NASA Technical Paper 3615

Review of Our National Heritage of Launch Vehicles Using Aerodynamic Surfaces and Current Use of These by Other Nations (Center Director's Discretionary Fund Project Number 93-05 Part II)

C. Barret

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TECHNICAL PAPER

REVIEW OF OUR NATIONAL HERITAGE OF LAUNCH VEHICLES USING AERODYNAMIC SURFACES AND CURRENT USE OF THESE BY OTHER NATIONS
(Center Director's Discretionary Fund Project 93–05 Part II)

I. INTRODUCTION

A. Background

The space shuttle was only the first step in achieving routine access to space. Recently, the NASA Marshall Space Flight Center (MSFC) has been studying a whole new spectrum of launch vehicles (L/V's) for space transportation. Some of these could transport components of the space station to orbit, and some could take us to Mars and beyond to boldly expand our frontiers of knowledge.

In all our future L/V designs, decreasing the structural weight will always be of great concern. This is tantamount to increased payload capability, which in turn means reduced cost-per-pound to orbit. One very significant increase in payload capability has been defined. In an L/V recently studied at MSFC, it has been shown that a sizable weight savings can be realized by a rearrangement of the internal propellant tanks. Studies have been conducted both at MSFC and at Martin Marietta Corporation, maker of the space shuttle external tank (ET), which show that approximately 10,000 lb can be saved by inverting the relative positions of the liquid hydrogen (LH_2) and the liquid oxygen (LOX) propellant tanks in a particular L/V studied.

As the vehicle sits on the launch pad, in the conventional configuration the heavier LOX tank is located on top of the lighter LH_2. This requires a heavy structural member between the two tanks to prevent the lighter LH_2 tank from being crushed. This configuration also requires large, long, and even drag producing LOX feed lines running the length of the vehicle on the exterior fuselage. If the relative position of the propellant tanks is inverted, both the heavy structural separation member and the long LOX feed lines could be deleted, and the fueling time would be reduced.

However, the LOX tank aft configuration gave the vehicle an aft center-of-gravity (cg) location that caused controllability concerns to surface. In the conventional configuration, the L/V is controlled in the ascent trajectory by the gimbaling of its rocket engines. Studies have been conducted at MSFC that showed that the resulting aft-cg configured L/V would not be adequately controllable with the engine gimbaling alone.

B. Problem Statement

It is known that the controllability of an aft cg L/V is decreased. In addition to an aft cg being caused by an internal rearrangement of propellant tanks, aft cg L/V's may appear for other reasons such as the addition of solid and/or liquid strap-ons. Therefore, in the new spectrum of L/V's being considered, the controllability of the aft-cg configured vehicle must be assessed. When the available control authority has been determined to be inadequate or marginal using engine gimbaling alone, some means of flight control augmentation is required.

In this research effort, the author has proposed a novel solution to provide the required flight control augmentation for an aft-cg configured L/V when needed most in the ascent trajectory, during maximum dynamic pressure.[1 2] The L/V used in this research is one that has recently been studied at MSFC. The LH_2 and LOX propellant tanks in the ET have been interchanged, giving the vehicle an aft cg. It has been determined that engine gimbaling alone does not provide adequate control. The required flight control augmentation is provided by aerodynamic flight control augmentors. This solution proposes to not only solve the original problem of augmenting the control of the aft cg vehicle, but also may be used in the marginal control configuration to enhance controllability, as load alleviators, to reduce engine gimbaling requirements, to provide engine actuator failure protection, and to enhance crew safety and vehicle reliability by providing more control in engine-out events.

These devices can reduce wind restrictions. Conventionally, the L/V loads during ascent are alleviated by turning the vehicle into the wind, thereby reducing the flight angle-of-attack. Thus, load relief is accomplished at the expense of trajectory deviation. Load relief control is most necessary when the L/V experiences maximum dynamic pressure and the aerodynamic loads are greatest. This would be when the flight control augmentors would provide the most significant assistance. The proposed added control capability through the use of these surfaces allows greater tolerance of wind magnitudes and a minimization of bending moments on the vehicle both during ascent and during launch. For prelaunch, the unfueled vehicle on the pad is assumed to withstand peak loads of 75 kn, and fueled at lift-off peak winds of 50 kn. The environmental disturbances are multiplied by 1.5 to account for von Karman vortex shedding effects. Wind profiles show that the greatest steady wind speeds occur between 20,000 and 60,000 ft, with a gust overshoot of up to 50 percent.[3] The more the engines are required to gimbal, i.e., the greater the required engine gimbal deflection angles, the more engineering design and cost is involved to have the propellant ducts move with the gimbal action while maintaining a full flow of fuel. Gimbaled engines are difficult to seal and have high actuation torques. The extension, compression, and torsion of propellant ducts become limiting factors of engine gimbaling. Thus, the designed aerodynamic surfaces of this research provide not only the required control augmentation, but a plethora of additional significant benefits.

C. Approach

As a starting point for the novel design of aerodynamic flight control augmentors for a *Saturn* class, aft cg L/V, which is the mission of Center Director's Discretionary Fund (CDDF) project 93-05, this report undertakes a review of our national heritage of L/V's using aerodynamic surfaces, along with a survey of current use of aerodynamic surfaces on large L/V's of other nations. NASA has a rich national heritage of L/V's that have used aerodynamic surfaces, both to provide flight stability and to provide flight control. The *Saturn V* L/V has flown 13 successful missions. The *Saturn V* missions to the Moon utilized 300 ft^2 of aerodynamic surfaces. Today, there is a myriad of L/V's actively launched from almost two dozen geographic sites, many of which are using aerodynamic surfaces.

This CDDF research effort draws on advancements in many other fields. Since NASA journeyed to the Moon with the *Saturn V* and its 300 ft^2 of aerodynamic surfaces, the wealth of smart materials and advanced composites that have been developed allow for the design of very lightweight, strong, and innovative L/V flight control augmentors. A previous companion publication[4] conducted a state-of-the-art assessment of smart materials and advanced composites which are directly applicable to aerodynamic flight control augmentors of future L/V's. Thus, any added weight concerns are addressed.

In a subsequent CDDF Project 93-05 publication, the actual control requirements of the experimental aft-cg configured L/V of this research are determined. These determined flight control requirements, together with the review of this report, the L/V mass properties, and the ascent trajectory data are used to design the candidate flight control surface augmentors. A wind tunnel test program has been designed for these candidate flight control augmentors and the host experimental aft cg L/V. The wind tunnel test data are then utilized to conduct the vehicle static and dynamic stability analyses and to demonstrate the augmented control authority achievable with the use of the flight control augmentor designs. Figure 1 shows the flow chart of this conducted research effort (CDDF Project 93-05) and the relationship of previous and subsequent publications to this one.

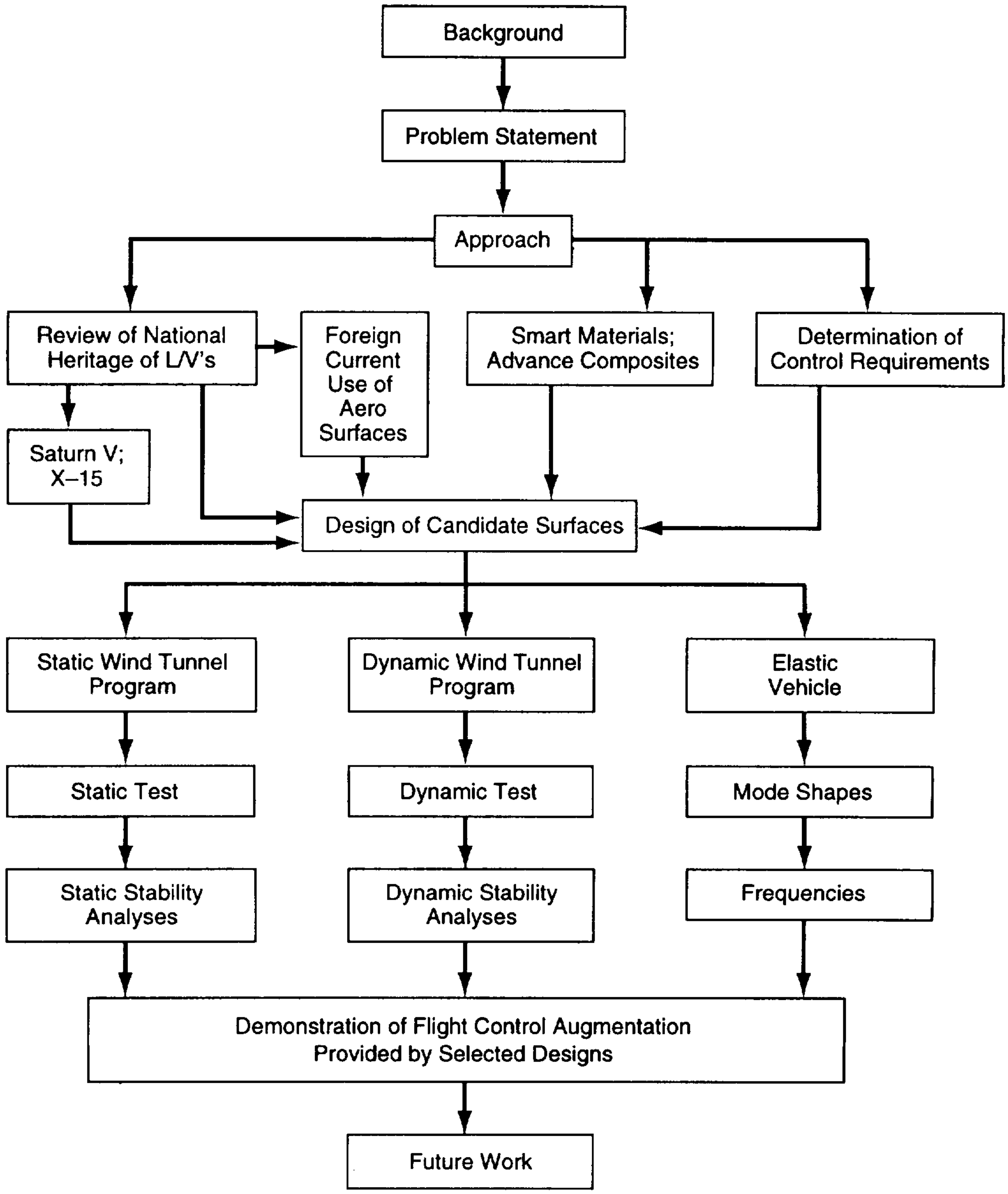


Figure 1. Flow chart of CDDF research.

II. REVIEW OF NATIONAL HERITAGE OF LAUNCH VEHICLES USING AERODYNAMIC SURFACES TO PROVIDE FLIGHT STABILITY AND CONTROL

We have a rich national heritage of L/V's that have used aerodynamic surfaces for both flight stability and flight control. Traditionally, the required control torque for the vehicle can be provided by aerodynamic flight control surfaces, a reaction control system (RCS), or thrust vector control (TVC) that includes both movable jet vanes internal to the exhaust flow or gimbaling of the entire engines. Figure 2 lists the more prominent use of aerodynamic surfaces in our national heritage of large L/V's.

A. Dr. Wernher von Braun's *V–2*

Although today, movable canards, trailing edge (TE) air vanes, movable fins, movable wings, and TE flaps are used on many missiles, our heritage of aerodynamic surface use on large *Saturn* class L/V's begins with Dr. Wernher von Braun's *V–2*. Figure 3 shows the *V–2* with its use of aerodynamic surfaces for flight stability and for flight control (air rudders), and jet vanes internal to the rocket engine exhaust flow (jet rudders) for TVC. The *V–2* was an aerodynamically stable vehicle. The jet vanes provided primary control; however, since they were located close to the single engine's longitudinal axis, they provided only weak roll control. The effect of side winds on the stability fins created rolling

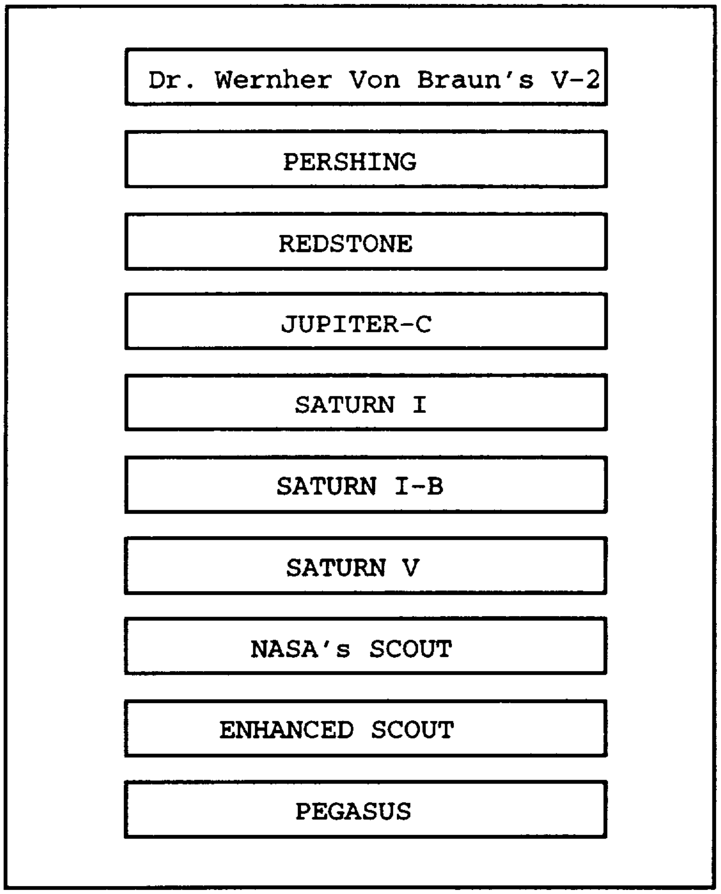
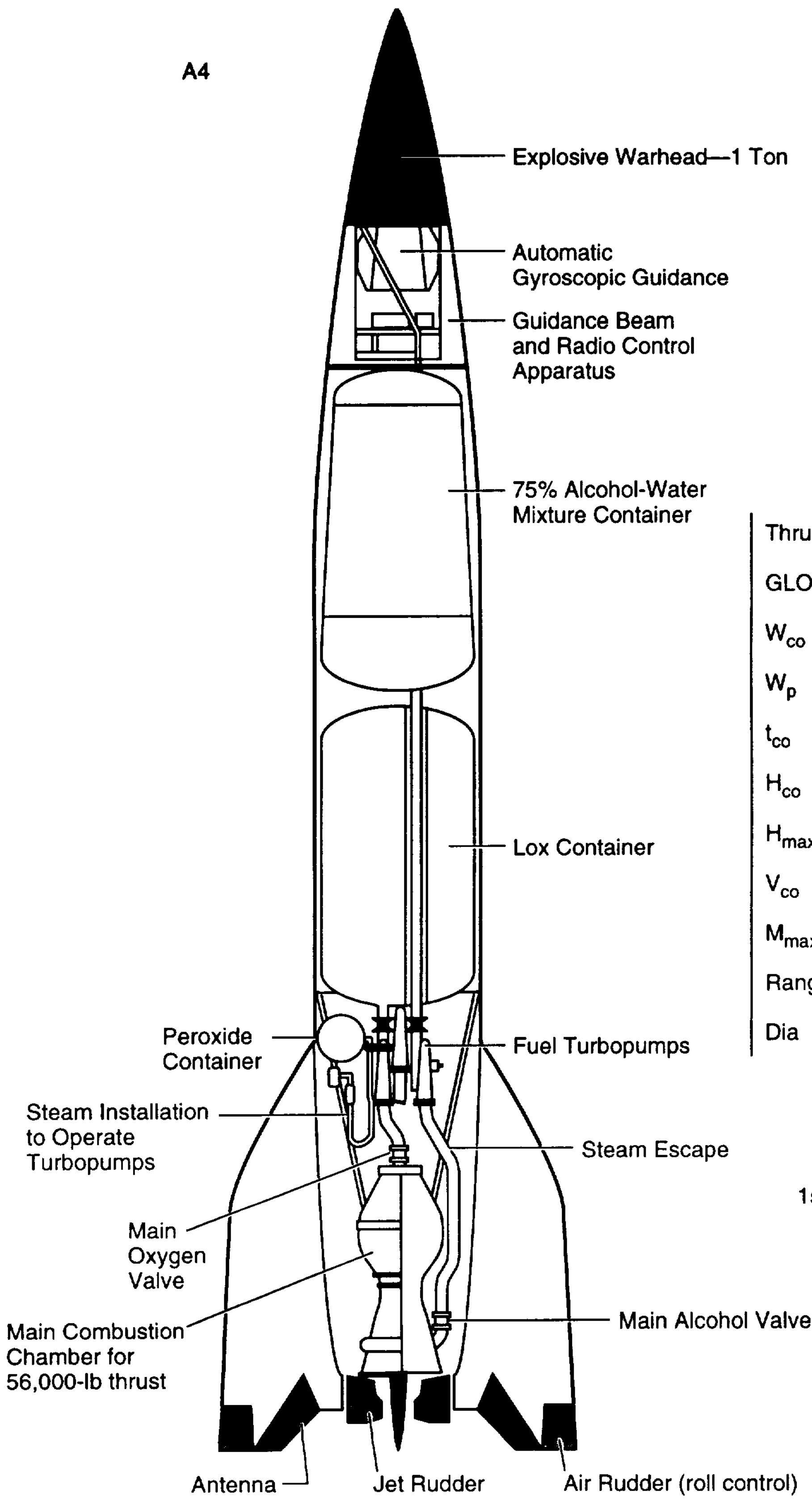


Figure 2. National heritage of launch vehicles using aerodynamic surfaces.

moments due to combined pitch and yaw, which was proportional to the dynamic pressure. The jet vanes could not overcome these moments, therefore, small aerodynamic flight controls were added to the tips of the fins. These flight control surfaces were coupled with the jet vanes and were driven by the same actuators. Figure 3 shows that the alcohol fuel was located forward and the heavier LOX oxidizer was located aft. Figure 4a shows the winged version of the *V–2*, the Wasserfall, and the planforms that were tested subsonically and supersonically. These control surfaces had sharp TE's. Figure 4b shows the winged *V–2* trial planforms. Figure 5 shows the *Hermes II* that was a *V–2* with blunt TE aerodynamic flight controls located on the forward fuselage (pitch control canards) and enlarged aft aerodynamic surfaces for flight stability, since it was the first attempt to fly an unstable L/V. In spite of the enlarged fins, the large ramjet wing rendered the L/V unstable. An accelerometer control was supposed to stabilize the vehicle. That control system worked well in bench tests, but failed in flight because the vehicle vibrations swamped the accelerometer. The vehicle lost control during a White Sands launch and the project was canceled[5,6]



Thrust	26 to
GLOW	13 to
W_{co}	4.8 to
W_p	1 to
t_{co}	65 sec
H_{co}	28 km = 92 kft
H_{max}	70 km = 230 kft
V_{co}	1,700 m/sec = 5,578 ft/sec
M_{max}	5.8
Range	250 km = 155 miles
Dia	1.65 m = 65 inch

1st Successful Shot: 10 – 3 – 42

Figure 3a. *V–2* ballistic missile.

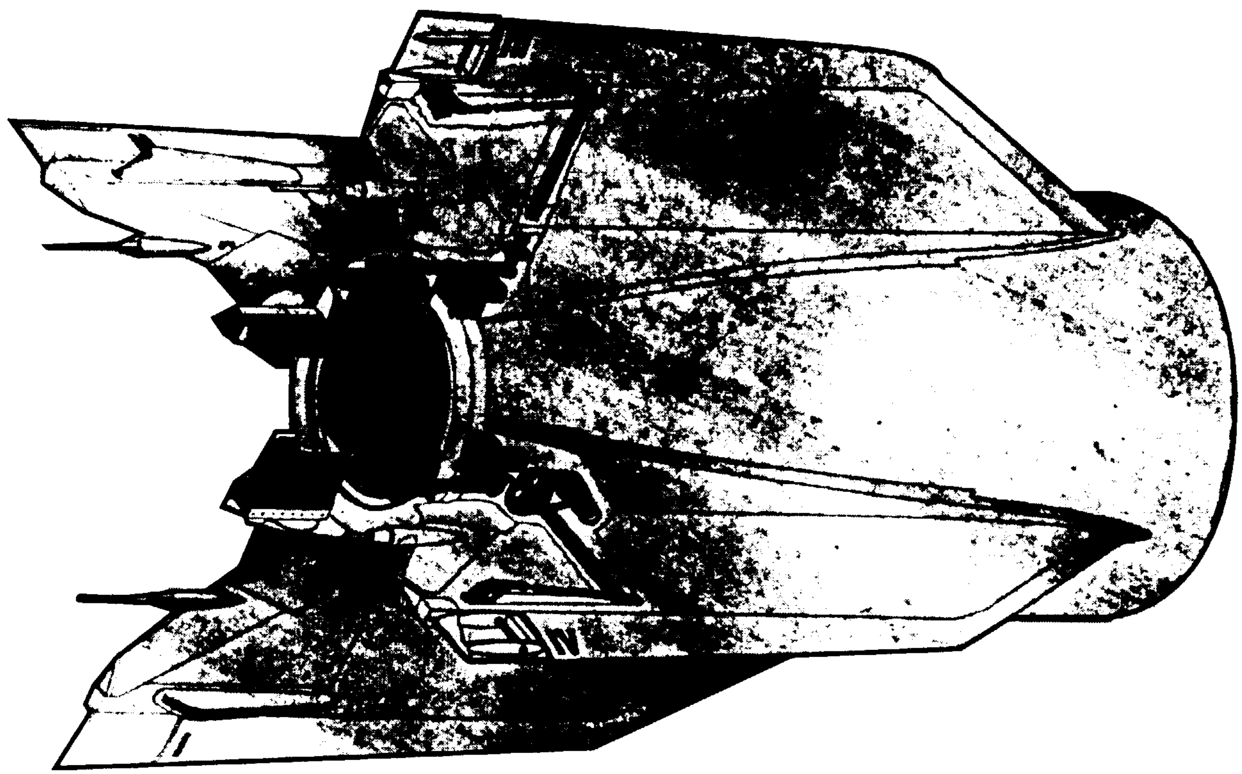


Figure 3b. *V–2* flight controls and jet vanes.

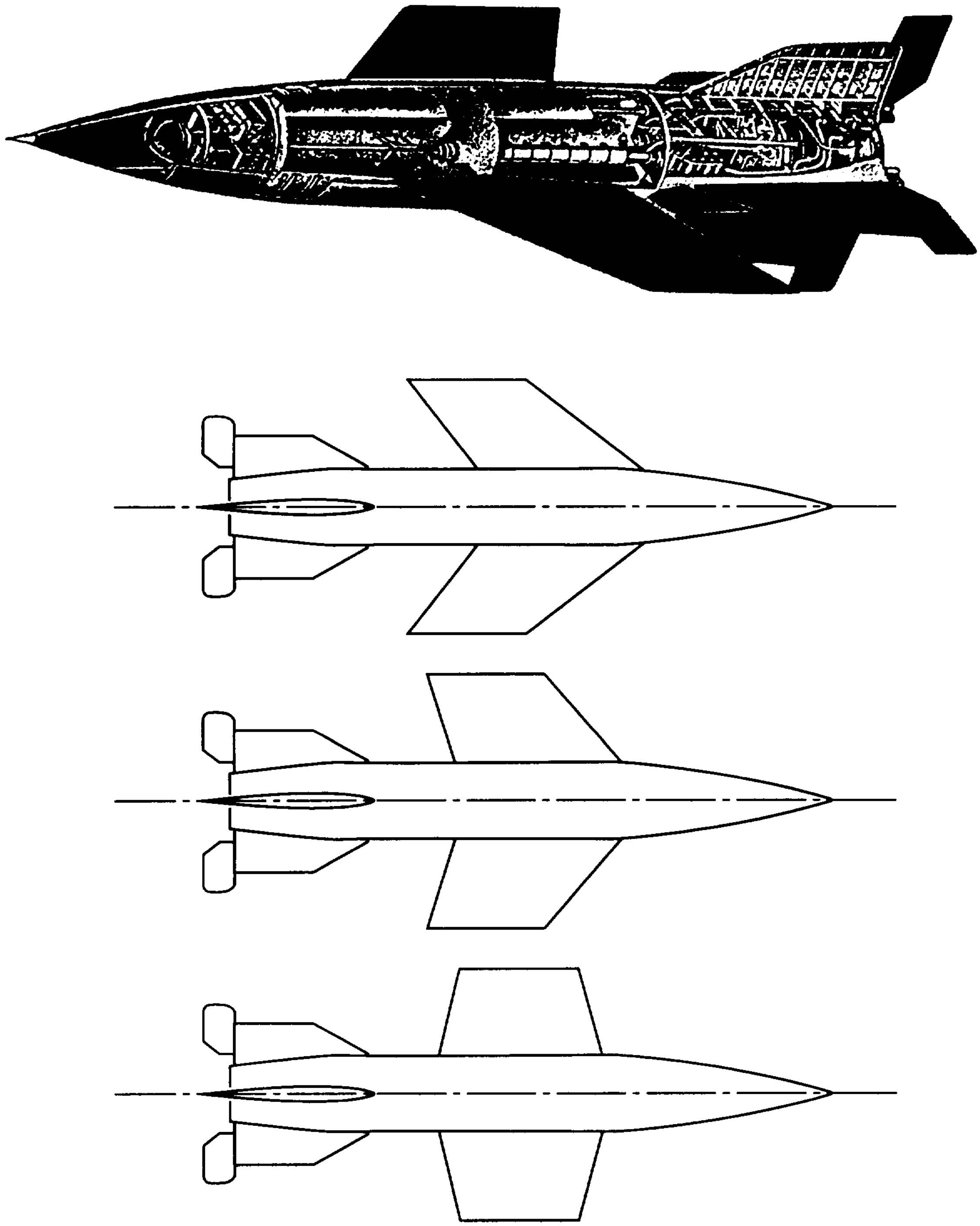


Figure 4a. Winged *V–2* configurations tested in subsonic and supersonic flow.

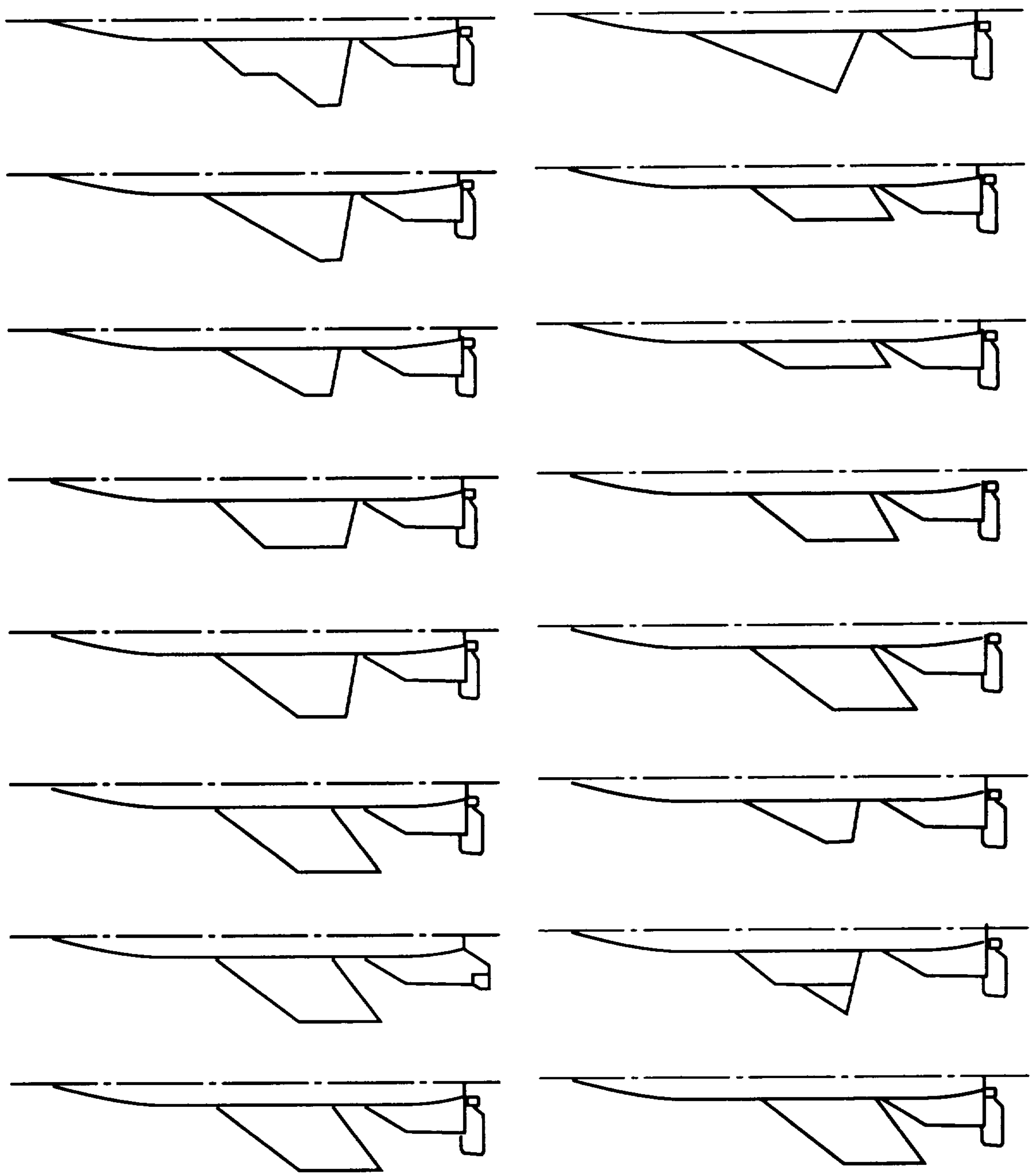


Figure 4b. Winged V–2 trial planforms.

