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# Titan Launch Vehicle: Ground Test History

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**The major aerodynamic wind-tunnel tests that span the time frame from the early Titan I vehicle developed in 1955 to the most recent Titan-family vehicle, the Titan IV solid rocket motor upgrade, last tested in 1996, are summarized. These tests cover all aspects of single- and multibodied aerodynamics including nozzle hinge moments, staging, vehicle forces and moments, dynamic and static pressure distributions, and launch facility impingement pressures. Angle of attack/side slip covers the range primarily from 0 to 10 deg and, in select cases, from 50 to 90 deg. Principal emphasis is placed on the ground tests affecting the predicted aerodynamic environment of the Titan IV launch vehicle. Significant conclusions drawn from various three-body wind-tunnel tests are presented.**

## Nomenclature

$C_A$ = drag coefficient
$C_l$ = rolling moment coefficient
$C_m$ = bending moment coefficient in the pitch plane
$C_N$ = normal force coefficient in the pitch plane
$C_n$ = bending moment coefficient in the yaw plane
$C_Y$ = side force coefficient in the yaw plane
$\alpha$ = pitch plane angle of attack
$\beta$ = yaw plane angle of side slip

## I. Introduction

A HISTORY of the major aerodynamic wind-tunnel tests that were conducted for the Titan family of launch vehicles is contained herein. Particular emphasis is given to those tests used to describe the aerodynamic environment of the most recent configuration, the Titan IV (TIV) type 1 [with solid rocket motor (SRM)] and type 2 [with solid rocket motor upgrade (SRMU)] launch vehicles. The description of the external aerodynamic environment acting on the TIV vehicle is made up of a mélange of wind-tunnel investigations of earlier Titan configurations spanning the time frame from 1955 through 1971. (The TIV U.S. Air Force program officially commenced in February of 1985.) Wind-tunnel investigations of the actual TIV configuration were conducted from 1984 through 1988 for the TIV/type 1 and from 1988 through 1996 for the TIV/type 2. The launches of all Titan vehicles were from either the Eastern Test Range (ETR) at Cape Canaveral Air Force Station in Florida or the Western Test Range (WTR) at Vandenberg Air Force Base in California.

To clarify the names and designations of the launch vehicles referred to, a brief synopsis of the mergers and acquisitions of the current Lockheed Martin Corporation (LMC) is as follows. The Glenn Martin Company was founded in 1909. In 1961, the Martin Company consolidated with American–Marietta Company and was renamed Martin Marietta Technologies, Inc. In 1993, Martin Marietta expanded by acquiring the Space Systems Division of General Dynamics and its Atlas series of launch vehicles. Merging of Martin Marietta with the Lockheed Corporation occurred in March of 1995. To help distinguish the Martin Company, Martin Marietta, or Lockheed Martin test program vs the U.S. Air Force contract program, the following evolutionary perspective of the various Titan vehicles is provided.

In October 1955, the Titan program began in earnest at the then Martin Company with the Titan I vehicle, a two-stage, single-body, silo-based intercontinental ballistic missile (ICBM). Launches of the Titan I occurred between 1959 and 1965. The Titan II (TII) was the next ICBM program that began in 1960. The TII was launched between 1962 and 1976 and was the first missile to use an inertial guidance system. This single-body weapons system was deactivated in 1987. Offshoots of the TII weapons program were the TII/Gemini, consisting of 12 launches between 1964 and 1966, and the TII space launch vehicle (SLV). The TII SLV was used for various small Department of Defense (DOD) payloads launched from the WTR spanning the contract period from 1986 through 1995. Clementine, the moon-mapping mission, was launched using a TII in January of 1994.

The need for a launch platform capable of carrying heavy payloads into geosynchronous, polar, and low Earth orbits necessitated the design of a three-body configuration. A three-bodied launch vehicle consists of a payload fairing (PLF) (sometimes referred to as a shroud) that protects the spacecraft, a core afterbody (usually two stages each of a liquid propellant fuel system), and two SRMs (or type 1 solids) of near equal diameter as the core. The Martin Company 624A program is the earliest mention of a three-body configuration found in the archived aerodynamic test documents on site at LMC. It was a developmental test program conducted in the early 1960s to accumulate aerodynamic data for various three-body launch vehicle designs. However, the 624A vehicle, per se, was never flown.

The first U.S. Air Force-sponsored program of a two-stage liquid-propellant core vehicle augmented with two SRMs began in the early 1960s with the Titan III (TIII) program. One of the single-body versions, that is, no SRM strap-ons, of the TIII program was the TIIIA vehicle. This Titan vehicle used a transtage upper module for the third stage, and it flew four developmental missions from 1964 through 1966. Another core-only program was the launch vehicle called Titan IIIB. Of the 68 TIIIB launches, 67 were successful. A TIIIB vehicle with the Agena upper stage was last launched at WTR in the middle 1970s. The TIIIA and TIIIB vehicles evolved into the TIIIC launch vehicle configuration with two five-segment strap-ons.

The TIIIC (launched from ETR) and TIIID (WTR launched) were three-bodied vehicles that flew from July of 1965 to March of 1982. Non-DOD payloads were launched on the Titan IIIE vehicle. The TIIIE, a 14-ft-diam bulbous PLF with a 25/15-deg biconic nose cone (similar to the TIV biconic nose cone), used a Centaur upper stage to boost the interplanetary missions of the Viking spacecraft to Mars and the Voyager spacecraft to Jupiter and Saturn. Launched out of ETR, the TIIIE flew from 1974 to 1977.

