan I is used for consistency's sake.
4. Greene, page vi; *The Development of SM 68, Volume 2, Document 52,* AFC GM-BD Memorandum for Record, Subject: Storable Titan Representation to Mr. Holaday, 18 April 1958, p. 1.
5. J. L. Chapman, *Atlas: The Story of the Missile*, (Harper and Brothers, New York, 1960), page 61; I. Pike, "Atlas: Pioneer ICBM and Space-Age Workhorse," *Flight International,* Volume 81, January 1962, pages 89-96.
6. G.P. Sutton and O. Biblarz, *Rocket Propulsion Elements*, *Eighth Edition*, (John Wiley and Sons, New Jersey, 2010), page 31. The propellant remaining at booster engine cut off was calculated from L S. Swenson, Jr., J. M. Grimwood and C. C. Alexander, *This New Ocean: A History of Project Mercury,* (NASA History Office, Washington, DC, 1998), pages 26, 384, 426.
7. J. Coan, J.C. Hemphill, and K.J. Boothroyd, "Structural Description SM-68," February 1961, (Aeronautics Department, Martin Company), page 10.
8. V. Selby, personal interview and correspondence, June, 1996.
9. Personal communications, V. Selby. One area of concern early in the fabrication process for Titan I Stage I was that the longeron structures that served as the point of attachment of the missile to the launch mount were bolted onto the Stage I fuel tank and then sealed. Leaks were common in this area.
10. Greene, page 114.
11. L.C. Meland and F.C. Thompson, "History of the Titan Liquid Rocket Engines," AIAA/ASME/SAE/ASEE 25th Joint Propulsion Conference, Monterey, California, July 10-12, 1989, pages 1-5
12. *Flight Summary Report Series D Atlas Missiles,* (San Diego, CA: General Dynamics/Astronautics, 21 June 1961), 8-32 to 8-37. Available from Defense Technical Information Center, AD0833337. *Progress of ICBM and IRBM Programs, April, May, June 1960*, Department of Defense, Office of the Director of Defense Research and Engineering, Declassified Documents Online (U.S. Declassified Documents Online, htttp://www.gale.com/c/us-declassified-documents-online, CK2349126998), page 17.
13. *Titan Ballistic Missile Development Plan, 30 April 1960*, IRIS # 2055834, page 1-1-6. AFHRA, Maxwell AFB, AL.
14. *Titan I Missile Complex 2A, Historic American Engineering Record, HAER CO-89*, page 36.
15. D. K. Stumpf, Ballistic Missile Shock Isolation Systems, *Air & Space Power History,* Winter 2022, Volume 69, Number 4, pages 31-42.
16. *Operation and Organizational Maintenance: USAF Model HGM-25A Missile Weapon System,* T.O. 21-HGM25A-1-1, 1 August 1963, page 3-153 to 3-176. Author's collection.
17. L. J. Adams, "Evolution of the Titan rocket-Titan I to Titan II," *A History of Rocketry and Astronautics: Proceedings of the 24th Symposium of the International Academy of Astronautics,* (American Institute of Aeronautics and Astronautics, Washington, DC, 1990), page 211.
18. Greene, page 91.
19. *Strategic Air Command Missile Chronology: 1939-1973,* (Office of the Historian, Headquarters, Strategic Air Command, Offutt AFB, 2 September 1975), page 55.
20. F.X. Ruggerio, "Missileers' Heritage," Student Research Report , ACSC 2065-81, Air Command and Staff College, Air University, Maxwell Air Force Base, Alabama, page 54.
21. *WS 107C, Titan II Weapon System Final Report, January 1965*, (Headquarters, Ballistic Systems Division, Air Force Systems Command, Norton Air Force Base, San Bernardino, California), page v. Hereafter *Final Report*; WS 107A-2 was used to identify both Titan I and II and was synonymous with Weapon System 107C. LGM-25C designated the operational missiles which were formally known as the SM-68B. XLGM-25C designated the research and development missiles, also referred to as Lot N missiles.
22. Adams, pages 212-217.
23. Greene, pages 114.
24. P. O. Larson, "Titan III Inertial Guidance System," AIAA Second Annual Meeting, San Francisco, California, July 26-29, 1965, page 3; "Detailed Design Specification for Model SM-68B Missile (including addendum for X SM-60 8B), 15A. Hereafter referred to as Detailed Design; *Final Report,* 139-140; "Ballistic Missile Inertial Guidance Mechanic/Technician SM-68B," Student Study Guide, January 1962, page 1.
25. "History of Strategic Air Command, 1 July 1975 to 31 December 1976, Historical Study No. 161, Vol. XI, Chapter V, Exhibit 40-Operations Plan Number 83-76: Titan II Launches in Support of Universal Space Guidance System," K416.01-161, page ii. This document is classified SECRET. The information used is unclassified. Air Force Historical Research Agency (AFHRA), Maxwell AFB, AL.
26. "Inertial Guidance System Description and Diagrams, Missile Weapon System USAF Model LGM-25C," T.O. 21M-LGM26C-2-4-1, 1 December 1979, pages 1-5 to 1-7. Titan Missile Museum Archive.
27. Personal communications, Robert Popp, May 1998. Popp was the Delco Field Service Supervisor that scheduled all of the installation of the USGS modification. He credits the success of the USGS modification program during RIVET HAWK to six key Delco staff members: Marion Sanders, Engineering Test Conductor; Hal Gebhardt, Field Service Senior Engineer; Jack Hoeft, Titan Electronic Technician; John Coutley, Senior Telemetry Engineer; Kamal Odeh, Senior Technical Writer; and Don Bueschel, Quality Control Engineer.
28. "Special Operational Test Exercise Report, Integration Test Flight 1, LGM 25C AFSN 61-02771," 28 July 1976, (Headquarters 1st Strategic Aerospace Division, Vandenberg AFB), K-DIV-0001-HI-Vol II, AFHRA, Maxwell AFB, AL, page 11.

29. The author wishes to thank Robert Popp, Ed Stapp and John Hanna, all Delco guidance system engineers for patiently explaining this problem and solution. Popp's final version was used verbatim; Personal interview and correspondence with Colonel Charles Simpson, USAF, (Ret.), July, 1996 and June 1997.
30. R. Jones, personal interview, August 1996; Louis D. Wilson, personal communications, September 1996.
31. *Final Report*, page 8.
32. *Final Report*, page 140; Meland and Thompson, page 3.
33. D. K. Stumpf, *Titan II: A History of a Cold War Missile Program,* (University of Arkansas Press, Fayetteville, Arkansas, 2000), pages 49-50. Hereafter referred to as *Titan II*.
34. L. D. Wilson, personal conversation and correspondence, September, 1996; W. Dinsmore, personal conversation and correspondence, July, 1996.
35. R. Jones, personal interview, August, 1996.
36. R. Jones, personal interview, August 1996.
37. *On the Shoulders of Titans: A History of Project Gemini,* B.C. Hacker and J.M. Grimwood, 1977, (Scientific and Technical Information Office, National Aeronautics and Space Administration), page 140. Hereafter referred to as OTSOT.
38. OTSOT, page 168.
39. R. Jones, personal interview, August 1996.
40. Air pressure at 70,000 feet is approximately 6 percent that at sea level, air pressure at 250,000 feet is approximately 0.001 percent that at sea level.
41. J. D. Clark, *Ignition! An Informal History of Liquid Rocket Propellants*, (Rutgers University Press, New Jersey, 1972), page 42-63.
42. N. Nieberlein, "Titan II Operation Wrap-Up and Its Effect upon the Gemini Launch Vehicle," October 1963, LV-301, page 3-6. Titan Missile Museum Archive.
43. N. Nieberlein, page 6.
44. *Titan II Propulsion Subsystem, September 1981*, (Aerojet Liquid Rocket Company, September 1981), Section 6, 24. See Figure 13. (a) The flow approaches the convergent or inlet section of the venturi shown in Figure 14 at a static pressure given by P1. As the area of flow is reduced, the fluid velocity must increase in order that the flow rate remain constant. This increase in flow velocity results in a decrease in the static pressure of the liquid. At the throat, the narrowest flow area, the static pressure is decreased to P2. Where the area of flow again increases, in the divergent or exit section of the venturi, the flow velocity is reduced, and the static pressure increases to the downstream pressure P3. (b) The cavitating venturi is designed so that throat pressure P2 is equal to the vapor pressure of the liquid. This causes the liquid to boil (cavitate) at the throat. This region of cavitation extends into the outlet section of the venturi to the point where the static pressure of the liquid is again greater than the vapor pressure. The lower P3, the greater the volume of cavitation; and, conversely, the higher P3 the smaller the region of cavitation. As long as any cavitation exists, P2 is constant; and if P1 and the throat area are also constant, the weight flow rate will remain constant. The cavitating venturi, therefore, controls weight flow against any fluctuation in downstream pressure P provided that P3 never gets great enough to prevent cavitation at the throat. It has been found, generally, that the condition of zero cavitation occurs for downstream pressures greater than 85% of the upstream pressure P1.
45. Adams, pages 212-217.
46. Stumpf, *Titan II*, page 37
47. *Final Report,* pages 415-416.
48. "Detailed Design Specifications for Model SM-68B Missile (including addendum for XSM-68B), page A-7.
49. "Detailed Design Specifications," page A-8. The Mark 4 reentry vehicle, including the W-49 warhead, weighed 4,000 pounds.
50. While all of the components were critical, the suggestion of n-butylphosphoric acid by I.J. Grundfest was a particularly key point. Personal interview, William T. Barry, February 1997.
51. Both dimensions are a cross section of the reentry vehicle created by Martin Marietta Company for use as a satellite fairing. Author's Collection.
52. Barry, personal interview, February 1997. This mechanism was developed by Barry in conjunction with the formulation of the Series 100 plastic, U.S. Patent 3,177,175; 1965.
53. C. Radaz, personal communication, November 2023.
54. Operational Test Report, LONG LIGHT, Titan II, LGM-25C, AFSN 62-12298 (B-53), 20 April 1966, page 23. Microfilm NO568, AFHRA, Maxwell AFB, AL.
55. Detailed Design Specifications, , page 16.
56. Models Aided Titan II Silo Shot , *Missiles and Rockets*, June 19, 1961, pages 27-30.
57. Personal communications with Rollo Pickford, May 1998.
58. The scaling factor was 36 for a 1/6th scale model so the Nike-Ajax engines were excellent matches for this program.
59. Models Aided, pages 27-30.
60. Scale-Model Test of Silo-Type Ducted Launcher, Volume V - Scale Tests Simulating Titan II (Phase III), R. Loya, C.W. Heinz, L.P. Rayno and T.R. Mills, May, 1961, Aerojet General Corporation, page 20.
61. A two-inch thick acoustic liner proved as effective as a 6-inch liner used in the earlier work. This meant that a 12-inch thick liner, rather than a 36-inch liner could be used in the full-scale silo.
62. Loya et al., page 3.
63. Models Aided, page 27-30.
64. *Study of Shock Isolation for Hardened Structures, 560-563; Technical Manual, Missile Weapons System Operation, USAF Model LGM-25C, (T.O 21M-LGM25C-1, 18 December 1986)*, pages 1-76. Titan Missile Museum Archive.
65. *Titan II Propulsion Subsystem, September 1981, Aerojet Liquid Rocket Company*, no date, Section 3-17; "Missile Systems Analyst Specialist, Volume 3: Launch Site Operations," 1973, 56. Both documents Titan Missile Museum Archive.
66. Personal interview, Andy Hall, October 1996; Personal correspondence, Elmer Dunn, April 1997.
67. *Design Analysis WS 107 A-2 Titan II Operational Base Facilities, Phase II Construction, Volume II, 5 January 1961*, page 2. Titan Missile Museum Archive.
68. *Final Report Silo Door System Test Program, WS 107 A-2 Titan II*, 22 June 1962, Section 2-3, pages 4-10. TMM Archive.
69. *Ibid*.
70. *Final Report*, 458; *WS 107 A-2 Titan II Operational Base Facilities Design Analysis, Phase II Construction, Ralph M. Parsons Company, 6 January 1961,* page 12. TMM Archive. In 1965, the doors were modified with two 18-ton pads of concrete placed on the sloping sides to provide further protection against neutron incursion through the exhaust duct pathway.
71. *Final Report*, page 394.
72. "GLV POGO Study, Structural Configuration Changes of Titan II R&D Missiles, N-1 thru N-28)," A.E. Bees, December 1963; Addendum February 1964, pages 1-10. Lockheed Martin Astronautics Research Library, Document 125961. Titan Missile Museum Archive.
73. *Final Report*, 396; D. K. Stumpf, "Did We Hit the Target? A Brief History of Missile Impact Location Systems, 1959-2020, *Air and Space Power History,* Winter 2021, Volume 68, Number 4, 23-38.
74. *Final Report*, pages 397-398.
75. Stumpf, *Titan II*, pages 76-79.
76. *Final Report*, pages 439-451.
77. *Final Report*, page 27.
78. "Special Report N-7 Flight Analysis," March 1963, Martin-Denver, page 2.TMM Archive.
79. "Special Report," pages 3-5.
80. Personal interviews with Don Kundich, October 1996; John Adamoli, June, 1996.
81. "Special Report," pages 6-11.
82. Stumpf, *Titan II,* pages 131 and 141.
83. Stumpf, *Titan II*, page 184.

A Question of Vulnerability

David K. Stumpf

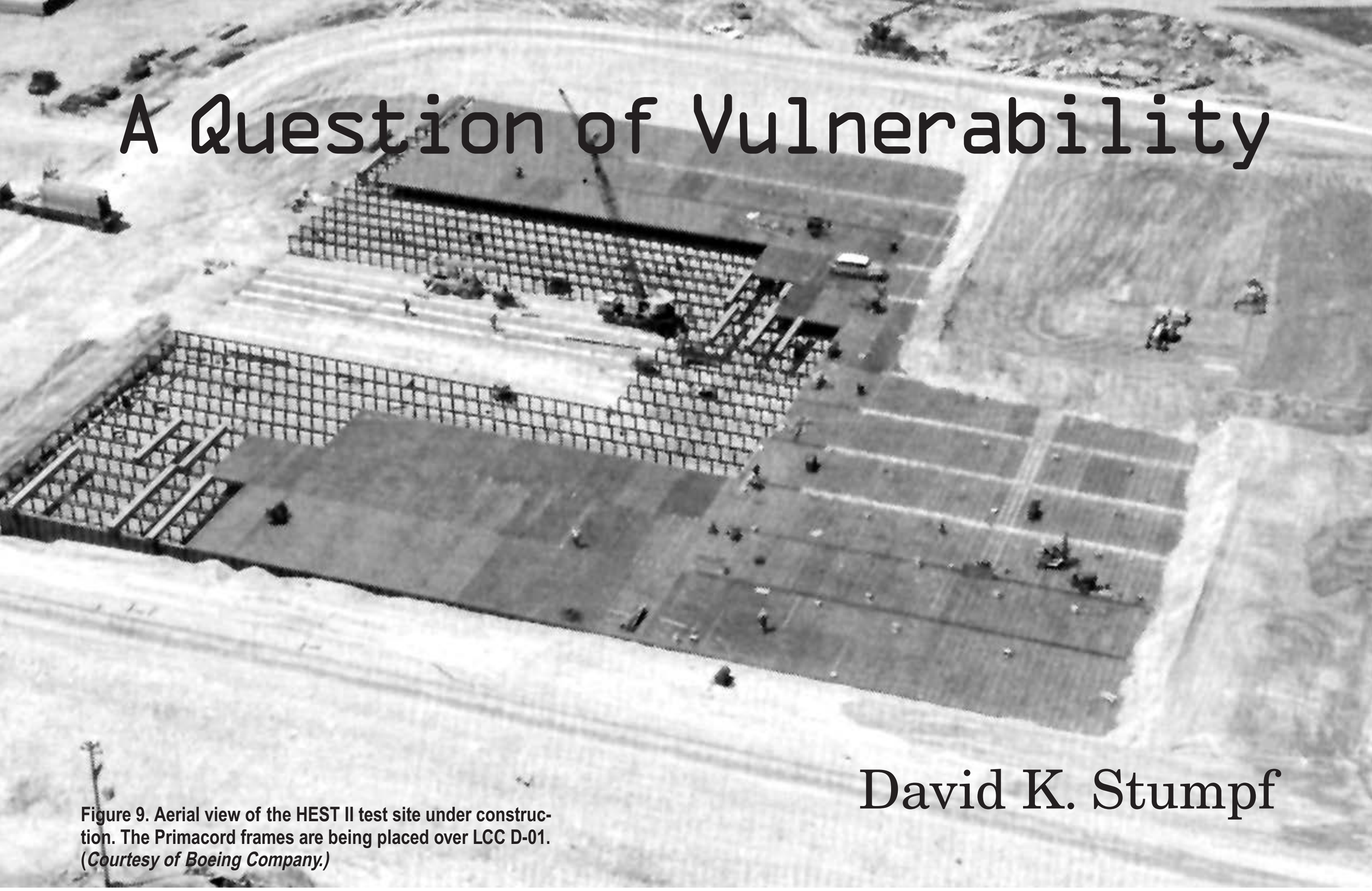


Figure 9. Aerial view of the HEST II test site under construction. The Primacord frames are being placed over LCC D-01. (*Courtesy of Boeing Company.)*

On September 24, 1963, the United States Senate ratified the Limited Test Ban Treaty which prohibited nuclear weapons testing in the atmosphere, space or underwater. President Kennedy signed the treaty on October 7, 1963 and the treaty went into effect on October 10, 1963, the Russians having ratified the treaty in August 1963.