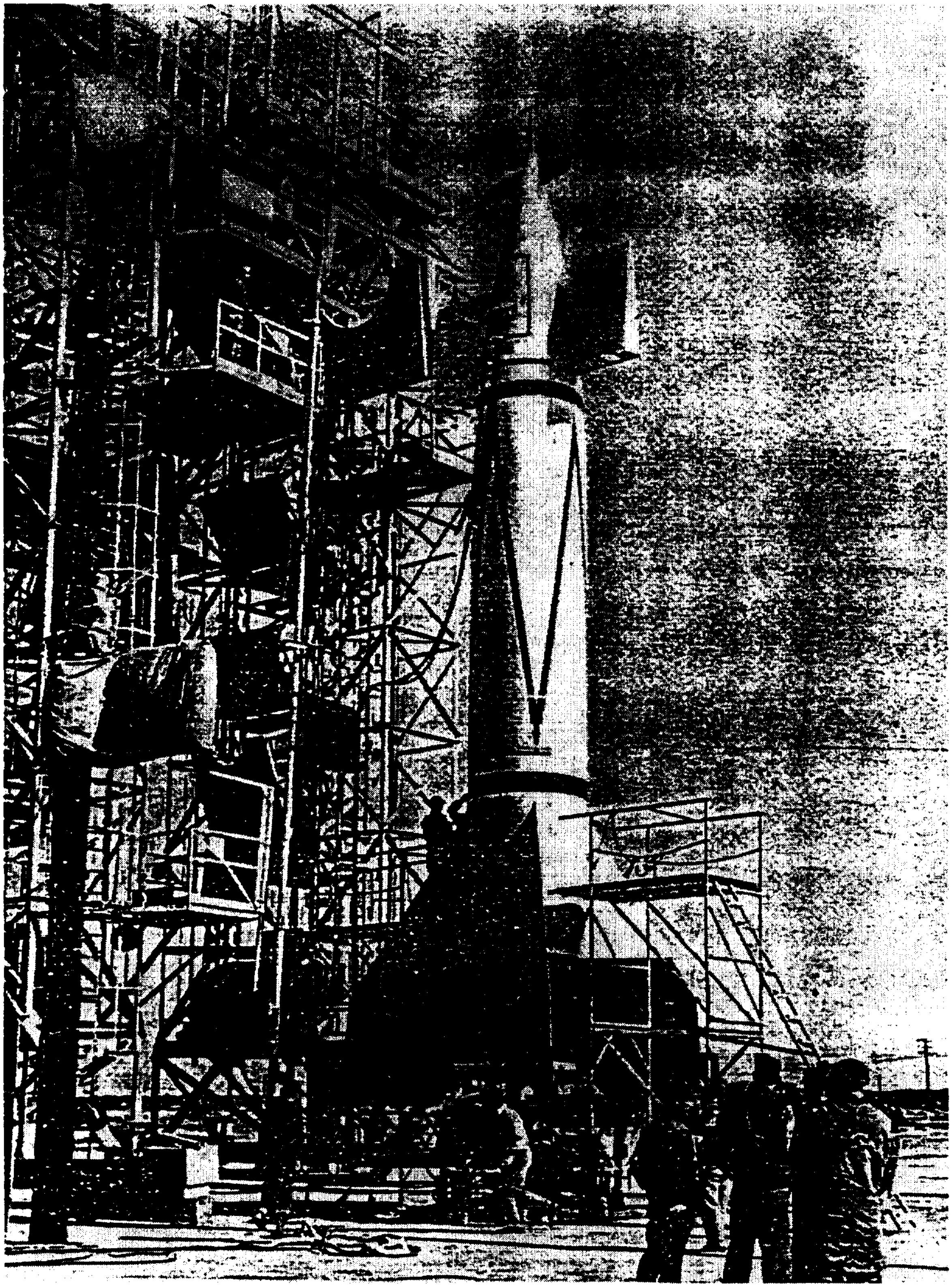
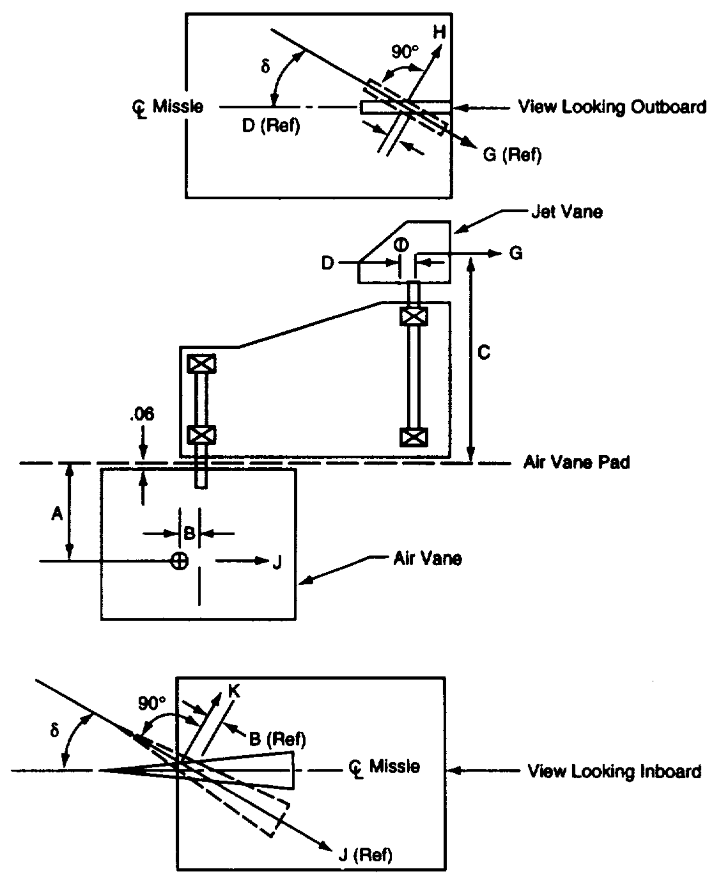


Figure 5. The *Hermes II*.

B. *Pershing*

Many MSFC engineers worked on the *Pershing*, which was a two-stage solid-propellant flight vehicle. Launch weight was 10,229 lb, length was 34.05 ft, diameter was 40 in, and range was 400 nmi. *Pershing* used the solid propellant polybutadiene acrylic acid, giving 20,000 lb of thrust. The *Pershing* was an unusual three-aerodynamic-flight-control design with the flight controls located 120° apart around the exterior fuselage circumference. Also used for flight control were three jet vanes in the exhaust flow.

Figures 6 and 7 show the two sets of three aerodynamic flight controls (air vanes) located forward and aft on each stage of the fuselage, the three aerodynamic surfaces located aft that provided flight stability, and the three jet vanes located internal to the exhaust flow that provided TVC. Each aerodynamic flight control was connected to its respective jet vane and was synchronously deflected proportionally to the error signal input in a one-to-one ratio by a unitized hydraulic package. The unitized hydraulic package consisted of an electric motor pump, accumulator, reservoir, servovalve, actuator, and connecting linkages in one integrated package. The maximum output stall torque of the unitized package was 3,000 in-lb, and the normal maximum operating torque was 2,104 in-lb at a deflection rate of 250° per second.



All Loads (Ultimate)									
Conditions	A	B	C	D	δ	G	H	J	K
Max. HGH & Torque	8.13	±1.112	13.6	±.118	26°	235	1375	132	5150
Max. Tur. Vane Fix.	7.76	4.52	0.0	0	0°	0	0	200	2288

Figure 6. *Pershing* aerodynamic flight controls and loads.

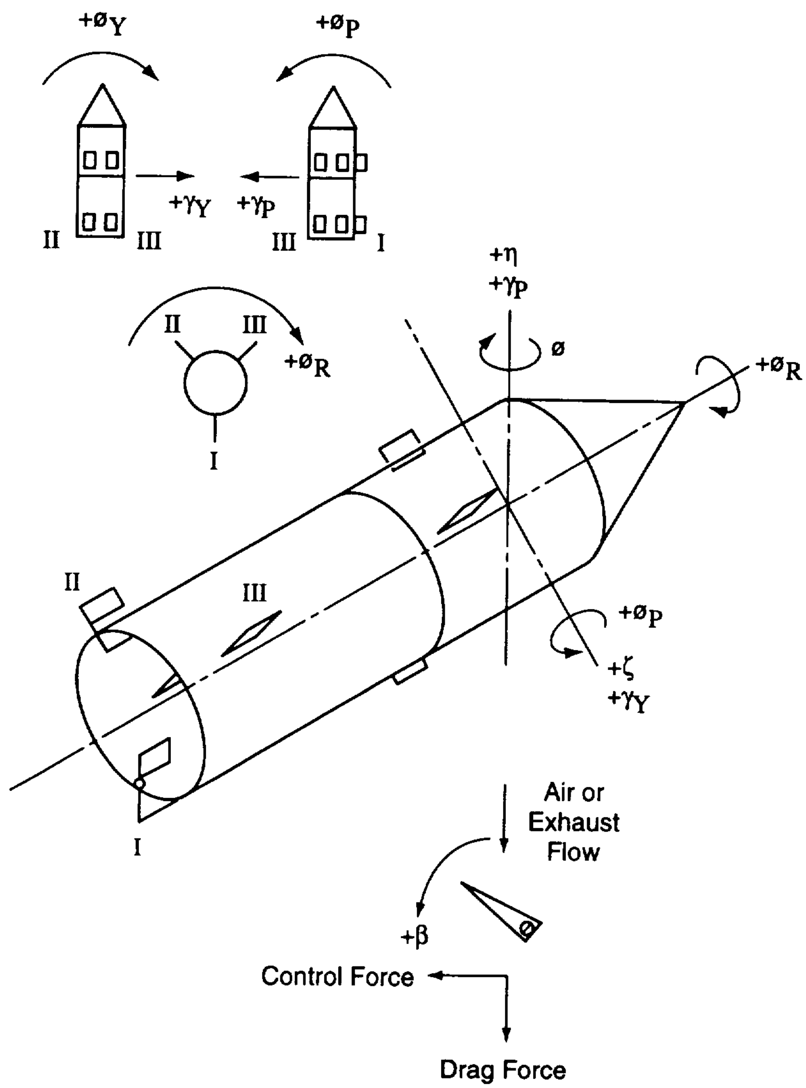


Figure 7. *Pershing* aerodynamic flight control orientation.

The three rectangular aerodynamic flight controls had blunt TE's and were made of plastic laminate with a high-pressure-molded, phenolic leading edge (LE). The three internal jet vanes were made of arc cast alloy of 15-percent molybdenum and 85-percent tungsten by weight. *Pershing* was wind tunnel tested with 8- and 4-percent thick aerodynamic flight controls as well as 10-percent thick biconvex. The 8-percent thick double-wedge aerodynamic flight controls yielded a normal force gradient which was 50 percent higher in the subsonic range and 10 percent higher in the supersonic range than the original 12.8-percent thick aerodynamic flight controls that were used.[7]

C. *Redstone*

Redstone was the first large L/V developed by the United States. It began operation in 1958, had a launch weight of 62,000 lb, a range of 175 mi, and launched the *Mercury* spacecraft. The *Redstone* was a single-stage L/V 69-ft long and 70 inches in diameter. It used liquid propellants, alcohol (19,094 lb) and LOX (25,134 lb), with the heavier LOX located in the aft position. It had a cg travel of 7.3 ft forward (10.5 percent of body length) (fig. 8). The thrust was 78,000 lb from the single bipropellant rocket engine (NAA 75–110).[8]

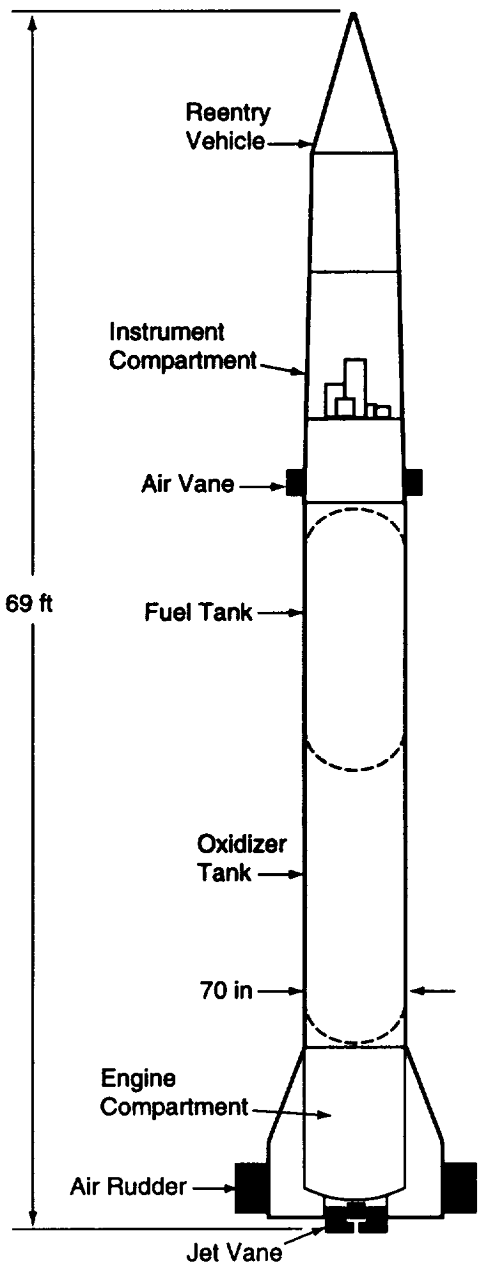


Figure 8. *Redstone* launch vehicle.

The *Redstone* was an aerodynamically stable vehicle throughout its entire flight spectrum of Mach numbers. The jet vanes provided primary control; however, as in the *V–2*, since they were located close to the single engine's longitudinal axis, they provided only weak roll control. To assist the TVC (jet vanes) in overcoming moments, small aerodynamic flight controls were added to the tips of the fins. These were coupled with the TVC and driven by the same actuators. Four carbon vanes were located in the exhaust flow for TVC. Four aerodynamic flight controls were located at equidistant points around the exterior fuselage (figs. 9 and 10). The aerodynamic flight controls had blunt TE's and were constrained to fit the railroad tunnel profiles. The internal controls provided control until the dynamic pressure warranted the use of the aerodynamic flight controls. Cold gas control jets (RCS) were located at the roots of the warhead (forward) flight control surfaces for attitude control during exoatmospheric flight. These were hard coupled to the flight control surfaces.[5]

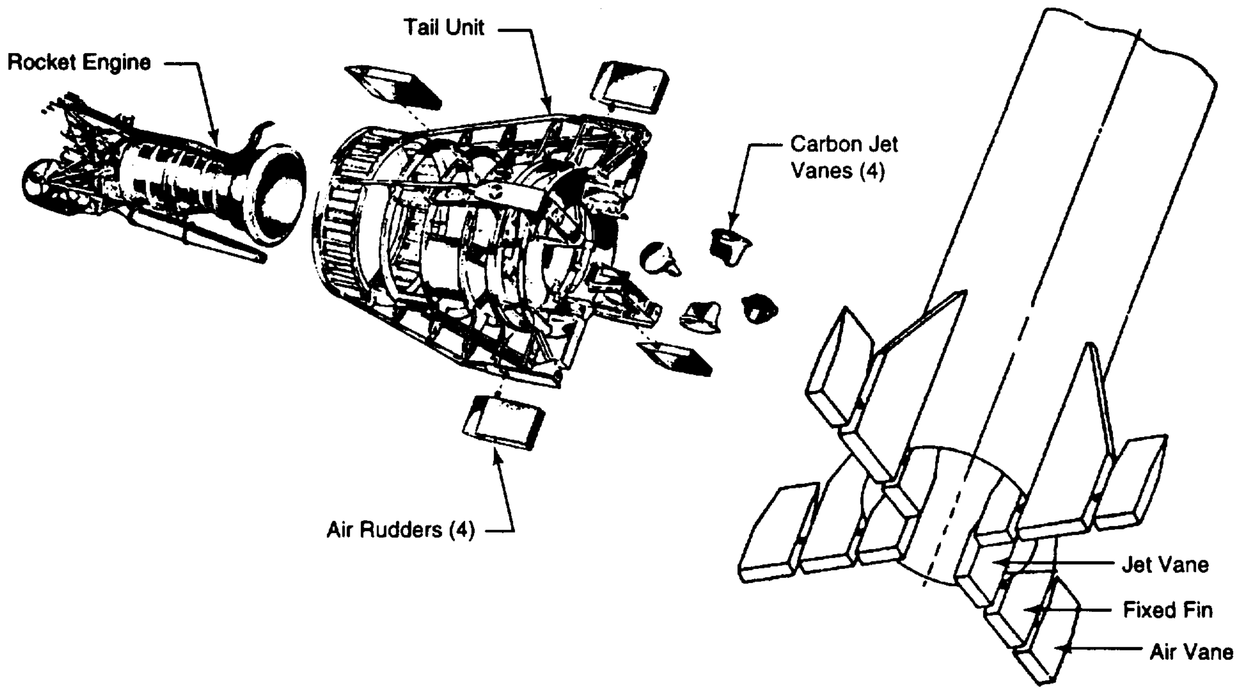


Figure 9. *Redstone* aerodynamic flight controls and jet vanes.

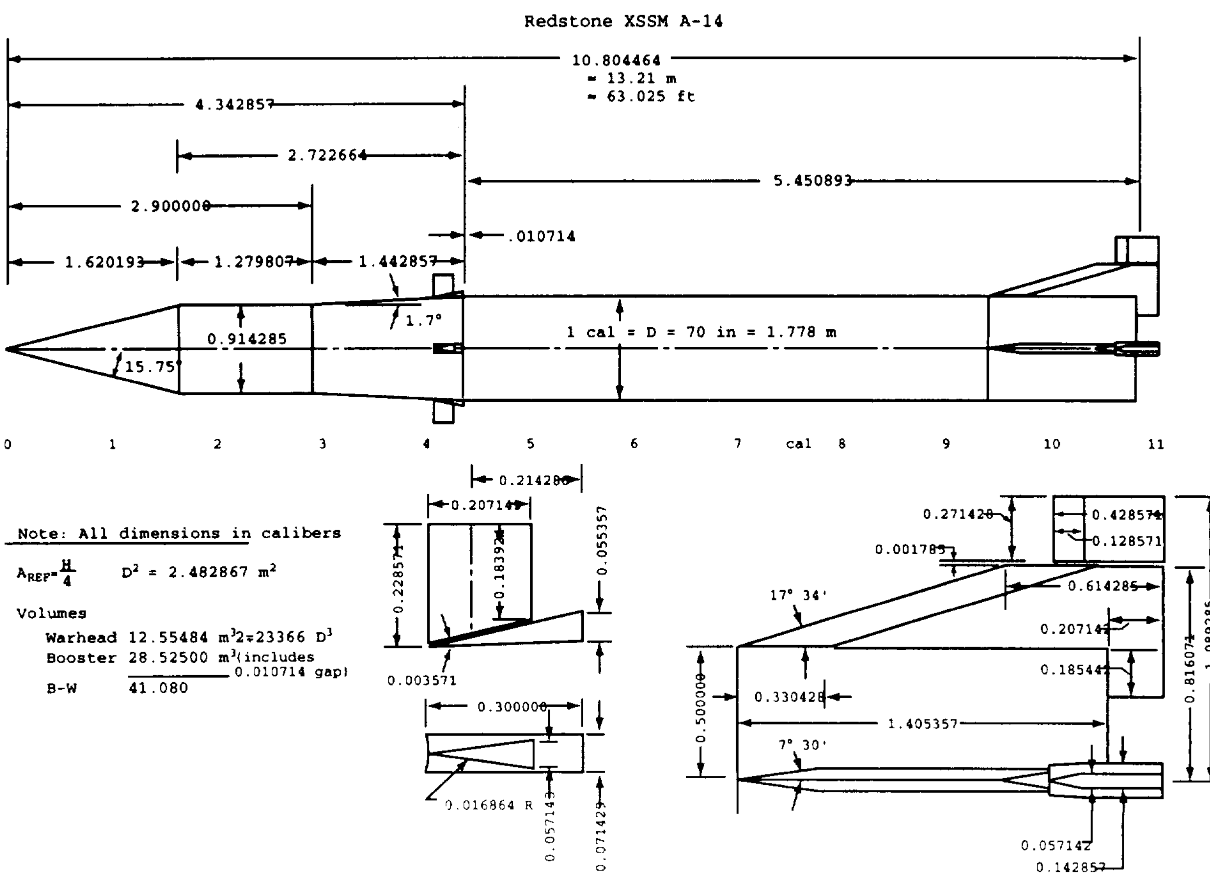


Figure 10. *Redstone* geometry.

D. *Jupiter–C*

The *Jupiter–C*, shown in figure 11, was a three-stage L/V, 67.3-ft long and 70 inches in diameter, with a lift-off weight of 64,610 lb. It also had the LOX tank located aft and employed an elongated *Redstone* as a booster for a nose-cone-cluster assembly. The *Jupiter–C* had two upper stages, developed by the Jet Propulsion Laboratory and carried in a cylindrical tub which could be rotated for stability at a

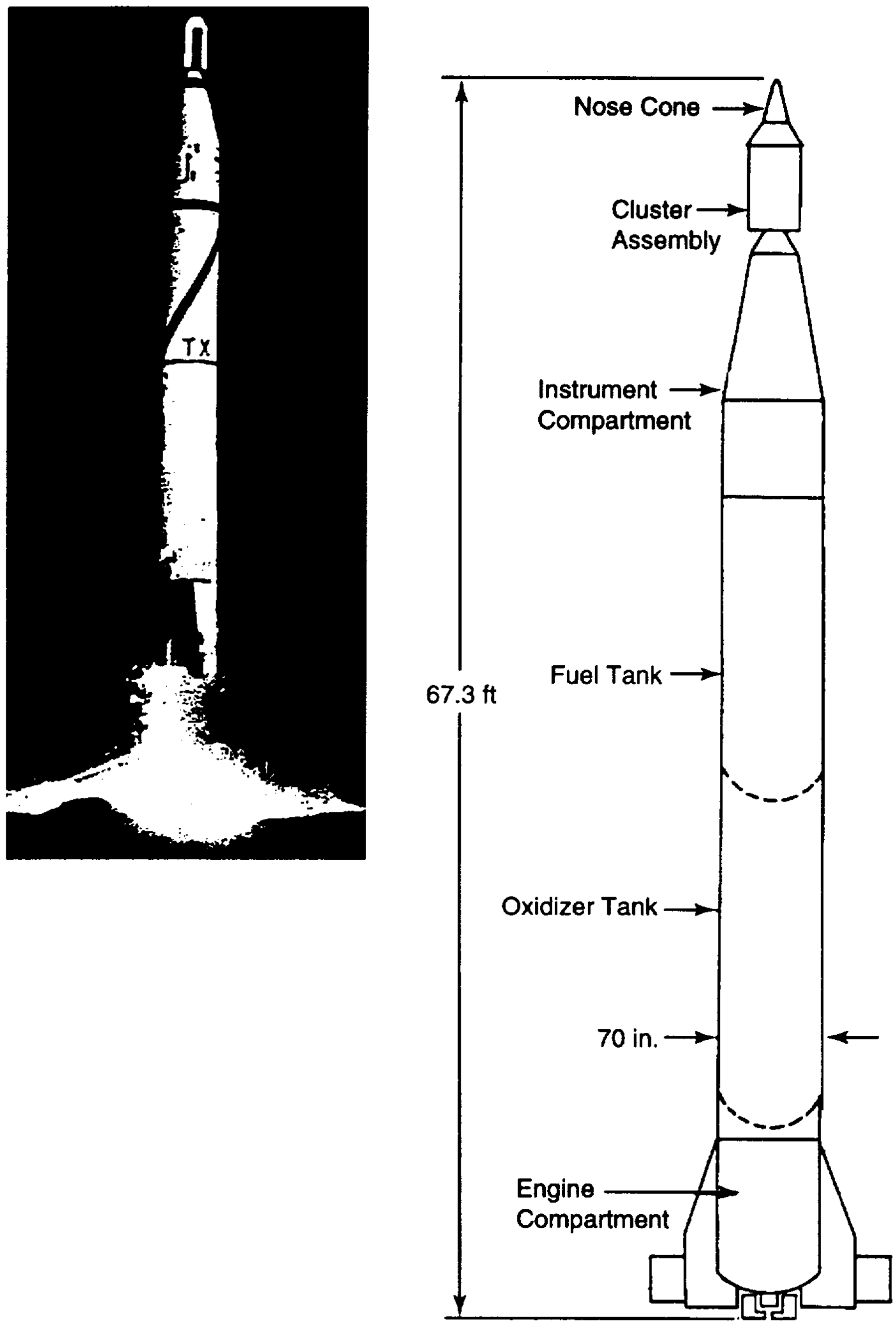


Figure 11. *Jupiter–C.*

spin speed of 380 r/min. The second stage was a cluster of 11 scaled-down, 6-inch, solid propellant *Sergeant* rockets; the third stage was a cluster of three. The nose cone was recovered after water impact and carried a deceleration parachute and a balloon to keep it afloat. In 1957, the first nose-cone recovery was made from a *Jupiter–C* fired to a range of 1,100 nmi. The *Jupiter–C* used one set of aerodynamic flight controls and one set of internal jet vanes the same dimensions as those of the *Redstone*. The control system included four cylindrical angle-of-attack meters that stuck out from the surface of the instrument compartment, two each in the pitch and yaw planes. They compensated for the instability of the basic configuration. The system was successful and reliable. *Jupiter*'s role control was accomplished by using the thrust of the engine's turbine exhaust, discharged through a swiveling pipe knee at the flank of the engine compartment.[5 8]

E. *Saturn* I

The *Saturn* program, which landed us on the Moon, included three basic vehicles, all of which used aerodynamic surfaces: the *Saturn I*, *Saturn I–B*, and *Saturn V*. There were 32 *Saturn* launches in all.

Ten *Saturn I* L/V's were launched by NASA from the Kennedy Space Center (KSC) from 1961 to 1965. The first four flights were a Block I test vehicle without aerodynamic surfaces and inert upper stages. The next six flights began the flight operations and sported a corolla of aerodynamic surfaces at the base, a live second stage, and the Block II designation. The *Saturn I* series of missions performed a multitude of atmospheric tests and meteoroid experiments. The *Saturn I* launched the *Pegasus I*, *Pegasus II*, and *Pegasus III* meteoroid detection satellites.[9]

The *Saturn I* Block II stood 173-ft tall with a diameter of 21.4 ft, had a lift-off weight of 1,138,000 lb, and utilized eight aerodynamic surfaces, four full-size fins and four stub fins. The small fins provided support on the launch pad (figs. 12 and 13). The *Saturn I* used an eight-engine cluster of H–1 engines. The performance of the *Saturn I* Block II L/V's progressed so well that the *Saturn I*'s were declared fully operational by NASA officials three launches earlier than expected.[9]

The original concept for yaw, pitch, and roll called for hinged outer engines: two hinged for pitch, two hinged for yaw, and all four hinged for roll. But application of adequate control forces required fairly high deflection of the engine thrust vector, and the engine contractor (Rocketdyne) complained that this would put excessive stress on the propellant flex lines. Consequently, gimbaling of all four outer engines was adopted, achieving adequate control force with less engine deflection. The gimbal system for mounting engines permitted each engine in the cluster to swivel about for either pitch or yaw control.