The next three-bodied configuration, designated the TIIIM vehicle, was designed to launch the Manned Orbiting Laboratory (MOL) from Vandenberg Air Force Base. This vehicle incorporated

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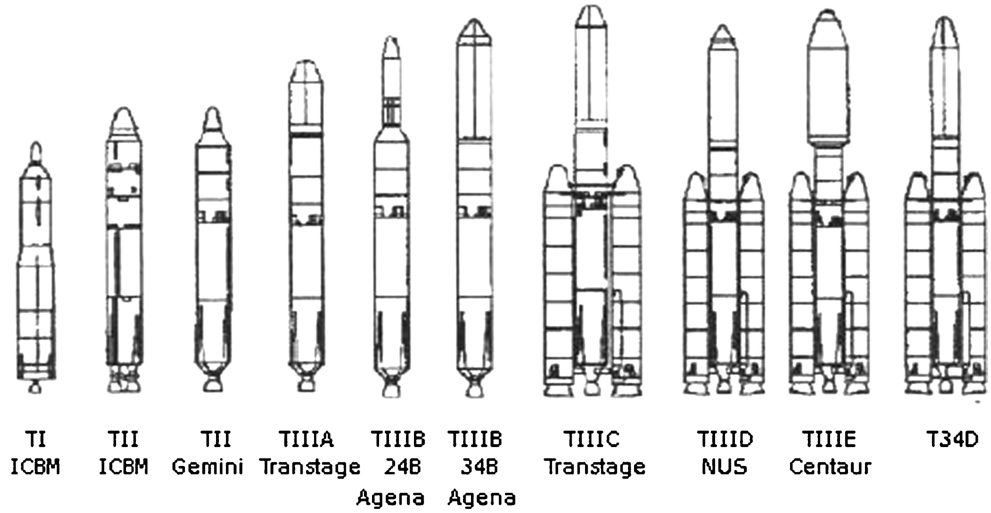


**Fig. 1 Titan launch vehicle evolution.**

seven-segment solid rocket motors. However, the program was canceled, and the TIIIM was never flown. It did provide for the completion of several successful wind-tunnel test programs that were used extensively for the development of subsequent Titan vehicles. The TIII class vehicles were the forerunner to the T34B and T34D (a stretched version of the T34B core) vehicles. These vehicles had a 10-ft-diam PLF with up to 60-ft PLF lengths. They were used with several upper stages including an inertial upper stage (IUS), Agena, and Transtage.

Developed as a backup for the shuttle, the T34D was first launched in 1982 from ETR. It provided heavy-lift capability, using $5\frac{1}{2}$-segment SRMs. Keep in mind that the T34D launch vehicle configuration was never tested in a wind tunnel. Its pressures, loads, and aerodynamic coefficients were determined solely from TIIIC, TIIIM, and TIIIE wind-tunnel tests. The Commercial TIII launch vehicle, developed in the late 1980s, was an upgraded version of the T34D. Evolution of the various Titan vehicle designs are shown in Fig. 1. (Note that the figures presented herein are intended to give the reader a qualitative sense of the various vehicle configurations discussed. They come from test reports of up to 45 years old where the original type face was sometimes faded and difficult to read. Some were copied from engineering working papers where the original test report was not available.)

The TIV, named SLV-X, IELV, CELV and T34D-7 at various times in its early developmental stages (1984–1986), consists of a 10-ft-diam core, 16.67-ft (200-in.)-diam bulbous PLF and various PLF lengths with a 25/15-deg biconic nose cone. Two SRMs, each providing 1,500,000-lb thrust, are symmetrically located in the yaw plane of the TIV. Thrust vector control (TVC) steering with a fixed 6-deg nozzle cant angle, canted outboard in the yaw plane, describe the SRMs. In 1987, a $10\frac{1}{2}$-ft-diam × 40-ft-long PLF was considered for the Titan IV family, but later canceled. The various TIV configurations are denoted by U.S. Air Force specification numbers SS-ELV-401, 402, 403, 404, and 405.

Launch vehicle configurations SS-ELV-401 consists of PLF lengths of 86, 76, and 66 ft with a Centaur upper stage that lifts up to 10,000-lb payloads into a geosynchronous Earth orbit (GEO). Centaur vehicles are launched exclusively from ETR. The SS-ELV-402 configuration, also launched from ETR, is a 56-ft PLF with an IUS designed to boost approximately 5000-lb spacecraft into GEO. Both 56- and 66-ft PLF length TIVs with no upper stage (NUS) lift spacecraft to a low Earth orbit (LEO) on SS-ELV-403 configurations and are typically launched from WTR. A SS-ELV-404 NUS boosts the integrated TPA 50+ ft PLF into LEO and is solely launched from WTR. The uniqueness of the TPA is due to a 4-in.-high forwardfacing outboard flange located on the aft portion of the PLF (an aerodynamicist's nightmare). The SS-ELV-405 configuration consists of a 56-ft PLF and lifts spacecraft into LEO. There are 405 configurations that have the capability to launch from both ETR and WTR. WTR is used to launch all polar orbital missions.

The SRMU (or type 2 solids) is advertised to add approximately 25% additional payload-carrying capability to the TIV launch vehicle. Differences between the SRM and SRMU are an increase in diameter from 120 to 126 in. and approximately 10 in. in nose cone length. The SRMU utilizes a gimbaled engine for steering, thus, no TVC tanks.

Included herein are summaries of the major Titan wind-tunnel tests, a view of the vehicle configuration tested in the tunnel, and the primary use of the data from each test. Summary Tables 1–5 are provided to give details concerning the wind-tunnel model scale, program name, test location, configuration description, Mach number, Reynolds number, and angle-of-attack/side-slip range with the specific type of data taken during each test. Specifically, Tables 1 and 2 summarize the five staging and hinge moment tests of Refs. 1–5. Tables 3 and 4 encapsulate the 11 force, moment, buffet, and pressure tests of Refs. 6–16. Finally, Table 5 provides the details of the ground wind contamination study of Ref. 17 (which is the only Titan test conducted in a water tunnel) in addition to the remaining eight ground wind-load and wind-induced-oscillation tests of Refs. 18–25.

## II. Pre-TIV Wind-Tunnel Test Summary

### A. 1% Scale Cold-Flow Staging Tests[1] and SM-68 Cold-Jet Staging Force and Pressure Test[2]

The test programs described in Refs. 1 and 2 were the primary source of data used to describe the pressures and forces on the stage I oxygen dome and the pressures within the interstage compartment of stage II during the fire-in-the-hole staging event. Fire-in-the-hole is used to describe this staging event due to the fact that the stage II nozzle fires and impinges on the oxygen dome of step 1. Step 1 is referred to as the portion of the rocket that is ejected from the vehicle during fire-in-the-hole staging. The exhaust exits through the vents located in the walls of the interstage compartment. Puffs of red dust observed during the actual staging event of a T34D launch have been attributed to the stage II nozzle burning through the insulation on the oxygen dome.

The staging data from Refs. 1 and 2 are used in designing the hardware and structure of the stage I and II compartments. Also, the forces acting on step 1 are used in the separation analysis. These data were updated in the computational analysis documented in Ref. 26. The vehicle configurations used in Refs. 1 and 2 are shown in Figs. 2 and 3, respectively.