The treaty presented a quandary to the Air Force and the other military services. In the case of the Air Force, design of the Atlas, Titan and Minuteman launch and launch control facilities had relied, in part, on the results of experiments during the 1957 Operation Plumbbob nuclear weapon test series. The signing of the Limited Test Ban Treaty meant that a new method for verifying the design of missile base facilities was needed.

This article describes the two major techniques that used conventional explosives to simulate the air-blast and surfaceblast shock environments from a nuclear weapon detonation.

High-Explosive Simulation Technique (HEST) was used to evaluate as-built Minuteman launch facility and launch control center vulnerability to air-blast induced ground motion.

The Direct-Induced High-Explosive Simulation Technique (DIHEST) simulated the ground motion from a surface burst, and in combination with HEST, was used to evaluate the feasibility of the Hard Rock Silo (HRS) basing concept. HRS was the proposed rebasing mode for a portion of the Minuteman fleet, as well as the WS 120A Advanced ICBM, both of which would serve to counter the deployment of the highly accurate Soviet SS-9 ICBM.

HEST was also used to evaluate the M-X/Peacekeeper basing options in conjunction with Giant Reusable Airblast Simulator on Vertical Shelter (GOVS), Compact Reusable Airblast Simulator (CRABS), and Dynamic Airblast Simulator (DABS). These are described in less detail.

Developing Alternative Testing Methods

Five months after the treaty went into effect the Air Force Weapons Laboratory began a three-phased project to simulate, with conventional explosives, the air-blast-induced ground motion associated with an air-burst attack. Phase I involved small-scale experimental method development; Phase II consisted of a large-scale field experiment to validate the Phase I method development and Phase III was a proof test at an operational hardened facility. Several simulation techniques were evaluated and discarded before the selection of two techniques for further development, detonable gas and Primacord.[1]

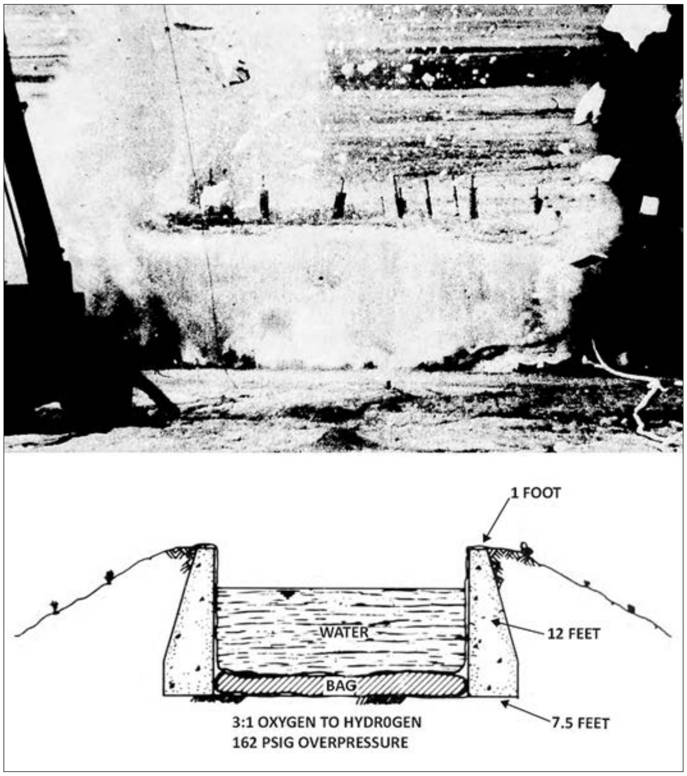


Figure 1. HEST Phase I Primacord Experiment, August 1964. Upper: Primacord with water overburden explosion; Lower: Design of the test bed. ***(Unless otherwise noted, photo credit is the United States Air Force.)***

Detonable Gas

The detonable gas technique was first investigated by the Stanford Research Institute. The near stoichiometric mixtures of hydrogen and oxygen used resulted in detonation velocities that were too high. The Air Force Weapons Laboratory investigators varied the hydrogen and oxygen ratio and were able to produce overpressures from between 300 to 1,200 psi.

The next step in development of this technique was to predict the effect of the motion of the overburden. The overburden was necessary to contain and maintain the overpressure for the desired duration. This involved varying the size of the flexible container of the gas mixture, the weight of the overburden, and the distance from ignition. The test apparatus to verify the calculations was a 20 x 40-feet pit lined with concrete, 1-foot thick at the top and 7.5-feet thick the base. The 12-feet-deep pit held a flexible container for the low-pressure gas mixture. A waterproof cover was placed over the bag and then the calculated amount of water overburden was added to the pit. The bag was inflated with the gas mixture at 0.12 atm and detonated at one end. The combustion products from the explosion acted like a piston by loading the cylinder of air in front of the detonation, which then formed a shock wave closely simulating the passage of the shock wave from a nuclear detonation. As the overburden moved upward as a result of the detonation, the cavity volume was increased and caused a corresponding decrease in pressure, as would be seen with a nuclear detonation blast wave passing over a launch facility (Figure 1).

Three tests were run which successfully demonstrated the required shock front. The overburden served to generate a greater duration of the pressure pulse. The gas mixture was ignited on one edge to form a pressure wave which moved through the container and over the ground. Finding a suitable container for the higher-pressure system, 2 atm, proved elusive. Development of the proper container was abandoned due to the success of the simultaneous Primacord experiments.[2]

David K. Stumpf, Ph.D., is a retired plant biochemist living with his wife, Susan, in Tucson Arizona. He has written three nuclear weapon histories, Regulus the Forgotten Weapon*, a history of the Navy's Regulus I and II cruise missiles;* Titan II: A History of a Cold War Missile System *and* Minuteman: a Technical History of the Missile that defined American Nuclear Warfare*. His latest book,* The Last 30 Seconds*, a book about the evolution of hit-to-kill technology, will be available in September 2024. Dr. Stumpf volunteered at the Titan Missile Museum, as an historian and as a tour guide for 15 years.*

Primacord

The initial Primacord technique used a steel and wooden structure to support layers of Primacord 2-3 feet above the soil. The Primacord racks were covered with plywood, forming a platform for the soil or water overburden. The wrap angle of the Primacord determined the rate at which the combustion products were formed along the length of the cavity. This was necessary because the detonation velocity for Primacord was higher than needed for the desired shock front simulation (Figure 2).[3]

High-Explosive Simulation Technique

Both the detonatable gas and Primacord techniques produced a reasonable simulation of the air-blast-induced ground motion from a large nuclear weapon. The detonable

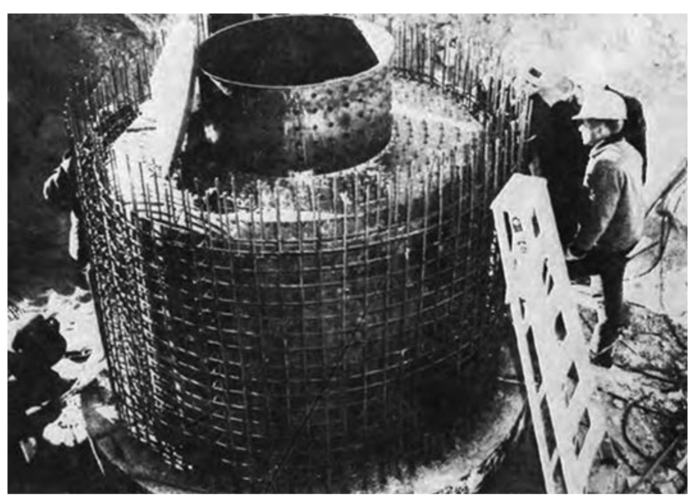


Figure 2. One-fourth scale model of a Minuteman launch facility used in the HEST Phase II experiment.

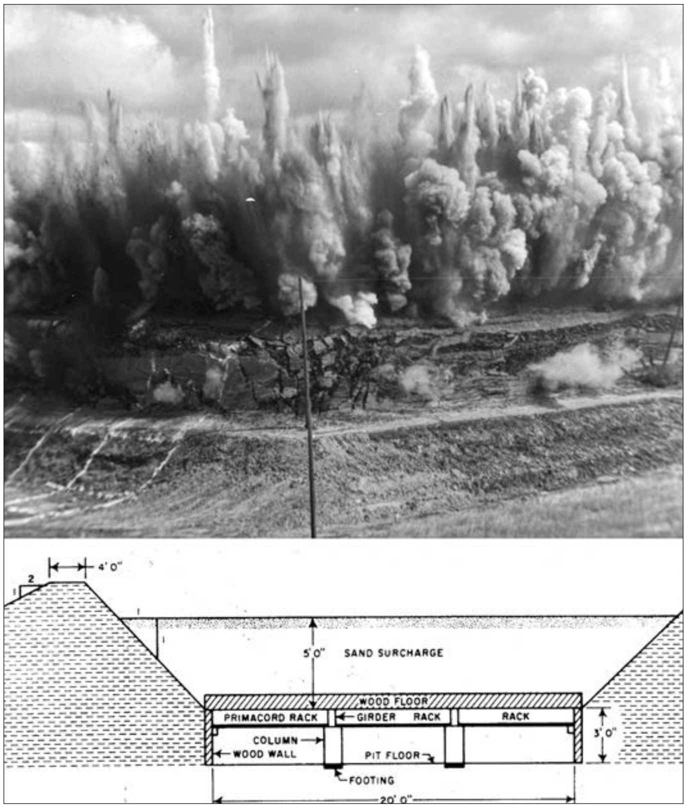


Figure 3. HEST Phase II. Upper: Seconds after detonation on December 15, 1964. This was the first large HEST structure test, 151 x 97 feet. Lower: Test bed details.

gas method required a flexible container that could hold a 2-atmosphere mixture while supporting the overburden weight. Additionally, it required a much larger facility than the Primacord technique. The Primacord technique was much safer and was more flexible as a wider range of peak overpressures could be produced. The General American Research Division of General American Transportation Corporation won the contract to further develop the Primacord technique in conjunction with AFWL.[4]

On December 15, 1964, the first large HEST structure, HEST Phase II, 151 x 97 feet, was used to expose a one-fourth scale structural model of a Minuteman launch facility to a 300-psi peak overpressure from a simulated 1 MT air-burst explosion. This overpressure would occur at a ground range of 2250 feet from the point of detonation. The test bed was a grid of Primacord assemblies attached to 5-by-7-feet wooden frames of 2-by-4-inch lumber. A continuous strand of Primacord was laced to each frame, thereby approximating the properties of a solid sheet explosive. The experiment produced a peak overpressure of 312 psi. The overburden reached a height of 125 feet at the firing end. There was mention of a structural displacement of the scale-model silo but further details were not given (Figure 3).[5]

The system was further refined through six additional tests which focused on studying the parameters controlling the air-pressure time histories. The grid sizes varied from 1,024 to 7,748 square feet. At the end of the development program, the HEST system was able to simulate overpressures up to 3,000 psi for approximately the first 200 milliseconds of air blast. This meant that simulations up to 10 MT were now possible:[6]

It should be recognized that at the present time this simulation technique will not reproduce the exact pressure-time history with more than a 400-millisecond duration. The system is best suited for testing shallow buried and surface flush structures since their principal failure mode was directly related to overpressure loading. Since the peak overpressure was uniform over the entire test area, structures with large surface areas could now be more realistically tested.

Minuteman Operational Base Testing

The Air Force now had a tool to investigate the as-built hardness of the Minuteman operational facilities. A Space and Missile Systems Organization (SAMSO) hardness review panel, which had been organized in 1963, had identified 40 problem areas in Minuteman Wings I-V. Twenty-seven items such as blast valve mechanisms, missing conduit attachment points and similar items did not meet design specifications. Launch facility and launch control center construction was basically sound but when all factors were considered, the launch facility, designed for 300 psi overpressure protection was now rated at approximately 70 psi. The launch control center, designed to survive 1,000 psi overpressure, was now estimated to have only 125 psi protection.[7]

Immediately after this announcement, SAMSO Plan 1 was developed to restore a satisfactory degree of protection, 500 psi for launch control centers and 125 psi for launch facilities, by fixing the most serious problems as quickly as possible. The $30 million cost would be spread across seven years with the goal of completing the program simultaneously with completion of the Force Modernization program. Force Modernization was designed to bring Wings I-V to the standard of Wing VI (Grand Forks AFB) and the 564th Strategic Missile Squadron (Malmstrom AFB).[8] Secretary of Defense Robert McNamara accelerated the program, saying "It is absolutely essential to correct hardness deficiencies as soon as possible and the Air Force should spend whatever funds are required." McNamara added $28.6 million in Fiscal Year 1966 and $4.8 million for Fiscal Year 1967 for the hardness test program using the HEST system. By the end of the Minuteman and Hard Rock Silo (see below) programs in 1970, $56.4 million had been spent on 16 experiments during the HEST program (Table 1, following page).[9]

QH 1 (HEST I)

On August 2, 1965, the Air Force authorized Boeing, serving as a subcontractor to the Air Force Weapons Laboratory, to proceed with planning for the first HEST hardness evaluation of a Minuteman launch facility. Codenamed Gas Bag Hardness Test (Quick HEST, QH-1, later renamed HEST I), the test was conducted at the 90th Strategic Missile Wing (90 SMW) F. E. Warren AFB.