In the process of refining the design of the *Saturn I*, two major problems emerged: flight stability and base heating. As with most large L/V's, the *Saturn I* was highly unstable, with the overall cg located aft on the heavy, lower-stage booster, while the center-of-pressure in most flight conditions was forward on the upper stages. The low natural frequency of the elastic vehicle was such that the engines had to be very carefully gimbaled in order not to resonate with the vehicle bending frequencies. The eight-engine cluster caused considerable base heating. To cope with this, a heavy fire wall was installed across the base of the booster near the throat of the engines, with flexible engine skirts to permit gimbaling. For the four fixed center engines, the fuel-rich exhaust gases were piped to the edge of the booster skirt and dumped overboard into a region of high-velocity air flow. In the later vehicles, the exhaust gases were dumped exactly into the "anterstar" created by the four fixed engines. The gimbaled outboard engines required a different approach. The turbopump was fixed to the gimbaled engines; therefore, an overboard duct for them would have required a flexible coupling that could withstand the high temperature of the turbine exhaust gases. Instead, MSFC devised outboard engine attachments called aspirators, which forced the turbine exhaust into hoods on the stub fins as shown in figure 12.[5]

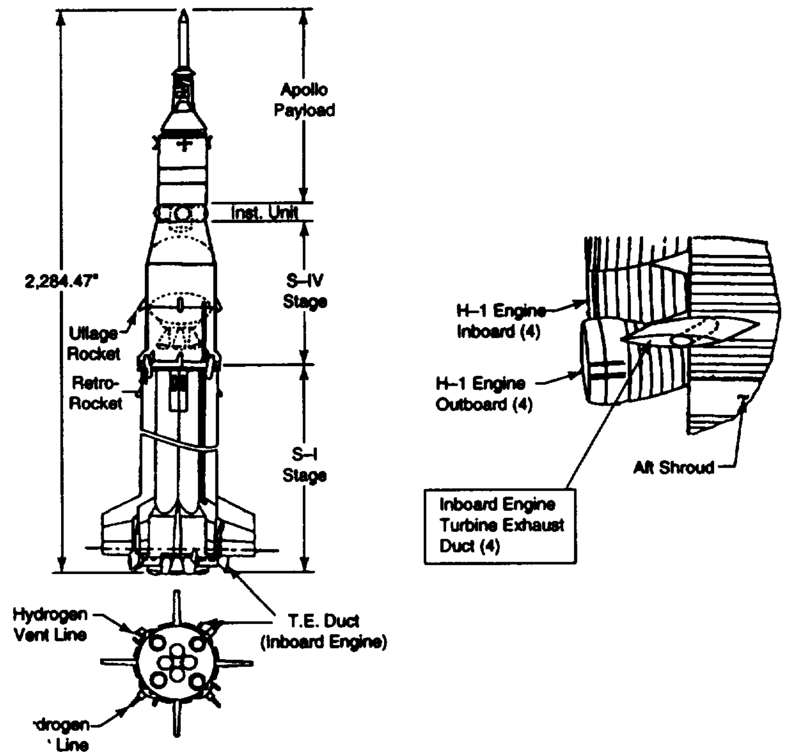


Figure 12. *Saturn I*, Block II.

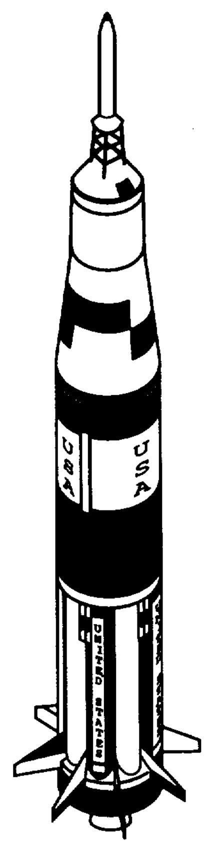


Figure 13. *Saturn I–B*.

F. *Saturn I–B*

Nine flights were made on the *Saturn I–B* between 1966 and 1975 to test *Apollo* program hardware and to launch three crews to the Earth orbiting space station, *Skylab*. The *Saturn I–B* missions included the first manned command/service module (CSM) operations (10 days), seven CMS's total; the lunar module (LM); manned launches to *Sklyab 4* (28 days, 59 days, and 60 days); and the manned rendezvous and docking with the Russian *Soyuz*.

The *Saturn I–B* was a two-stage L/V which stood 225-ft tall, had a 21.4-ft diameter, had a lift-off weight of 1,280,000 lb, and used liquid propellants, LOX and RP–1, providing 1,640,000 lb of thrust. The main body stage was a cluster of nine propellant tanks; four fuel tanks and four LOX tanks arranged alternately around a larger center LOX tank. The *Saturn I–B* also used eight aerodynamic surfaces designed at MSFC, but of a different design than those of the *Saturn I*, since the *Saturn I–B* was a longer and heavier vehicle (figs. 14 through 17).[11]

Eight H–1 engines were used, four stationary inboard and four gimbaled outboard for TVC. The outboard engines were gimbaled by two hydraulic actuators. The upper stage, the S–IVB stage, used a J–2 engine that was gimbaled ±7° for pitch and yaw control and two auxiliary propulsion systems for roll control. The H–1 engines were each canted outward 6°, the outboard engines were also gimbaled in a ±8° square pattern.

The eight aerodynamic surfaces were 10° wedges with blunt TE's of a semimonocoque construction. They provided aerodynamic stability in the midregion of the first stage flight. They were also used to support the L/V on the launch pad prior to ignition and during the holddown period after ignition. A heat shield was attached to the TE of each aerodynamic surface to protect them from engine exhaust. The new design of the *Saturn I–B* aerodynamic surfaces was eight identical surfaces and replaced the *Saturn I*'s four large and four small surfaces. These aerodynamic surfaces had 2.5 times the lift and weighed 1,800 lb less.[10, 11]

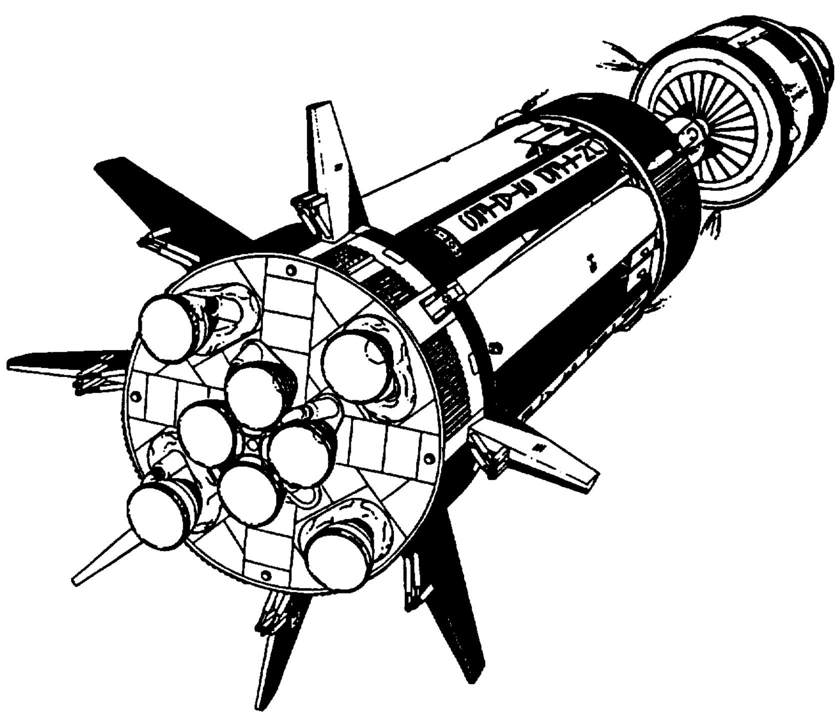


Figure 14. *Saturn I–B* aerodynamic surfaces.

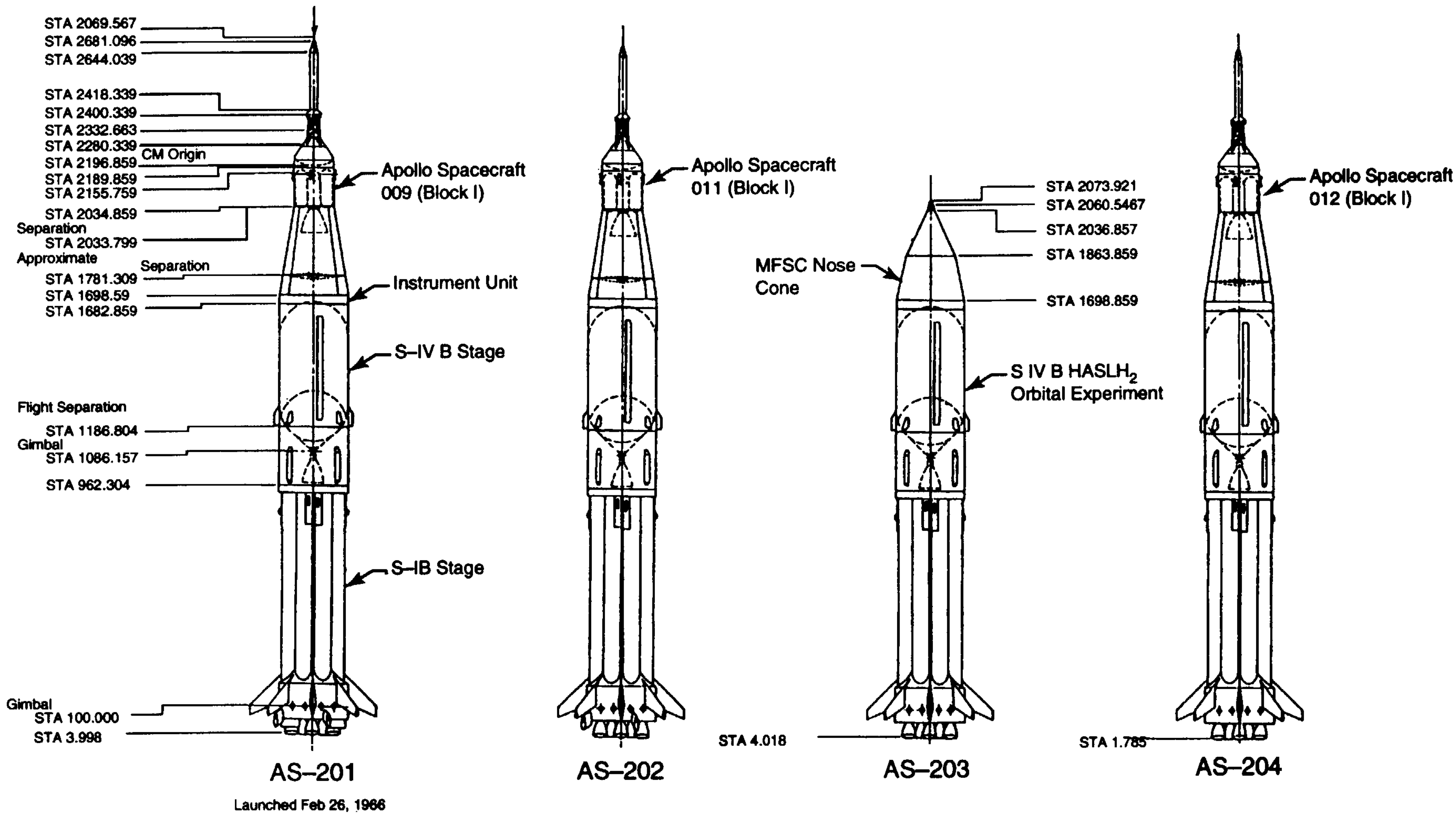


Figure 15. *Saturn I–B* series.

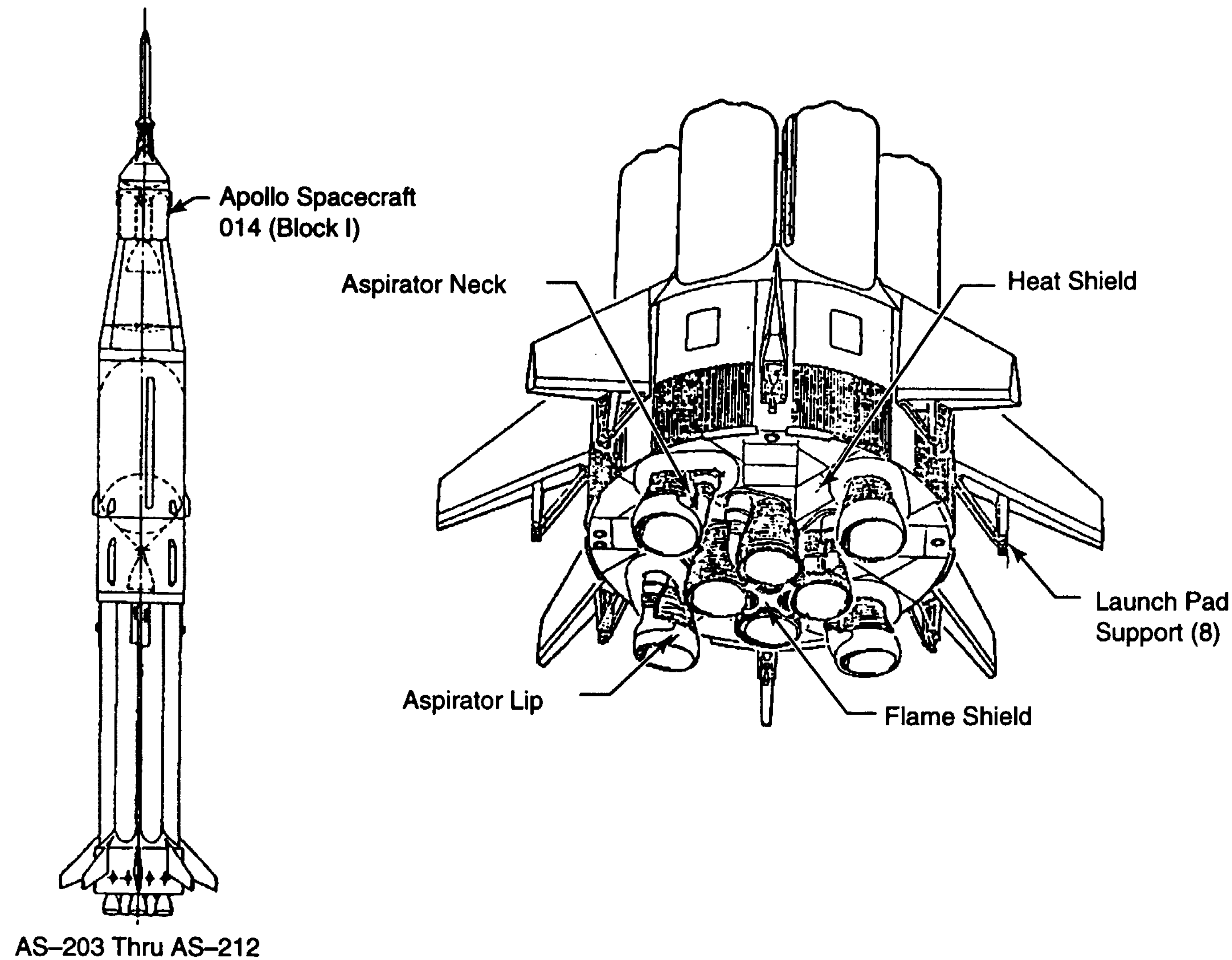


Figure 16. *Saturn I–B* inner engine turbine exhaust (no air vanes).

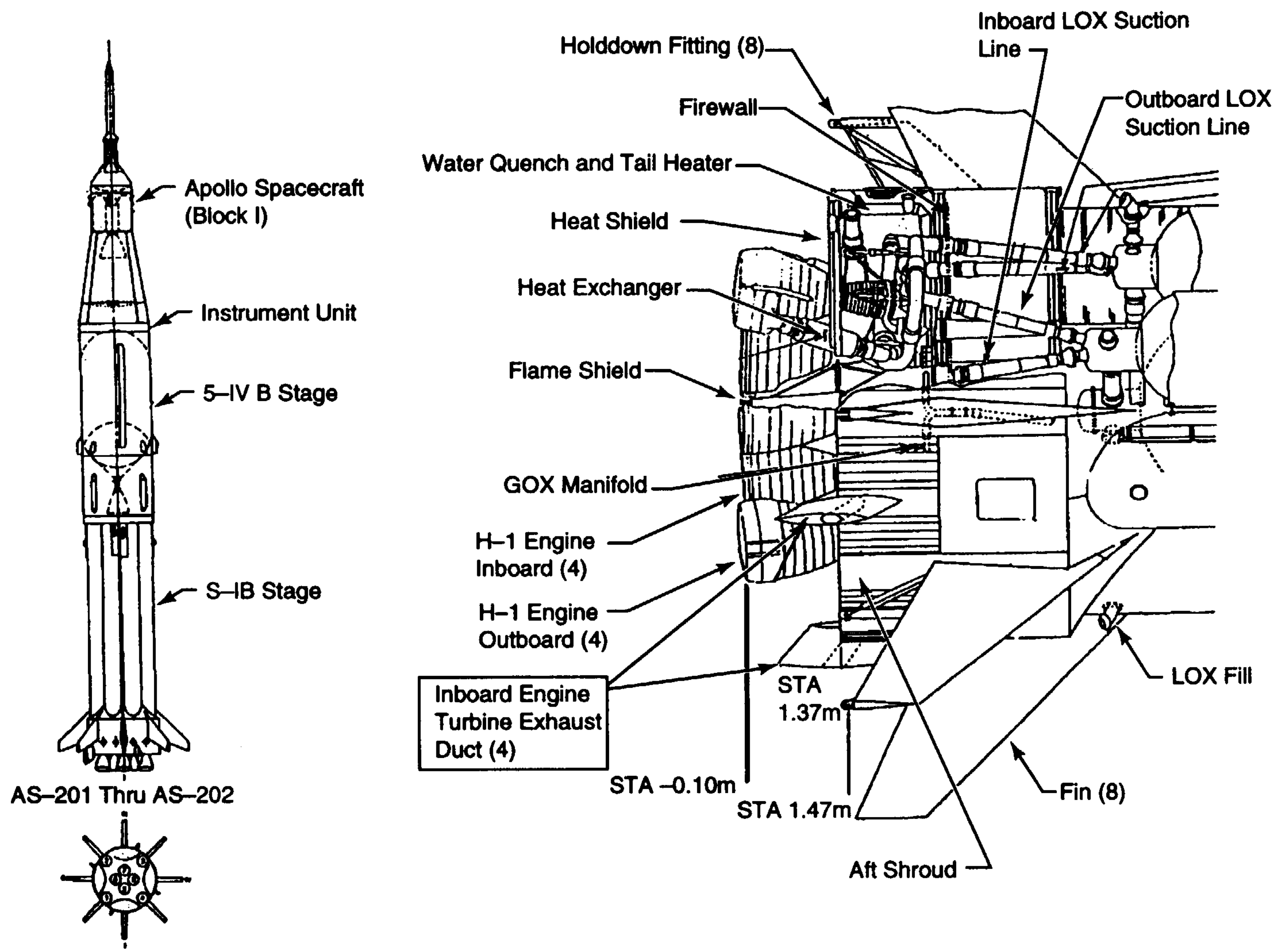


Figure 17. *Saturn I–B* base exhaust configuration.

G. *Saturn V*

Thirteen flights were made on the *Saturn V* between 1967 and 1973. These missions included *Apollo 4* through *Apollo 11*, the first manned lunar orbital flight (20 h in lunar orbit), the first manned CSM/LM orbit rendezvous (10 days), and the *Apollo 11* historic landing on the Moon on July 20, 1969.

Saturn V flights were used for the return of 21 kg of lunar samples from the first landing at the Sea of Tranquillity; the second manned lunar landing in November 1969 and the return of 34 kg from the Ocean of Storms; the third manned lunar landing January 1971 and the return of 43 kg from the Fra Mauro; the fourth manned lunar landing July 1971 and the return of 77 kg from Hadley Appennines; the fifth manned lunar landing April 1972 and the return of 97 kg from Descates; the sixth manned lunar landing December 1972 and the return of 117 kg from Taurus Littrow; and the launch of the *Skylab* space station in May of 1973.[9]

The *Saturn V* stood 365-ft tall, had a diameter of 33 ft, and was a three-stage L/V that incorporated 300 ft^2 of aerodynamic surfaces during all of its missions (figs. 18 and 19). The *Saturn V* used five F–1 engines with the center engine fixed and the four outer engines gimbaled. Lift-off weight was 6,228,000 lb and the total thrust was 7,500,000 lb. Propellants for the first stage were 3,307,855 lb of LOX and 1,426,069 lb of RP–1 (kerosene). The second stage was powered by five J–2 engines, each producing 250,000 lb of thrust. Propellants for the second stage were 821,000 lb of LOX and 158,000 lb of LH_2. The third stage was powered by one J–2 engine. The *Saturn V* payload capability was 250,000 lb.

The first stage of the *Saturn V* included 24 tons of thrust structure for the five F–1 engines, each of 1,500,000 lb of thrust. Four engine shrouds were attached to the thrust structure and fitted over each of the four outboard engines to smooth the air flow. Four aerodynamic surfaces of 75 ft^2 each were used at the base of the first stage for flight stability and were attached to the engine shrouds. The engine shrouds housed the engine actuator support structures and the eight RCS jets, which generated 86,600 lb of force for $^2/_3$ second, to blow off the shrouds and separate the first stage at an altitude of 205,000 ft. The shrouds were 15° cone halves and were constructed of aluminum. The four aerodynamic surfaces were titanium covered.[12]

The gimbaled engines of the five-engine cluster of F–1 engines used a spherical universal joint gimbal consisting of a socket-type bearing with a bonded Teflon™-fiberglass insert that provided a low-friction bearing surface. The first stage engines were gimbaled ±6° in pitch and yaw for TVC. The second-stage outboard engines were gimbaled ±7° in pitch and yaw. The third stage used a single gimbaled J–2 engine for pitch and yaw control and RCS for roll control.

Aerodynamic vibration suppressors can be used to reduce or eliminate wind-induced oscillation on the pad. An unusual aerodynamic surface of note on the *Saturn V* was a set of helical strakes (fig. 20). These were proposed to control the wind-induced oscillations due to vortex shedding as the vehicle was transported to the launch pad and while waiting on the launch pad. When a circular cylindrical structure, such as an L/V on the pad, is exposed to winds, vortices are shed alternately from the sides of the fuselage, which cause alternating lift forces to act upon the sides. Under certain conditions, large oscillations can occur. Increased vehicle slenderness ratio results in increased wind-induced oscillations on the pad due to vortex shedding. Wind tunnel tests have shown that helical strakes not only prevent wind-induced oscillations, but also damp out vibrations from other sources. The helical strakes attached to the *Saturn V* fuselage were among the proposed solutions.[13]

	Saturn I	Saturn IB	Saturn V
Dry Weight	152,000 lbs	159,000 lbs	560,000 lbs
Liftoff Weight	1,138,000 lbs	1,280,000 lbs	6,228,000 lbs

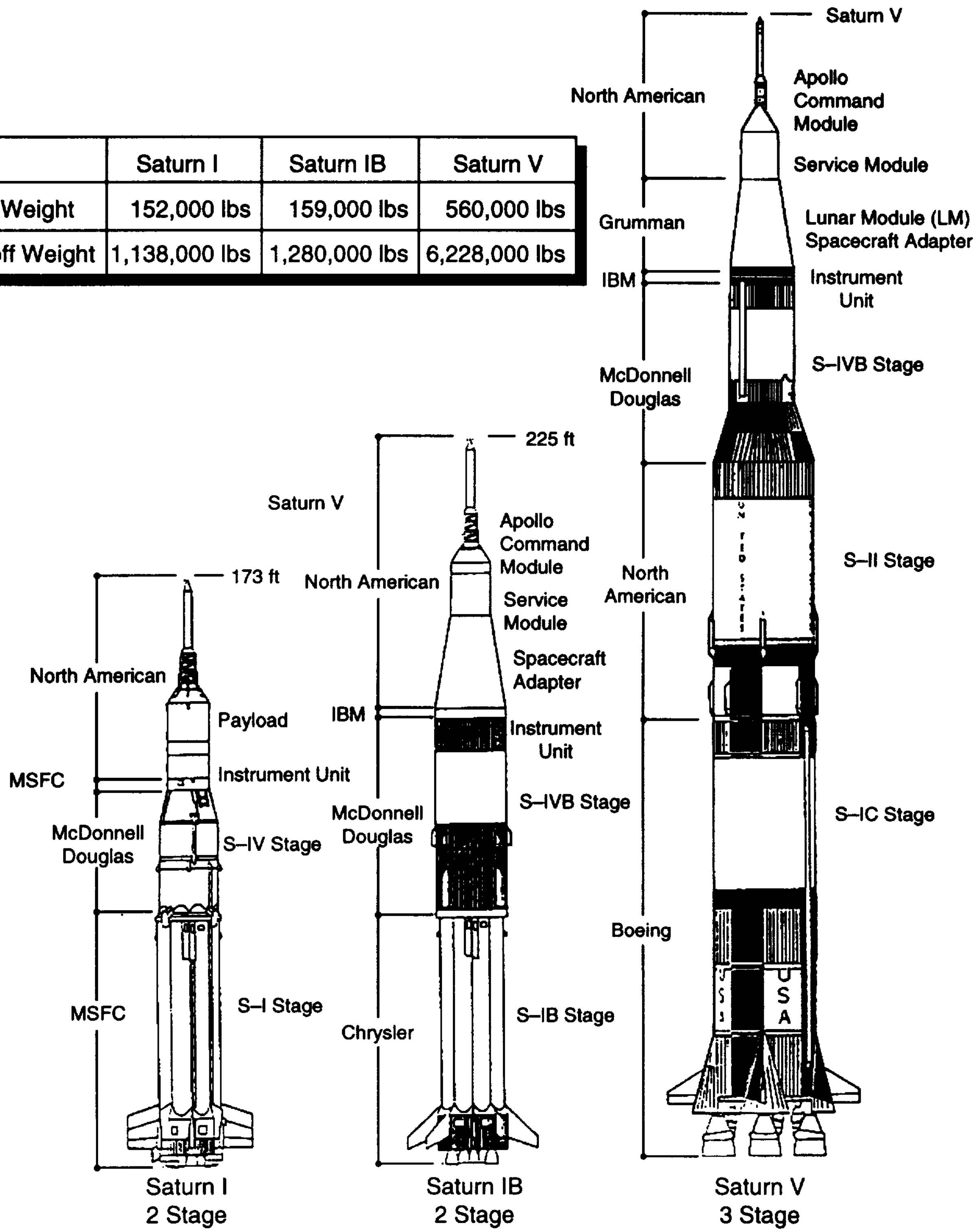


Figure 18. Comparisons of *Saturn* configurations.