**Table 1 Staging and hinge moment wind-tunnel tests; test conditions**

| | | | | | Freestream conditions | | Vehicle attitude range, deg | | |
|---|---|---|---|---|---|---|---|---|---|
| Ref. | Test year | Test type | Model scale, % | Program | Mach no. range | Reynolds no.[a] | Angle of attack | Angle of side slip | Roll angle |
| 1 | 1959/1960 | Staging | 1 | Titan | n/a | n/a | n/a | n/a | n/a |
| 2 | 1960 | Staging | 4 | SM-68B | n/a | n/a | n/a | n/a | n/a |
| 3 | 1967 | Staging | 1.5 | TIIIM | 5.01, 5.42, 5.85 | $0.12E6$–$0.31E6$ | $-4, 0, 4$ | 0, 2, 5 | $-30, 0, 30, 90$ |
| 4 | 1967 | Hinge-Moment | 8 | TIIIB | 0.7–1.6 | —— | $0 < \alpha < 12$ | $0 < \beta < 12$ | 0, 22.5, 45, 90 |
| 5 | 1989 | Hinge-Moment | 4 | TIV/SRMU | 0.6–1.6 | 3E6 | $-8 < \alpha < 8$ | $-8 < \beta < 8$ | 0, 22.5, 45, 67.5, 90 |

[a]Based on vehicle core diameter.

**Table 2 Staging and hinge moment wind-tunnel tests; test description**

| Ref. | Wind-tunnel facility | Configuration description | Available data | Comments |
|---|---|---|---|---|
| 1 | Martin Environmental Laboratory | Stage II engine impinging on stage I Liquid Oxygen (LOX) dome | Pressures | Cold-flow stage II engine exhaust, fire-in-the-hole staging |
| 2 | Naval Ord. Laboratory and Rocket Test Facility[a] | Stage II engine impinging on stage I LOX dome | Pressures, step 1 forces and moments | Cold-flow stage II engine exhaust, fire-in-the-hole staging |
| 3 | Tunnel A[a] | Three-body with TVC PLF type: conical with manned orbiting laboratory protuberances | $C_N$, $C_m$, $C_A$, $C_l$ for solids only | Step 0 staging, full $\Delta X/D$, $\Delta Y/D$ movement of solids, coefficients normalized to thrust |
| 4 | 16-ft transonic[a] | Single-body TIIIB | Load distribution on nozzle | Stage I 12:1 engines, gimbal angles $\pm 7$ deg |
| 5 | 16-ft transonic[a] | Three-body, with and without aerofairings of 15 and 25 in. | Load distribution on nozzle | Test showed no aerofairing gives lowest hinge-moment, gimbal angles 0–5 deg |

[a]At AEDC.

**Table 3 Force and moment, buffet and pressure wind tunnel tests; test conditions**

| | | | | | Freestream | | Vehicle attitude range, deg | | |
|---|---|---|---|---|---|---|---|---|---|
| Ref. | Test year | Test type | Scale % | Program | Mach range | Reynolds no.[a] | Angle of attack | Angle of side slip | Roll angle |
| 6 | 1962 | Force and moment | 4 | 624A | 0.12–0.35 | $1.6E6$ | $50 < \alpha < 90$ | —— | $0 < \phi < 180$ |
| 7 | 1962 | Force and moment | 4 | 624A | 0.6–3.52 | —— | $-12 < \alpha < 12$ | $-8 < \beta < 8$ | —— |
| 8 | 1965 | Force and moment pressure | 4 6 | TIIIB/Agena | 0.6–3.1 | $2E6$–$3E6$ | $-8 < \alpha < 11$ | $-4 < \beta < 11$ | —— |
| 9 | 1966 | Buffet/acoustic | 7 | TIII Class | 0.6–1.6 | $1.2E6$–$3.7E6$ | $0 < \alpha < 4$ | —— | —— |
| 10 | 1969 | Pressure | 1 | TIIID | —— | —— | —— | —— | —— |
| 11 | 1970 | Force and moment pressure | 2.8 | TIII Class | 0.6–2.0 | $1.5E6$–$4.3E6$ | $-2 < \alpha < 12$ | $0 < \beta < 10$ | —— |
| 12 | 1971 | Force and moment pressure acoustic | 3 | TIIIE | 0.6–1.96 | —— | $-10 < \alpha < 5$ | $-10 < \beta < 5$ | —— |
| 13 | 1984 | Force and moment | 2.8 | IELV TIV/SRM | 0.6–2.0 | $3E6$–$5E6$ | $-6 < \alpha < 6$ | $-6 < \beta < 6$ | —— |
| 14 | 1985 | Force and moment pressure | 2.35 2.8 | T34D7/CELV TIV | 0.6–2.0 | $3E6$ | $-6 < \alpha < 6$ | $-6 < \beta < 6$ | —— |
| 15 | 1988 | Pressure buffet acoustic | 7.9 | TIV/SRM TIIIC, TIIIE | 0.6–1.6 | $3E6$ | $-4 < \alpha < 4$ | $-4 < \beta < 4$ | —— |
| 16 | 1989 | Force and moment | 2.8 | TIV/SRMU | 0.6–1.6 | $3E6$ | $-8 < \alpha < 8$ | $-8 < \beta < 8$ | —— |

[a]Based on vehicle core diameter.

### B. Crossflow Tests of a 0.04-Scale Model of the Martin 624A SLV[6]

Data from this low-speed crossflow wind-tunnel test of a three-bodied 624A standardized space launch vehicle model at angles of attack between 50 and 90 deg contribute to the launch aerodynamic description of the TIV. The behavior of the force data at 50 deg shows a marked increase in the force coefficient relative to that observed between 70 and 90 deg. This behavior is one of the reasons why it is difficult to interpolate force coefficients for angles of attack less than 50 deg and more than the typical maximum tested angle of 10 deg. Experimental data are not available for a force and moment description of a three-bodied launch vehicle between the angle-of-attack/side-slip range $10 < \alpha/\beta < 50$ deg. A view of the configuration used in this test is shown in Fig. 4.

These data provided the source for all launch aerodynamics of Titan three-bodied vehicles until 1995. In 1995, a methodology[27] was described that couples the data from Ref. 6 and that of Refs. 18–25 to give a more complete launch aerodynamic description for the TIV SRM/SRMU. These data are used in vehicle drift analyses, that is, analyses that describe the vehicle motion with respect to the launch pad in the presence of a crosswind. Typically, these data are not used in ascent simulations because "aero" is not turned on until after a vehicle rise of approximately 5000 ft. At this altitude, the angle of attack/side slip of the launch vehicle becomes less than 10 deg, and other data sources for vehicle aerodynamics are used.