Table 1. HEST Test Summary 1964-1968[a]

Date	Test	Location	Pit Size (ft)	Purpose
Feb-Aug 64	HEST Phase I	Kirtland AFB	20x40	evaluate gas mixture/water overburden and detonating cord with sand overburden
15 Dec-64	HEST Phase II	Kirtland AFB	96x150	determine pressure area and instrument requirements for a full-scale Minuteman facility, using 1/4 scale model
5 Feb-65	(HEST-2)	Kirtland AFB	32x36	study parameters controlling the HEST air-pressure time histories
10 Mar-65	(HEST-3)	Kirtland AFB	40x48	Double overpressure, change surcharged containment, and improve instruments, using same test structures as for Phase II
6 May-65	HEST Phase IIA	Kirkland AFB	88x100	Double overpressure, change surcharge containment, and improve instruments, using same test bed structures as Phase II.
30 Oct-65	(HEST-1)	Kirtland AFB	32x36	Study parameters controlling the HEST air-pressure time histories
1 Dec-65	HEST I (Quick Test)	F. E. Warren AFB Wing V	302x304	OPERATIONAL TEST: Test at an operational Minuteman launch facility and a ground test missile on simulated alert
15 Mar-66	(HEST-6)	McCormick's Ranch, Albuquerque		Study free field ground motion
May-66	HIP-1	Kirtland AFB	40x60	Improve HEST environment
Jun-66	HIP-1a	Kirtland AFB	40x60	Improve HEST environment
22 Jul-66	HEST II	F. E. Warren AFB Wing V	304x352	OPERATIONAL TEST: test at an operational Minuteman launch control center
14 Sep-66	HEST III	Grand Forks AFB Wing VI	304x302	OPERATIONAL TEST: test the hardness at a Minuteman II launch facility
29 Jul-67	Backfill (HEST-4)	McCormick's Ranch, Albuquerque	56x72	Study free field ground motion
Oct-67	(HEST-5) demonstration	Grand Forks AFB Wing VI	64x83	Demonstrate maximum SOR environment; evaluate surcharge disposal; evaluate gauge placement techniques; provide planning bases for HEST Test V. Used smaller pit
5 Sep-68	HEST V	Grand Forks AFB Wing VI	300x300	OPERATIONAL TEST: determine structural survivability and functional capability of launch-essential equipment; obtain data useful for force hardness assessment
21 Nov-68	ROCKTEST I	Estancia Valley, NM	180x204	Evaluate design for increased overpressure for use with the HEST-DIHEST series of tests

a) Designing Facilities to Resist Nuclear Weapons Effects Hardness Verification; Simulation of Airblast-Induced Ground Motion Phase IIA

Launch Facility Q-04 was selected for the test and electronically isolated from the remainder of the squadron. A ground test missile was emplaced and preparations for the test commenced. The test took place on December 1, 1965, generating an estimated 300 psi over the 91,000 square feet structure with no serious damage to the launch facility or the ground test missile. The refurbished site was returned to the Strategic Air Command on November 10, 1966 (Figures 4, 5, 6) .[10]

HEST II

With the success of HEST I, the overpressure goal for HEST II, testing the hardness of a launch control center, was increased from 600 to 1000 psi. The 90 SMW Launch Control Center D-01 was isolated from the rest of the squadron on February 15, 1966, aboveground structures removed, and the test structure (107,000 square feet) installed with 80,000 pounds of Primacord. The test took place on July 22, 1966 and was again successful, as the launch control center and launch control equipment building continued to function despite damage from the blast.

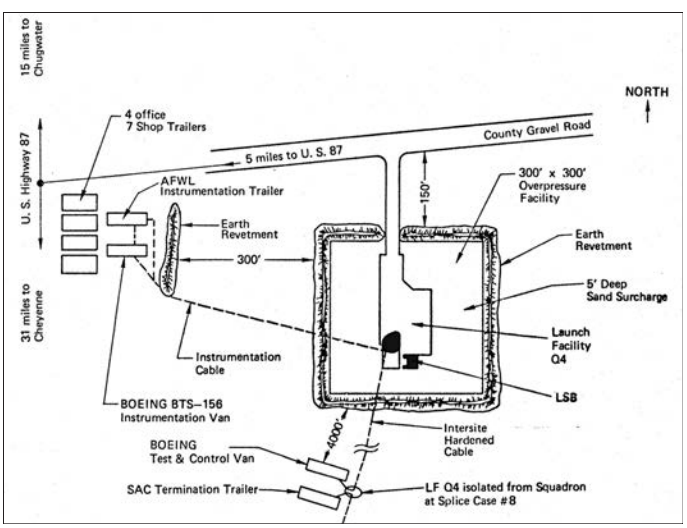


Figure 4. Layout of the QH-1 (HEST I) test facility at LF Q-04, 90th Strategic Missile Wing, F. E. Warren AFB. *(Courtesy of Boeing Company.)*

Figure 5. Minuteman IA Launch Facility.

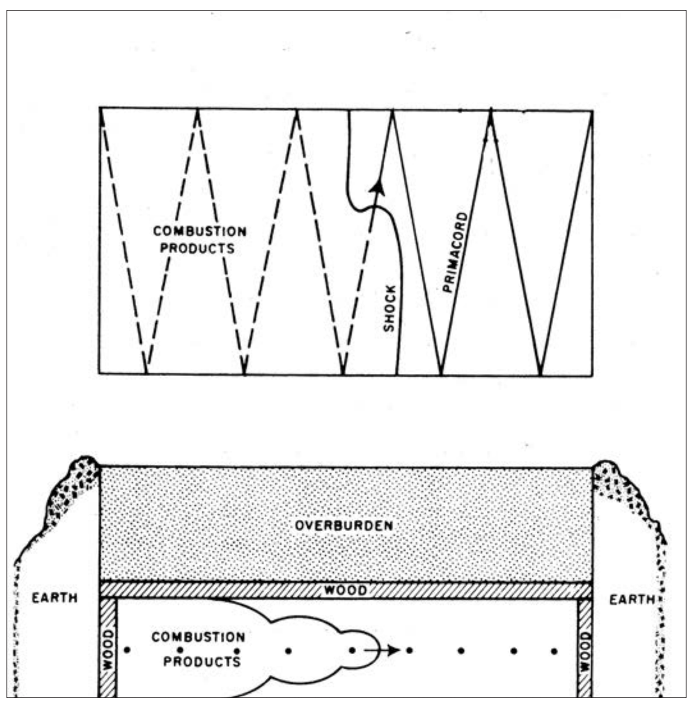


Figure 6. HEST-I. Upper: The Primacord had to be laid at a specific angle, 8.6 degrees, to achieve the wavefront needed for the experiment. Lower: propagation of the combustion gases took place in the air gap. This illustration does not show the movement of the overburden.

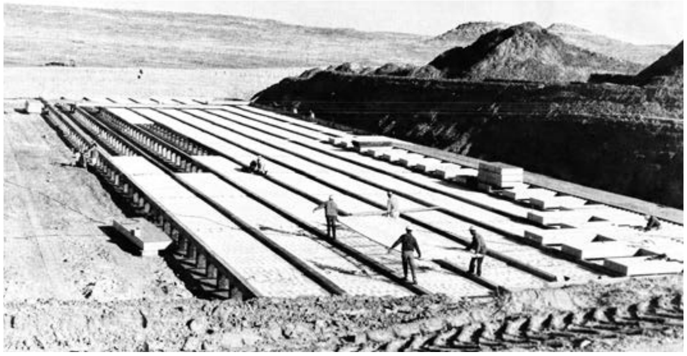


Figure 7. HEST-I. Workers are laying out the floor before installing the frames with Primacord. *(Courtesy of Boeing Company.)*

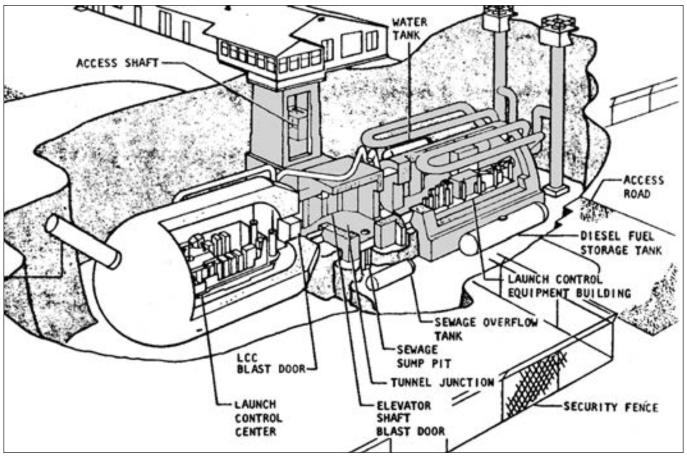


Figure 8. Typical 90 SMW Launch Control Facility. All the aboveground structures had to be dismantled. The structures highlighted with gray indicate what needed to be repaired after the test.

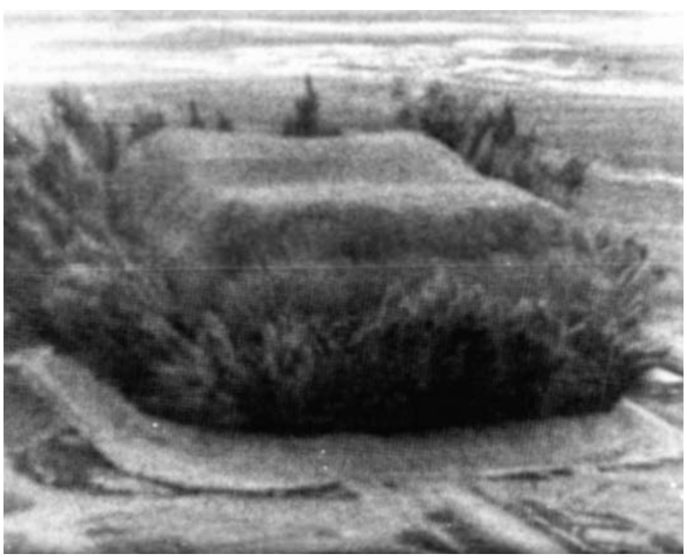


Figure 11. HEST II shortly after detonation. The overburden could be lifted as high as 180 feet depending on the amount of Primacord used. One complication was the need to remove all the overburden from the surface to investigate the damage, if any, to the test structures. *(Courtesy of Boeing Company.)*

The launch control equipment building had to be rebuilt along with the tunnel junction and access elevator shaft (Figure 7, 8, 10, 11).[11]

Figure 10. HEST II. Detail showing the layers of Primacord laced on 2x4 frames. *(Courtesy of Boeing Company.)*

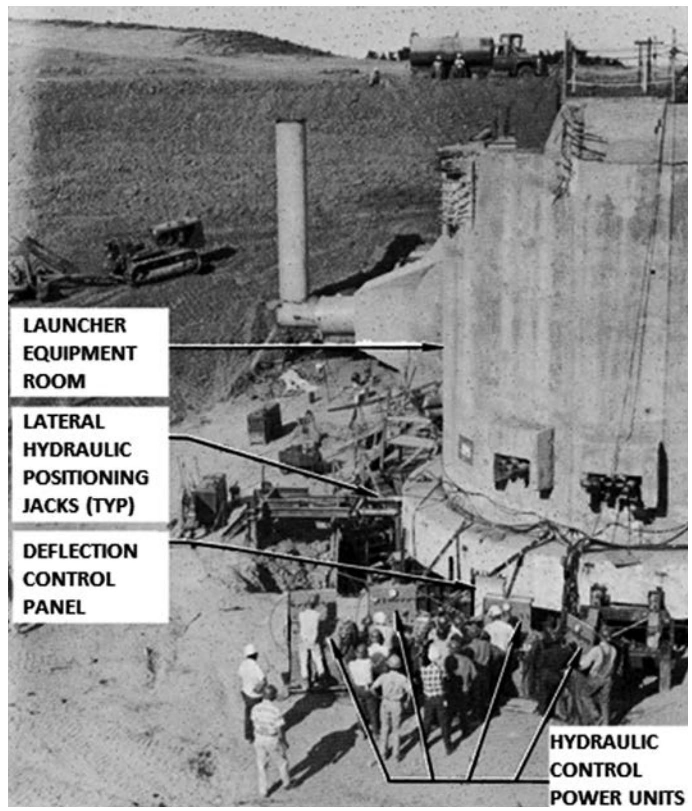


Figure 12. During construction at Grand Forks AFB two of the launcher equipment rooms settled beyond specifications. The structures were excavated and repositioned using massive hydraulic jacks. A similar technique was used to repair LF-28. *(Courtesy of Boeing Company.)*

HEST III

Though the 321 SMW, Grand Forks AFB, North Dakota, was not fully activated, the Air Force moved the HEST program to Grand Forks to investigate the hardness of the newly completed Minuteman II operational facilities. On September 22, 1966, HEST III took place at Launch Facility M-28 with a test facility of 91,000 square feet. (Figures 12, 13) The explosion generated the expected 1000 psi overpressure. While the launch facility remained operational for

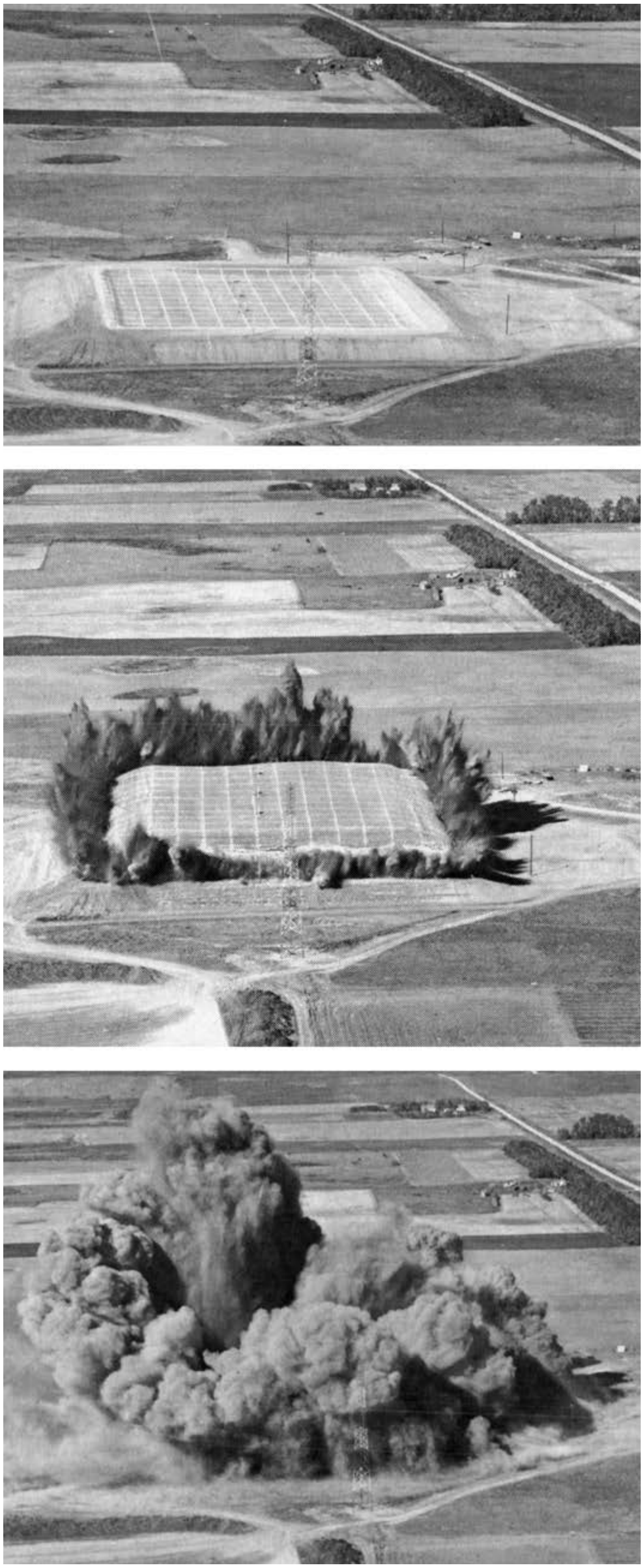


Figure 13. Upper: HEST III one second before detonation; Middle: one second after detonation; Lower: 15 seconds after detonation. (*Courtesy of Boeing Company.)*

72 minutes following the blast, it suffered significant damage. There was flooding in the lower level of the launcher equipment room as well as in the launch tube. The launch tube flooding would normally have been taking care of by a sump pump but the movement of the lower level of the launcher equipment room had been sufficiently violent to break the emergency power line, preventing the pumps from operating. The blast also forced mud into the air-conditioning system and covered the emergency power batteries as well. That the facility remained operational for slightly more than an hour after the blast was encouraging. The amount of damage validated the value of the test in revealing problems in the hardness of Minuteman II at Grand Forks as well as the 564 SMS at Malmstrom AFB.[12]

Repairs to Launch Facility M-28 involved not only cleaning and repairing the interior of the launcher equipment room and launcher equipment building, both had to be repositioned. Fortunately, during initial construction at Grand Forks, two launcher equipment rooms had settled beyond acceptable limits and a technique for repositioning the 3-million-pound structure had been developed. Twenty-five 100-ton hydraulic jacks were used to raise the launcher equipment room to the required elevation for placement of the lateral movement system. The next step was to place 12 lateral movement assemblies under the launcher equipment room footing and wedge them firmly in place. The structure was then lowered onto the lateral movement assemblies and four sets of horizontal jacks were used to move it into position. After an optical survey to assure the building was in the proper location, steel wedges were positioned between the bearing surfaces, locking further movement. The wedges were welded in position and the bearing assemblies left permanently in place. The lateral position jacks were removed and the space filled with concrete to within 4 inches of the foundation. The remaining space was filled with non-shrinking pressure grout. The 1-million-pound launcher equipment building also had to be repositioned using a similar technique. Repairs to Launch Facility M-28 were completed on November 30, 1967.[13]

HEST V

Results from the first three tests generated hardening improvements throughout the six Minuteman wings. While the Air Force Systems Command recommended abandoning the program after the third test, Gen. John P. McConnell directed that it should continue. HEST IV was deferred, and later canceled. In October 1967, the Air Force conducted a scale model test to correct a flaw in the simulation technique. The problem was a secondary shockwave caused by the collapse of the earth overburden onto the test site once the explosive gases had escaped. The revised design caused the overburden to scatter, reducing the secondary jolt without interfering with the desired rolling shockwave.