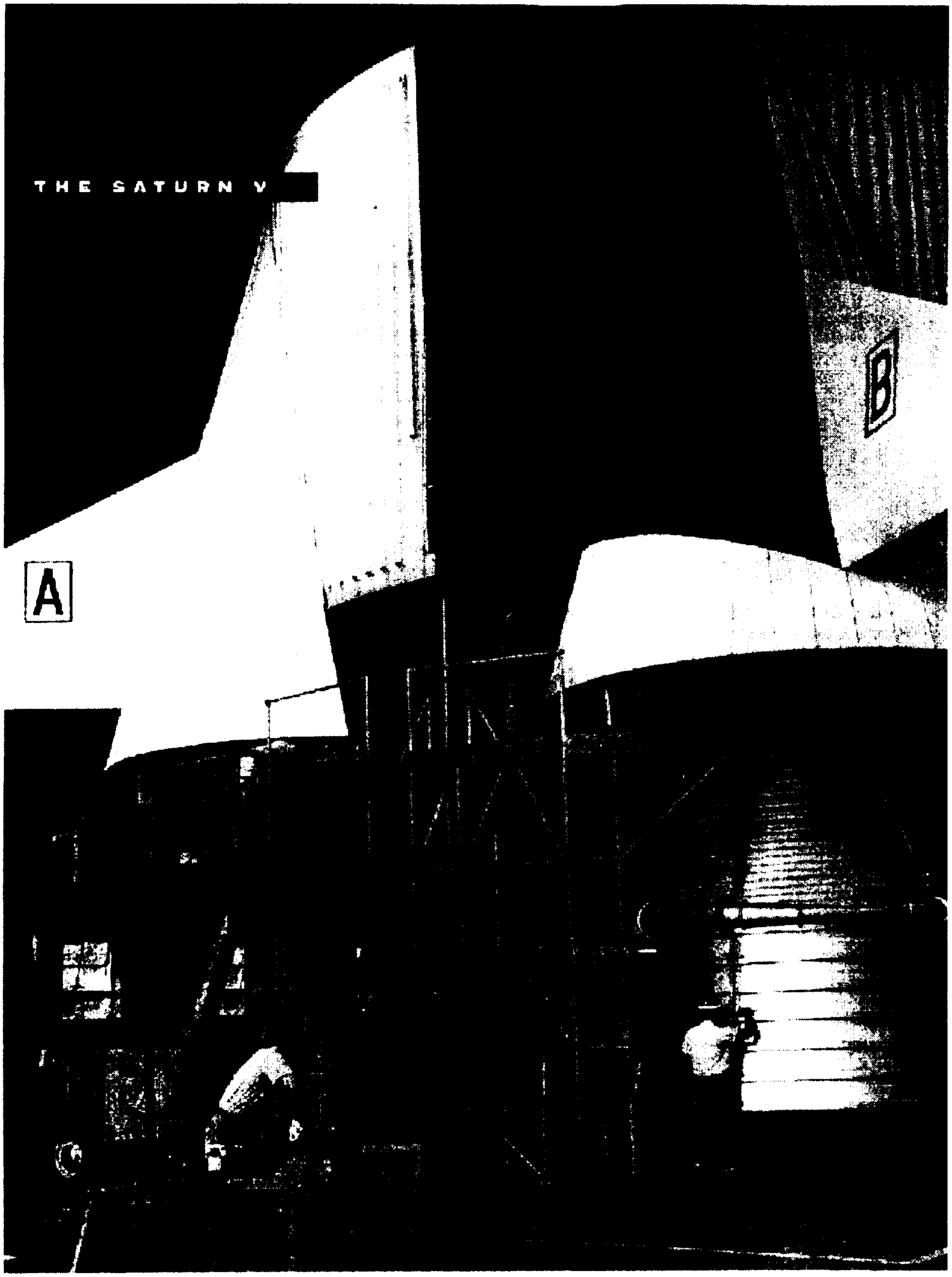


Figure 19. *Saturn V* aerodynamic surfaces.

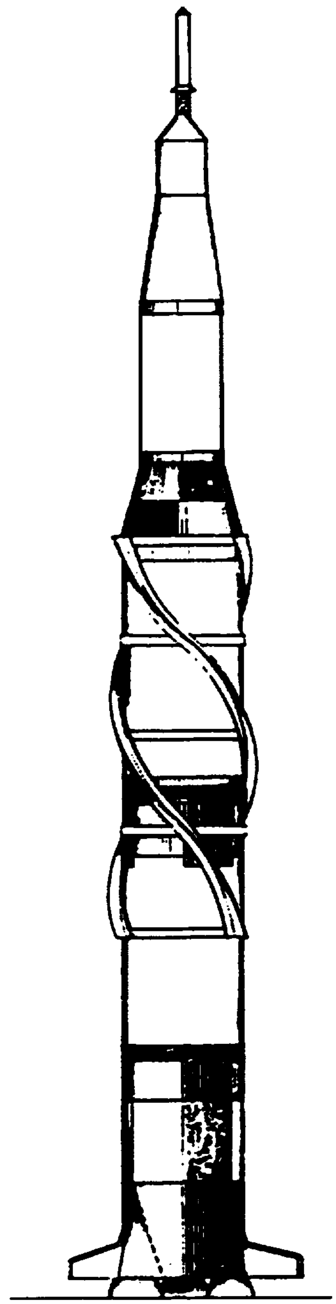


Figure 20. *Saturn V* helical strakes.

H. NASA's *SCOUT*

The *SCOUT* L/V is the first U.S. L/V to use exclusively solid propellant. *SCOUT* is an acronym for solid controlled orbital utility test. It was designed for NASA space probes and orbital and reentry research payloads. Flights began in 1960 and have continued to the present with well over 110 flights. The standard vehicle is a four-stage L/V 75.1 ft in length, 45 inches in diameter, and producing 104.5 klb of thrust. *SCOUT* has launched a variety of payloads from the launch sites of Vandenberg Air Force Base, Wallops Island, and San Marco off the coast of Kenya. Primary operations are low-Earth orbit (LEO) and geosynchronous transfer orbit (GTO) to all inclinations. *SCOUT* launches up to 600 lb of payload to LEO and 120 lb to GTO. There are five *SCOUT* L/V's in use by NASA and the Department of Defense.

SCOUT employs four aerodynamic surfaces for flight stability, and four very small aerodynamic controls at the tips of these (fig. 21). At lift-off, the L/V is aerodynamically stable. A proportional control system, featuring a combination of internal jet vanes and aerodynamic tip flight controls operated by hydraulic servo actuators, is used to control the vehicle throughout the entire first-stage burning period. The jet vanes provide the majority of the control torque during thrusting. The aerodynamic flight controls provide all the control after burnout of the first stage. The second and third stages use RCS for control. The second stage uses four 500-lb and four 40-lb thrusters. The third stage uses four 60-lb and four 14-lb thrusters. The fourth stage uses a combination of four impulse spin motors to spin stabilize the payload.[14]

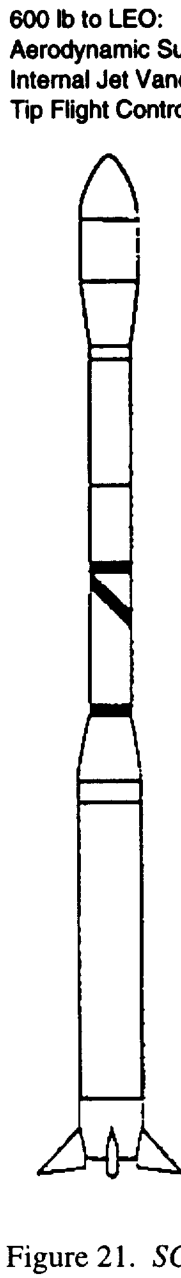


Figure 21. *SCOUT*.

I. *Enhanced SCOUT*

The *Enhanced SCOUT* is 75.1 ft in length, 45 inches in diameter, uses two strap-on solid rockets of 42 inches in diameter each, and generates 397.9 klb of thrust (fig. 22). The *Enhanced SCOUT* takes 1,160 lb of payload to LEO or 240 lb to GTO. The *Enhanced SCOUT* also uses four triangular aerodynamic surfaces and four very small triangular tip controls, along with internal jet vanes. In development beyond the *Enhanced SCOUT* is the *SCOUT II*, which will use a higher energy fourth stage. The *SCOUT II* will provide up to 12 percent more performance for a low polar orbit than the *Enhanced SCOUT* and may add two additional strap-ons. The *SCOUT II* will also use four aerodynamic surfaces for flight stability and four tip flight controls and internal jet vanes for control.[14]

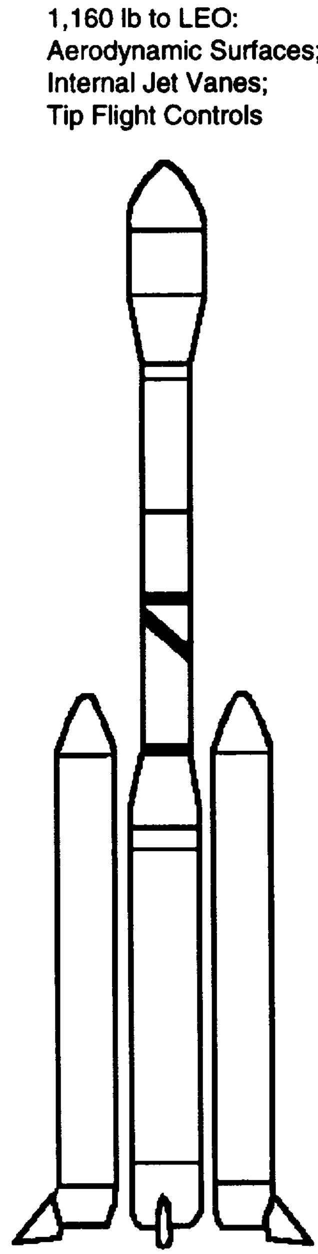
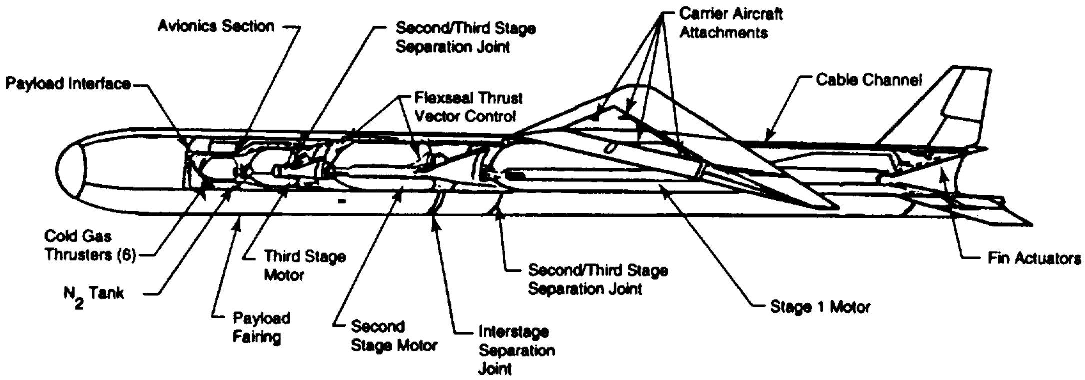


Figure 22. *Enhanced SCOUT.*

J. *Pegasus*

Pegasus is a three-stage, solid-propellant, air-launched vehicle capable of launching 1,000 lb to LEO. It is launched from an altitude of 44,000 ft at Mach 0.8. *Pegasus* flights began in 1990. It uses a 20-ft span, triangular, double-wedge airfoil wing (Scaled Composites, Inc.) with a LE sweep of 45°. Both aerodynamic surfaces for flight stability and aerodynamic flight controls are used (fig. 23).[14] The first-stage thrust is 109,420 lb, second-stage thrust is 27,600 lb, and third-stage thrust is 7,770 lb. The first stage uses three hydraulic aerodynamic flight controls for pitch and yaw and three aerodynamic flight controls for roll control. The second and third stages use RCS for flight control.



Pegasus	
Length	50.9 ft (15.5 m)
Gross Mass	42,000 lb (19.000 kg)
Thrust at Liftoff	109,400 lb (486.600 N)

Figure 23. *Pegasus.*

The aerodynamic surfaces and aerodynamic flight controls are fabricated of lightweight graphite composite material. Thermal protection of the wing during hypervelocity is achieved by selectively applied additional layers of graphite composite, which are allowed to char and ablate. The flight control LE's are protected with Korotherm™, while artificial cork is used over less critical areas of the wing and fuselage.

The flight control actuators are electromechanical and part of the "smart" actuator and sensor assemblies. Microprocessors manage the actuators and include self-test and health reporting via telemetry. The *Pegasus* wing and set of aerodynamic flight controls are mounted on the first stage. They aerodynamically provide pitch, yaw, and roll control during the first-stage powered flight and the coast period after burnout. Maximum dynamic pressure is 1,000 lb/ft^2, after which the first-stage burnout occurs at 200,000 ft of altitude and Mach 8.1. Second-stage ignition is at 213,000 ft.[14]

The second and third stages use engine nozzle gimbaling and RCS for control. The RCS can also provide up to 1,000 lb-in-s impulse for payload spin-up. *Pegasus* is launched from the same *B–52* aircraft that performed the numerous *X–15* drops. *Pegasus* is similar in size and shape to the *X–15*.

III. THE *X–15* AND *SATURN* SERIES AERODYNAMIC SURFACE DESIGN CONCEPTS

NASA and MSFC have compiled much knowledge during the *Saturn* era. In the aerospace field today, the lessons learned, the programs, and the design concepts of two very significant flight series, the 199 flights of the *X–15* and the 32 flights of the *Saturn*, are being reevaluated.[16] These programs may hold the keys to many of our future L/V programs and designs.

A. The *X–15*

As mentioned previously, the current-day *Pegasus* is similar in size and shape to the *X–15* and is launched from the very same *B–52* aircraft that performed numerous *X–15* drops. The *X–15* flew to an altitude of 354,200 ft, reached Mach 6.7, and made almost 200 flights over a 9-year period. In the words of Neil Armstrong: "The *X–15* rocket research vehicle is a large ring of keys for unlocking the mysteries of future flight."[15] The *X–15* was part L/V, with an RCS and a thermal protection system, and was designed to explore the hypersonic speed regime and near-space environment. It was actually the second stage of a two-stage system. The first-stage was the *B–52* that released it at an altitude of 45,000 ft and Mach 0.8. (The Dyna-Soar *X–20* follow-on was to reach Mach 18 but was canceled.) Both NASA Langley Research Center (LaRC) and NASA Dryden Research Facility have published ample documentation of the *X–15* being an important source of hypersonic stability and control data, and also of the lessons learned from the *X–15* program having direct applicability to our current and future launch vehicle programs.[16]

The *X–15* rocket engine had almost as much thrust as the *Redstone* L/V and was also comparable in performance to the *Redstone*. The *X–15* had 60,000 lb of thrust and the *Redstone* had 76,000 lb. The *Redstone* reached a maximum speed of 5,180 mi/h and 116 mi altitude on the *Mercury* flight, while the *X–15* achieved 4,520 mi/h and 67 mi altitude. (The *X–15* theoretically had the performance to reach 100-mi altitudes but could not safely reenter from there.) The maximum dynamic pressure recorded was 2,027 lb/ft^2 and the maximum temperature measured on the vehicle was 1,323 °F. The *X–15* used an XLR99 rocket engine and 33,000 lb of propellants (1,000 gal of LOX and 1,400 gal of anhydrous ammonia). The outer skin of the fuselage was the exterior wall of the propellant tanks. Figure 24 shows the configuration of the three *X–15*'s that were built and figure 25[15] shows the proposed delta-wing *X–15* that is similar to current reusable L/V configurations.

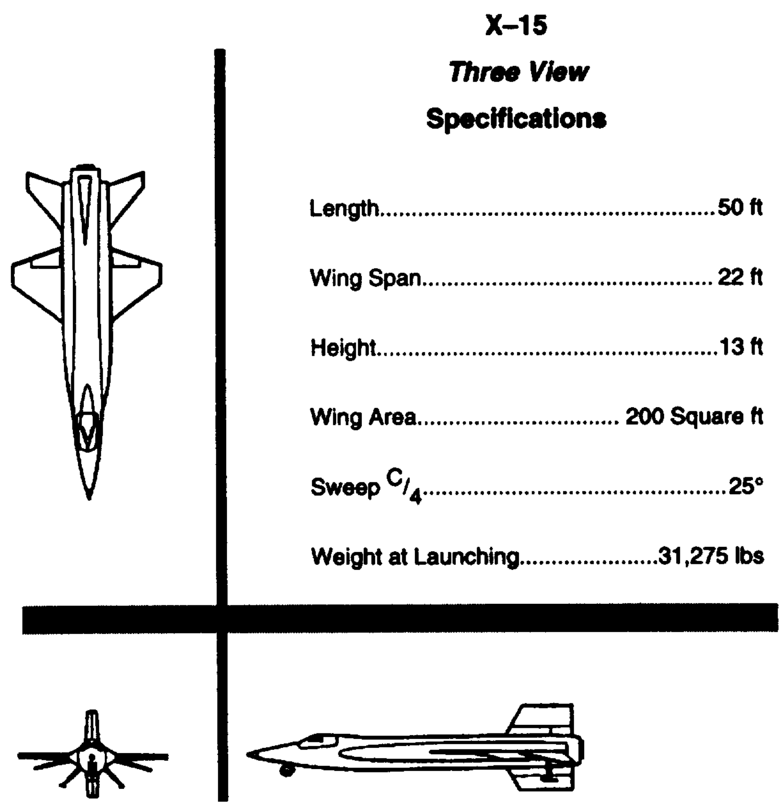


Figure 24. The *X–15*.

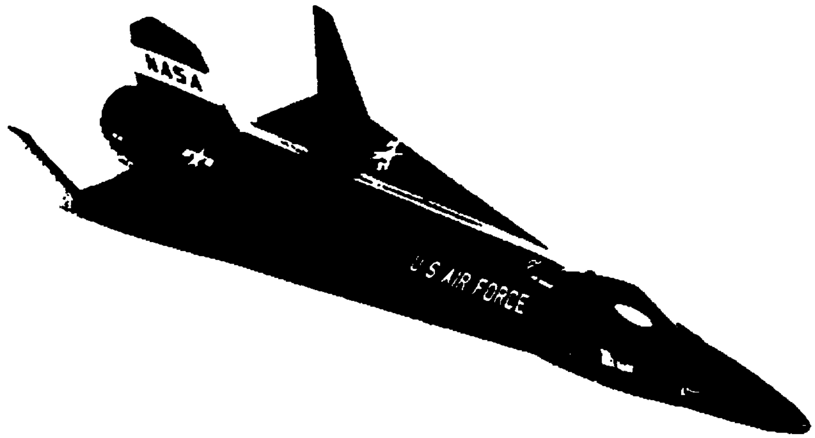


Figure 25. Delta-winged *X–15*.

The empennage was unusual, with four aerodynamic flight control surfaces that provided both stability and control, two all-movable NACA 66–005 airfoil horizontal stabilizers with 15° anhedral that could be operated differentially, and two 10° wedge airfoil section vertical stabilizer-rudders, one above and one below, with 55 percent for the dorsal fin and 45 percent for the ventral fin. The lower rudder extended below the landing gear and had to be jettisoned before landing. The vertical wedge-shaped surfaces had blunt TE's. This was a solution to the hypersonic directional stability problems. (Chuck Yeager in the *X–1* program found that the all-movable horizontal tail was needed to fly through Mach 1.) The *X–15* empennage resembled cruciform missile fins and also the empennage of the experimental L/V of this research. Wind tunnel test data are available for the *X–15* horizontal stabilizer deflections without its trapezoidal wing and are compared to the L/V of this research in a forthcoming publication. The flight control surfaces were hydraulically actuated. No ailerons were used on the small wings. Roll control was achieved by differential deflection of the two horizontal stabilizers. There were TE flaps on the wing and four speed brake segments located on the rear portions of the upper and lower vertical fins. They opened in a V shape to produce drag and some directional control.

The control system was a high-gain, high-authority, stability augmentation system (SAS) with advanced command augmentation. (A notch filter was chosen to stabilize the SAS loop for the 12- to 14-Hz resonance of the horizontal surface.) The vehicle was neutrally stable in ballistic flight. RCS jets were located in the nose and on the stub wings. Pitch and yaw RCS were located behind the nose sensor. There were two nozzles on the top of the nose pointing up and two on the bottom pointing down. Two yaw jets were located on each side of the nose. The roll jets were located in the outboard wing panels, two on each wing.

The original vehicle configuration suffered at high angle-of-attack (α) at hypersonic speeds from loss of effectiveness of the upper vertical stabilizer and a large increase in effectiveness of the lower vertical stabilizer, leading to an undesirable high anhedral effect. The large ventral fin was necessary for controllability to cope with thrust misalignments. The vehicle could be controlled without SAS at high α in spite of the anhedral, as shown in figure 26.[17] Thus, the symmetrical tail was used. In flight, it was found unflyable at $\alpha > 8°$ without dampers due to the influence of secondary aerodynamic effects, such as trim on the stability derivatives, effects which were not included in the simulation. Space attitude control along with threshold aerodynamics were demonstrated. Transitions from RCS to aerodynamic controls were made, and a control mode in which the two systems were blended was developed. The *X–15–3* had integrated aerodynamic controls and RCS, and automated three-axis stabilization.[7]

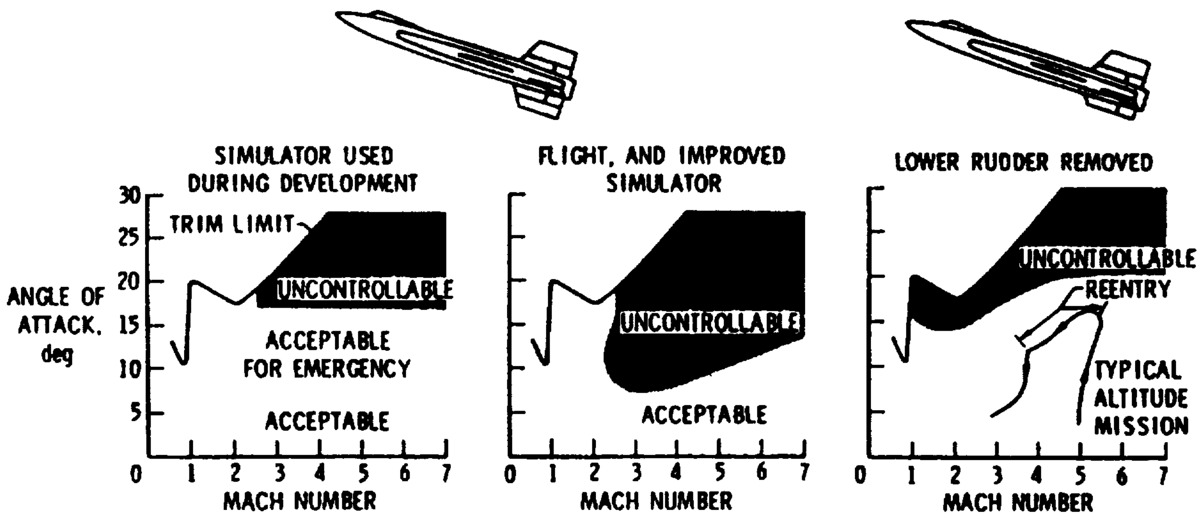


Figure 26. Handling characteristics of *X–15* with dampers inoperative.

A great many different configurations of the *X–15* aerodynamic surfaces and flight controls were wind tunnel tested at NASA LaRC. The airfoil sections tested included symmetrical double wedges with thickness ratios of 5, 10, and 15 percent (Jordan, G.H., "*X–15* Project," NASA LaRC, 1961). The taper ratios were varied on the all-movable horizontal stabilizers, which had a sweep angle of 45°. Three different designs were wind tunnel tested for flutter at the Mach ranges of 0.72 to 1.32 and 0.79 to 1.47. Full and semispan models were tested (fig. 27), one of which used a 1-percent chord thickness at the TE. Required flutter margins were met.[18]

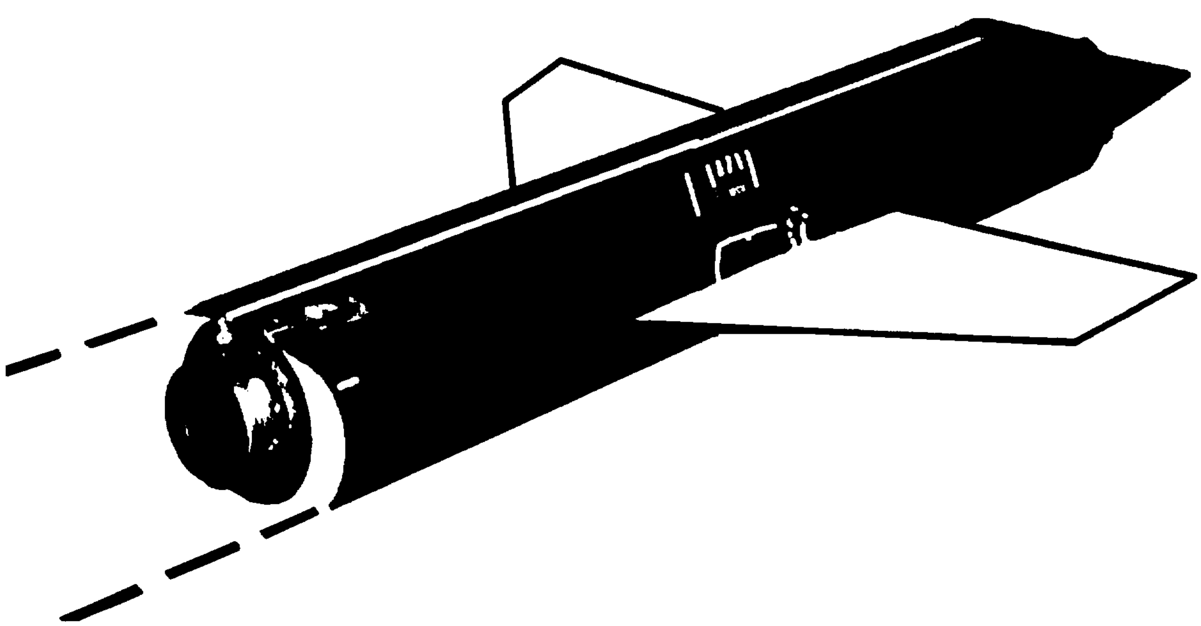
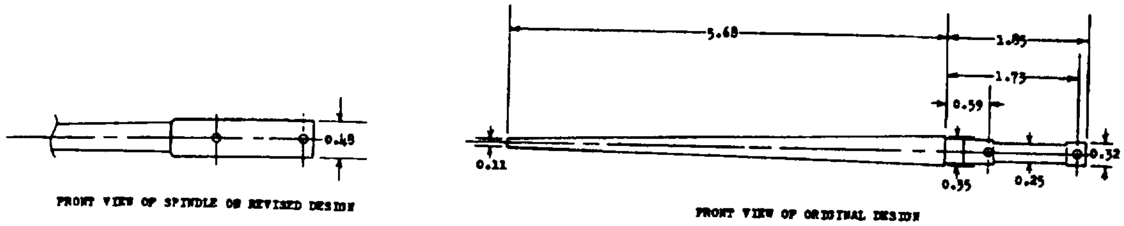


Figure 27a. *X–15* horizontal aerodynamic surface being wind tunnel tested.



MODIFIED 66A005

AIRFOIL ORDINATES PERCENT CHORD		
STATION	ROOT ORDINATE	TIP ORDINATE
L.E.	0.00	0.00
.10	.27	.35
.25	.41	.54
.50	.55	.73
.75	.58	.95
1.25	.65	.97
2.50	.79	1.05
5.00	1.04	1.20
7.50	1.27	1.35
10.00	1.46	1.50
15.00	1.77	1.77
20.00	2.00	2.00
25.00	2.18	2.18
30.00	2.32	2.32
35.00	2.42	2.42
40.00	2.48	2.48
45.00	2.50	2.50
50.00	2.49	2.49
55.00	2.44	2.44
60.00	2.35	2.35
65.00	2.18	2.18
67.00	2.09	2.08
T.E.	.50	.50

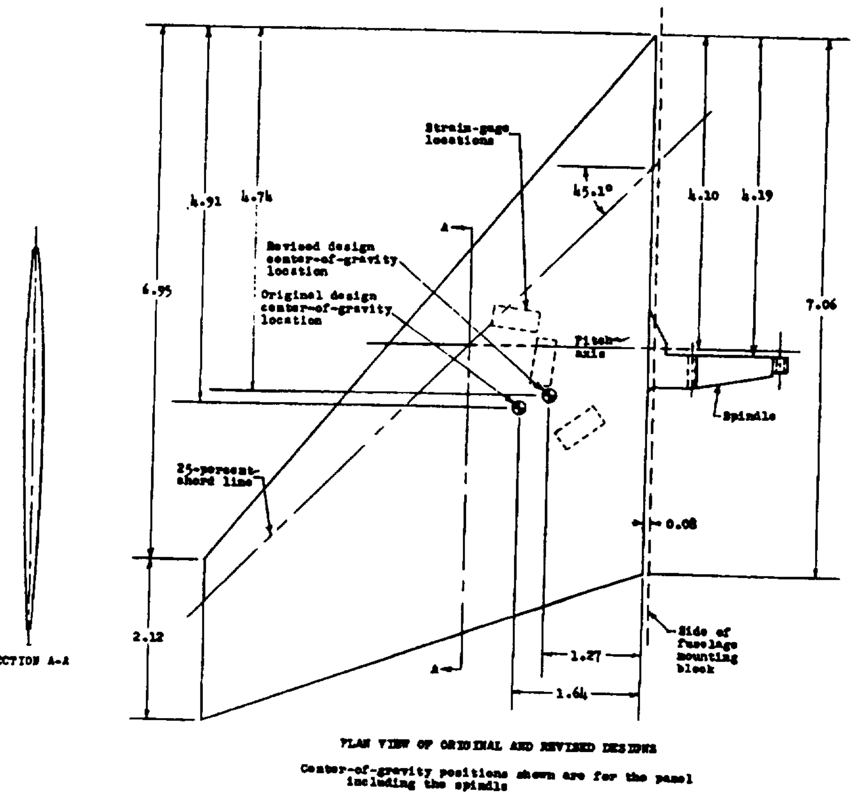


Figure 27b. *X–15* horizontal aerodynamic surface geometry.