### C. 4% Scale 624A Force and Pressure Test in the NASA Ames Research Center Unitary Plan Wind Tunnel[7]

This test was used to evaluate the consequence of a Dyna-Soar payload fairing on the stability of a three-bodied configuration. It also shows the effect of SRMs on the vehicle force and moment coefficients. The schlieren photographs taken during testing are excellent and show the interaction of the flow adjacent to the nosecone of the

Table 4 Force and moment, buffet and pressure wind-tunnel tests; test descriptions

| Ref. | Wind tunnel | Configuration description | Available data | Comments |
|---|---|---|---|---|
| 6 | Cornell 8-ft | Three-body with TVC PLF type: conical, bulbous, Dyana-Soar | $C_N, C_m, C_Y, C_n, C_A, C_l$ | No boundary layer, data describing launch aerodynamics for TIV |
| 7 | Ames Unitary Plan | Three-body with TVC PLF type: conical, bulbous, Dyna-Soar | Pressure distributions $C_N, C_m, C_Y, C_n, C_A, C_l$ | |
| 8 | Propulsion Facility[a] | Single-body TIIIB | Pressure distributions static, acoustics $C_Y, C_n, C_A, C_l$ | |
| 9 | Propulsion Facility[a] | Single-body, three-body, no TVC PLF type: conical, bulbous | Strain gauges, accelerometers | Vehicle stability, vortex generator placed on boattail |
| 10 | Martin Cold-Flow Laboratory | SLC-4E umbilical tower and cold jet simulating solid exhaust flow | Pressures on umbilical tower | Exhaust flow of solids above umbilical tower simulates vehicle above the pad |
| 11 | Unitary Plan[b] | Multibodied various PLFs | Pressure distributions $C_N, C_m, C_Y, C_n, C_A, C_l$ | 9 configurations, 4 PLFs and 2 afterbodies |
| 12 | 8 × 6 ft NASA[c] | Three-body truncated SRMs bulbous PLF and TIIID base | Pressure distributions static, acoustics $C_Y, C_n, C_A, C_l$ | Hydrogen vent fin, field splices on PLF |
| 13 | 4-ft transonic[a] | Three-body with TVC | $C_N, C_m, C_Y, C_n, C_A, C_l$ | |
| 14 | 4-ft transonic[a] | Three-body with TVC | Pressure distributions $C_N, C_m, C_Y, C_n, C_A, C_l$ | PLF boattail to SRM nose distance varied forcing function, acoustics, and aero |
| 15 | 16-ft transonic[a] | Three-body truncated | Static, dynamic, acoustic pressures | Forcing function, acoustics, and aero |
| 16 | 16-ft transonic[a] | Three-body, with aerofairings | Pressure distributions $C_N, C_m, C_Y, C_n, C_A, C_l$ | Various aerofairing configuration |

[a]At AEDC. [b]At NASA Ames Research Center. [c]At NASA John H. Glenn Research Center at Lewis Field.

Table 5 Major Titan wind-tunnel tests; ground wind loads

| Ref. | Test year | Model scale | Program | Location | Wind azimuth, deg | Configuration description | Comments |
|---|---|---|---|---|---|---|---|
| 17 | 1992 | 1.5% | TIV | ETR, WTR | 0–360 | 200-in. diam PLF only | Contamination study conducted at Colorado State University water tunnel |
| 18 | 1986 | 1:100 | TIV/CELV | ETR LC-41 | 0–360 | Three-body SRM | With and without MST |
| 19 | 1986 | 1:150 | TIV/MST | WTR SLC-4E | 0–360 | Mobile service tower only | Wind loads on MST |
| 20 | 1986 | 1:150 | TIV/MST | WTR SLC-4E | 0–360 | Mobile service tower only | Wind loads on MST |
| 21 | 1987 | 1:100 | TIV | ETR LC-41 | 0–360 | Three-body SRM, 56 and 66 PLF | No MST |
| 22 | 1989 | 1:100 | TIV | WTR SLC-4E | 0–360 | Three-body SRM, 56 and 66 PLF with SRMU 56 PLF with SRM | |
| 23 | 1995 | 1:100 | TIV | ETR, WTR | 100,112.5 at ETR 60, 240 at WTR | Three-body, 56, 66, and 44 PLFs, SRM/SRMU | Supplemental data to Refs. 13 and 14 |
| 24 | 1996 | 1:100 | TIV | ETR | 0–270 | Three-body SRMU modeled above pad | Pre/postlaunch loads |
| 25 | 1996 | 1:100 | TIV | ETR LC-40 and 41 | 0–360 | Three-body SRMU 86 and 66 PLF | Determine effect of MST at various pull-back positions |

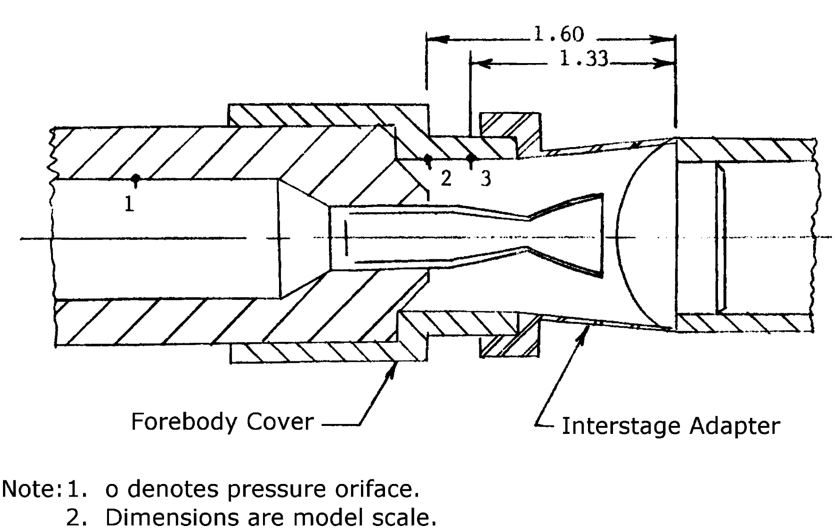


Fig. 2 Test configuration, 1% scale model cold flow fire-in-the-hole staging.[1]