HEST V, simulating a 10 MT blast with 300 psi overpressure, took place on September 5, 1968, at 321 SMW Launch Facility L-16. This time the air conditioning continued to function, there was no flooding and a simulated launch was successfully conducted almost 6 hours after the blast.[14]

FOAM HEST

The HARDPAN Event 3, December 1975, was the last large-scale test employing the original HEST design. A more cost-effective design known as FOAM HEST replaced the expensive and complicated steel and wood platform with planks of beaded polystyrene in direct contact with the soil.[15]

Hard Rock Silo

In the Fall of 1963, the Soviets began flight testing the Soviet R-36 ICBM (NATO designation SS-9 Scarp). Deployment started in 1966. The SS-9 was similar to the Titan II, using both hypergolic propellants and an inertial guidance system. The SS-9's improved accuracy and large payload, 10 to 25 MT, represented a direct threat to the Minuteman force. As far back as 1961, the Air Force had known that once the Soviet missiles had sufficient accuracy to target the 100 launch control centers, the hardness protection evaluation needed to include direct crater-induced ground motion from a surface burst. With the SS-9, relatively few missiles would be necessary to eliminate Minuteman in a first strike on the launch control centers compared to targeting all 1000 launch facilities.[16]

There were three possible solutions to this new problem: (1) Reinforce the existing Minuteman launch facilities and launch control centers as Minuteman III had been designed to be launched from the existing facilities; (2) build dual-capable launch facilities that at first could house Minuteman III but which would be replaced in the not-too-distant future with the proposed Advanced ICBM (AICBM); (3) build new facilities designed specifically for the AICBM. The Force Modernization Program addressed hardening improvements for the Minuteman launch facilities and launch control centers. Force Modernization did not involve substantial construction.[17]

On November 1, 1966, the Advanced Research Project Agency contracted with the Institute for Defense Analysis (IDA), DAHC I-15-67-CV-0011, Task Order T-56, to evaluate alternative basing concepts for the WS 120A.[18]

Research by the Department of Defense and industry teams, including Boeing, indicated that an increased hardness Minuteman launch facility for Minuteman III would provide an effective solution to counter the new threat of the SS-9. The dual-capable launch facility concept was to build a new launch facility (hardened to 3000 psi) adjacent to existing Minuteman launch facilities size to accommodate a 100-inch diameter, 7000-pound payload missile at some future date. In the interim, the facility would house Minuteman III.[19]

The IDA alternative basing report, known as STRAT-X, was released in August 1967. The report was:[20]

a technological study to characterize US alternatives to counter the possible Soviet ABM deployment and so the Soviet potential for reducing US assured-destruction-force effectiveness during the 1970's. It is desired that the US alternatives be considered upon a uniform cost-effectiveness well as from solution sensitivity to Soviet alternative actions. Particular attention to US technology and production limitation versus time during the mid-1970's is desired. The studies should consider further proliferation of our current forces and/or protection of these forces as well as new system concepts, both land-based and sea-based.

The STRAT-X report reviewed one hundred twenty-five basing concepts and recommended only eight for further consideration. The land-based alternatives studied included: hard rock silo (HRS), soft silo, rock tunnel, soft tunnel, canal-based and land mobile. The HRS basing concept was selected for further study.[21]

On October 4, 1967, McNamara denied the Air Force the start of development of the WS-120A missile. He directed the Air Force to look instead at the development of HRS for Minuteman III.[22] On May 1, 1968, Headquarters USAF issued a System Management Directive to initiate the Hard Rock Silo (HRS) Development Program for Minuteman III. The goal of the program was to develop and test a new, significantly harder basing system that would be dual-compatible with a future advanced ICBM.

There were six major components to the Hard Rock Silo program:

Demonstrate the capability to survive a nuclear attack of significantly higher magnitude than the current Minuteman system.
Accommodate the Minuteman III missile with its associated command control system modified to provide increased communication survivability.
Accommodate the future installation of the AICBM and its related systems.
Minimize lead time to the IOC date.
Preserve the Minuteman relocation/proliferation option as long as possible.
Demonstrate high confidence for achieving technical objectives at low development program costs.[23]

Experimental facilities would have to be designed to demonstrate the efficacy of using a hard rock environment. This required construction of subscale to full-scale facilities and testing these facilities to demonstrate the required hardness could be achieved.[24]

Direct-Induced High-Explosive Simulation Technique

The deployment of the SS-9 and its greatly improved guidance system meant that surface bursts and subsequent cratering would likely be the mode of attack. In 1967, AFWL researchers began development of a modified HEST system named DIHEST. DIHEST was designed to simulate the crater-induced horizontal ground shock motions that occur as result of a surface-burst nuclear weapon detonation. DIHEST used buried vertical arrays of explosives to produce a blast wave characteristic of a surface detonation. Coupled with the HEST system modified to generate higher overpressures, the HEST-DIHEST combination pro-

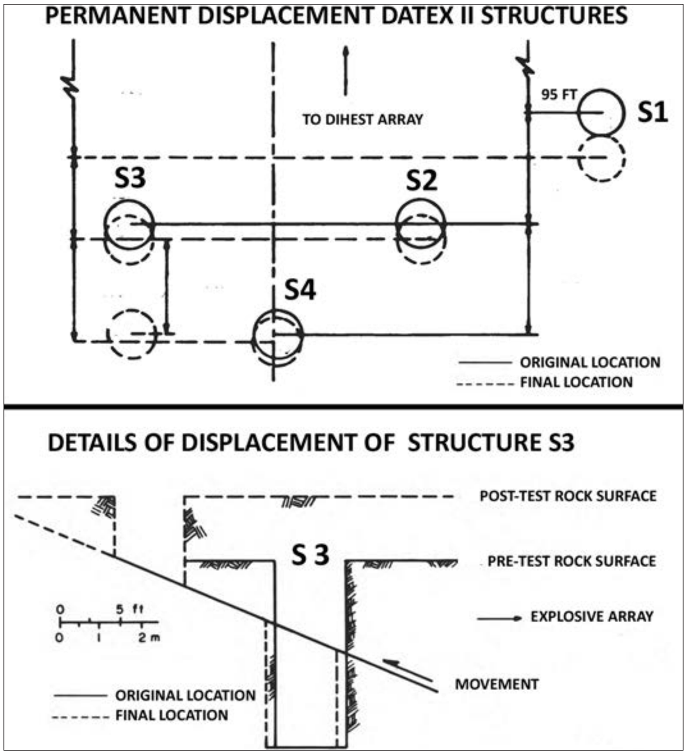


Figure 14. DATEX II. Upper: Plan view showing displacement of the four test structures. Structure S4, within 20 feet of Structures S2 and S3, was only slightly damaged. Lower: elevation view of the displacement for S3.

Figure 15. DATEX II. Close up of the top of Structure S3. S3 was 6 feet in diameter and 15 feet deep with a liner consisting of a 6-foot diameter section of steel culvert backfilled to the rock walls with approximately 9 inches of non-reinforced concrete. The top 5 feet was sheared off the silo and moved 13 feet laterally. The lower portion of the silo also moved approximately 6 inches laterally.

vided simultaneous simulation of both air-burst and crater-induced ground motion.

PLANEWAVE and DATEX

The PLANEWAVE and DATEX test series developed and refined the DIHEST concept. The fourth DIHEST experiment, DATEX II, fired on July 17, 1969, served as a proof test for a more effective explosive, DBA-X2M slurry aluminum ammonium nitrate. Four silo models were used: Structures 1, 2 and 4 were unlined, smooth walled, 6-feet in diameter and 15-feet deep. Structure 3 was also 6-feet in diameter with a steel culvert liner backfilled with 9 inches of nonreinforced concrete. Structures 1, 2 suffered relative displacements of approximately 2 feet along horizontal joints. Structure 4, only 20 feet away from Structures 1 and 2, suffered little damage. Structure 3 suffered a severe relative displacement with the top 5 feet of the structure displaced 13 feet relative to the bottom section. (Figures 14, 15) Other nearby structures showed minor damage. These results pointed out the inability to predict block motion prior to the explosion.[25]

HANDEC

The HANDEC (HEST And DIHEST Combined) test series developed the parameters of combining the two techniques to: (1) produce an overpressure and air-blast induced ground motion environment; (2) simulate a ground shockwave similar to that produced by the cratering from a nuclear explosion as specified by AFWL in rock media; (3) test the time phasing of HEST and DIHEST; (4) test an instrumentation system in protective piping; (5) test instrumentation anchored to the rock versus cable and trench excavation.

The HANDEC I and II tests were fired with a 54 and 42.5 millisecond delay, respectively, between the HEST and DIHEST explosions. This allowed the two shockwaves to be induced into the rock with timing similar to that of a specific yield nuclear explosion. The DIHEST component of HANDEC I consisted of 11 holes, 9 inches in diameter, 10 feet on center, 13 feet below the test bed floor, in a line parallel to and located 25 feet from the inside face of the test facility concrete wall. The total explosive force was 4400 pounds of aluminum ammonium nitrate. HANDEC II had explosives in 29 holes 12 inches in diameter and spaced 7 feet 2 inches on center. The holes formed a 200-foot line parallel to and located 96 feet from the inside face of the test facility wall and extended approximately 70 feet below test bed elevation. Approximately 92,440 pounds of aluminum ammonium nitrate slurry explosive was used. To reduce rock ejecta, an earth berm was constructed 60 feet wide by 290 feet long directly over the 29 holes. The berm height was approximately 50 feet.

Nine test structures were built for HANDEC II. Structure S11, a concrete lined silo model 6-feet in diameter and 20-feet deep, suffered major structural damage below a depth of 10 feet due to a relatively minor horizontal displacement of 0.3 feet. Structure S12, also a silo model of similar dimensions, located 45 feet to the northwest showed no appreciable damage.[26]

ROCKTEST I

Validation of the increased overpressure component of the HEST-DIHEST system took place on November 21, 1968 at Estancia Valley, New Mexico. ROCKTEST I gen-

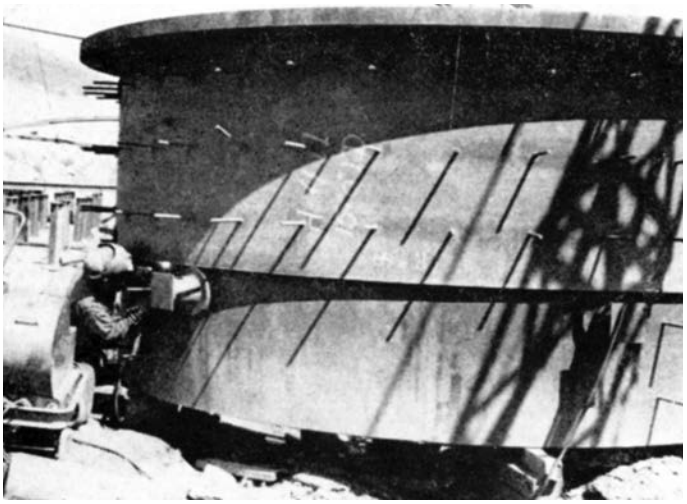


Figure 16. ROCKTEST I. The upper full-scale closure liner for the 30-foot-deep Stub Silo S01. The liner was 7.5 feet tall with an interior diameter of 17 feet and was fabricated from 2-inch-thick steel. The walls of S01 were 5-feet thick. The closure doors were cast in place.

erated the expected 3,000 psi peak overpressure using a 3,300 square feet test array which covered 13 experiments (there was no DIHEST component in this test).[27] In the center was a 17-feet interior diameter, 27-feet exterior diameter, 30-feet-deep stub silo and closure door. A one-quarter scale model silo closure, four 6-feet diameter and two 3-feet diameter experimental silo closures were also part of the experiment. Intersite cable samples were exposed to the blast, as well as antenna housings. Damage to the structures was slight.(Figures 16, 17) [28]

ROCKTEST II

The first full-scale HEST-DIHEST experiment, ROCKTEST II, took place on March 26, 1970, on the eastern slope of the Three Peaks Mountain Range, west of Cedar City, Utah. The primary goals were: 1) to test a full-scale half depth, heavily reinforced conceptual missile silo, S01, and 2) to demonstrate the ability to simulate a combined nuclear air-blast overpressure and subsequent ground motion followed by the direct-induced pulse on a large-scale.

Structure 01 was composed of six vertical cylindrical openings cast in a 56-feet diameter reinforced concrete cap; a 19-feet diameter launch tube, an 18-feet diameter equipment tube, two 2.5-feet diameter air entrainment shaft, a 17-feet diameter personnel access shaft and a 6.75-feet diameter closure column, all 75 feet in depth. The thinnest exterior wall section, located at the launch tube, was 4 feet thick.[29]

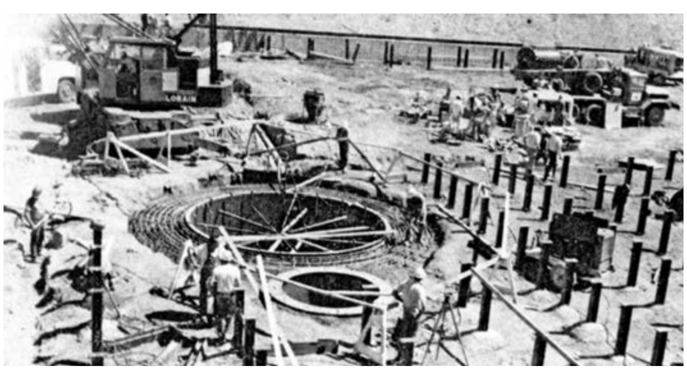


Figure 17. ROCKTEST I test facility under construction. The large diameter circle is the top of 30-foot-deep stub silo wall. The full-scale closure liner has not been installed. The smaller diameter circle is an access tube for post-test inspection of the closure.

A total of 10 experiments included: S01, the conceptual silo; site-by-side silo models S02 and S04, half scale, 35-feet deep; S03A, 12-feet diameter, 10-feet deep; S05, S06, S07, 6-feet diameter, 40-feet deep. S05 was lined with a reinforced concrete liner; S06 was unlined and S07 was lined with a reinforced concrete liner surrounded by a foam back packing. Additionally, antenna elements, samples of hardened intersite cable and samples of silo closures of various diameters were tested. The test bed covered 100,000 square feet.