Control characteristics of two preliminary *X–15* models with two different vertical fins and two different horizontal fins were investigated at Mach numbers of 2.98 and 4.01 and Reynolds numbers (Rn) of 2×10^6 to 4×10^6 based on wing mean aerodynamic chord ($\bar{c}$). Six component data were obtained for α from –4° to 22° and for angle-of-sideslip (β) from –5° to 1°. When the NACA 66–005 airfoil section horizontal fins were replaced with 10°-wedge horizontal fins, the longitudinal control effectiveness (C_{m_δ}) increased by 30 percent (fig. 28).[17] The all-movable controls led to increased interest in wind tunnel flutter tests. Several configurations, including a rectangular planform, were flutter tested on 1/12-size dynamically and elastically scaled models of the all-movable horizontal surfaces at Mach 6.86 at the NASA LaRC 11-inch hypersonic tunnel. Five horizontal surface configurations and two vertical surface configurations were tested at Mach numbers of 1.64, 2.0, 3.0, and 4.0. No flutter problems were encountered.[20] Static longitudinal, lateral, and directional stability and control were investigated on many stabilizer configurations including both a sharp TE and a 5°-wedge TE, dihedral of 0° and –15°, 60-percent dorsal fin and 40-percent ventral fin, vertical fin deflections of 0° and –5°, and speed-brake deflections of 20°, at Mach 6.86 and Rn of 640,000 based on $\bar{c}$, through α ranges of –4° to 24° and β ranges of 0° to –5° (figs. 29 and 30).[21] Nine alterations were made on the vertical stabilizer. In final configuration tests, the horizontal surface was deflected from –35° to 15°, the vertical surface from –7.5° to 0°, and the speed brake from 0° to 50° (Penland, NASA LaRC).

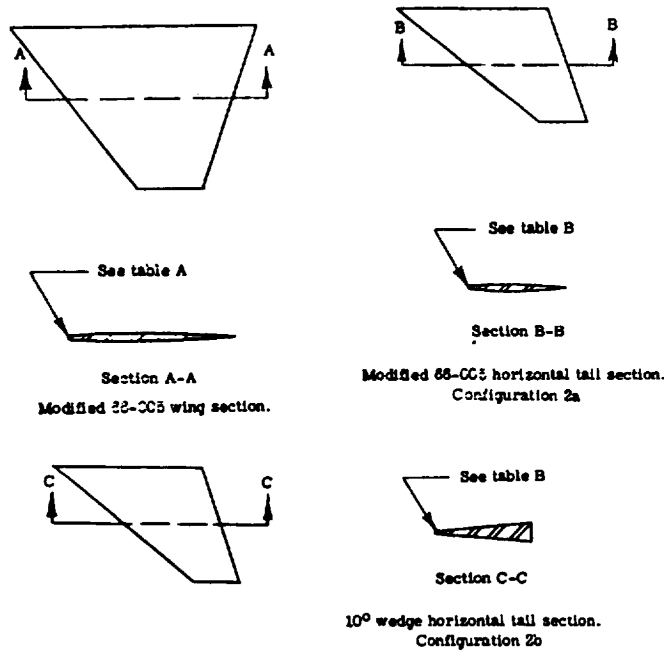


TABLE A

Wing sections (NACA)

Configuration	Section	L.E.R. (root)	L.E.R. (tip)
1	Modified 66-005	.004	.001
2	Modified 66-005	.014	.008
3	Modified 66-005	.014	.008

TABLE B

Horizontal tail sections (NACA)

Configuration	Section	L.E.R. (root)	L.E.R. (tip)
1	Modified 66-005	.003	.001
2a	Modified 66-005	.010	.005
2b	10° wedge	.010	.005
3	Modified 66-005	.010	.005

Figure 28a. *X–15* horizontal aerodynamic surfaces tested.

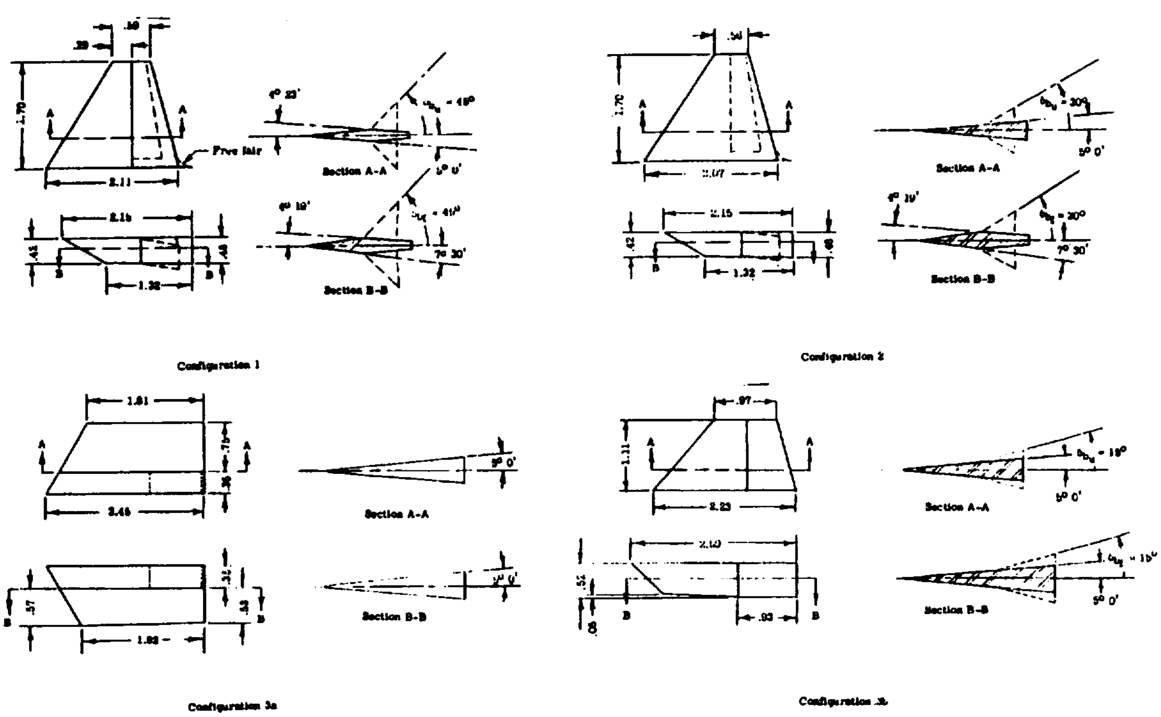


Figure 28b. *X–15* vertical aerodynamic surfaces tested.

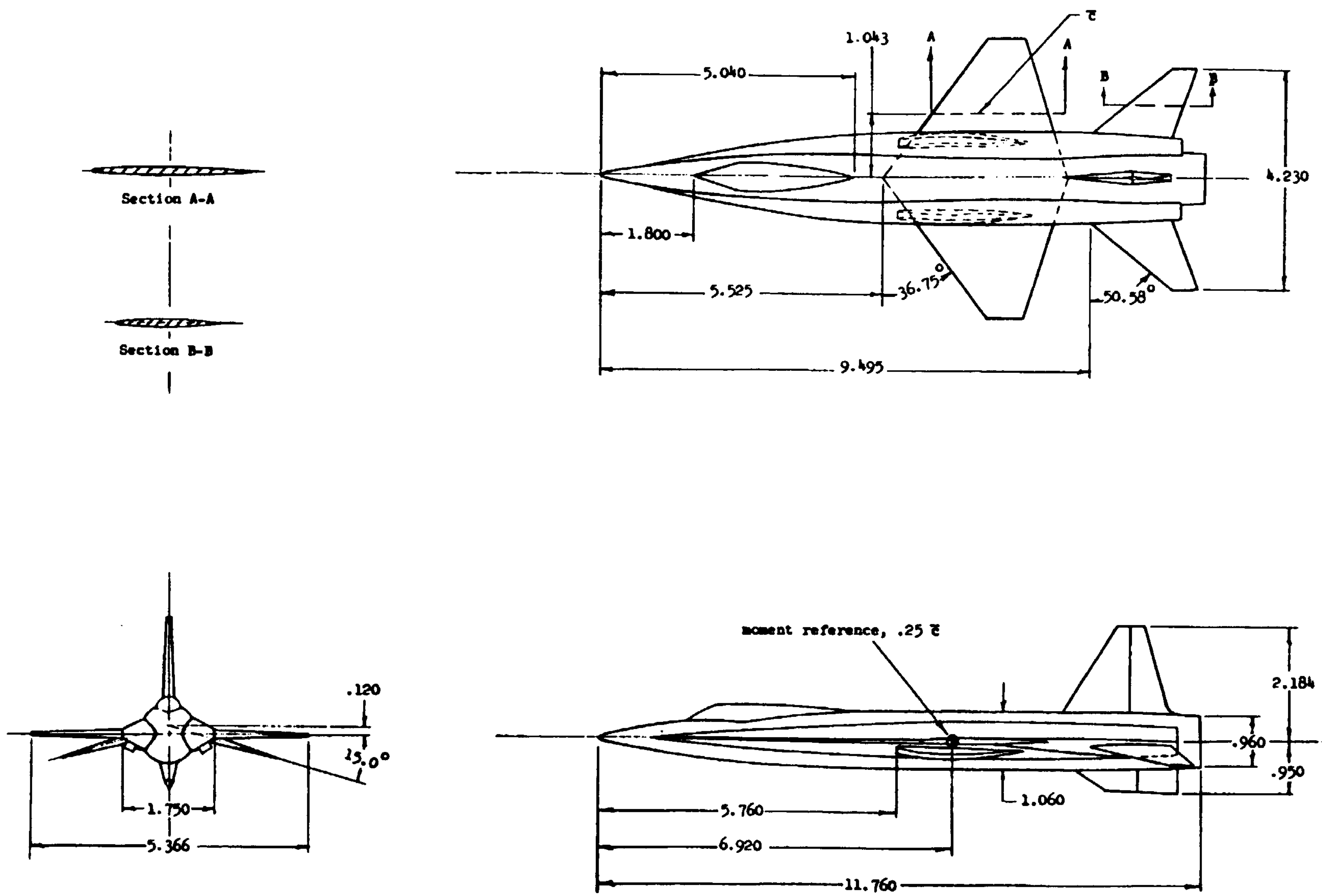


Figure 29a. Details of *X–15* configuration 1 tested (BWXHV$_U$V$_L$), all dimensions are in inches.

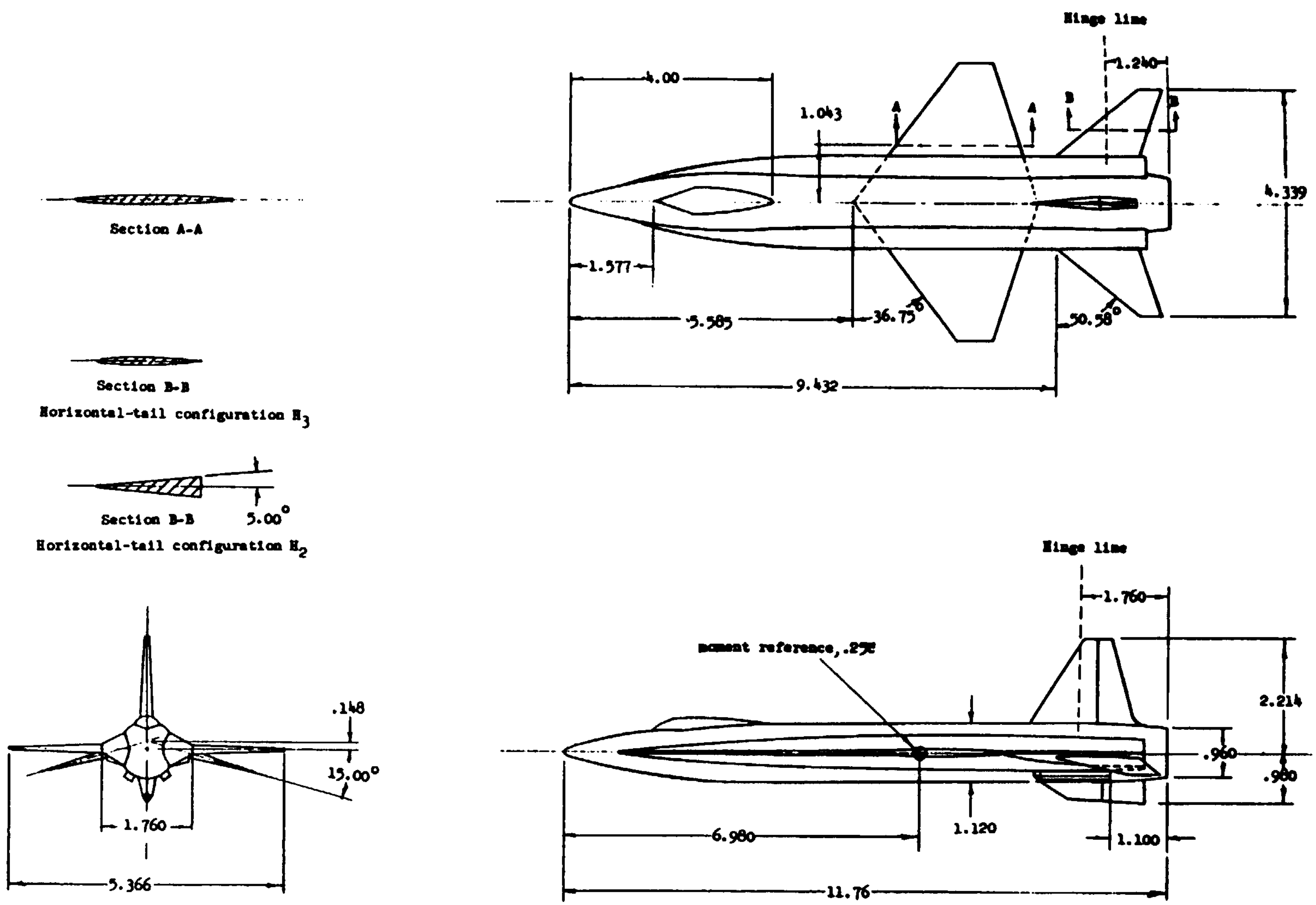


Figure 29b. Details of *X–15* configuration 2 tested ($B_2W_2X_3H_3V_{U2}V_L$), all dimensions are in inches.

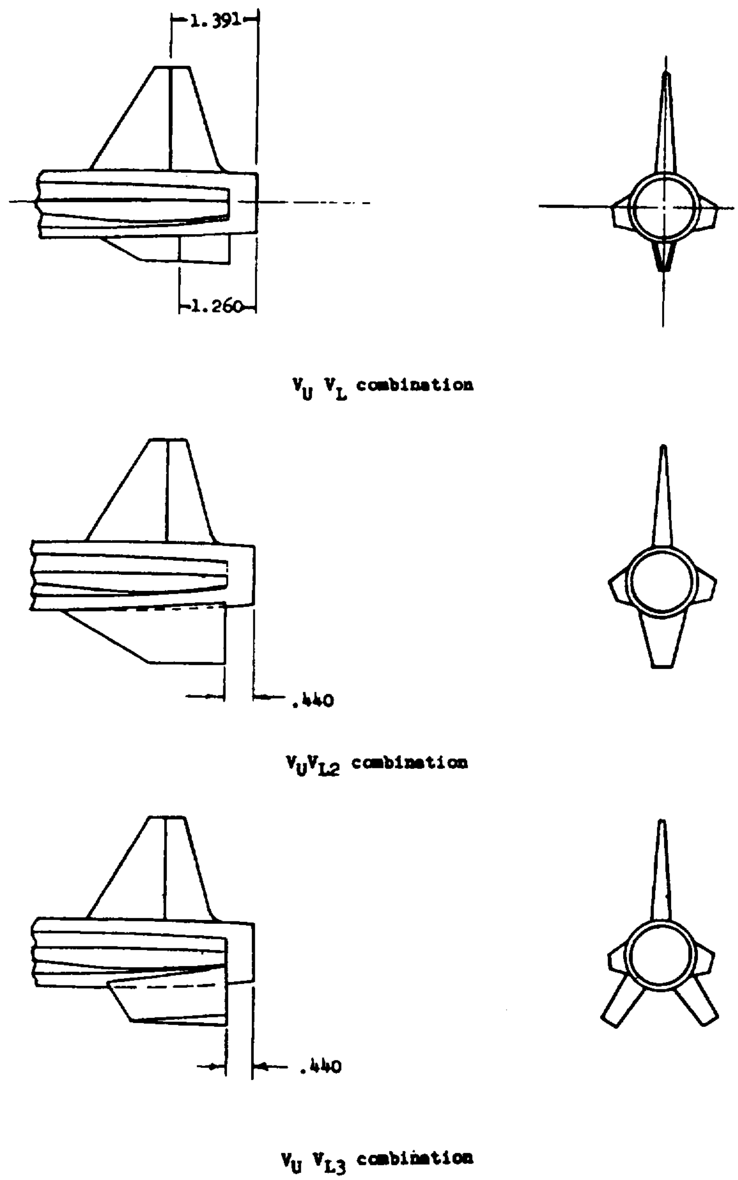


Figure 30. *X–15* vertical aerodynamic surface positions.

B. *Saturn I*

The *Saturn I* Block II finally flew with eight aerodynamic surfaces consisting of four large fins and four stub fins. Before this design was chosen, many combinations and configurations were wind tunnel tested. Figure 31 shows the eight fins of 121.2 ft^2. Figure 32 shows the eight stub fins. Figure 33 shows the eight fins of 181.9 ft^2. Figure 34 shows the dimensions of the 181.9-ft^2 fins. Figure 35 shows the dimensions of the stub fins. Figures 36 and 37 show the full fin. Figure 38 shows a combination of *Saturn I* aerodynamic surfaces being tested in the wind tunnel at NASA MSFC.[22]

The final combination and planform area that flew was: four large fins of 121.2 ft^2 each and four stub fins of 53.3 ft^2 each. The total planform area of these surfaces was 698 ft^2, span was 42.833 ft, and fin $\bar{c}$ was 14.2778 ft. All the fins had blunt TE's.[22]

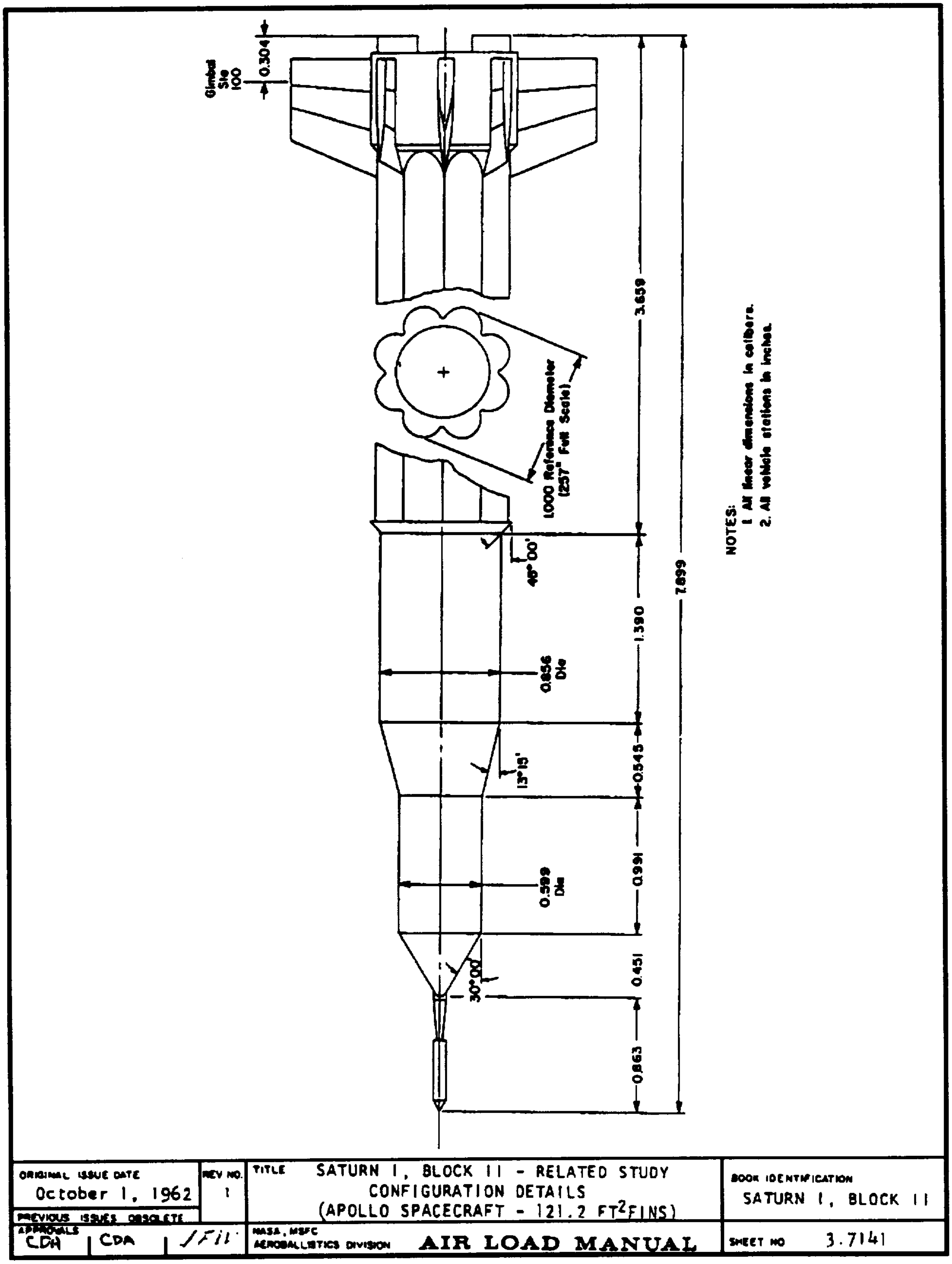


Figure 31. *Saturn I* geometry with 121.2 ft^2 aerodynamic surfaces.

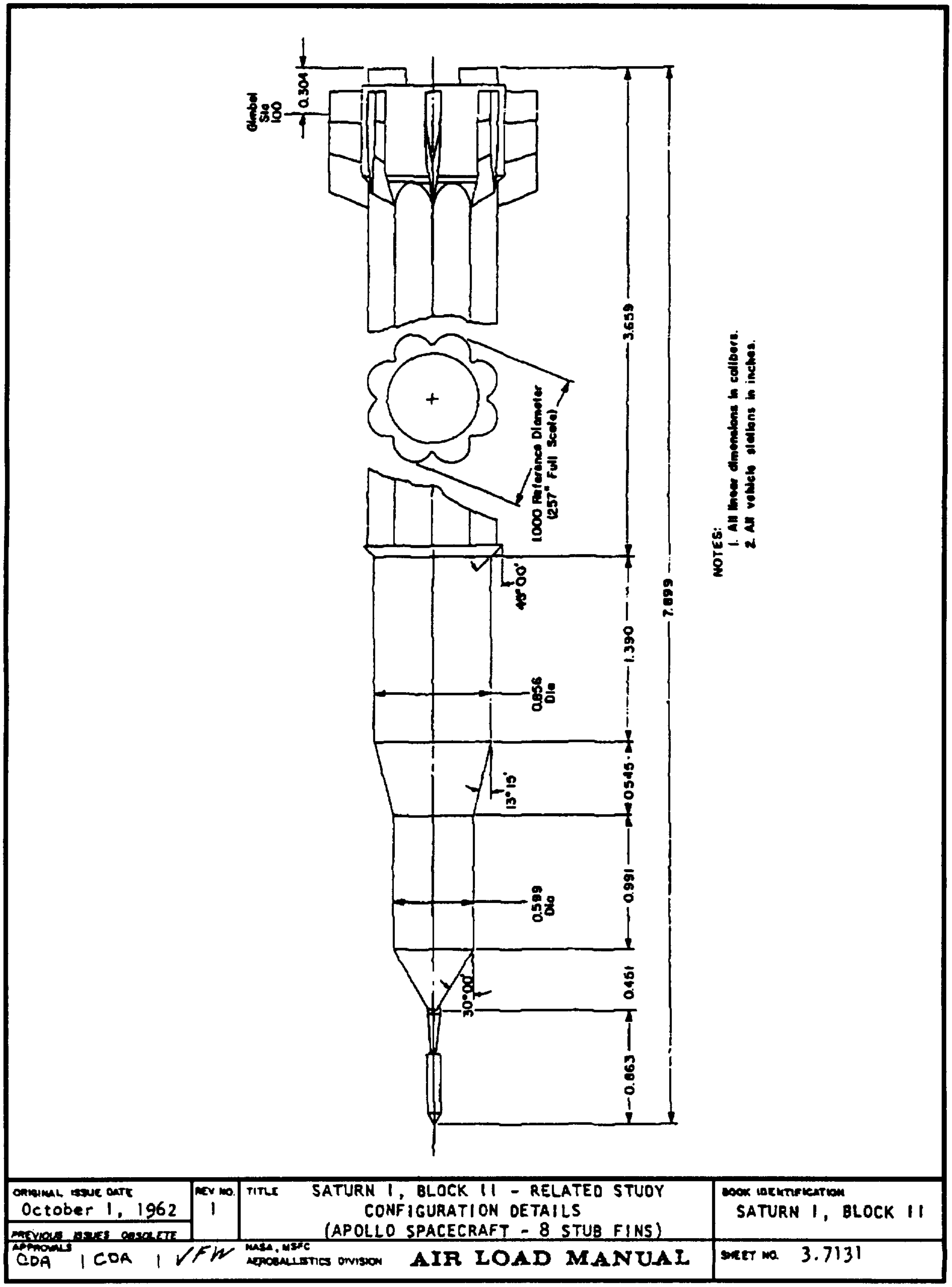
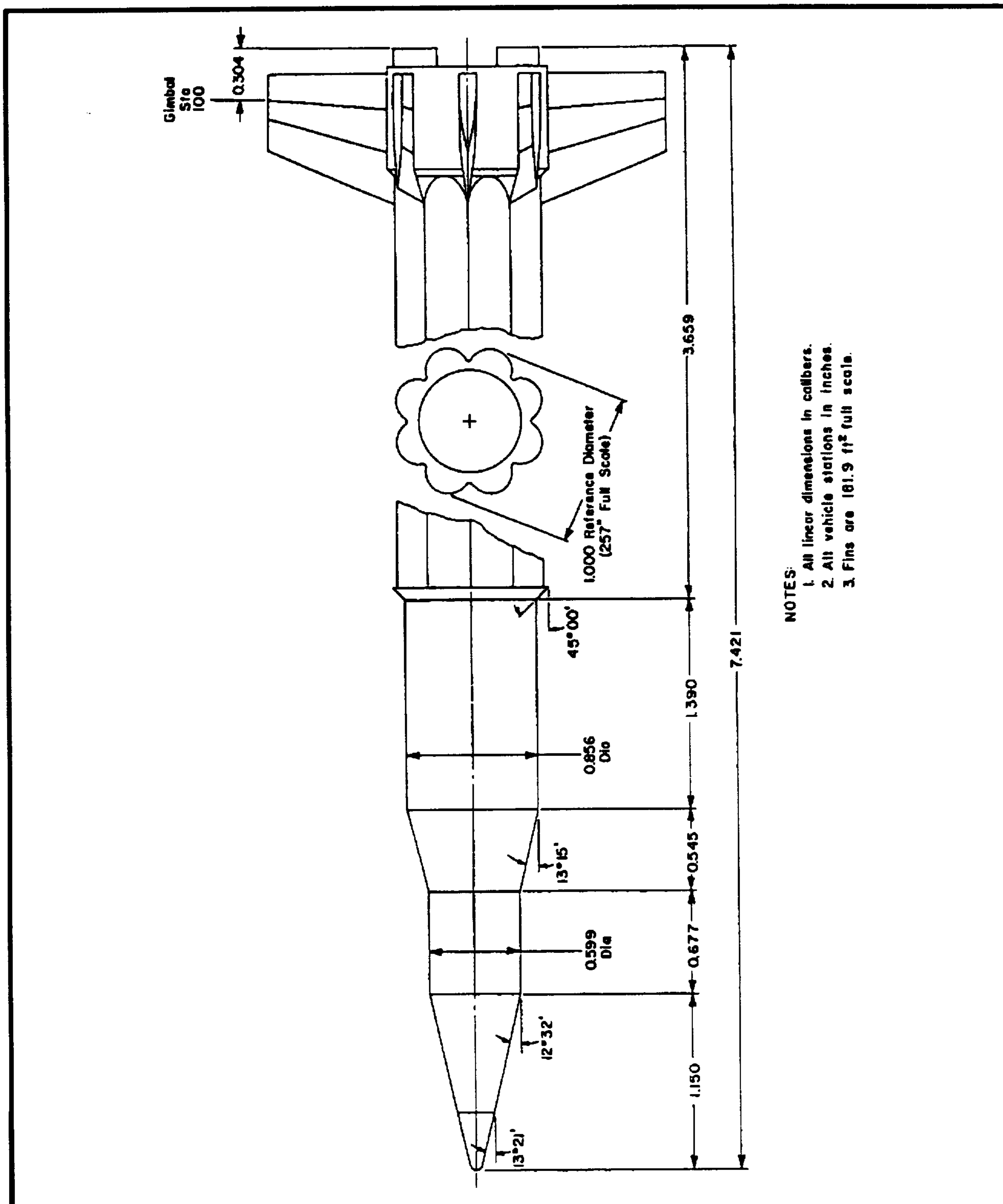


Figure 32. *Saturn I* geometry with eight stub fins.