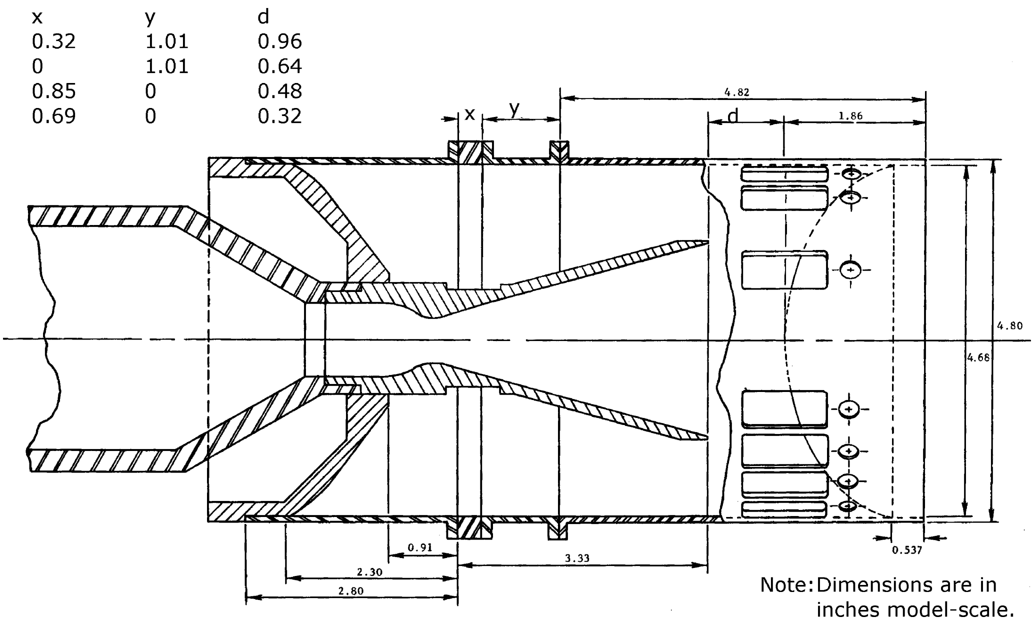


**Fig. 3 SM-68 cold jet fire-in-the-hole staging model force and moment test configuration.[2]**

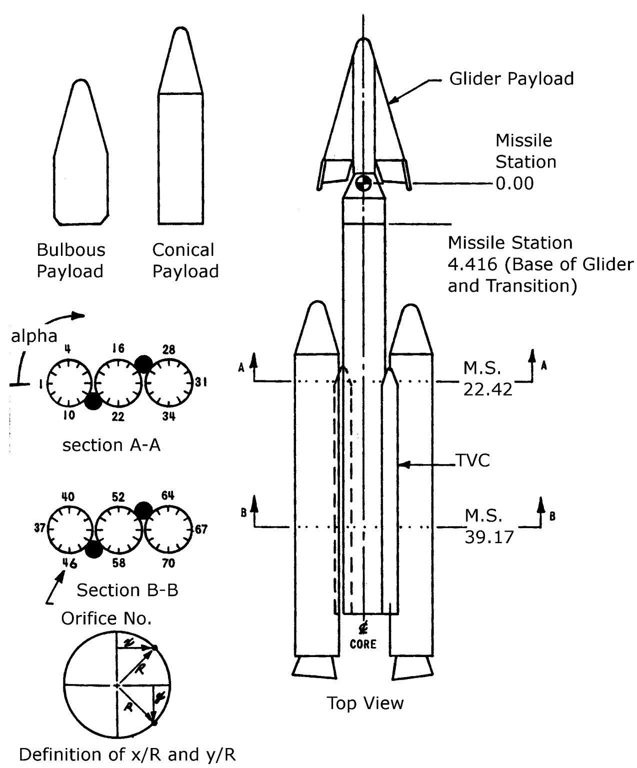


**Fig. 4 Low-speed wind-tunnel crossflow tests for 624A vehicle configuration.[6]**

solids and downstream of the PLF boattail. However, these data are not directly used in any TIV analyses. See Fig. 5 for the vehicle configuration used in this test.

### D. TIIIB Aerodynamic Test[8]

The TIIIB Agena single-body launch vehicle configuration was used in this wind-tunnel investigation. Two scale models were utilized in the test, a 6% vehicle model in the pressure portion and a 4% model in the force portion of the test. A substantial amount of sound pressure data was taken to define the acoustic–vibration environment of internal compartments of the vehicle that would house critical equipment. The vehicle configuration is shown in Fig. 6. These data are not directly used in any TIV aerodynamic analyses.

### E. 7% Transonic Buffet Model Test for Various Titan III Configurations[9]

The primary objective of the wind-tunnel investigation described in Ref. 9 was to measure the launch vehicle bending moments produced by the transonic buffeting pressures on several TIII configurations. Buffeting pressures arise from the fluctuating nature of pressures along the external skin of the entire launch vehicle. High-buffet loads are particularly prevalent during transonic flight. Second, acoustic pressure levels were obtained.

The test article was a 7% dynamically scaled model of the TIII with various payloads, upper stages, and five- and seven-segment SRMs (Fig. 7). Two booster configurations included a TIIIA single body and a TIIIC three body. The TIIIC configuration consisted of two different upper stages of 8.3- and 24.5-ft PLF lengths, both 22-ft-diam bulbous shrouds included a 15-deg conic nose section. Boattail angles of 45 deg and a biconic boat-tail with 6.45/35-deg angles were used on the bulbous TIIIC configuration. A 15-ft-diam shroud with a 17-deg conic nose, 35-deg boattail angle, and lengths of 20, 40, and 44 ft was also tested. Upper stages were designated as transtage or Centaur. To try to stabilize the flow aft of the boattail region, vortex generators were mounted both forward and aft of the boattail junction in several configurations.

The model was instrumented with strain gauges and accelerometers. Unique in this test was the measurement of the response of the elastic model, rather than the forcing function itself. Based on the results of this test, the following conclusions are drawn:

1) The TIIIA (single-body) configuration had no appreciable buffet loads and was stable.

2) The TIIIC (three-body) configuration with a standard fairing had appreciable buffet loads, but was stable.

3) The bulbous TIIIC configuration was unstable with the shorter (8.3-ft) shroud, unstable with the biconic boattail (however, with vortex generators attached became stable), and stable with the longer (24.5-ft) shroud.