The DIHEST explosion displaced a 140x150-foot block causing a horizontal displacement of approximately 10-12 inches encompassing the top portions of S03A, S06 and S07. The S03A closure was upturned by the movement of the block. The top of S07 was displaced 6.5 inches horizontally and 2 inches vertically. The further damage details remain classified.[30]

Evaluation and Termination of Hard Rock Silo Program

Nine DIHEST/HEST-DIHEST experiments in rock were conducted between October 1967 and November 1970 as part of the HRS test program (Table 2).[31] Five of the nine experiments produced significant block motions which disrupted the model structures:

The lack of ability to predict exact block motion locations in advance of an experiment where the location and properties of the dynamic loading are known, present difficult design and analysis problems. It is vital that these uncertainties be incorporated into any design philosophy for hardened structures in rock.

Based on a very limited amount of data generated by the DIHEST series, it would appear that a "sure safe" zone from a cratering burst in rock might begin beyond three crater radii from the burst point. The accuracies of today's weapons delivery systems however make the utilization of such a "sure safe" zone impractical, so that the system designer is left several options, all of which require extensive

Table 2. DIHEST and HEST-DIHEST Test Summary 1967-1970[a]

Experiment	Type	Date	Location	HEST Bed Dimen. (ft)	HEST Design Overpressure (psi)	DIHEST Array lengthxdepth (ft)	DIHEST Array weight (lb)
PLANEWAVE I	DIHEST	Oct-67	Estancia Valley, NM	na	na	20x20	800
PLANEWAVE II*	DIHEST	Mar-68	Estancia Valley, NM	na	na	45x20	4200
DATEX I	DIHEST	Apr-69	Cedar City, UT	na	na	100x38	4400
DATEX II*	DIHEST	Jul-69	Cedar City, UT	na	na	200x36	82000
HANDEC I	HEST-DIHEST	May-69	Cedar City, UT	40x60	6000	100x38	4400
HANDEC II*	HEST-DIHEST	Aug-69	Cedar City, UT	60x90	1000	200x40	92000
PRESTARMET II	DIHEST	Jan-69	Pedernal Hills, NM	na	na	50x38	2400
ROCKTEST II*	HEST-DIHEST	Mar-70	Cedar City, UT	250x400	classified	500x40	234000
STARMET*	DIHEST	Nov-70	Pedernal Hills, NM	na	na	100x38	4360

a) Blouin * indicates significant block motion

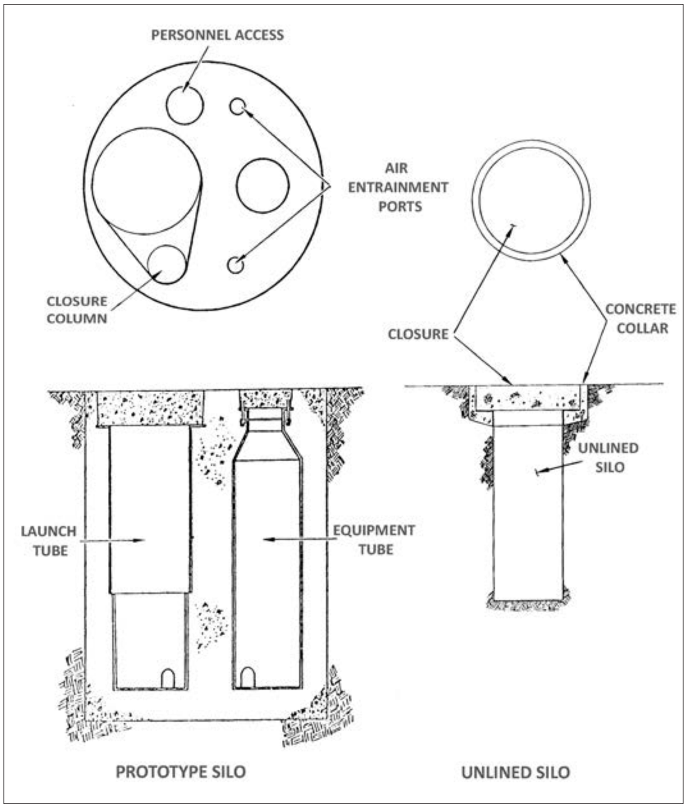
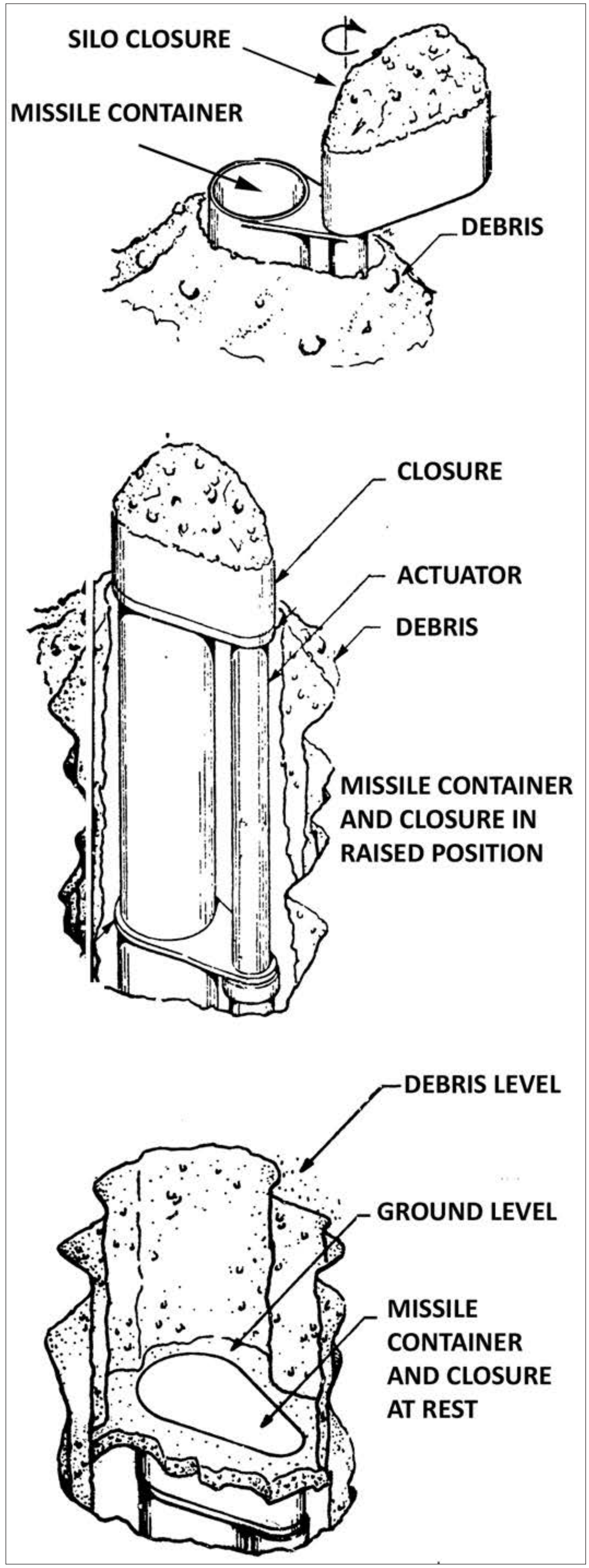


Figure 18 (Above). Side view of an early conceptual design of a HRS configuration. Note that the closure door is flush to the ground plane and there does not appear to be any consideration for debris capture. Minimum thickness of exterior walls of the prototype silo, S01, was 4 feet.

Figure 19 (Right). One of the early conceptual designs of a HRS closure. Lower: the lid is completely flush with the ground surface. Middle: on command, the missile container and actuator shaft would be pushed upward through the debris. Top: the lid then rotated to clear the silo opening. While this matches the conceptual design of Figure 18, it was rated as not feasible due to the bending loads of the cantilevered closure as well as having no provision for clearing the debris from the top of the closure prior to rotation. *(Courtesy of the Boeing Company.)*



additional analysis and proof testing. (Figures 18, 19) These actions are the following:

1. Make near-surface components non-critical to system performance. In other words, the designer would "write off" near-surface portions of the system in the event of attack (this, of course, leaves the definition of near-surface to future research).
2. Use redundant and dispersed critical near-surface components; i.e., make the attacker use an unacceptable number of weapons to assure a hit on the system.
3. Design critical system components to absorb anticipated relative displacements. This might be accomplished by the inclusion of soft back-packing, rattle space, etc. This option depends on the development of a prediction technique for both near-surface and deeply buried displacement magnitudes.
4. Mitigate both the occurrence and magnitude of relative displacements by using rock reinforcement, such as bolts and grouting. Other schemes, e.g., dewatering or aeration might be effective in saturated rock were dynamic for pressure buildups would lower effective stresses.
5. Employ combinations of options 1-4.[32]

On April 30, 1970, Gen. O. J. Glasser testified before the House of Representatives Subcommittee on Appropriations that $51.2 million had been spent on the Hard Rock Silo program through Fiscal Year 1970. "As a result of the information gained from these and other tests, we are confident we can construct silos to survive the hard rock silo environment, but we are learning that they will be quite expensive."[33] On August 21, 1970, Headquarters USAF announced the termination of the HRS program for Minuteman.[34]

M-X Enters the Picture

The Nixon administration revived the idea of the advanced ICBM. On November 19, 1971, Headquarters Strategic Air Command issued a Required Operational Capability for an advanced ICBM. Four months later, on April 4, 1972, the resurrected AICBM was designated as Missile-X (M-X) .[35] Concomitant with the need for a new missile was the need for a new basing concept.

The STRAT-X report basing modes were re-investigated over the next seven years, encountering strenuous political and environmental opposition as well as funding delays. A summary of the major basing options studies listed 30 possibilities. The selection was narrowed down to land-based concepts and eight reached various levels of development: Midgetman, HRS, covered trench, hybrid trench, Minuteman multiple protective shelter and M-X multiple protective shelter.[36]

On June 12, 1979, Pres. Carter approved M-X full-scale engineering development but did not choose a basing option. Congress moved swiftly and on June 27, 1979 passed a supplemental spending bill funding the development of M-X as well as advocating the choice of Multiple Protective Structure (MPS). This concept involved concealing the actual location of the missiles among a large number of hardened launch points under the assumption that an enemy would not want to expend the large number of missiles necessary to cover all of the possible location. On September 7, 1979, Pres. Carter announced his decision to use the MPS basing mode.[37]

The Reagan administration reviewed the M-X program and on October 1, 1981, Pres. Reagan abandoned MPS in favor of deployment in the existing Minuteman III launch facilities. This MPS costs had risen dramatically and political opposition was even more strenuous. Uncertainty with the overpressure environment in the trench and the detectability of the missile during normal operations promised increased costs:

In the dry deep alluvial valleys under consideration for basing, the surface/vertical shelter design would reduce the effective peak blast loading by as much as a factor of eight and, as a result, the hardness and cost required to survive a given threat. The primary advantage of the horizontal concept was the ability to rapidly move the missile (termed a "dash" capability) between shelters since the trench concept had on-site garages for the various transportation vehicles. With the vertical concept, the transfer vehicle had to pick up the missile at one shelter and unload it at another. As the M-X system evolved, the requirement for a "dash" capability was reevaluated and dropped. With this change in requirements the vertical shelter became the preferred basing mode.[38]

On November 22, 1982, Pres. Reagan officially designated M-X missile as the "Peacekeeper" and announced his decision to deploy the missile in the Closely Spaced Basing (CSB or Dense Pack) which gave rise to the concept of the Superhard Silo. The rationale behind CSB was that the missiles were super hardened in the single Soviet missile could not destroy all of them but would instead cause fratricide of other incoming Soviet reentry vehicles. This assumed one warhead per missile which again meant an inordinate number of missiles would be necessary to destroy the CSB.

With the advent of multiple independently targetable reentry vehicles the argument for CSB was no longer valid.[39] Pres. Reagan, meeting continued opposition to the need for M-X or its deployment in the CSB mode, formed the President's Commission on Strategic Forces on January 3, 1983. Named after its chairman, Brent Scowcroft , the Scowcraft commission was tasked with the review of the strategic weapons modernization programs with particular attention to the future of the ICBM forces and to recommend basing alternatives.

The Scowcroft Commission report was released on April 6, 1983. It endorsed Pres. Reagan's decision to deploy up to 100 M-X missiles in the current Minuteman III launch facilities as an interim measure while the final basing method was determined. The commission members noted that new developments in hardening the Minuteman facilities meant that launch facilities and launch control centers could be hardened to levels much greater than that which had been available just a few years earlier. The commission report also called for specific program or programs to resolve the uncertainties regarding silo or shelter hardness.[40]

Members of Congress were skeptical of his decisions, both the need for M-X and need for such vast deployment areas. Legislation passed in 1985 required a firm basing decision that had to be approved by Congress if there was to be any hope of more than 100 Peacekeeper missiles deployed.[41]

Basing System Concepts

By the time of the Scowcroft Commission, five basing concepts had reached physical modeling stage: continuously hardened buried trench; hardened aim point buried trench; horizontal shelter; vertical shelter; and verifiable horizontal shelter. Each of these had to be evaluated against thermal issues, radiation issues, depth of the ejecta from craters due to surface or subsurface bursts as well as electromagnetic pulse. The horizontal shelter and buried trench concepts were designed to be hardened against 400 to 600 psi overpressure; the vertical shelter silos were designed to withstand 1,000 to 1,500 psi overpressure. Testing was completed by the end of 1981.[42]

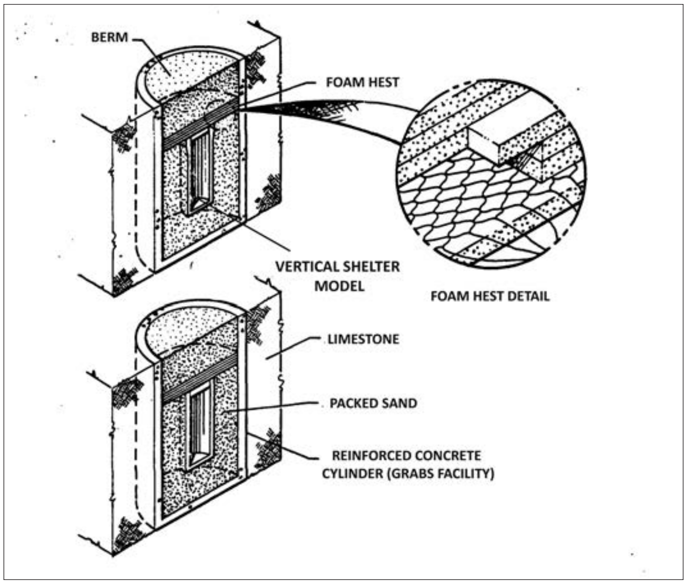


Figure 20. GRABS On Vertical Shelter (GOVS) program evaluated the response of vertical shelter models to vertical airblast and airblast-induced surface-blast loadings.

M-X Basing Modes Hardness Evaluation

Airblast and surfaceblast simulation for the evaluation of M-X basing modes utilized HEST as well as the Giant Reusable Airblast Simulator (GRABS) and Dynamic Airblast Simulator (DBS) as well as the Compact Reusable Airblast Simulator (CRABS).