ORIGINAL ISSUE DATE	REV. NO.	TITLE	BOOK IDENTIFICATION
October 1, 1963	1	SATURN I, BLOCK II - RELATED STUDY CONFIGURATION DETAILS (JUPITER NOSE CONE - 181.9 FT2FINS)	SATURN I, BLOCK II
PREVIOUS ISSUES OBSOLETE			
APPROVALS: ael / CDA / JFW		NASA, MSFC AEROBALLISTICS DIVISION — AIR LOAD MANUAL	SHEET NO. 3.7111

Figure 33. *Saturn I* geometry with 181.9 ft² aerodynamic surfaces.

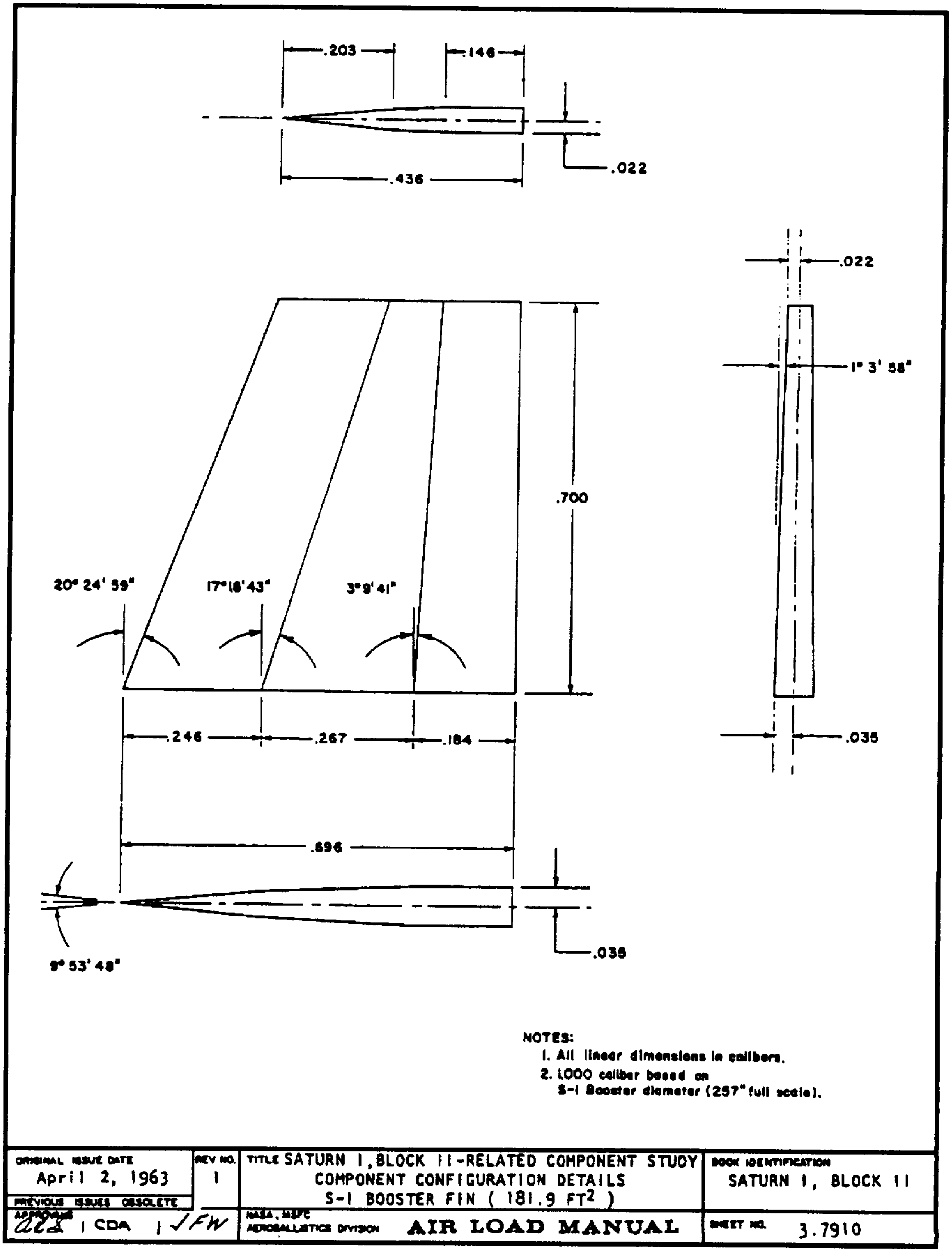


Figure 34. *Saturn I* 181.9 ft^2 fin detail.

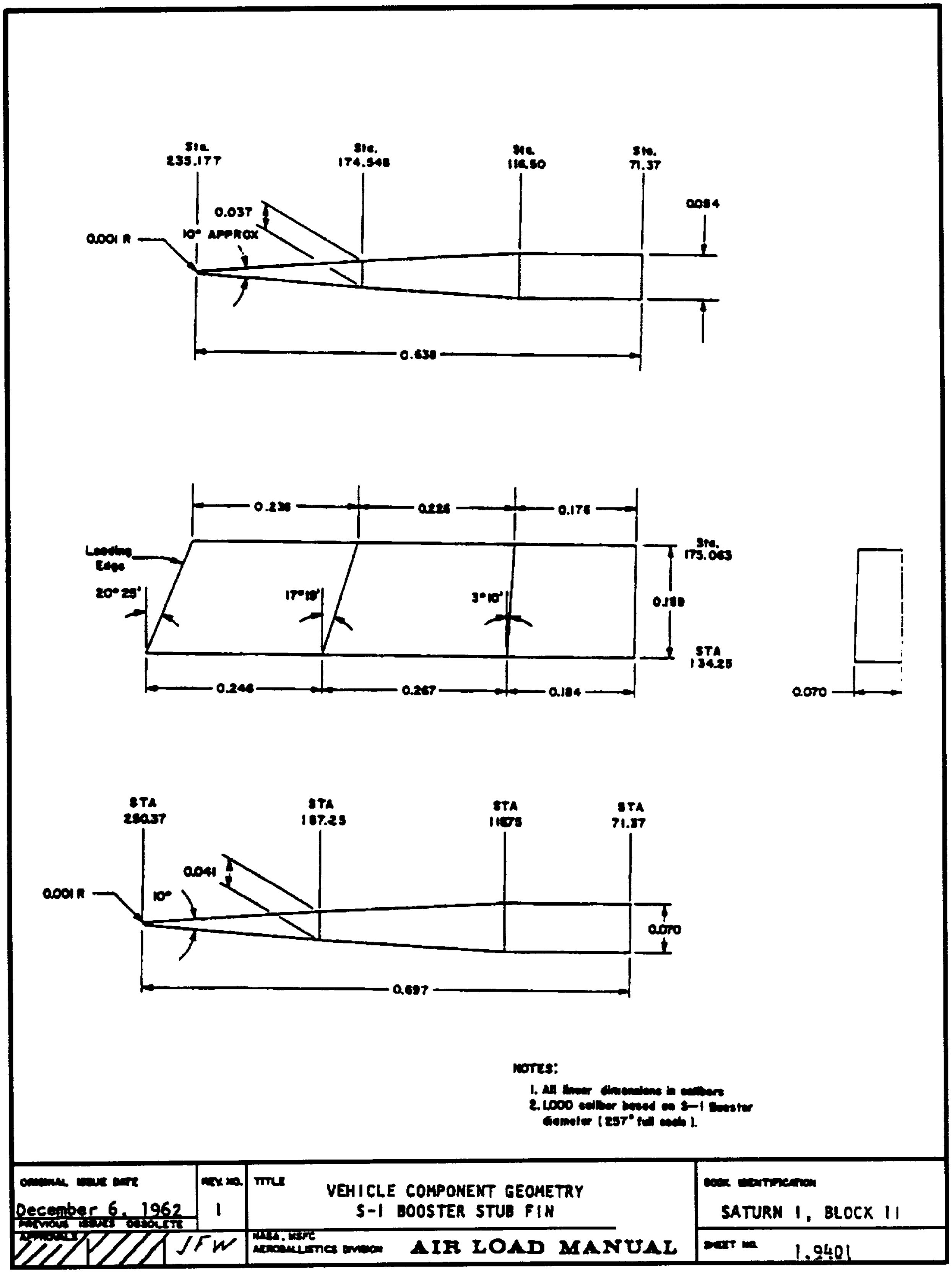


Figure 35. *Saturn I* stub fin detail.

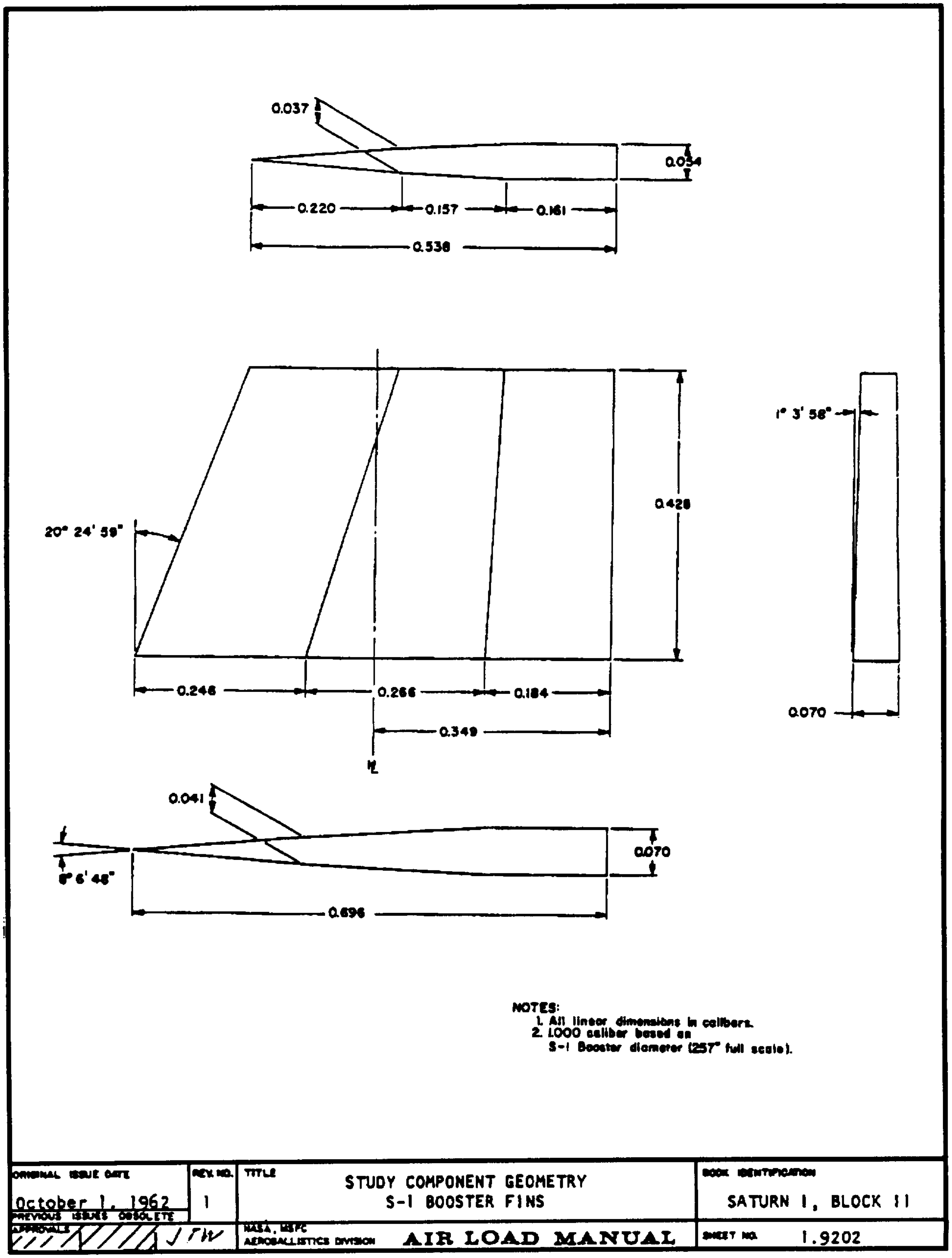
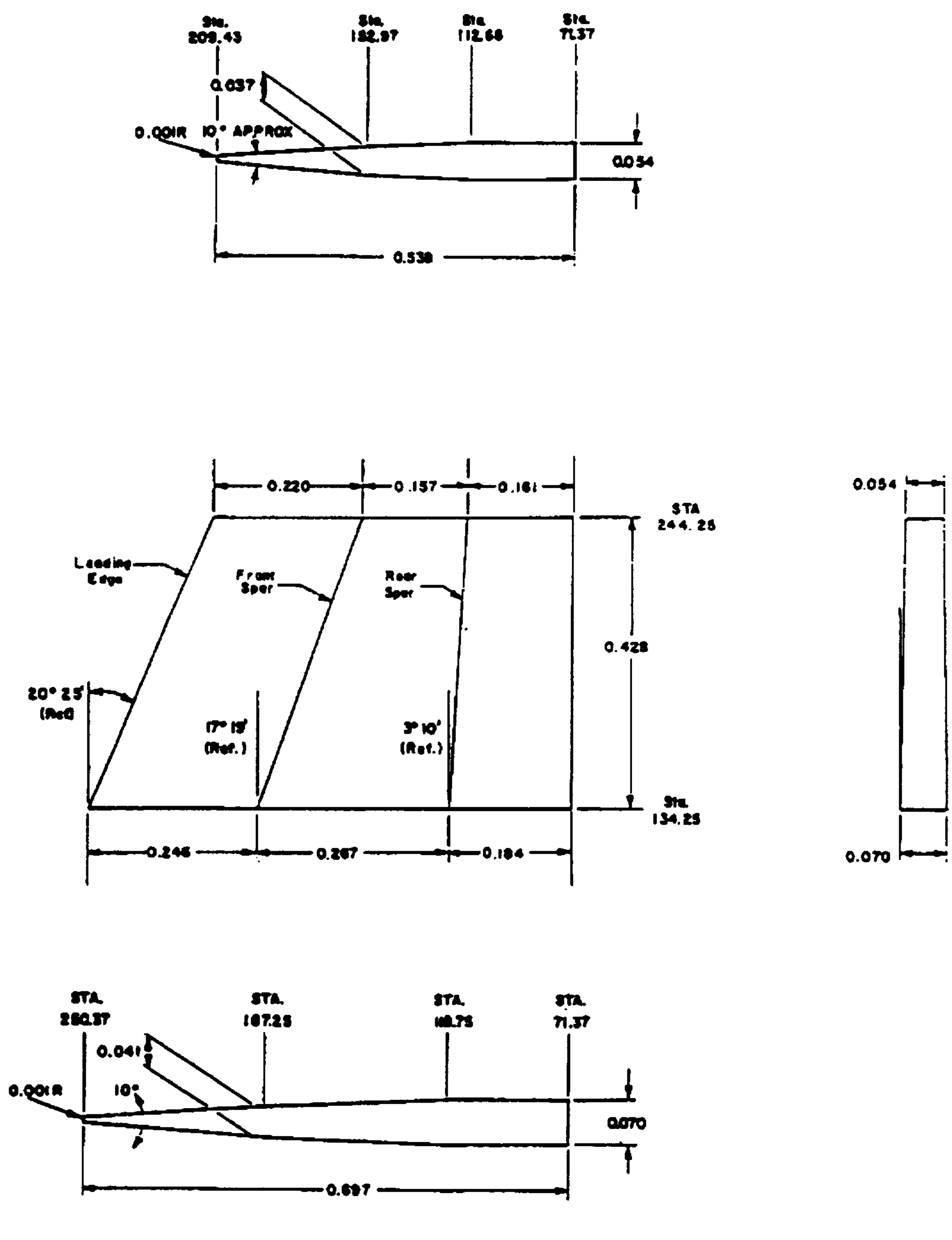


Figure 36. *Saturn I* geometry with 121.2 ft² fin detail.



NOTES:
1. All linear dimensions in calibers.
2. 1.000 caliber based on S-I Booster diameter (257" full scale).

ORIGINAL ISSUE DATE	REV. NO.	TITLE	BOOK IDENTIFICATION
October 1, 1962 PREVIOUS ISSUES OBSOLETE	1	VEHICLE COMPONENT GEOMETRY S-I BOOSTER FINS	SATURN I, BLOCK II
APPROVALS JFW		NASA, MSFC AEROBALLISTICS DIVISION — AIR LOAD MANUAL	SHEET NO. 1.9201

Figure 37. Station numbers of $121.2\ ft^2$ fin.

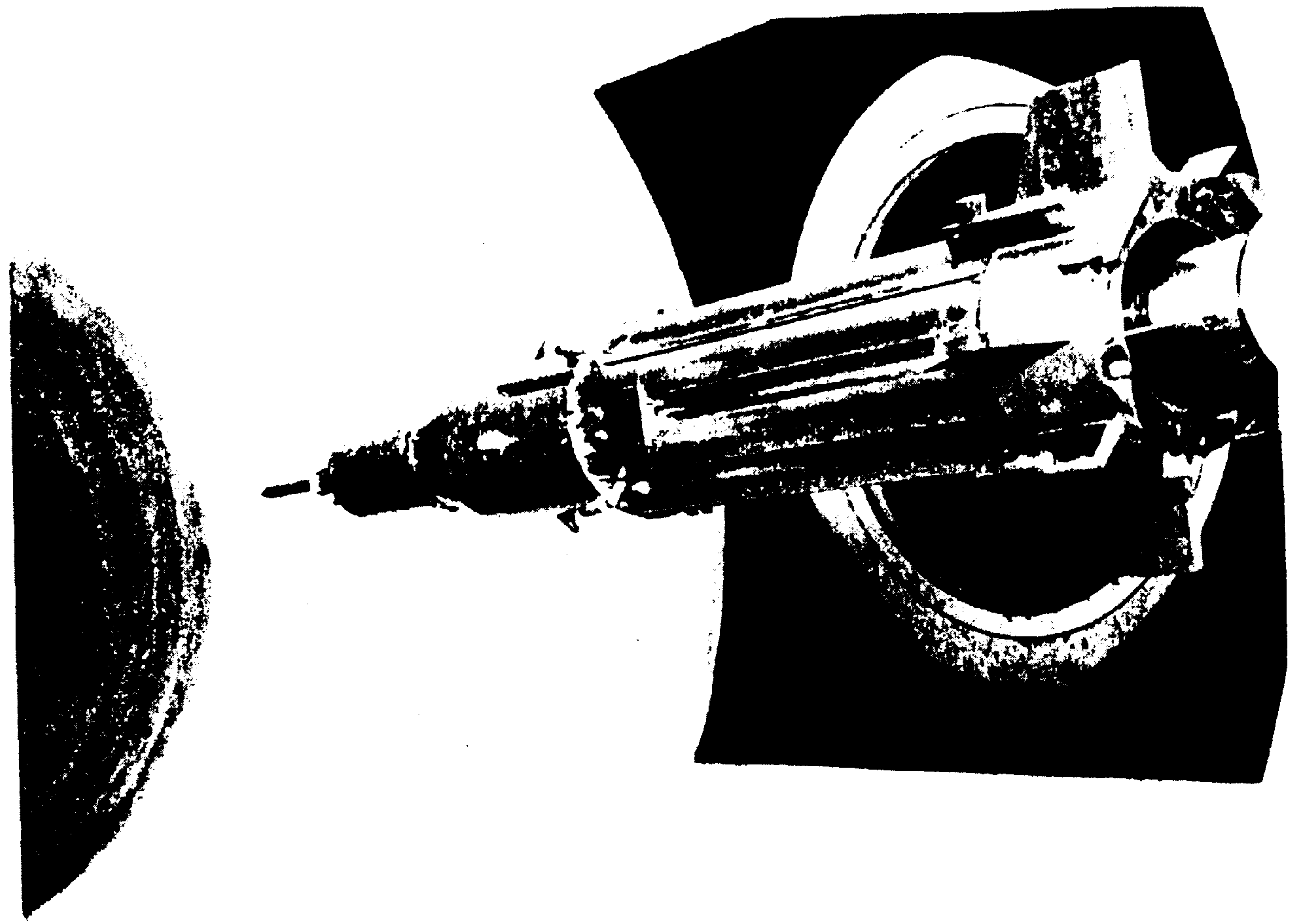


Figure 38. *Saturn I* being wind tunnel tested (AEDC Von Karman facility hypersonic tunnel B).

C. *Saturn I–B*

The *Saturn I–B* aerodynamic surfaces underwent extensive redesign and produced nearly 2.5 times the lift as the eight stubs of the previous designs, and weighed 1,800 lb less. Because of the long chord and short span, the eight stub fins on the *Saturn I* were very inefficient aerodynamic surfaces. The goal in the *Saturn I–B* fin redesign was to achieve the same lift with eight uniform fins of 53.3-ft^2 area each, i.e., the same lift with less planform area. The same thickness as used on the *Saturn I* was retained in order to use the same attach points on the L/V as the old stub planforms, thereby keeping the surface redesign from affecting the basic L/V design. The *Saturn I–B* fins also had blunt TE's. Figure 39 shows the 53.5-ft^2 area.[23 24] Figure 40 shows a 5-percent scale *Saturn I–B* being wind tunnel tested with the fin redesign.

The final design produced more lift and provided more flight stability transonically, where it was needed most, and less lift supersonically than the four full fins and four stub fins of the *Saturn I*. The eight uniform fins of the *Saturn I–B* had a 45° sweep of the LE's and a 24.4° sweep of the TE's. Figure 41 shows the internal structure of the *Saturn I–B* aerodynamic surface, and table 1[23] lists the pertinent detail geometry. The profile was a triangular tapered-wedge with a blunt TE. The redesigned *Saturn I–B* surfaces significantly increased the aerodynamic static flight stability of the vehicle and also increased the dynamic flight stability of the vehicle in pitch and yaw.

Table 1. *Saturn I–B* fin redesign.

Item	Value
Length, M.A.C.	$\bar{c}$ = 74 inches
Location, M.A.C.	y = 47 inches
Leading Edge Sweep	$\Lambda_{LE} = 45$
Trailing Edge Sweep	$\Lambda_{TE} = 24.5$
Thickness Ratio	t/c = 17.25 percent
Aspect Ratio	$AR = 3.14$
Planform Area	$S = 53.3$ ft^2
Taper Ratio	c root/c tip = 2.50
Half Angle Leading Edge	$\theta = 5.5$
Spanwise Taper Angle	$\lambda = 2.88$

D. *Saturn V*

The *Saturn V* used four aerodynamic surfaces of 75 ft^2 each to enhance flight stability (fig. 42).[25] Each fin had a span of 139 inches, a root chord of 138 inches, a tip chord of 55 inches, an outboard chord depth of 4 inches, a root chord depth of 15 inches, an LE sweep angle of 30°, and a wedge angle of 10°. The surface was designed for a maximum dynamic pressure (q max) of 1,440 lb/ft^2. The fin assembly was mechanically attached to the engine fairing assembly (fig. 43). The *Saturn V* aerodynamic surfaces were constructed of 7075–T6 aluminum and were titanium coated to withstand as much as 2,000 °F heat from the engine exhausts. Figures 44, 45, and 46 show the engine shrouds to which the surfaces were attached. Total aerodynamic surface weight was 2,035.2 lb.[25 26] The fins and shrouds of the *Saturn V* were shown in the wind tunnel test to be more efficient when the L/V was rolled 45°, because then they were located on the side of the vehicle and received the full effects of upwash. Since the lift on the fin-shroud combination increased, the total vehicle center of pressure was moved farther aft, which further increased the *Saturn V* flight stability.

This coverage of the detailed design developments of the aerodynamic surfaces used on the *Saturn* and *X*–15 series shows the considerable amount of design evolution.

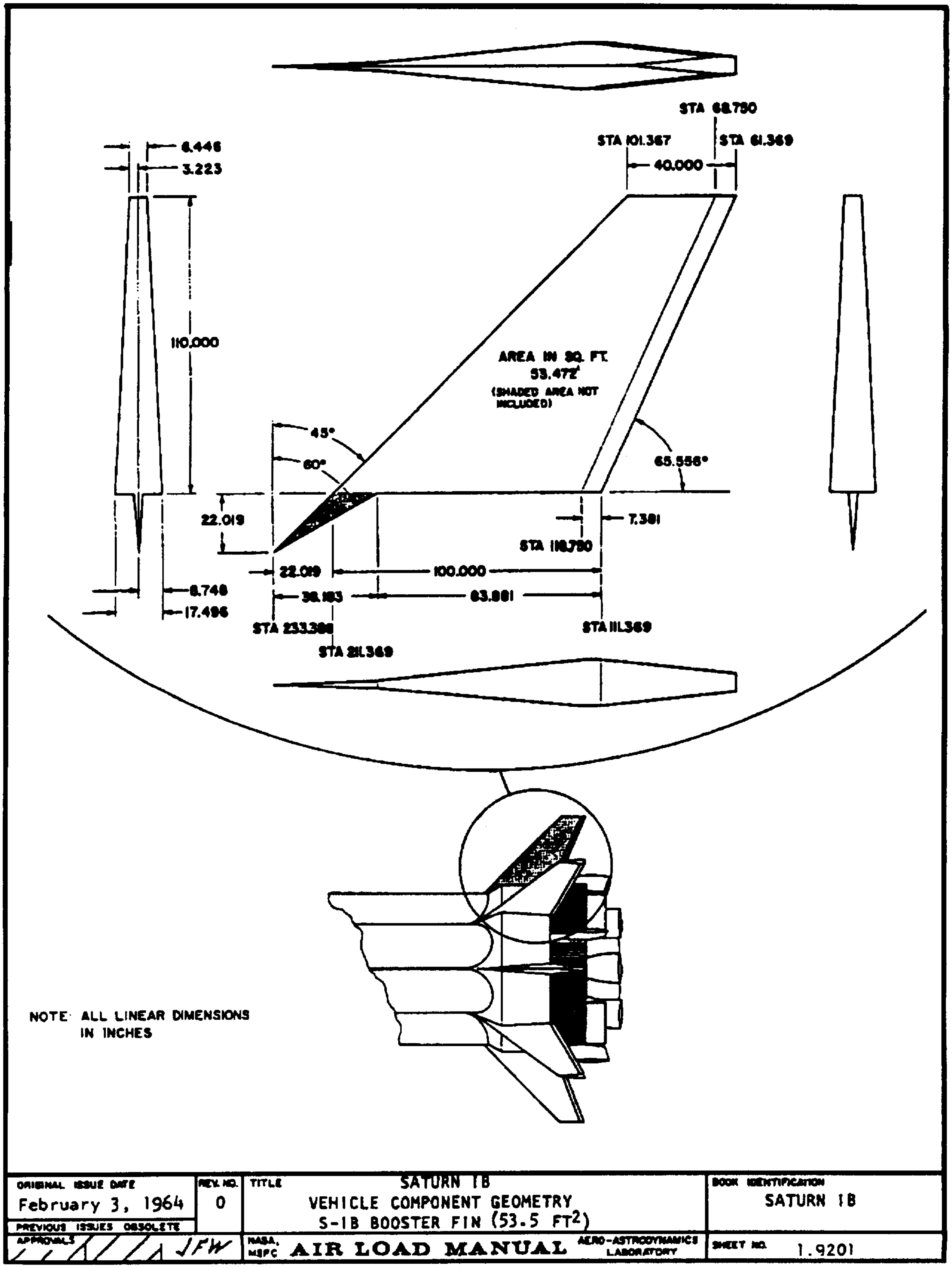


Figure 39. *Saturn I–B* aerodynamic surface geometry.

Figure 40. *Saturn I–B* (5-percent scale) in wind tunnel test.