### F. TIIIM Aerodynamic 1.5%-Scale Model Staging Test[3]

The test described in Ref. 3 identified the forces and moments that act on the SMRs and the core during stage zero/one (O/I) separation (step-0 staging). A TIIIM vehicle configuration with seven-segment solids, TVCs, and a Gemini/MOL PLF was used. The core and each solid were sting mounted and staging was simulated at discrete $\Delta X/\Delta D$ and $\Delta Y/\Delta D$ solid rocket separation distances. Here, $\Delta X$ and $\Delta Y$ are longitudinal (aft positive) and lateral (outward from the core positive) SRM displacement distances, respectively, and $\Delta D$ is the core diameter. Core angles of attack/side slip

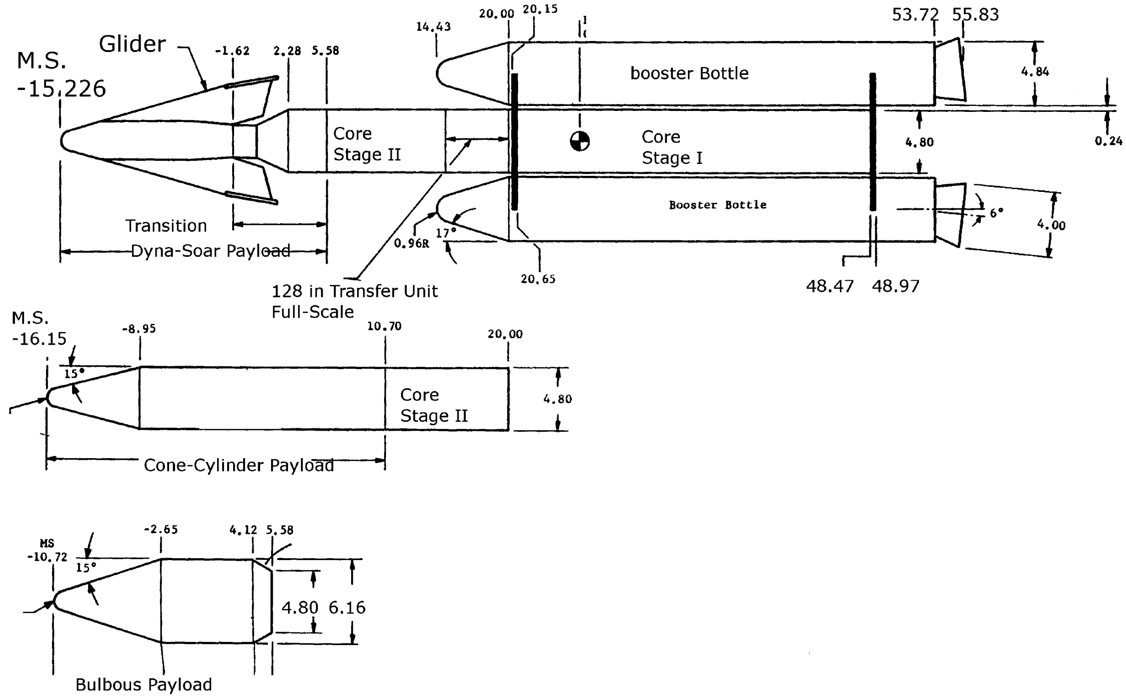


**Fig. 5 Scaled 624A force and pressure test vehicle configuration.[7]**

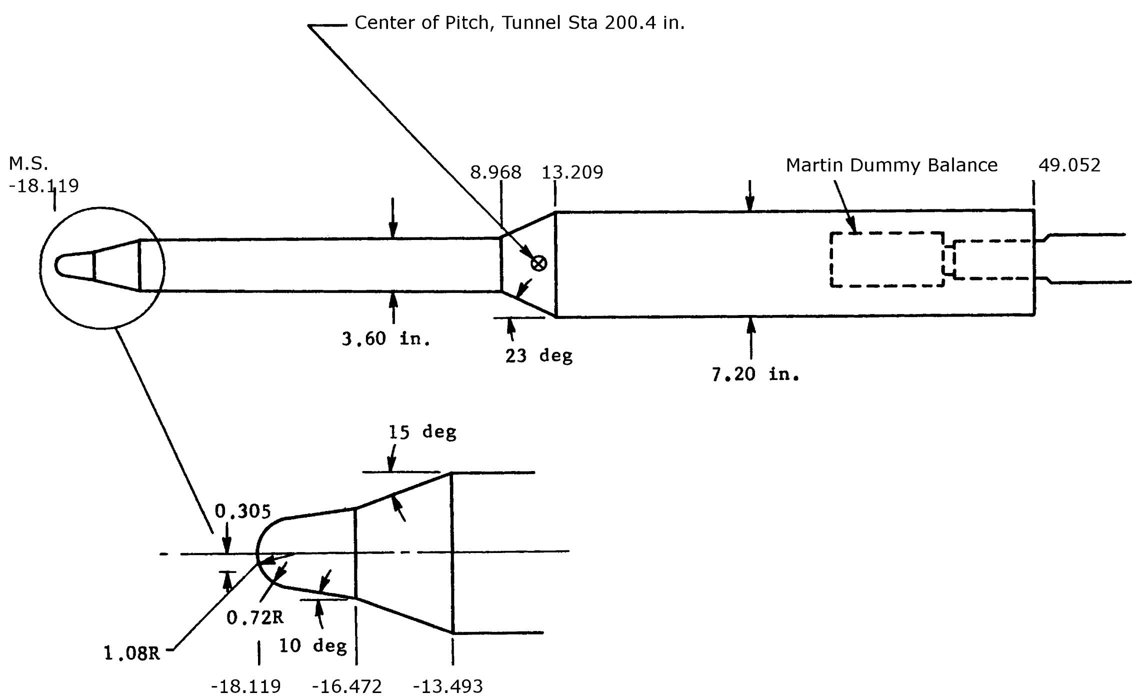


**Fig. 6 Aerodynamic test for TIIIB/Agena vehicle configuration.[8]**

varied ±4 deg. See Fig. 8 for the vehicle configuration used in this test.