GRABS

The GRABS facility was located at Kirtland AFB, New Mexico. It consisted of an 18-foot diameter, 50-foot-deep reinforced concrete cylinder emplaced in a massive limestone formation with 1.75-foot-thick walls and base. The cylinder interior was lined with 0.25-inch steel plate.[43] The GRABS On Vertical Shelters (GOVS) test series used the HEST system to achieve a peak overpressure of 12,000 psi, simulating a 3 MT blast within the GRABS test cell. The three 1/6 scale vertical shelter models, one model of configuration A and two models of configuration B reinforced canisters with a removable closure, were evaluated (Figure 20). There were two major findings from this experiment: (1) a vertical shelter should not be placed directly on bedrock and (2) that the headwork structure transition to the launch tube was susceptible to increase flexure. (Figure 21)[44]

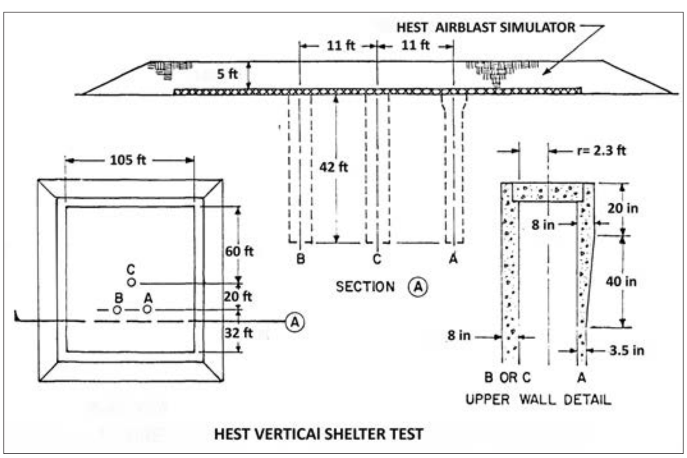


Figure 21. Phase III Vertical Shelter Test (HEST) 1/3 Scale. Three similar models were tested, two designed to respond without significant damage (B and C) and one (A) designed to have major longitudinal compression damage in the launch tube wall. The test was extremely successful and proved not only the value of the mathematical model but also the value of subscale testing.

Dynamic Airblast Simulator

The purpose of the DABS was to simulate the airblast loading that would be developed by a nuclear device at a given range. A typical installation consisted of a tunnel or trench with an arched concrete roof covered with overburden. The high explosive charge was placed at the closed end of the tunnel and as the blast wave traveled down the tunnel subscale vertical shelter closures were exposed to the blast wave (Figure 22.)[45]

Compact Reusable Airblast Simulator

1/30 and1/6 scale vertical shelter experiments were carried out in the CRABS facility at the Stanford Research Institute. It was geometrically similar to the GRABS device but on a much smaller scale.[46]

A comparison of the responses of the 1/30 and 1/6 test showed that the direct loading wave, reflections from the base of the closure, the base and the closure fixture, interface fiction, and soil resistance to punch down while accurately reproduced at 1/30 scale. Concrete surface change measured in the 1/30 scale test in the reinforcing steel strains measured in the 1/6 scale test showed excellent agreement.[47]

HAVE HOST

On April 28, 1977, the first of 12 HAVE HOST vulnerability tests were conducted at Luke AFB, Arizona. Over the next four years, high explosive simulation tests were conducted at Luke AFB, Arizona as well as Kirtland AFB and White Sands Missile Range, New Mexico. These tests included the HEST as well as GRABS, GOVS and DABS.

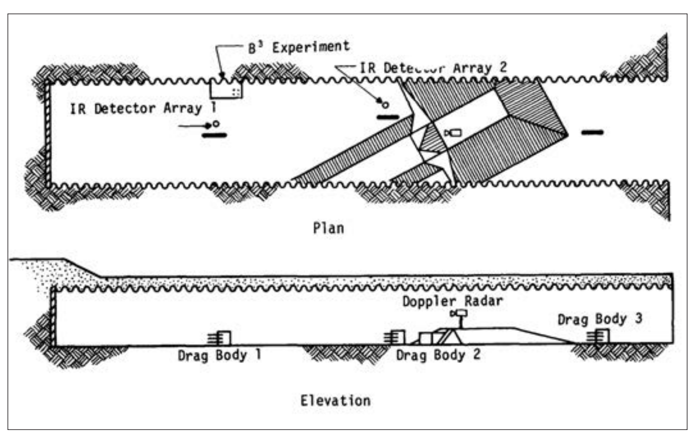


Figure 22. DABS Phase II S3 Event Test Layout.

Extensive modeling, from small-scale 1/100 to 1/40 up to 1/2 to 3/4 models of complete structural systems for the buried trench, horizontal and vertical shelter concepts help further define the designs. These early experiments resulted in increased cost estimates for the various trench concepts. By the early 1980s, the horizontal shelter and buried trench designs were abandoned in favor vertical shelter systems. One year later, the concepts came full circle as the vertical shelter designs had arms limitation complications. Work resumed on a more austere horizontal shelter concept (Figure 23).[48]

On May 23, 1985, the Senate approved the Nunn–Warner Amendment to the Department of Defense Authorization Act of 1986, limiting Peacekeeper deployment to 50 Minuteman III LFs. Four months later, on September 18, 1985, the Senate and House Conference Committee approved the amendment.[49] Peacekeeper LF conversion began on January 3, 1986 at the 400 SMS's LF Quebec-02 at F. E. Warren AFB. Peacekeeper became fully operational on December 30, 1988 with final installation at LF Quebec-10.[50]

Superhard Silos

On May 29, 1969, the Air Force awarded Bechtel Corporation $41.8 million for construction and testing of a superhard underground missile platform built in solid rock.[51] Superhard silos were intended to survive the detonation of a large yield nuclear weapon surface burst within a football length of the launch control center or the launch facility. An improved understanding of nuclear weapons effects indicated that such an idea was conceivable. A superhardened silo would be in the shape of a thermos bottle with exceptionally heavy steel reinforcement coupled with high-strength concrete. The missile-canister shock isolation system of Peacekeeper coupled with an external shock mitigation system of energy absorbing material surrounding the outer walls of the silo completed the design.[52]

A key component was a new form of concrete, slurry-infiltrated fiber concrete (SIFCON), developed by David Lankard at the Lankard Materials Laboratory, Columbus, Ohio. SIFCON has both high-strength as well as ductility not found in typical concrete applications.

Limited funding and time precluded building a HEST or DIHEST environment for testing a full-scale structure. The Air Force Weapons Laboratory utilized the already

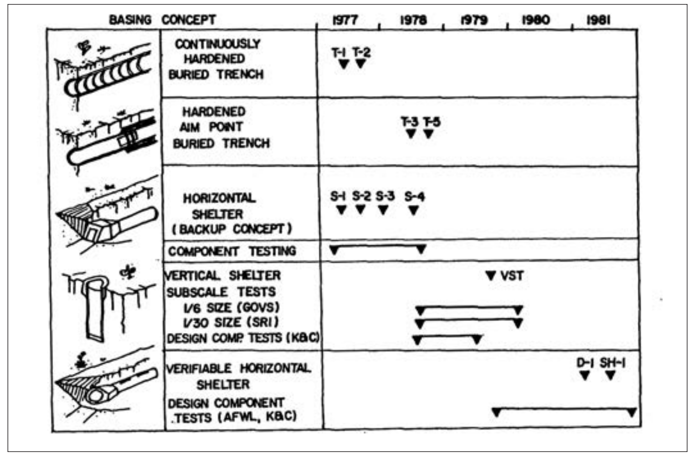


Figure 23. Basing Concept and Test Chronology.

scheduled Intercontinental Ballistic Missile Silo Superhardening Technology Test Program, Fall 1983, at Yuma, Arizona, to evaluate this new concept. The results demonstrated the potential of SIFCON as a key ingredient for hardened structures.[53]

Summary

Concern over the as-built hardness of the Minuteman launch facilities and launch control centers led to the development of the HEST system. Now the Air Force had the ability to simulate the air-blast and the induced ground motion effects of nuclear weapons. In the case of the HEST and DIHEST systems, entire operational facilities could be evaluated. The HEST program revealed substantial deficiencies in the Minuteman facilities, especially at Grand Forks AFB. It was not so much they were built incorrectly; it was more a matter of local geology. The problems were mitigated, to a large extent, by the system-wide Force Modernization program.

The DIHEST program clearly demonstrated that while the hard rock silo concept was "feasible," it would be extremely expensive to implement. Hindsight says this was a reasonably obvious conclusion which has not changed with the passing of half a century. However, at the time, the question of the vulnerability of our land-based strategic forces opened a debate that continued through the deployment of the Peacekeeper system. ■

NOTES

1. A National Intelligence Estimate, 11-8-65, Foreign Relations of the United States, 1964-1968, Volume X, National Security Policy, Document 97, 1. In late 1950s and early 1960s the relative inaccuracy and limited number of Soviet ICBMs would have necessitated the air-burst mode of attack rather than surface burst. That changed completely with the deployment of the SS-9 beginning in 1966.

2. D'Arcy, G. P., Auld, H. E. and Leigh, G. E., "Simulation of Air-Blast-Induced Ground Motion, Phase I, April 1965," AFWL-65-11, 1-3. Defense Technical Information Center (DTIC), AD614990.

3. D'Arcy, 12-32.

4. *Ibid.*, 28-29.

5. Auld, H. E., D'Arcy, G. P. and Leigh, G. E., "Simulation of Air Blast Induced Ground Motions, Phase II, April 1965," Volume I, AFWL-65-26, 3-5, 34, 53, 146. DTIC AD0613674. 118,000 feet of 175-grain Primacord was used.

6. Wampler, H. W., Leigh, G. G., Furbee, M. E., and Seusy, F. E., "A Status and Capability Report on Nuclear Air Blast Simulation Using HEST," *Proceedings of the Nuclear Blast and Shock Simulation Symposium*, 28-30 November 1978, Volume I, (Defense Nuclear Agency, Washington, DC, December 1978), 32, DTIC, ADA073766*; Designing Facilities to Resist Nuclear Weapons Effects: Hardness Verification,* TM 5-858-6, (Headquarters, Department of the Army, August 1984, Appendix B, 5; Bratton, J. L., Simulation of Air Blast Induced Ground Motion Using HEST, *Proceedings of the Conference on Military Applications of Blast Simulators, 1967*, Suffield Experimental Station, Canada, 189.

7. Nalty, B. C., *USAF Ballistic Missile Programs 1964-1966*, (USAF Historical Division Liaison Office, March 1967), 28. Declassified Documents Reference System, CK2349654796.

8. By June 1969, 90 percent of the Minuteman launch facilities were updated to the design requirement of 300 psi. SAMSO then proposed Plan 2 with three options for further increasing the hardness of Minuteman launch facilities. Several of the proposed features became part of the Force Modernization Program. *Strategic Air Command History, Fiscal Year 1970, Historical Study Number 117, Volume II, Narrative*, (Office of the Historian, Headquarters Strategic Air Command, Offutt Air Force Base, 20 April 1971), 236.

9. Nalty, 29-30; *Department of Defense Appropriations for 1970, Hearings Before a Subcommittee on Appropriations, House of Representatives, 91st Congress*, 753.

10. Nalty, 30; *Minuteman Historical Summary 1966-1967*, (Boeing Aircraft Corporation, 1974), Boeing Archives D2-26485-4, Sheet X-3 to Sheet X-12.

11. *Minuteman Historical Summary 1966-1967*, Sheet X-18, Sheet X-30.

12. Nalty, B. C., *USAF Ballistic Missile Programs 1967-1968,* 31-32; *Minuteman Historical Summary 1966-1967*, Sheet XI.

13. Nalty, 31-32; *Minuteman Historical Summary 1966-1967*, Sheets X-39 and X-40; *Minuteman Service News*, January-February 1968, Issue 36, 10.

14. Nalty, 1967-1968, 33; *History of the Strategic Air Command, FY 1969, Historical Study Number 116,* (Office of the Historian, Headquarters Strategic Air Command, March 1970), Digital National Security Archive, NT00502, 298-299.

15. Wampler, 32, 47.

16. *A Handbook of Selected Soviet Weapon and Space Systems*, (United States Air Force, June 1976), 162-167. The author thanks Hans Kristensen for copies of these pages; *Weapons System Evaluation Group Report No.50: Evaluation of Strategic Offensive Weapon Systems*, (Office of the Director of Defense Research and Engineering, Pentagon, Washington DC, December 27, 1960), 8.

17. Stumpf, D. K., *Minuteman: A Technical History of the Missile that Defined American Nuclear Warfare,* (University of Arkansas Press, 2020), 385-386.

18. *The STRAT-X REPORT*, *Volume 1, August 1967*, (Institute for Defense Analyses, Research and Engineering Support Division, Arlington Virginia), 1. Only STRAT-X Volume 1 has been declassified. Author's collection. I thank Jim Myers for my copy.

19. Nalty, 3-5.

20. STRAT-X, 1.

21. Grier, P., "STRAT-X," *Air Force Magazine*, January 2010, 53.

22. *SAC Missile Chronology, 1939-1988,* (Office of the Historian, Headquarters Strategic Air Command, Offutt Air Force Base, Nebraska, 1988), 53.

23. *Minuteman Historical Summary, 1968-1969*, Sheet VI-1.

24. *Minuteman Historical Summary 1968-1969,* (Boeing Aircraft Corporation, 1974), Boeing Archives, D2-26485-5, Sheet VI-1.

25. Blouin, S., "Block Motion from Detonations of Buried Near-Surface Explosive Arrays," Cold Regions Research and Engineering Laboratory Report 80-26, Army Corps of Engineers, 28-30. DTIC ADA095492.

26. Taylor, H. L., "Design and Construction of Test Facilities to Simulate the Effects of a Nuclear Detonation HANDEC I and HANDEC II," May 1970, AFWL-TR-69-171, 2, 3, Figure 97. DTIC ADA 872111; Blouin, 37, 40, 41.

27. *Strategic Air Command History, FY 1969,* 349; Whitehead, M., "High Explosive Simulation Technique," *The Military Engineer*, July-August 1970, Volume 62, 255-257.

28. Whitehead, 255.

29. Bagge, C. F., and Y. C. Lee, "Applicability of Continuum Models for Jointed Rock-Structure Interaction," *Applications of the Finite Element Method in Geotechnical Engineering Proceedings*, (U.S. Army Engineering Waterways Experiment Station, Vicksburg, Mississippi, 1972), 1165-1207.

30. Vergnolle, R. R., "Rock Excavation for ROCKTEST II," *The Military Engineer*, March-April 1971, Volume 63, 113; Blouin, 49-62.

31. Blouin, 1-3.

32. *Ibid.*, 61-62.

33. Glasser, O. J., testimony, *Department of Defense Appropriations for 1971, Hearings before a Subcommittee on the Committee on Appropriations, House of Representatives, 91st Congress, Second Session,* 699.

34. *SAC Missile Chronology 1939-1988*, (Office of the Historian, Headquarters Strategic Air Command, Offutt Air Force Base, Nebraska, May 1990), 56.

35. *SAC Missile Chronology: 1939-1988,* (Office of the Historian, HQ strategic air command, Offutt AFB, May 1990, Nebraska), 58.

36. *ICBM Basing Options: A Summary of Major Studies to Define a Survivable Basing Concept for ICBMs*, (Office of the Deputy under Sec. of Defense for Research and Engineering), 1-84. AD-A956443.

37. Public Law 96-29, Section 201; BMO Chronology, 158.

38. Cole, D. M., "MX Basing Design Development Derived From H. E. Testing," Eds. Krauthammer, T. and C. D. Sutton, *Physical Modeling Techniques for Missile and Other Protective Structures,* Papers Submitted for Presentation during the American Society of Civil Engineers National Spring Convention*,* Las Vegas, April 1982, 46-48. Hereafter abbreviated as *Physical Modeling Techniques*.,

39. "Pentagon Statement on M-X Missile Basing," *New York Times,* November 23, 1979, 14.

40. Scowcroft, B., *Report of the President's Commission on Strategic Forces*, (The White House, April 1983), 9.

41. Public Law 99-145, "Department of Defense Authorization Act 8 November 1985," Section 141, 99 STAT. 602-603.

42. Sevin, E., "The Use of Physical Models and Development of the M-X Protective Shelters," *Physical Modeling Techniques,* April 1982, 2; Cole, 3.