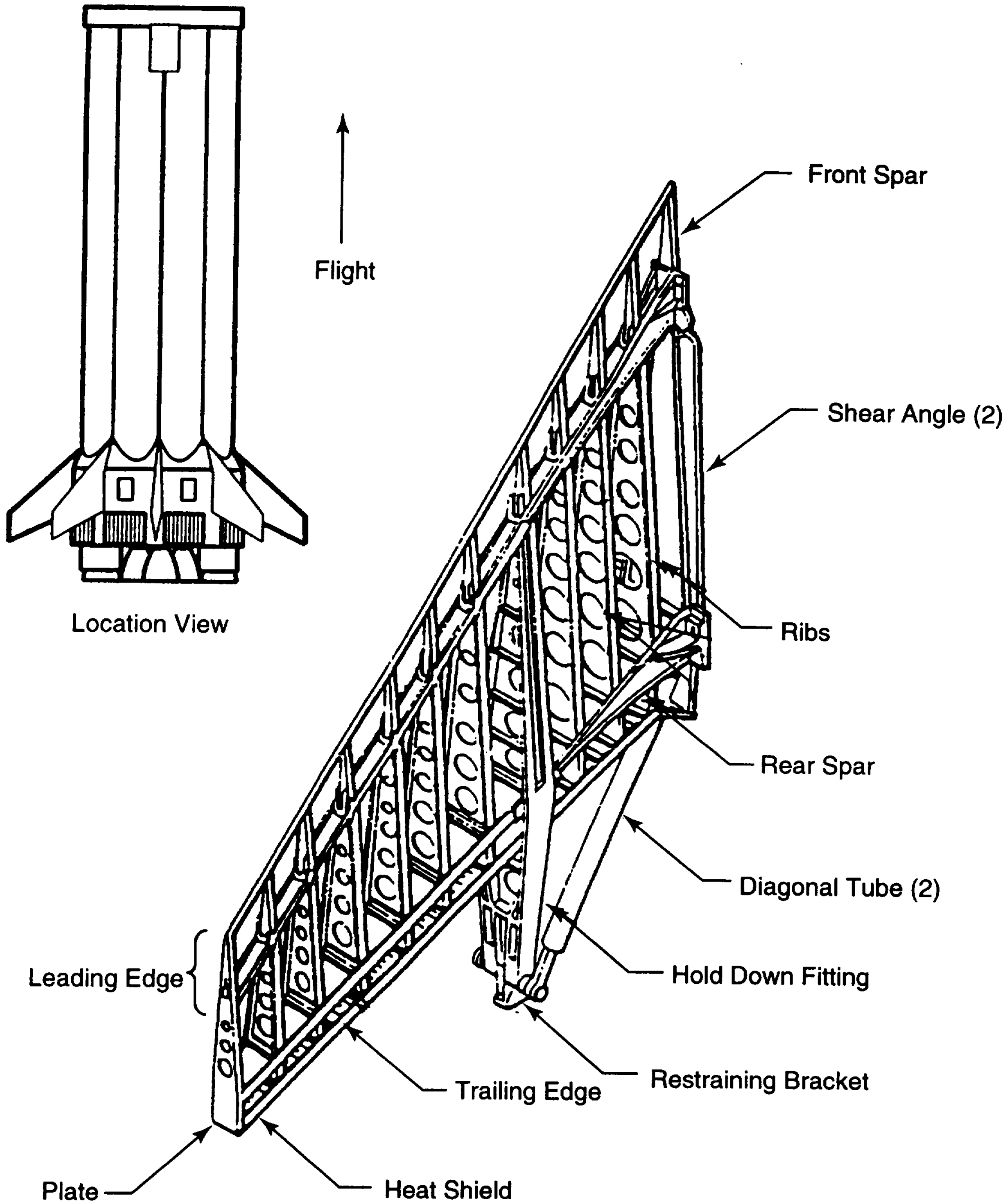


Figure 41. *Saturn I–B* aerodynamic surface internal structure.

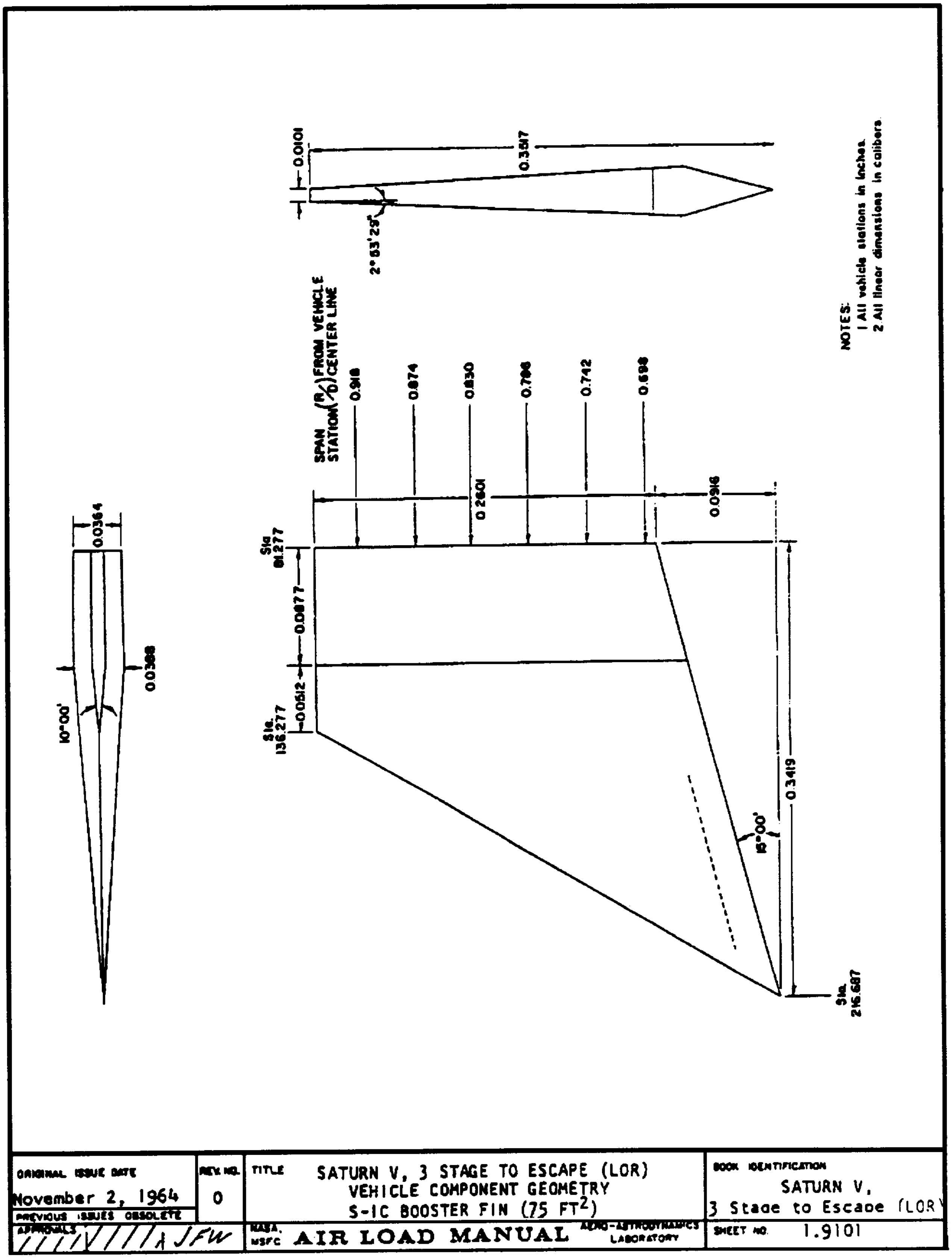


Figure 42. *Saturn V* aerodynamic surface geometry.

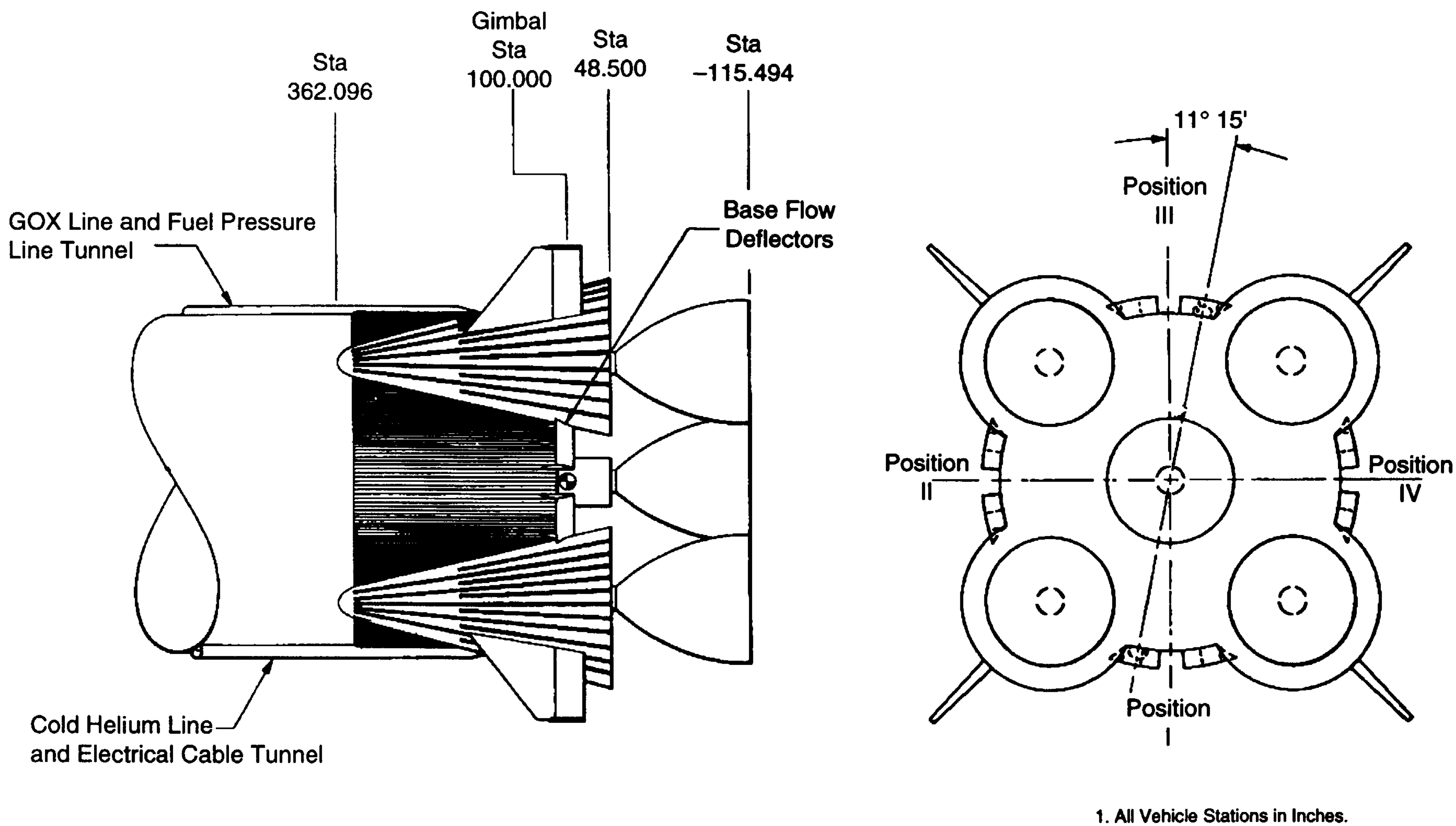
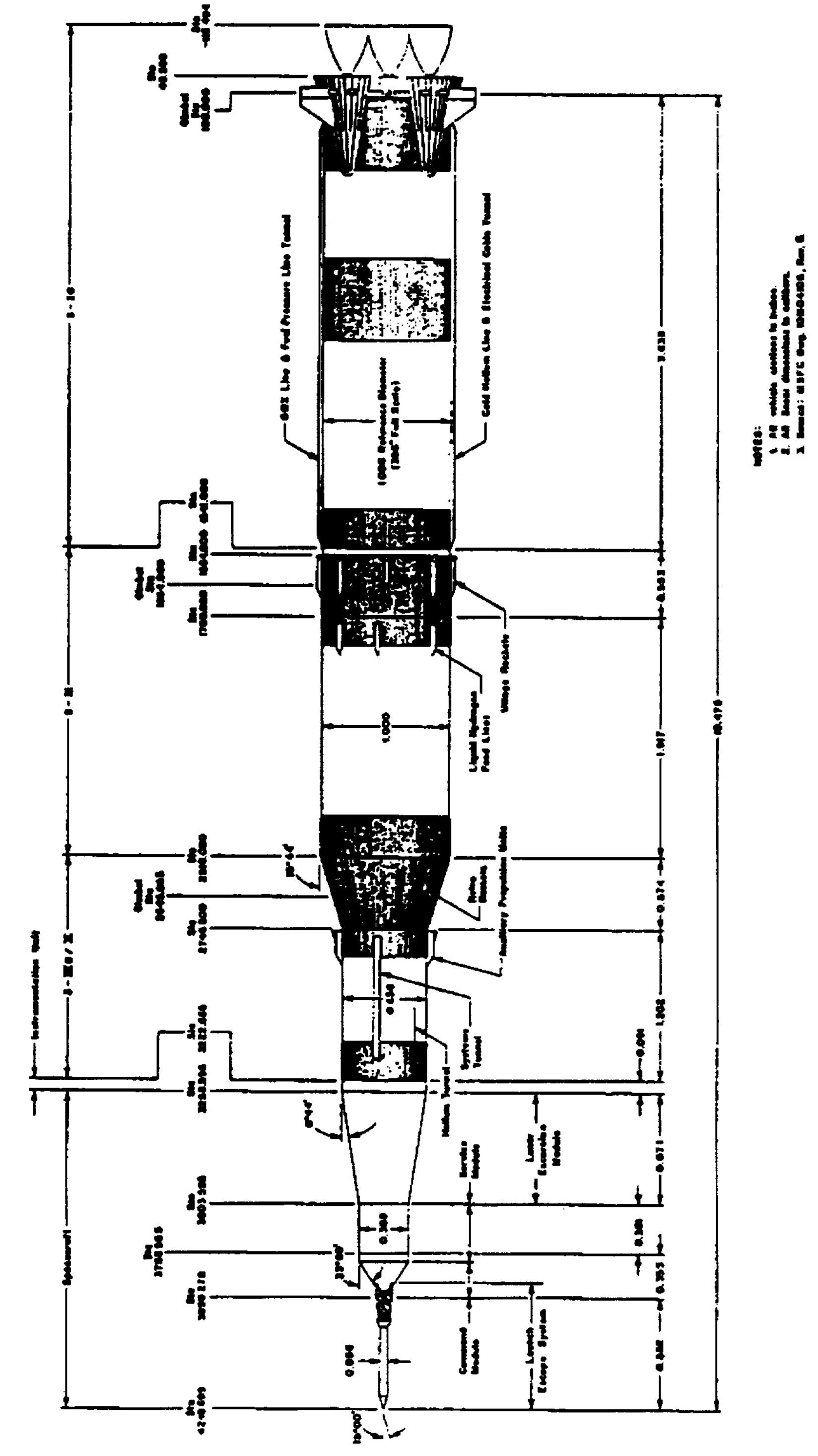


Figure 43. *Saturn V*, S–IC stage, base area geometry.



ORIGINAL ISSUE DATE	REV. NO.	TITLE	BOOK IDENTIFICATION
January 22, 1964	0	VEHICLE GEOMETRY SA-501	SATURN V, 3 Stage to Escape (LOR)
PREVIOUS ISSUES OBSOLETE			
APPROVALS / / / V / / / JFW		NASA, MSFC AIR LOAD MANUAL AERO-ASTRODYNAMICS LABORATORY	SHEET NO. 1.7011

Figure 44. *Saturn V* vehicle geometry.

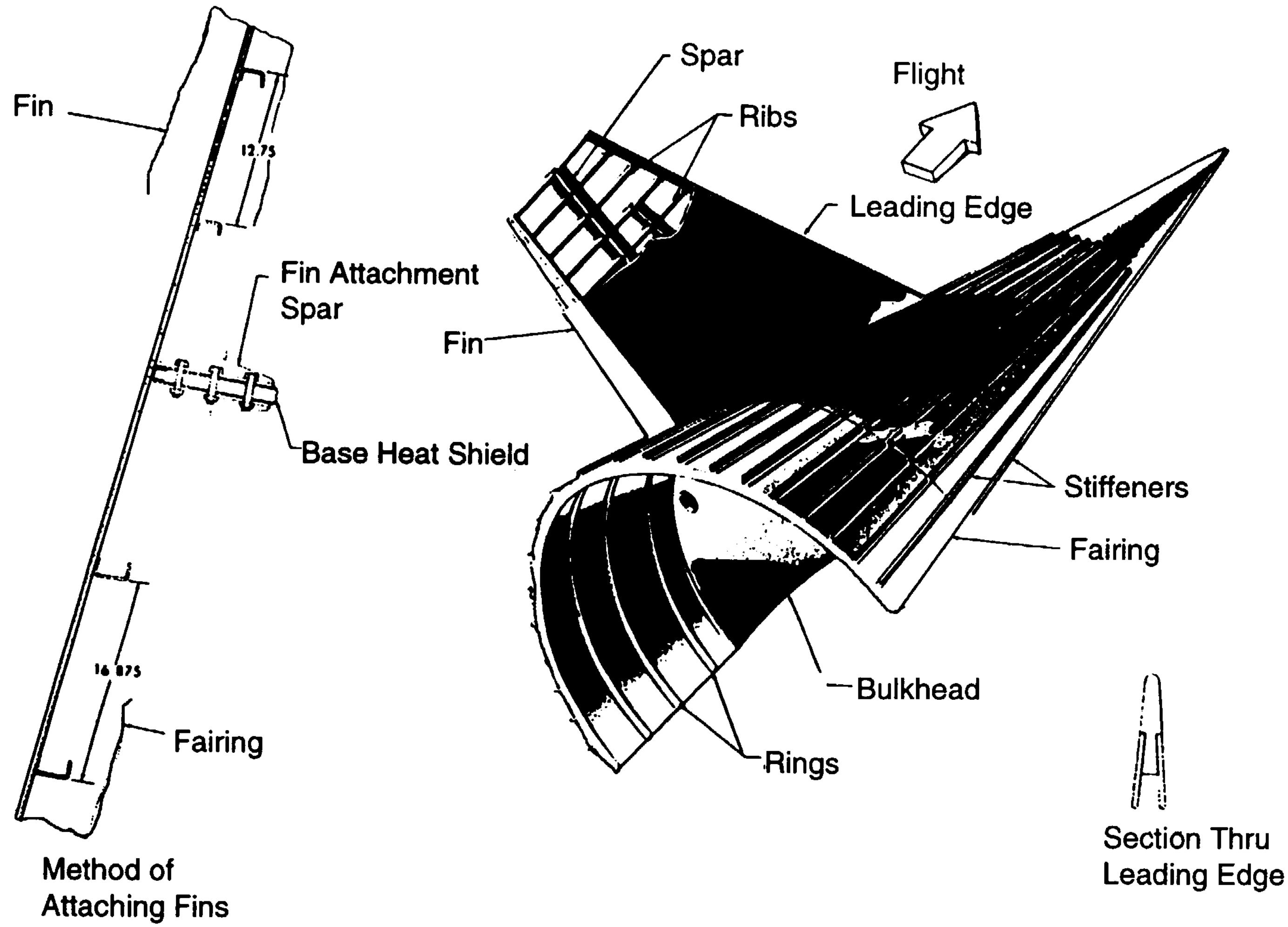


Figure 45. *Saturn V* aerodynamic surface and shroud assembly.

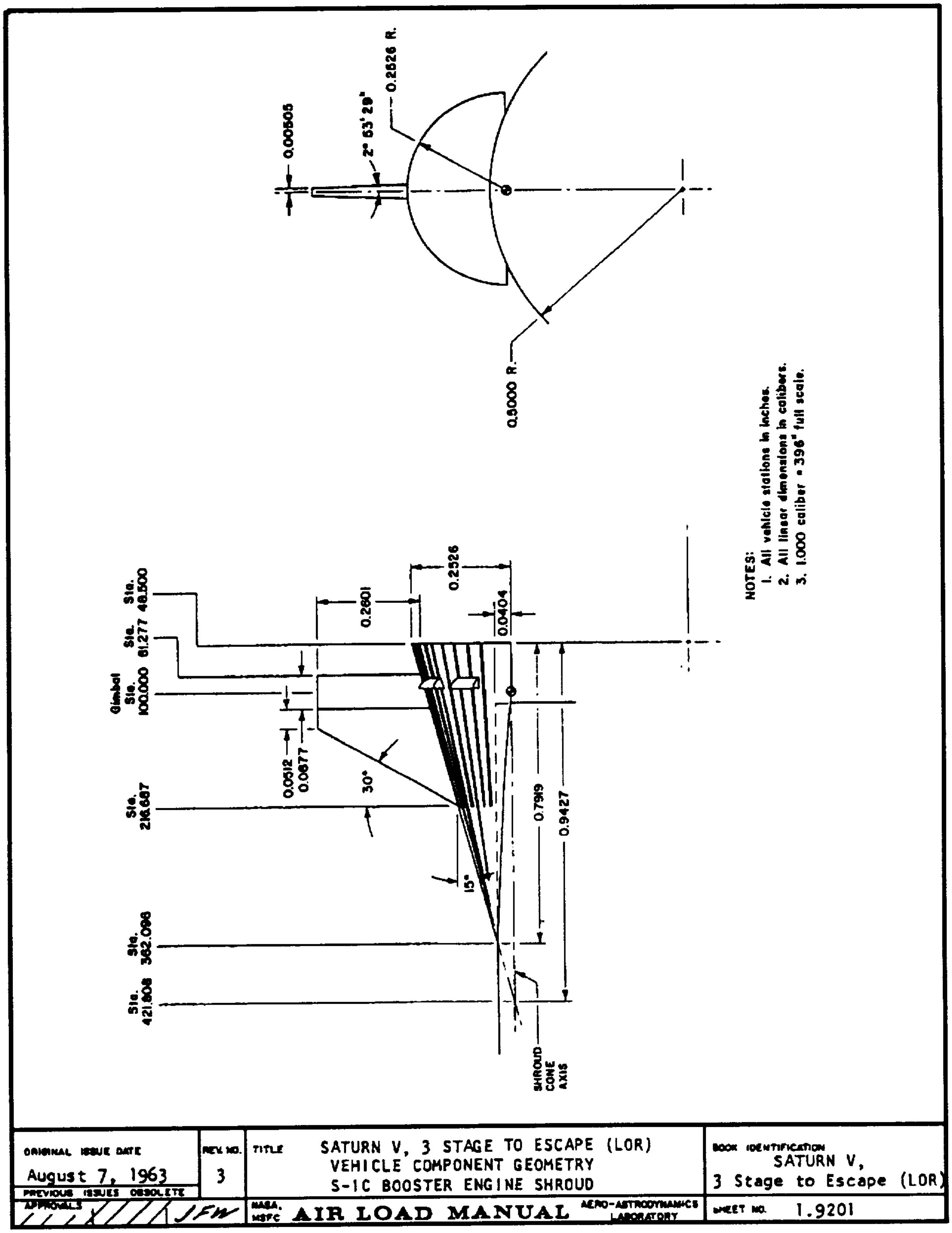


Figure 46. *Saturn V* shroud geometry.

IV. SUMMARY OF CURRENT USE OF AERODYNAMIC SURFACES BY FRENCH, RUSSIAN, CHINESE, AND JAPANESE LAUNCH VEHICLES

Today there are a myriad of L/V's actively launched from nearly two dozen geographic launch sites around the globe. Aerodynamic surfaces are currently being used on large *Saturn* class L/V's by many other nations. Only the most significant usages are summarized here.

A. French (ESA)

Although many countries have provided funding, France has provided the largest funding for the *Ariane* series of L/V's. The *Ariane 1*, *Ariane 2*, *Ariane 3*, *Ariane 4*, *Ariane 42L*, *Ariane 44L*, and *Hermes* all use aerodynamic surfaces for flight stability. *Hermes* uses aerodynamic surfaces for both flight stability and flight control (fig. 47).[27]

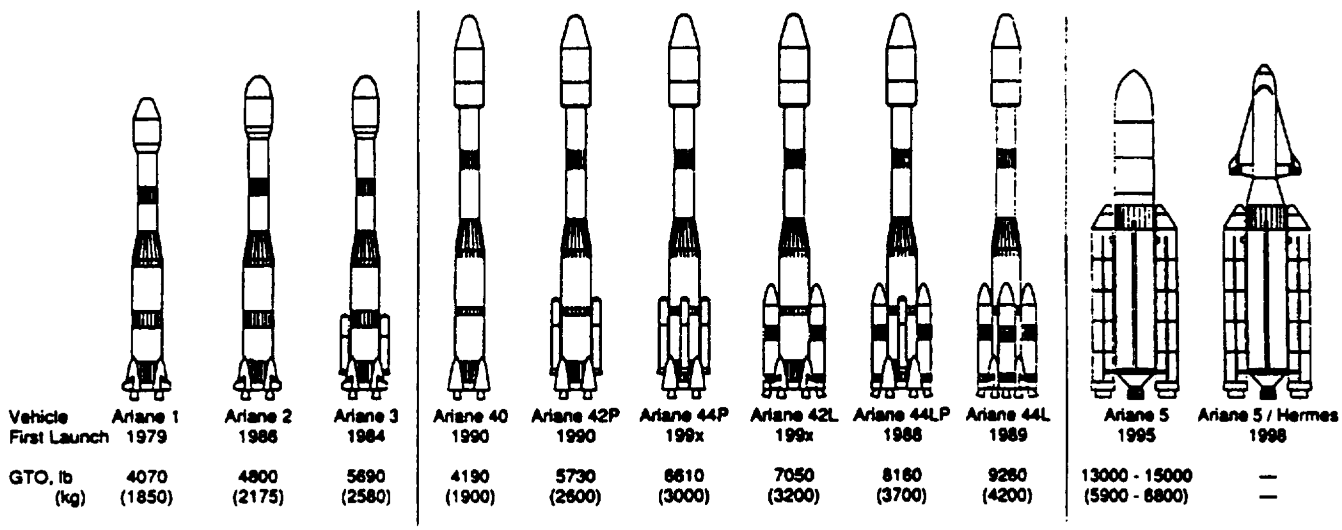


Figure 47. *Ariane* L/V's.

The *Ariane 4*, first launched in 1988, uses four fins, 21 ft^2 each, to improve flight stability during atmospheric flight (fig. 48).[28] *Ariane 4* can launch 21,100 lb to LEO or 9,260 lb to GTO. *Ariane 4* configurations include: *Ariane 40* with no strap-on booster, *Ariane 42P* with two solid propellant strap-on boosters, *Ariane 44P* with four solid strap-on boosters, *Ariane 42L* with two liquid propellant strap-on boosters, *Ariane 44L* with four liquid propellant strap-on boosters, and *Ariane 44LP* with two liquid and two solid propellant strap-on boosters.[27]

Figure 47 shows the conical shrouds which are used on the *Ariane 1*, *Ariane 2*, *Ariane 3*, *Ariane 40*, *Ariane 42P*, *Ariane 44P*, *Ariane 42L*, *Ariane 44LP*, *Ariane 44P*, and *Ariane 44L* to enhance the aerodynamic flight stability of the vehicles. The *Ariane 5* uses aft skirts on the solid boosters to the same advantage.[28] These L/V's launch payloads of 4,070 to 15,000 lb to GEO. *Hermes* takes 22,000 lb to GEO.