These data were used to describe the stage O/I separation loads for all three-bodied launch vehicles from the time of the test, 1967–1986. The data were provided in the form of coefficients and normalized with the freestream dynamic pressure. In 1986, the raw wind-tunnel data were reevaluated and adjusted for the TIV configuration using core engine thrust as the normalizing parameter. Several updates to these original loads were necessary to encompass the differences in staging altitude and core angle-of-attack/side-slip ranges of the TIV SRM.

In the 1987 time frame, a staging test of the new TIV/SRMU vehicle was suggested, but opposed by Martin Marietta management because the no-aero condition, that is, not accounting for the aerodynamic effect of helping the solids to stage by pushing them outward, was considered worst case in the analysis of the separation of the solids. Since that time, a "nose-in" condition and small clearances of the core shear tie by the solid is a driver in the staging analysis, thus negating the original reason for not testing the configuration.

In the opinion of the author, each vehicle configuration change that has occurred through the years and consequently the need to extrapolate the data adds undue conservatism (ideally, however, not guaranteed) to the original wind-tunnel data. Therefore, a new test for the next three-body vehicle configuration is imperative. New test data along with a comprehensive computational fluid dynamics investigation is necessary to gain confidence in understanding the

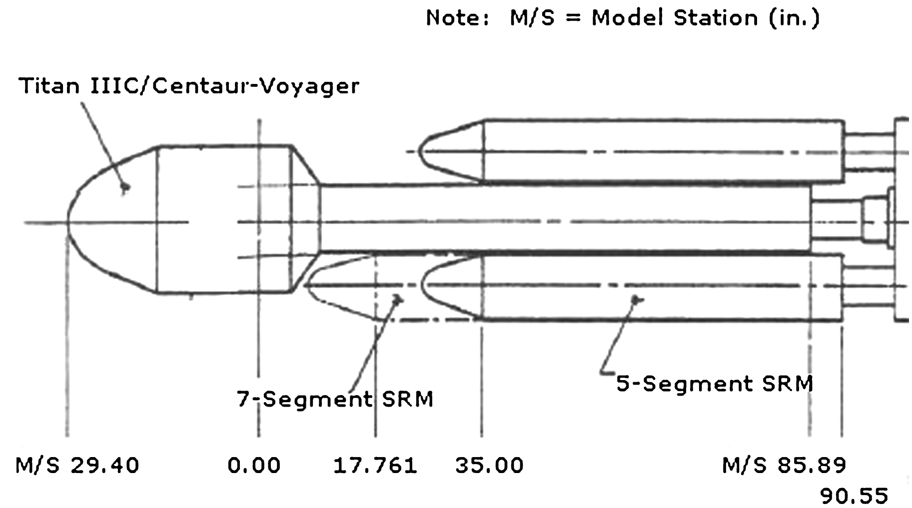


**Fig. 7 Transonic buffet model wind-tunnel configuration.[9]**

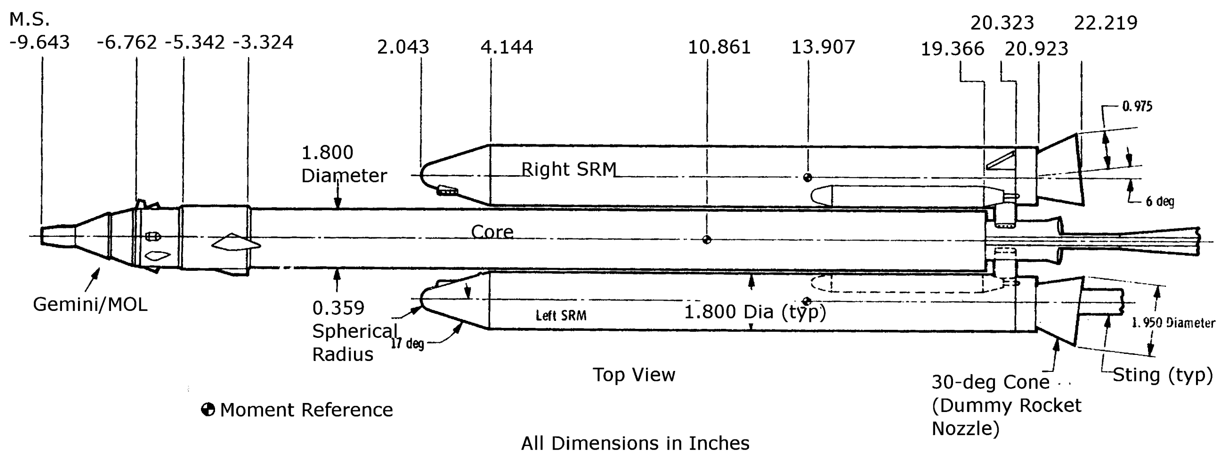


**Fig. 8 TIIIM aerodynamic model test configuration.[3]**

loads on the core vehicle, as well as the solid or liquid boosters during separation. A history of the TIV staging coefficients may be gleaned from Refs. 28–32.

### G. Category A Studies, 12:1 Stage I Nozzle Hinge Moment Test[33]

The test described in Ref. 33 was used to investigate the hinge moments on the two stage I (12:1) engines for a TIIIB single-body launch vehicle configuration. Various aft-end mounted scoop configurations directed freestream flow onto the nozzles. Small-diameter (40-in.) strap-on rockets were also tested. A strut was mounted to the floor of the wind tunnel and was used to provide cold-flowing air that simulated the nozzle and turbine exhaust flows. The data from this test were one of the sources for the preliminary prediction of the TIV/SRMU hinge moments.

### H. SLC-4E Umbilical Tower Impingement Test[34]

The test presented in Ref. 34 test describes a plume impingement investigation of the WTR Space Launch Complex-4 East (SLC-4E) 1% scale model umbilical tower. SRM exhaust was simulated by a cold-gas nozzle that was located at various positions above and to the side of the umbilical tower. The data from this test were used to develop the negative pressure correlation for all above-ground structures at the west and east coast launch complexes that was published in the 1986 time frame. Negative pressure is due to the plume impinging on, for example, a roof, and spilling over the side of the structure (expanding the flow) causing a low-pressure region that extends down the side of the edifice. Several figures describing negative pressure are included in both TIV design criteria documents for WTR and ETR. The architectural and engineering contractor that designs the launch pad are the primary recipients of these data.