43. Narain, I., J. Stephens, and G. Landon, "Protective Vertical Shelters," Physical Modeling Techniques, 41-42.

44. Narain, 30.

45. Cole, 48

46. Gran, J.K, J.R. Bruce and J. D. Colton, "Small-Scale Tests of M-X Vertical Shelter Structures," *Physical Modeling Techniques*, April 1982, 6-8.

47. Edgel, W. Reed and N.P. Baum, "Dynamic Airblast Simulator (DABS) Instrumentation Development-Phase II," Air Force Weapons Laboratory, AFWL-TR-79-155, June 1980, 10-11.

48. Sevin, E., "The Use of Physical Models in Development of the M-X Protective Shelter," *Physical Modeling Techniques*, 1-10.

49. *Congressional Record* (Sen.), 23 May 1985*,* 13544–13545. *Congressional Record* (H. R.)18 September 1985*,* 24126.

50. "90th Strategic Missile Wing History: January–March 1986," (History Office, 90th Strategic Missile Wing, 21 June 1986), ix–x. "90th Strategic Missile Wing History: January–December 1988," (History Office, 90th Strategic Missile Wing, 15 October 1988). These documents are classified; the extracts used are declassified IAW EO 13526. The author thanks Mike Byrd, 20th Air Force Historian, for these documents.

51. *Minuteman Historical Summary, 1968-1969*, D2-26485-5, Sheet XI-84.

52. Sevin, E., "ICBM Modernization: A Shock and Vibration Perspective," *57th Shock and Vibration Symposium, 1987*, 9-16.

53. Schneider, B., et al., *ISST Structure with SIFCON-HFC-2 Test*, Air Force Weapons Laboratory, April 1988, AFWL-TR-87-101, 1-2, 114.

Operation Button Up: Security at Minuteman Launch Facilities

David K. Stumpf

Workers prepare the sealing surface for the Personnel Access System hatch. This is the original hatch design, as can be determined by the interior hydraulic mechanism for raising and lowering the hatch. The hatch had to be large enough for equipment to be transferred to and from the Launcher Equipment Room. *(Library of Congress)*

Operation Button Up was the program to correct deficiencies in the design of the Minuteman launch facility Personnel Access System (PAS). The liquid propellant Atlas, Titan I and II systems required complicated propellant transfer equipment at the launch facilities, requiring adjacent launch control centers manned by launch crews. The solid propellant Minuteman obviated this requirement, greatly simplifying the launch facility design and allowing it to be unmanned.

Minuteman launch facilities are situated on 1.8 to 2 acres of land surrounded by a 7'6" security fence The original launch facility security system was divided into outer and inner zones. The outer zone included a radio frequency system that detected surface activity within the boundary of the fence. The inner zone included switches at the launcher closure, PAS hatch (primary door) and security pit which allowed access to opening and closing the primary door.

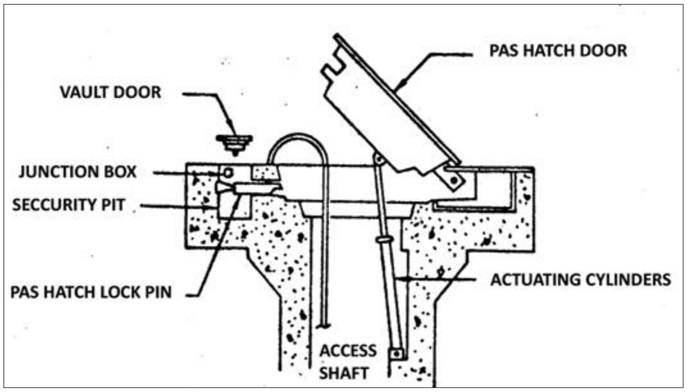
Operation Button Up began in June 1962.[1] The implementation was complicated by the need to modify a large number of partially or nearly completed launch facilities at the same time as the Army Corps of Engineers was completing their construction work or the Site Activation Task Force was installing the launch facility equipment. This article describes the genesis of Operation Button Up and major modifications made to the PAS.

Background

On April 1, 1960, Pres. Eisenhower approved deployment of 150 Minuteman IA missiles at the 341st Strategic Missile Wing (Wing I), Malmstrom Air Force Base, Montana.[2] Launch facilities were grouped 10 per flight with one launch control center per flight with the launch facilities approximately nine nautical miles from the parent launch control facility. Construction at Malmstrom began on 16 March 1961.

Col. Edward Hall's original concept for Minuteman was to have the ability to launch a squadron of 50 missiles at a time. An inadvertent or rogue launch of 50 missiles worried many inside and outside of the Pentagon. Two months earlier on February 12, 1960, Pres. Eisenhower's science advisor, Dr. George B. Kistiakowsky summarized his concerns about the Minuteman program command-and-control but no mention was made about security against unauthorized entry into the launcher.

On April 3, 1960, Lt. Gen. Bernard A. Schriever, Cmdr., Air Research and Development Command, requested an independent review of the technical and operational aspects of the entire ICBM program. The committee's report, sent to Schriever on May 31, 1960, listed the developmental problems with Minuteman but did not make recommendations on



Original PAS components. A portable ladder section was brought to connect to the retractable section attached to the wall and retracted or extended by the motion of the B-plug. ***(Minuteman Illustrated Technical Requirements)***

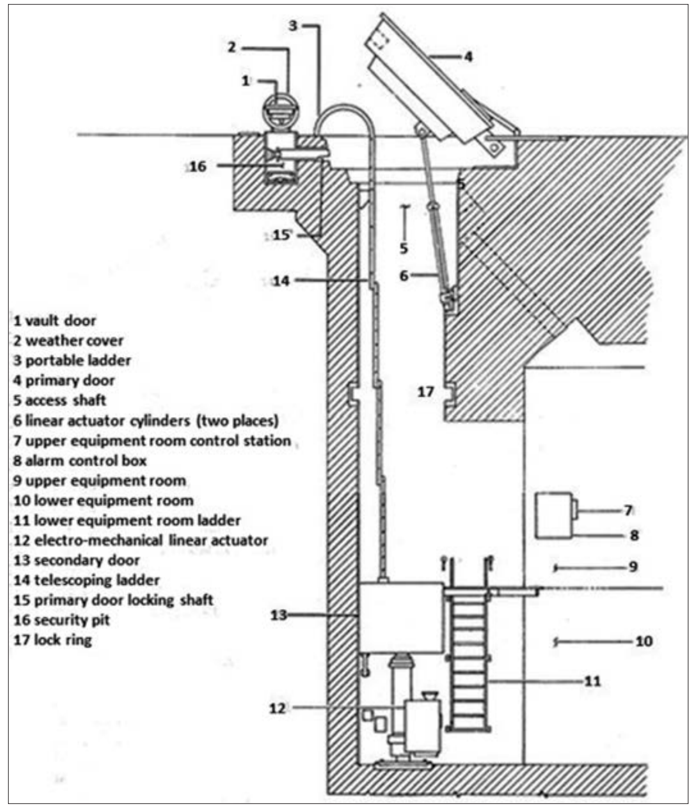
command-and-control nor reference to the physical security of the launch facilities.

A year earlier, in September 1959, the Joint Chiefs of Staff requested a study, by the Weapon System Evaluation Group (WSEG), of the strategic bombers, air-to-surface missiles, ICBM's, FBM's and IRBM's, with a recommendation for the number of each weapon system to be deployed. The preliminary findings of the WSEG Report 50: Evaluation of Strategic Offensive Weapons Systems, were released on September 15, 1960. Severe deficiencies in the command-and-control of the Minuteman force were discussed.

The Lauritsen Committee was reconvened in April 1961 to conduct a follow-on review of the Minuteman program in light of the WSEG Report 50 findings. The committee's report, released on June 15, 1961, concurred with the WSEG findings but again no mention was made of deficiencies of physical security of the launch facilities.

On July 6, 1961, the Air Force forwarded a report written by Brig. Gen. Phillips, director of the Minuteman program and Col. R. T. Hemsley, chief, Minuteman development branch, to Dr. Herbert York, director of the Directorate of Research and Engineering in the Defense Department. The report addressed the Lauritsen committee findings including budget estimates for their implementation. This triggered another round of review by outside experts as the Defense Department was in complete disagreement with the Air Force findings.

David K. Stumpf, Ph.D., is a retired plant biochemist living with his wife, Susan, in Tucson Arizona. He has written three nuclear weapon histories, Regulus the Forgotten Weapon*, a history of the Navy's Regulus I and II cruise missiles;* Titan II: A History of a Cold War Missile System *and* Minuteman: a Technical History of the Missile that defined American Nuclear Warfare*, published February 2021. Dr. Stumpf volunteered at the Titan Missile Museum, Sahuarita, Arizona, as an historian and as a tour guide for 15 years. He was instrumental in the effort to gain National Historic Landmark status for the museum.*

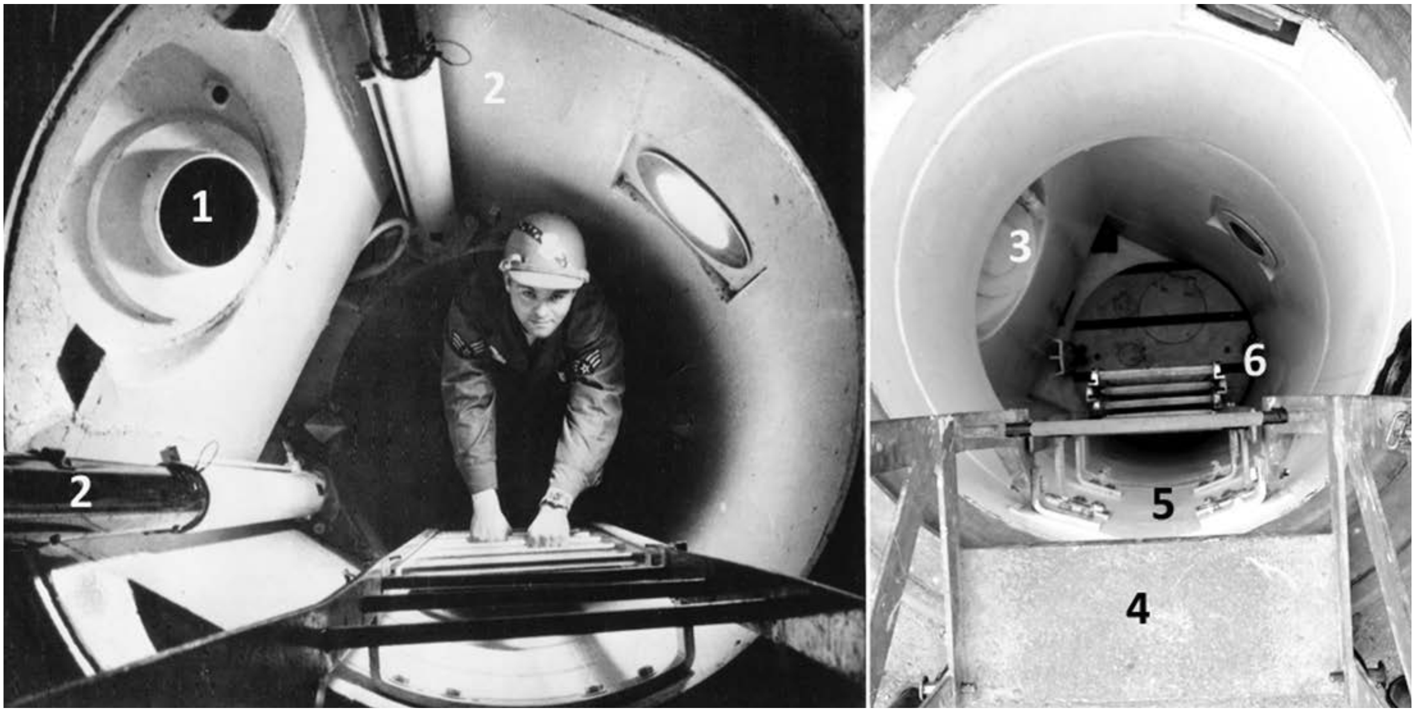


Installed PAS components circa 1962-1963. The most time consuming and difficult modification was the installation of the lock ring assembly due to the confined space of the access shaft. ***(Minuteman Familiarization)***

On July 30, 1961, the Fletcher Committee, chaired by James Fletcher and formally known as the Minuteman Flexibility and Safety Group was formed by Secretary of the Air Force Eugene Zuckert at the request of Secretary of Defense Robert McNamara. The committee focused solely on the question of Minuteman weapon system safety against accidental launch and the feasibility of increased target flexibility.

The first mention of the vulnerability of the Minuteman launch facility to unauthorized penetration occurred in the Fletcher Committee report released on September 15, 1961.While the major focus of the report was on command-and-control issues, the report recommended modification of the PAS.[3] This was in response to the results of tests run by the Nuclear Weapon Safety Group in August 1961 which had succeeded in defeating the operational PAS security system currently being installed at Malmstrom and Ellsworth.[4]

The response to the Fletcher Committee's recommendations was immediate. Boeing, the Minuteman assembly and checkout contractor, issued Contract Change Notice (CCN) 299 on October 24, 1961. CCN 299, also known as Block Change 1, implemented the command-and-control changes which involved substantial modifications to the majority of the existing command-and-control equipment. In April 1961, CCN 299 was amended to include modifications to the PAS. All of the modifications had to be accomplished without impacting the deployment date of October 1962 for Wing I.[5]



Left: Senior Airman Charles W. P. Michaels ascends PAS ladder, December 11, 1962. 1) original 22-inch autocollimator sight tube has been reduced in diameter to prevent unauthorized access. 2) the hydraulic system for opening and closing the door were originally inside the access shaft. Right: the sight tube was abandoned in place and the hydraulic system replaced with an exterior manual system during the Force Modernization program. 3, 4, 5) are the portable, fixed and extension ladder sections respectively. ***(Library of Congress)***

Operation Button Up

Original Personnel Access System

The original PAS security system consisted of the security pit weather cover, and the 166-pound security vault door. The security pit housed a combination lock, controls to raise or lower the 10,000-pound PAS shaft hatch and the hand-driven linear actuator which locked or unlocked the PAS shaft hatch. The original hatch door hydraulic actuators were in the upper part of the interior of the access shaft, protected by the hatch door.[6]

Records for the launch facility penetration tests conducted in August 1961 remain classified. Presumably they showed that well-prepared intruders could pick the combination lock on the security pit vault door and raise the PAS hatch door before a security team arrived.

Installation

Wing I

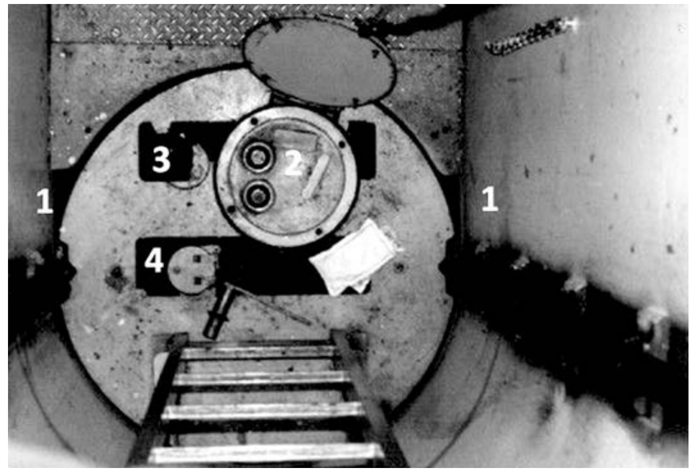
The R. M. Parsons Company won the contract for the Operation Button Up engineering design and hardware procurement for Wing I Flights A and B cook. Boeing received the contract for hardware installation and checkout. A preliminary installation was made at Launch Facility 06 at Vandenberg Air Force Base and the design was determined to be operationally feasible. On June 20, 1962, at the 45th meeting of the Designated Systems Management Group, Operation Button Up was approved and operational base implementation was begun at a cost of $70 million.[7]

Now the problem was how to get the system incorporated at this late period in construction at Wing I while working with an evolving design for the Button Up hardware. The Army Corps of Engineers phase of launch control center and launch facility construction at Wing I was completed on September 21, 1962. Scheduling the retrofit work around the Site Activation Task Force installation of operating equipment made a difficult situation even worse. Installation at Wing II began in March 1963. The remaining wings had the installation as part of the original construction.