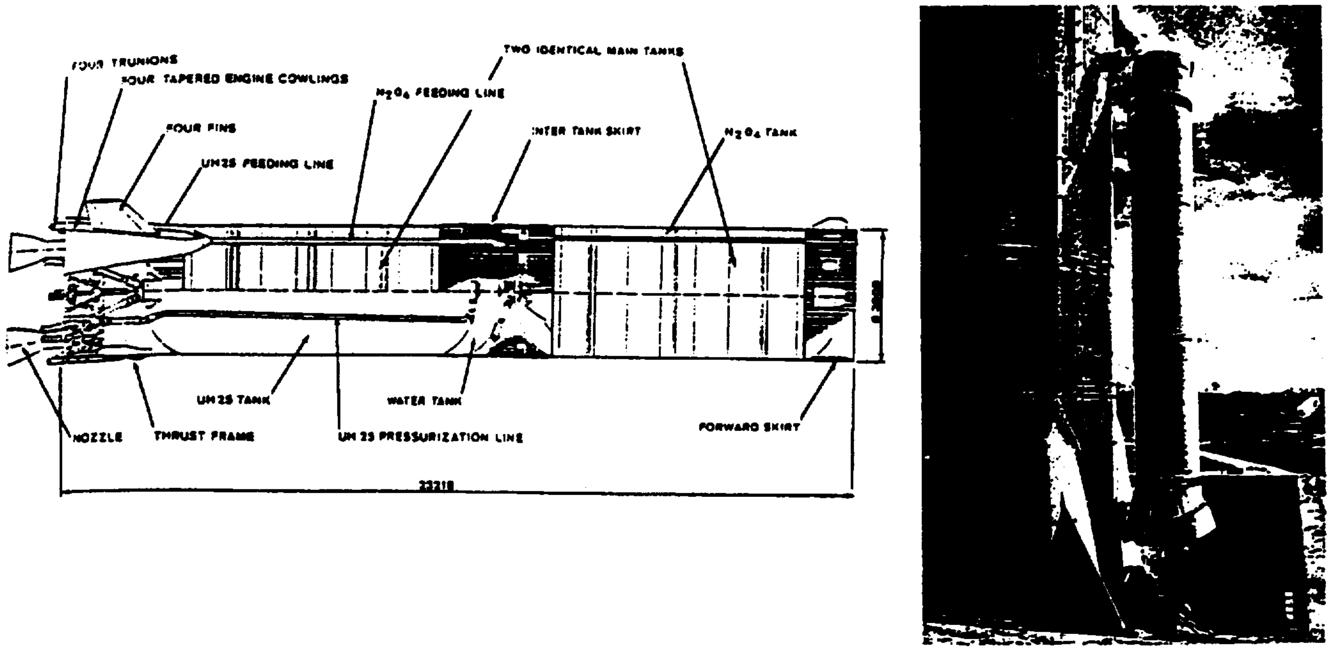


Figure 48. *Ariane 4* aerodynamic surfaces.

B. Russian

The Russians used aerodynamic surfaces of 4 ft^2 each on the *SL–1*, *SL–2*, and the *SL–5* of the 1960's. In current production, the two-stage *Kosmos* uses aerodynamic surfaces for flight stability and jet vanes for control. *Kosmos* launches 3,000 lb to GEO (fig. 49).[27] The liquid propellant first stage has a diameter of 7.9 ft with a base section that flares to a diameter of 9.35 ft. The four stabilization fins have a fin-tip to fin-tip diameter of 14.4 ft. The *Kosmos* has 400 successful launches to its credit.

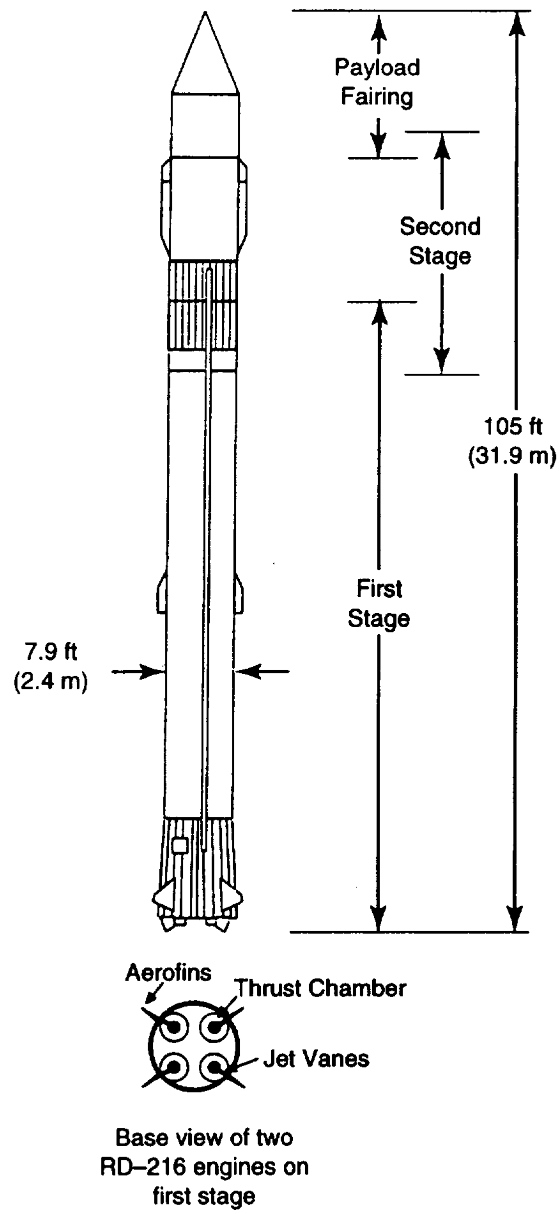
The *Tsyklon*, which means cyclone, also uses aerodynamic fins for flight stability. *Tsyklon* launches 8,800 lb to LEO and accounts for over 10 percent of all Russian launches with a success rate of 99 percent. Both the first and second stages have four vernier RCS for three-axis control. The eight vernier engines are positioned within aerodynamic shrouds which enhance the flight stability (fig. 50).[28]

The *Vostok*, *Soyuz*, and *Molniya* all use aerodynamic fins for flight stability. Sometimes they do not show up well in diagrams, but figure 50 (an actual photo) verifies their existence. In addition, the *Vostok*, *Soyuz*, and *Molniya* all use a similar set of four wide-angle, conical strap-on boosters.[28] The pronounced shape of the conical set of strap-ons has significant aerodynamic stability advantages. The *Vostok* is a 2$^1/_2$-stage L/V that launches 10,400 lb to LEO. The *Soyuz* has a more powerful core second stage and launches 15,400 lb to LEO. The *Molniya* has an additional third-stage core and its primary missions are the *Molniya*, highly elliptical, orbits. The attitude control system for all three consists of two gimbaling vernier engines on each strap-on, and four vernier engines on the core. The core second stage is controlled by four vernier engines.

Buran launches 66,000 lb to GEO and uses aerodynamic flight control of elevons, rudders, and a body flap.

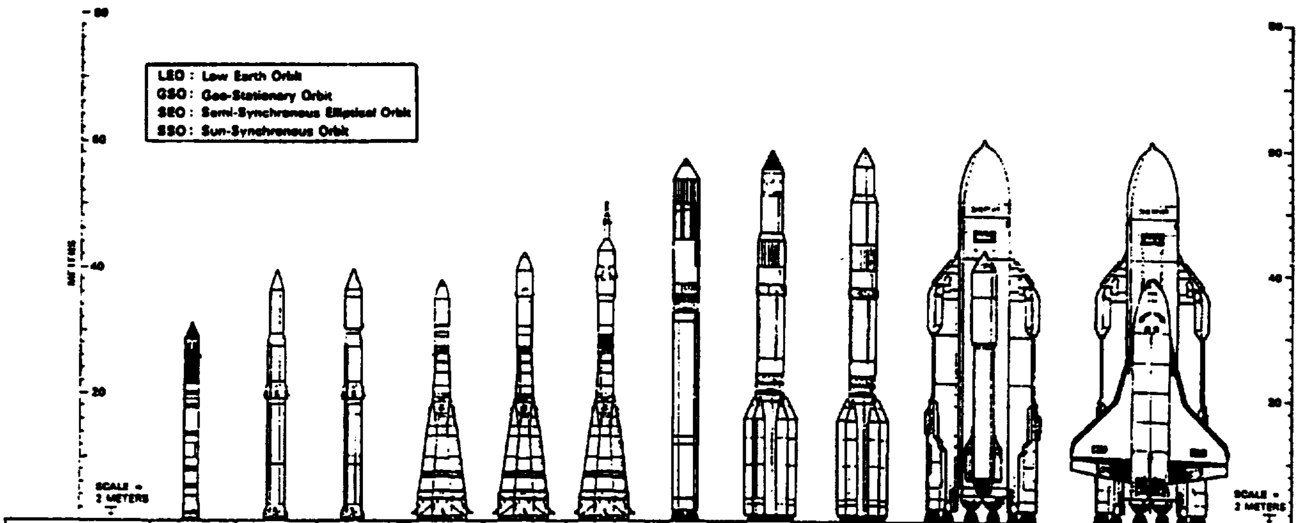
Overall

Length	105 ft (31.9m)
Gross Mass	264,000 lb (120,000 kg)
Thrust at Liftoff	330,000 lb (1,470,000 N)



Attitude Control System	The first stage is controlled by aerodynamic fins and jet vanes under the engine exhaust.

Figure 49. *Kosmos* launch vehicle.



USSR NAME	KOSMOS	—	TSYKLON	VOSTOK	MOLNIYA	SOYUZ	ZENIT	PROTON	PROTON	ENERGIYA	ENERGIYA/BURAN
US DESIGNATOR	SL-8	SL-11	SL-14	SL-3	SL-6	SL-4	SL-16	SL-12	SL-13	SL-17	SL-17
AVERAGE ANNUAL LAUNCHES (1980's)	15	5	7	2	11	41	2[a]	9	1	1[b]	1[c]
OPERATIONAL PAYLOAD CAPACITY (KG)	1,350(LEO)	—	4,000(LEO)	4,730(LEO) 1,840(SSO)	1,800(SEO)	7,240(LEO)	13,740(LEO) 11,380(SSO)	5,700(Moon) 5,300(Venus) 4,600(Mars) 2,500(GSO)	20,000(LEO)	105,000(LEO) 32,000(Moon) 28,000(Mars/Venus) 19,000(GSO)	30,000(LEO)

[a]SINCE 1985 [b]SINCE 1987 [c]SINCE 1988

Vostok: not shown publicly until 6yr after placing Gagarin in orbit, its cluster configuration is still in use *(Reginald Turnill)*

Figure 50. Russian LV's and close-up of *Vostok* fins.

C. Chinese

Most all of China's *Long March* family of L/V's incorporate aerodynamic surfaces. A variety of fin planform and sizes are used (fig. 51).[28] The *Long March 1* (*LM–1*), also designated *CZ–1* for Chang Zheng, launched China's first satellite in 1970 using aerodynamic surfaces for flight stability and was controlled in the first and second stages by jet vanes. The fin surfaces were of a trapezoidal planform, about 25 ft^2 each, and had both LE and TE sweep. The *LM–1* (*CZ–1*) was a three-stage L/V which launched 660 lb to LEO. An enhanced version, the *LM–1D* (*CZ–1D*), also wears similar trapezoidal fins for stability and uses jet vanes in the first and second stages for vehicle control. RCS is used in the ballistic coast phase. It launches 1,650 lb to LEO or 440 lb to GTO (fig. 52).[28]

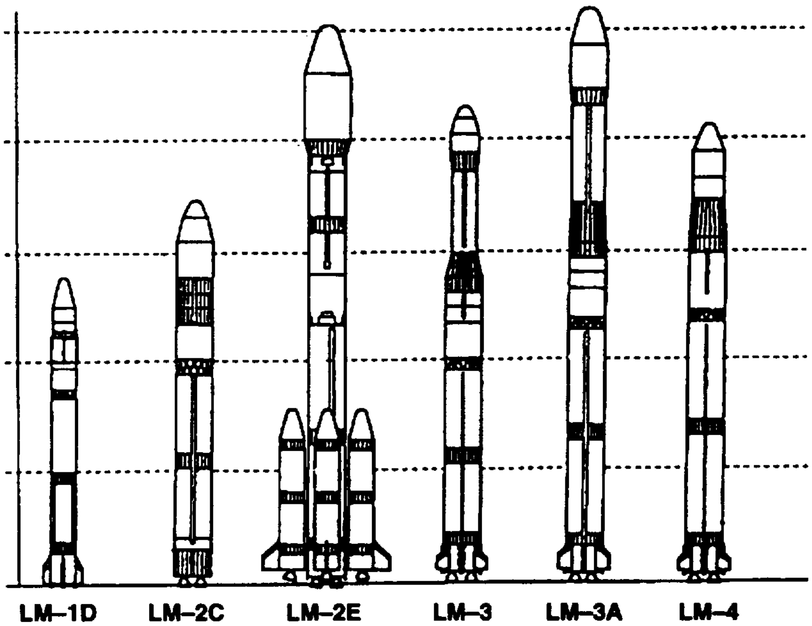
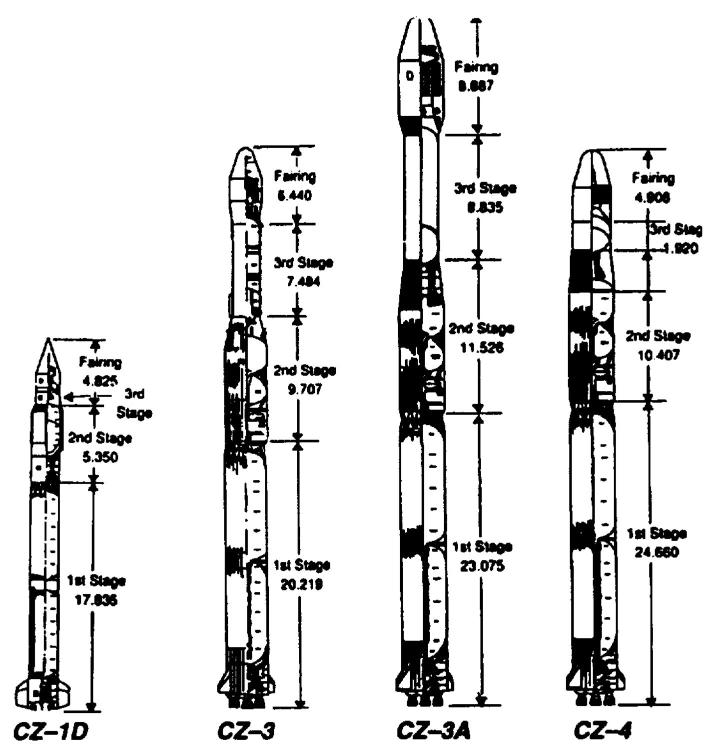


Figure 51. Chinese *Long March* L/V's.



	CZ–1D	*CZ–3*	*CZ–3A*	*CZ–4*
Length	92.6 ft (28.22 m)	144 ft (43.85 m)	172 ft (52.3 m)	138 ft (42 m)
Gross Mass	175K lb (79.4K kg)	445K lb (202K kg)	529K lb (240K kg)	549K lb (249K kg)
Thrust at Liftoff	246K lb (1,093K N)	626K lb (2,786K N)	660K lb (2,942K N)	660K lb (2,942K N)

Figure 52. Comparison of aerodynamic surfaces on *Long March* vehicles.

The *CZ–3* was first launched in 1984 and uses another planform of aerodynamic surface with an unswept TE. It is a three-stage LH_2/LOX propelled L/V and is controlled by hydraulic engine gimbaling of ±10°. The *CZ–3* launches 11,000 lb to LEO or 3,300 lb to GTO (fig. 52).

The *LM–4* (*CZ–4*) is also a three-stage L/V and was first launched in 1988. It uses trapezoidal fins about 22 ft^2 each with an LE sweep and no TE sweep. The *CZ–4* launches 8,800 lb to LEO or 2,430 lb to GTO. In 1990, China launched its first commercial satellite aboard a *CZ–3* using aerodynamic surfaces. Control is by hydraulic engine gimbaling ±10° (figs. 52 and 53).[28]

The *CZ–3A* began in 1992 as a commercial three-stage L/V for the international market. It also uses the trapezoidal fins with swept LE's and unswept TE's. The planform area of each fin is about 22 ft^2. The *CZ–3A* launched 15,800 lb to LEO and 5,500 lb to GTO (fig. 52). Control is provided by hydraulic engine gimbaling ±10°.

Figure 53. China's *CZ–4A* aerodynamic surfaces.

The *CZ–2E* also uses aerodynamic surfaces for stability and engine gimbaling of ±10° for control. The four aerodynamic fins are about 25 ft^2 each. *CZ–2E* began service in 1990 and uses liquid propellant strap-on boosters which enable it to launch 20,403 lb to LEO and 7,430 lb to GTO (fig. 51).

D. Japanese

The *L–4S* began flights in 1966 and is a four-stage L/V which uses two sets of aerodynamic surfaces for flight stability and flight control. The *TR–1* began flights in 1985 and uses aerodynamic surfaces for flight stability. The *M–3C* is a three-stage L/V using aerodynamic surfaces and launches 430 lb to LEO. The *M–3H* and *M–3S* began flights in 1980 and are both three-stage L/V's using aerodynamic surfaces and launch 640 lb to LEO. The *M–4S* began flights in 1970, and it is a larger four-stage L/V built by Nissan Motor Company. It uses aerodynamic surfaces for flight stability and launches 400 lb to LEO.

The *M–3SII* began flights in 1985 and was built for the Halley's comet mission. It is a three-stage, solid propellant L/V with two strap-on boosters. It uses four tapered aerodynamic surfaces about 17 ft^2 each with swept LE's and straight TE's for flight stability, with four small RCS attached to the tips for roll control. It launches 1,720 lb to GEO (fig. 54).[27]

The *M–5* is a 1995 L/V with launch capability of 4,300 lb. The *M–5* has been specially designed with aerodynamic surfaces that guarantee aerodynamic flight stability of the vehicle up to Mach 2.0. Thereafter, the vehicle is only slightly unstable until stage separation. Solid RCS jets are also attached to the tips of the fins for roll control (fig. 54). Three rate gyros on the first stage provide damping signals for first-stage pitch, yaw, and roll control. The *M*–5 uses INS and fiber optic gyros on the third stage. The *H*–2, also a 1995 L/V, uses a conical flare shroud.[27]

E. Other

Brazil's *VLS* began flights in 1992, launching satellites to LEO and using aerodynamic surfaces (fins) for flight stability (fig. 55).[27] India's four-stage *SLV*–3 was first launched in 1979 and uses four aerodynamic surfaces (fins) for flight stability and aerodynamic flight controls at the tips of the fins. The uprated version is the *ASLV*, which uses two strap-on boosters and launches 330 lb to LEO (fig. 56).[27] Israel's *Shavit* was first launched in 1988, taking 350 lb to LEO. It is a three-stage L/V using four aerodynamic surfaces, trapezoidal fins with swept LE's and TE's (fig. 57).[27] *Shavit* launched Israel's third Ofeq satellite in April of 1995. This launch took 600 lb to LEO (*Space News*; April 16, 1995).

V. CONCLUSIONS

This review of our national heritage of L/V's using aerodynamic surfaces for flight stability and flight control and a survey of current usage of these surfaces both in the U.S. and other nations, demonstrates their ability to provide increased flight stability and significant flight control augmentation, both in past and in current large L/V designs.

In today's aft cg L/V designs, when it has been determined that the required control authority cannot be provided by engine gimbaling alone, aerodynamic flight controls are a viable source of flight control augmentation.

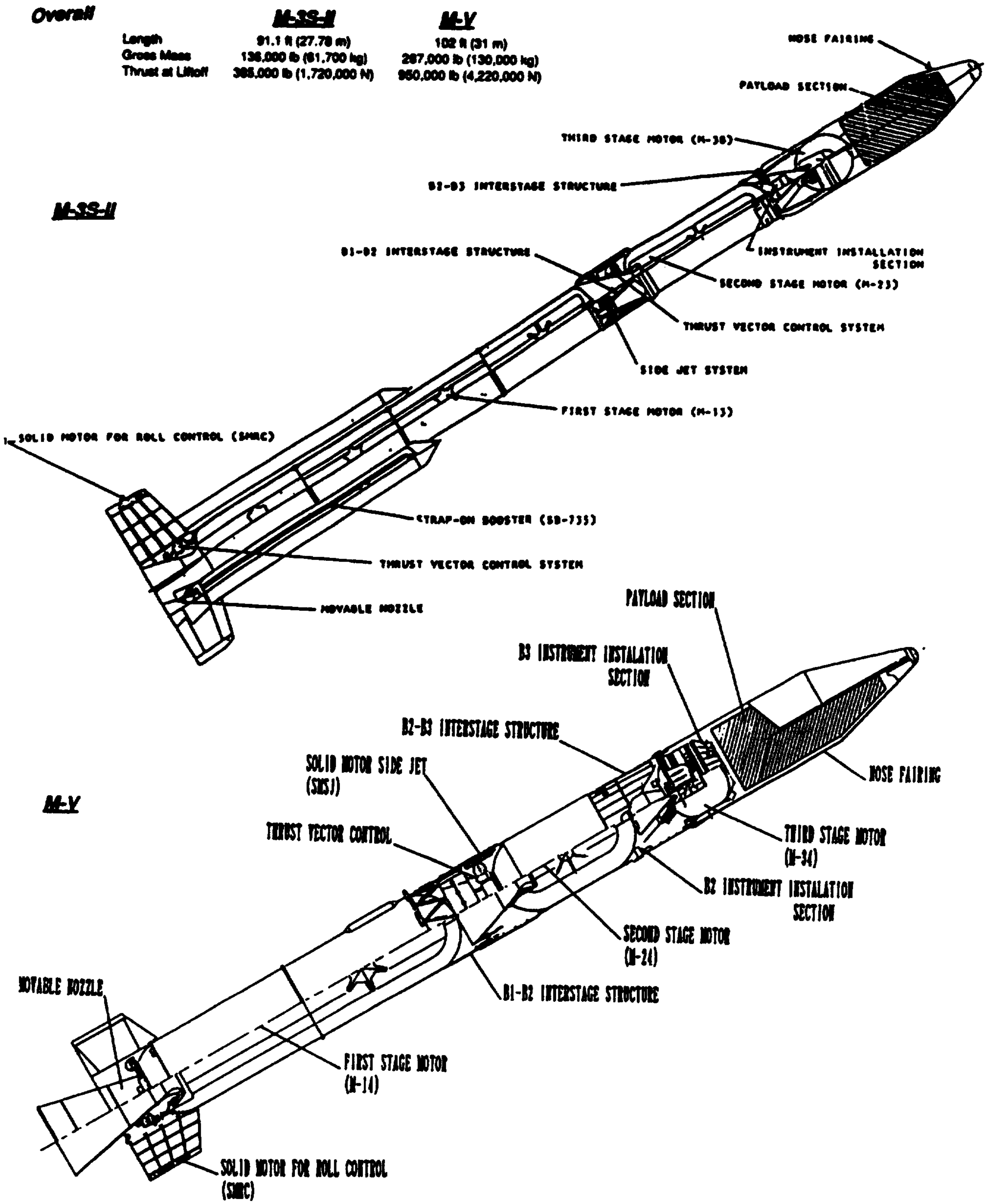


Figure 54. Japanese *M–3SII* and *M–5* L/V's.

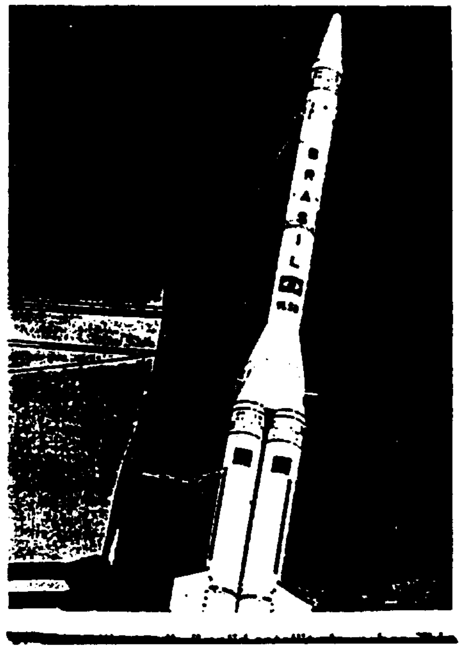


Figure 55. Brazil's *VLS* aerodynamic surfaces.

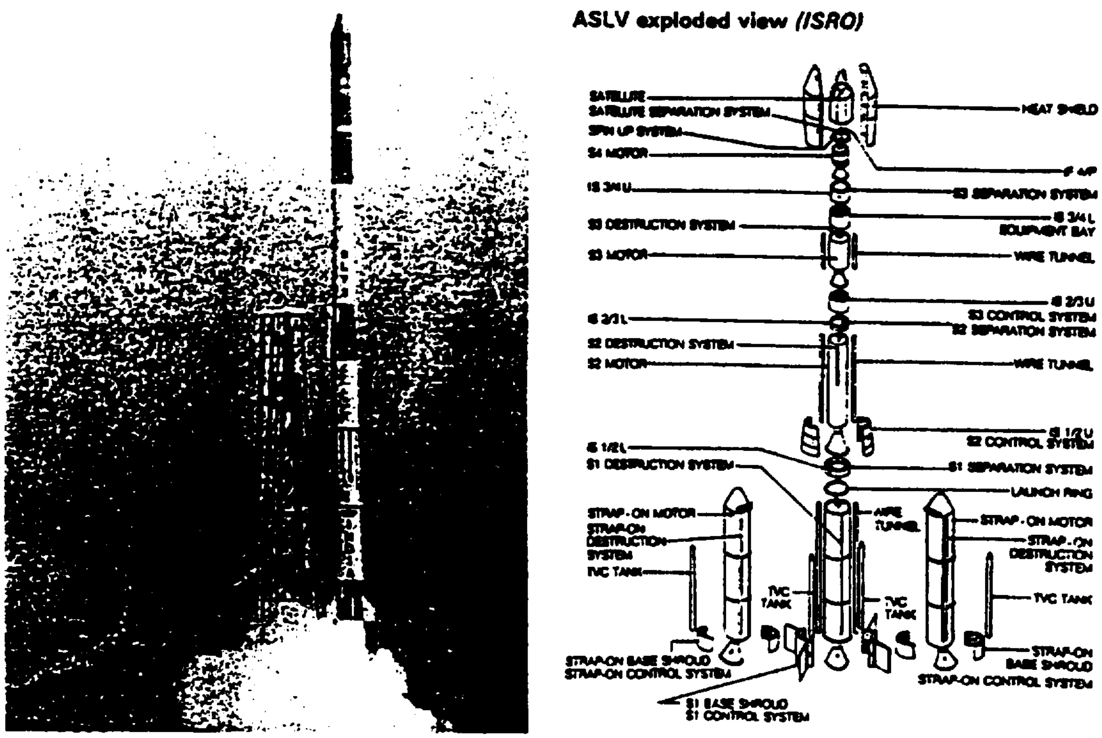


Figure 56. India's *SLV–3* and *ASLV* aerodynamic surfaces.

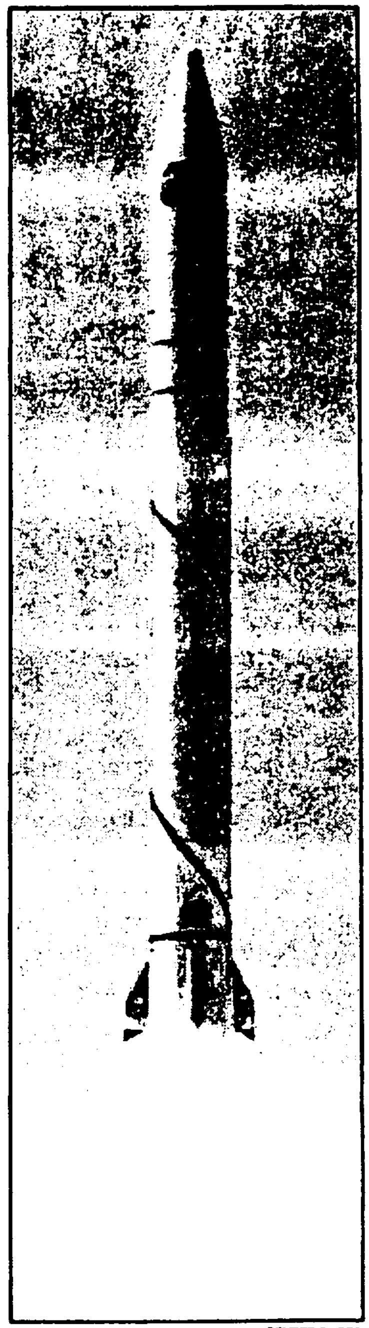


Figure 57. Israel's *Shavit* L/V.

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Marshall Space Flight Center has a rich heritage of launch vehicles that have used aerodynamic surfaces for flight stability and for flight control. Recently, due to the aft center-of-gravity (cg) locations on launch vehicles currently being studied, the need has arisen for the vehicle control augmentation that can be provided by these flight controls. Aerodynamic flight control can also reduce engine gimbaling requirements, provide actuator failure protection, enhance crew safety, and increase vehicle reliability and payload capability.

As a starting point for the novel design of aerodynamic flight control augmentors for a Saturn class, aft cg launch vehicle, this report undertakes a review of our national heritage of launch vehicles using aerodynamic surfaces, along with a survey of current use of aerodynamic surfaces on large launch vehicles of other nations. This report presents one facet of Center Director's Discretionary Fund Project 93-05 and has a previous and subsequent companion publication.

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