Installation took place in two phases. Phase I was the retrofit construction phase carried out by the Army Corps of Engineers. It involved modifying Launcher Equipment Room Level 1 floor framing and connections to the access shaft, adding the cutout for the locking ring in the access shaft, cutting out the steel floor at the bottom of the access shaft to accommodate the secondary door (see below) and its operating mechanism, rerouting hydraulic and electric lines, modifying the auto-collimator sight tube diameter, modifying the ladder in the access shaft, adding a ceiling mounted monorail for equipment handling as well as providing a new seal for the primary door (see below). Phase II, carried out by Boeing, was assembly, installation and checkout of the new equipment.[8]

The Facilities Engineering staff at Malmstrom worked closely with Parsons and Boeing as the design and installation was fine tuned to accommodate inevitable variation between launch facilities. Over 90 new drawings were prepared during this process, many of which were incorporated in the final design package. The Operation Button Up Phase I work at Flight A was completed by 13 July 1962, and Flight B followed a month later. Phase II was completed at both flights by early October.[9]

Secondary door fully retracted, Launcher Equipment Room Level 2: 1) 4-inch diameter locking bolts; 2) linear actuator; 3) manual override drive for linear actuator. *(Library of Congress)*



Top view of secondary door in the lowered position. 1) secondary door guide rails guide rails; 2) secondary door locks and cover, 3) emergency override port; 4) lock pin actuator gear shaft access. *(Author's Collection)*

Operation Button Up PAS Modifications

Vault Door

There were no modifications to the vault door (also referred to as the A-plug).

Security Pit

The security pit was modified with additional controls for lowering and raising the new secondary door (also referred to as the B-plug).

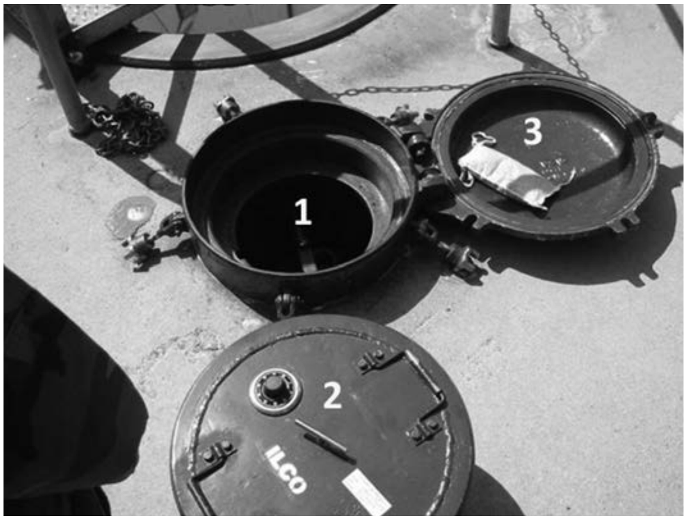
Secondary Door

The Parsons solution was elegantly simple as well as massive. The 42-inch inside diameter, 21-foot-deep access shaft was now blocked with a movable 14,000 pound, 41-inch diameter, 45-5/16 thick, the secondary door. The secondary door was built with four layers: copper to absorb heat from a torch, hardened steel to resist drilling, Mylar composites to resist impact, and dust creating devices to impair the vision of intruders.[10] The original be-plug was raised or lowered hydraulically a rate of 9.5 inches per minute. A time delay device provided added security to the system by delaying the time between withdrawal of the Be-plug locking bolts and the time the linear actuator began operation. The duration of the delay depended on the security team response time from the parent Launch Control Facility.[11]

The top of the secondary door had a large covered recess containing two combination lock dials and a lock release handle. Unlocking either of the combination locks permitted withdrawal of the locking bolts from the locking ring by means of a hand crank installed on the locking bolts actuator shaft. One smaller covered recess house the locking bolt actuator shaft and the other a mechanical override access adapter which was part of the manual B-plug lowering system.[12]

Table 1. Corps of Engineers Ballistic Missile Construction Office Start and Completion Dates

Wing	Start	Completion	Days
341 SMW Malmstrom AFB	16 Mar 61	21 Sep 62	585
44 SMW Ellsworth AFB	21 Aug 61	22 Apr 63	609
455 SMW Minot AFB	18 Jan 62	11 Jul 63	539
351 SMW Whiteman AFB	2 Apr 62	7 Nov 63	584
90 SMW F.E. Warren AFB	25 Oct 62	19 Jun 64	603
321 SMW Grand Forks AFB	12 Mar 64	10 Dec 65	638
Squadron 20 Malmstrom AFB	8 Mar 65	26 Oct 66	597



Primary Door Security Pit: 1) primary door security pit vault which houses the linear actuator unlocking mechanism for the primary access door as well as the hydraulic controls for raising and lowering the door; 2) 166 lb. vault door; 3) vault weather cover, the white packet is desiccant. ***(Author' Collection)***

Linear Actuator

The linear actuator consists of a hydraulically operated ball screw jack 51.3 inches long when retracted and 198.9 inches long when extended.[13] If the hydraulic system fails, a three-piece, 20- foot shaft can be lowered through the secondary door to a receiver in the linear actuator permitting manual operation from the top of the secondary door.[14]

Access Ladder

The base of a telescoping ladder was attached to the top of the secondary door. A short removable section of ladder and short fixed section of ladder mounted on the wall were installed between ground surface and the top of the telescoping ladder.

Lock Ring

A lock ring was embedded in the wall of the access shaft to receive eight 4-inch diameter secondary door lock bolts when the door is in the raised position. The lock ring supports the secondary door during ground shock or penetration attempts and maintains electrical continuity with the facility.[15]

Autocollimator Sight Tube

With the V-plug in the normal raised position, the original 22-inch inside diameter autocollimator alignment sight tube was now a potential entry point for an intruder. A 9-inch diameter tube was welded inside the larger tube and the remaining space filled with grout.[16]

Launcher Equipment Room Level 1 Platform

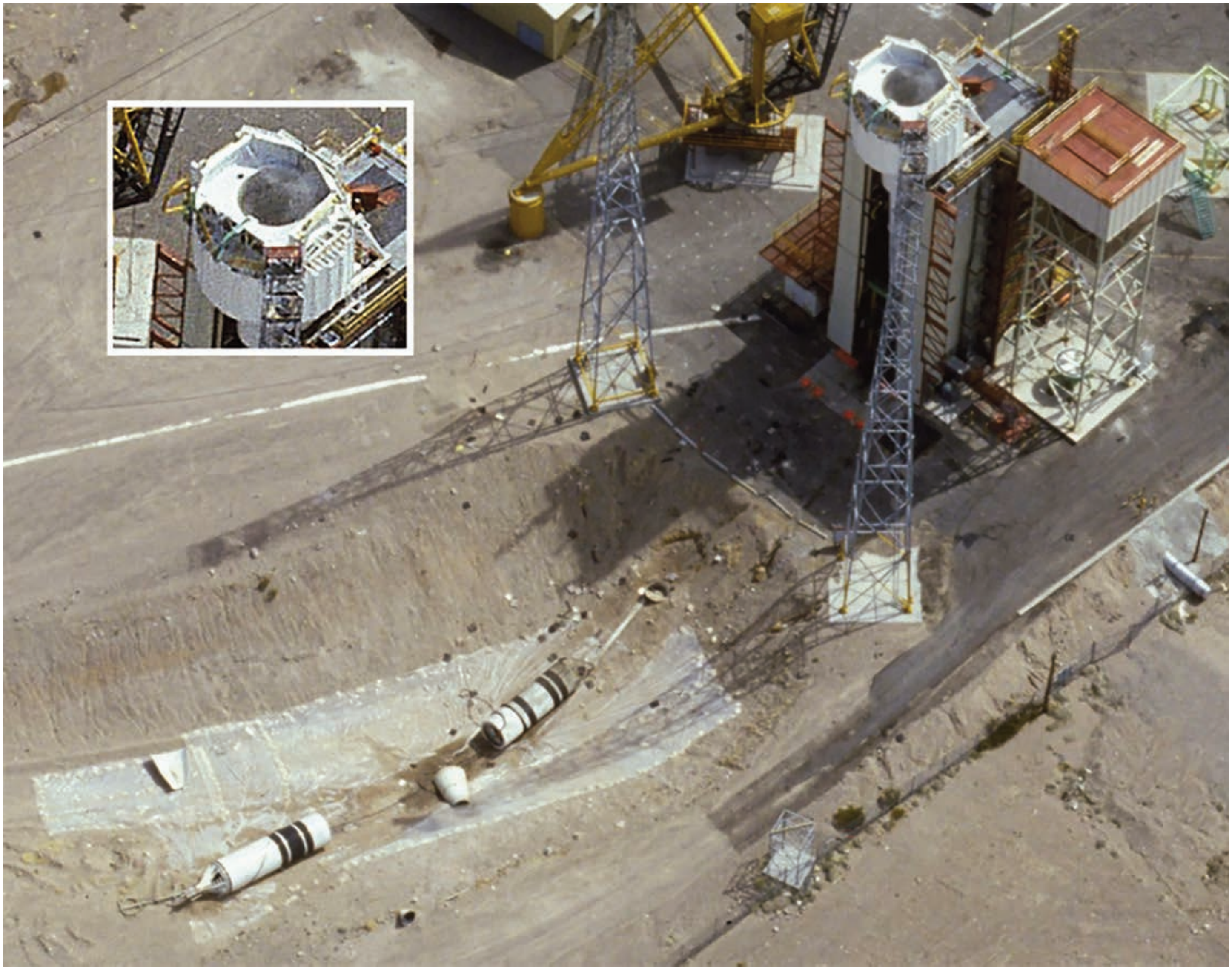
The top of the retracted Be-plug is flush to the floor of Launcher Equipment Room Level 1. The linear actuator is located on the floor of Launcher Equipment Room Level 2.

Summary

At first glance the original Minuteman launch facility and anti-penetration security design seems woefully insufficient and was readily proven so well after construction had begun on the first two Minuteman wings. Installation of the new system was part of the original construction for Wings III-VI and Squadron 20 at Malmstrom. $70 million Operation Button Up retrofit program solved the problem and has had a number of updates made over the 60 years of Minuteman deployment. ■

NOTES

1. C. H. Eger, "Minuteman Financial History 1955–1963" (Minuteman Special Project Office, undated), National Archives and Records Administration (NARA), Washington, DC, Samuel C. Phillips Collection, Folder 1, Box 11, 14.
2. Discussion at the 439th National Security Council Meeting Held on 1 April 1960, Declassified Documents Research Service, CK2349158797, 20.
3. Summary Report: Minuteman Flexibility and Safety Study Group, 27 September 1961 (Department of Defense), AFHRA IRISNUM 2054414, K243.8631–745, Section 3-3 Section 4-7. This document is classified; the extract used is declassified IAW EO 13526
4. Summary Report, 4-7.
5. Minuteman Historical Summary, 1960–1961, (The Boeing Company, Seattle, WA, 1974),
D2–26485, Sheet I-27, 28.
6. Launch Facility Personnel Access Systems, VAFB, Wings I-VI, USAF Series LGM30F and G Missile, T. O. 21M-LGM30F-2-19, 30 October 1978, Change 48-13 August 1993, Change 37, 2-3.
7. Eger, 89.
8. Minuteman Historical Summary, 1962–1963, (The Boeing Company, Seattle, WA, 1974), D2–26485-2, Sheet I-27; History of Minuteman Construction Wing II Ellsworth, Area Engineer Office, US Army Corps of Engineers, 1 August 1961-31 August 1963, (Army Corps of Engineers History Office, Fort Belvoir, MD), Military Files XVIII, box 9 BD 3, 96.
9. Debrief Exercise, Site Activation Task Force Detachment 16, Malmstrom Air Force Base, Montana, 12 July 1963, AFHRA, IRISNUM 919732, K243.0121-17, 62-63.
10. R. C. Anderson, Minuteman to MX, the ICBM Revolution, Quest 3, Autumn 1979, 42.
11. Minuteman Illustrated Technical Requirements, D2-31384-1, (The Boeing Company, Seattle, WA), Sheet 173.
12. Launch Facility Personnel Access System, 1-7.
13. Minuteman Illustrated Technical Requirements, Sheet 179.
14. Launch Facility Personnel Access Systems, 1-11.
15. Minuteman Illustrator Technical Requirements, Sheet 181.
16. History of Minuteman Construction Wing II Ellsworth, 154. This document refers to a 9-inch diameter insert, the as-built drawings reference an 8-inch diameter tube insert.



The last Minuteman Upper Silo Simulation launch took place on April 10, 1986. As was the case in all the previous MUSS and CALTP launches, the test missile landed in a pit approximately 100 feet from the launch tower. *(Official U.S. Air Force Photograph, National Archive and Records Administration)*

Guidelines for Contributors—We seek quality articles—based on sound scholarship, perceptive analysis, and/or first-hand experience—which are well-written and attractively illustrated. If a manuscript is under consideration by another publication, the author should clearly indicate this at the time of submission. Manuscripts should be prepared according to the Chicago Manual of Style (University of Chicago Press). Use civilian dates (month, day, year) and either footnotes or endnotes may be used. Because submissions are evaluated anonymously, the author's name should appear only on the title page. Authors should provide on a separate page brief biographical details, to include institutional or professional affiliation and recent publications, for inclusion in the printed article. Pages, including those containing illustrations, diagrams or tables, should be numbered consecutively. Any figures and tables must be clearly produced ready for photographic reproduction. The source should be given below the table. Notes should be numbered consecutively through the article with a raised numeral corresponding to the list of notes placed at the end. Submissions may be submitted either by mail or via email. Email is generally the norm. While Microsoft Word is the most common, any word processor may be used. Do not "Track Changes." Photographic illustrations are greatly appreciated. There is no restriction on the file format used. There is no standard length for articles, but 4,500-5,500 words is a general guide. Manuscripts and editorial correspondence should be sent to Richard Wolf, Editor, c/o Air Power History, 70 Shannon Way, Upton, MA 01568, e-mail: airpowerhistory@yahoo.com.

Air Force *Historical* Foundation
P.O. Box 405
Mechanicsville, MD 20659

To: Air Force *Historical* Foundation
P.O. Box 405
Mechanicsville, MD 20659

Visit Us Online at:
www.afhistory.org

Know the Past,
Shape
the Future

A I R F O R C E H I S T O R I C A L F O U N D A T I O N M E M B E R S H I P F O R M

NAME________________ PHONE ________________ E-MAIL________________

STREET ADDRESS ________________ CITY________________ STATE________ ZIP________

❑ **Associate Membership ($30/year) (on-line magazine access)** (Visit our Web site at www.afhistory.org)

❑ **Sustaining Membership ($50/year)**

❑ **Gift Membership ($50/year)**

❑ **President's Circle ($1,000) Benefactor ($500) Patron ($250) or Contributor ($100)**

GIFT FOR (NAME)________________

ADDRESS ________________

CITY________________ STATE________ ZIP________

* Non-US recipients please add $10.00 for postage (See Web site for additional membership options)

❑ **Check enclosed, payable in US Funds to Air Force *Historical* Foundation**

❑ **Please charge my credit card (VISA/MasterCard/Discover)**

CARD NUMBER: ________________ EXPIRATION DATE: ________

SIGNATURE: ________________ DATE: ________________

Send form, along with your remittance to:
Air Force *Historical* Foundation
P.O. Box 405
Mechanicsville, MD 20659