### I. Wind-Tunnel Tests on Multibodied Launch Vehicle Models with Bulbous Payloads[4]

The bulbous PLF test for a three-bodied launch vehicle was conducted to provide a database for the extrapolation to future Titan geometry changes. Various combinations of PLF and SRM configurations were tested as shown in Figs. 9 and 10. These include 1) two boattail-to-SRM nose separation distances of $L/D = 2.86$ and 0.5, where $D$ is the core diameter and $L$ is the separation distance; 2) two after-body configurations, that is, two and four SRMs located symmetrically around the core; 3) four PLF lengths and diameters of $L/D = 7.5$, 6.7, 6.12, and 5.89, where $L$ is the PLF length from nose to the end of the boattail and $D$ is the core diameter; and 4) two SRM length to diameter ratios of $L/D = 10.48$ and 8.03.

The data from this test are not directly used for TIV analyses today. However, this test showed that bulbous, three-bodied vehicles act in a predictable manner, and the test gave a sound aerodynamic database for the extrapolation to the TIIIE and early TIV bulbous PLF geometries.

### J. TIII/Centaur Wind-Tunnel Test[10]

Both force and moment and pressure data are reported in the Ref. 10 wind-tunnel test of a TIIIE (TIII/Centaur in the test report) launch vehicle configuration. The pressure data collected on the 25/15-deg biconic nose and that downstream of the cone/cylinder junction for several diameters have become "biblical" for the TIV configuration, that is, used extensively with no other testing. The full-scale PLF diameter in this test was 168 in., and the pressure coefficients were adjusted early in the TIV program to coincide (using similarity methods) with the 200-in.-diam TIV PLF. These pressure coefficients are used in all TIV venting analyses. The pressures at

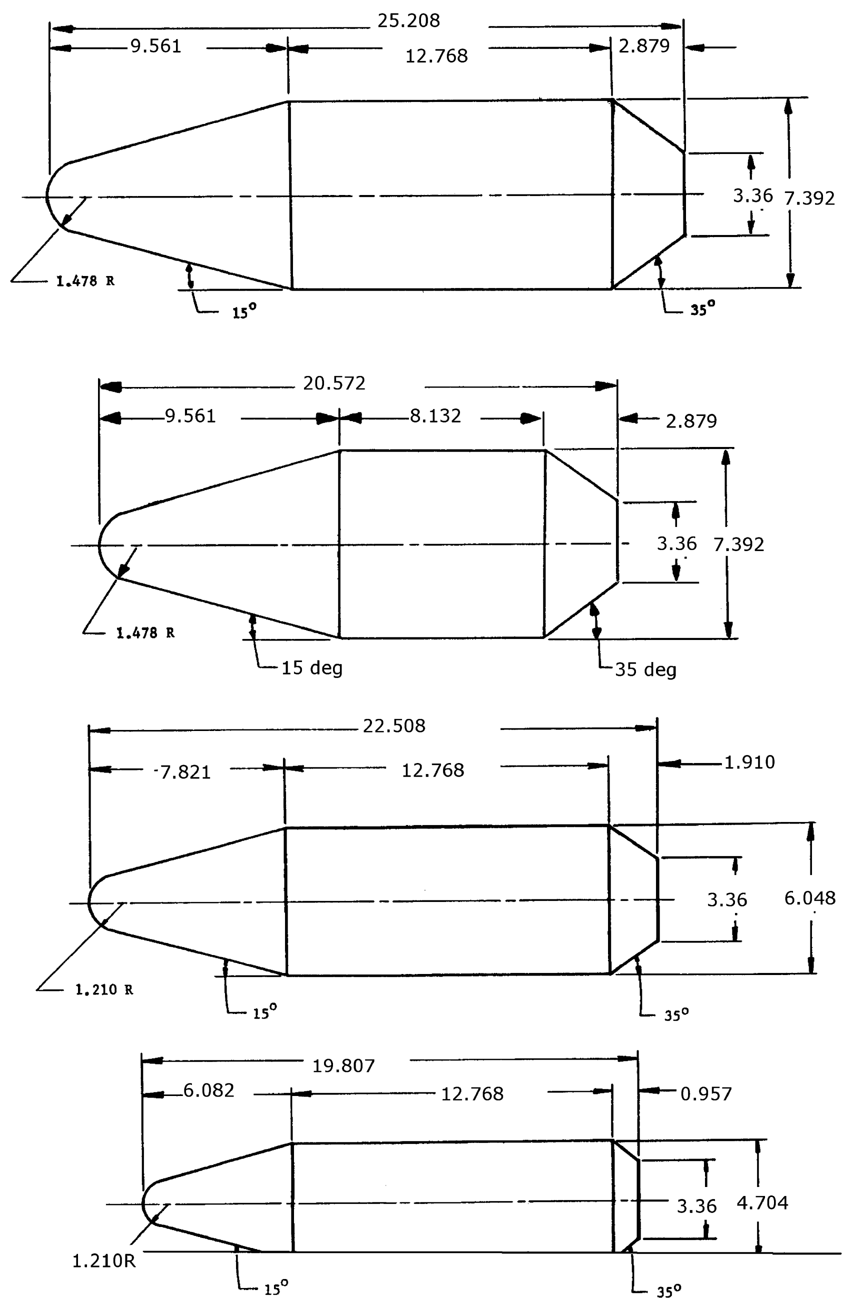


**Fig. 9 Multibodied launch vehicle models, bulbous PLFs.**[4]

angles of attack and at each axial location are integrated to form the running airloads. Note that no TIV configuration wind-tunnel test extensively instrumented the biconic nose and downstream of the cone/cylinder junction with static pressure taps. A schematic of the wind-tunnel model is shown in Fig. 11.

This test was the basis for the terminal shock description of pressures along the length of the PLF to the boattail. The terminal or normal shock first appears just aft of the cone/cylinder junction at approximately Mach 0.72. Its appearance is evidenced by a strong compression that allows the supersonic flow forward of the shock to become subsonic and recover freestream conditions aft of the shock. The intensity of this shock decreases with increasing distance aft the cone/cylinder junction. At approximately Mach 1.05, the terminal shock passes the boattail region of the PLF and merges with the bow shock of the SRMs. Analyses associated with TIV were the first to incorporate the progression of the terminal shock simultaneously in loads and venting studies.

Two reasons for neglecting the terminal shock in early Titan analyses are advanced. First, the responsibilities for the design of the PLF of some previous launch vehicles were divided between contractors in an associate contractor arrangement. For example, in the T34D program, Martin Marietta was responsible for the internal PLF pressure determination. The external wind-tunnel pressures were given to the McDonnell Douglas Corporation, and they then combined internal and external pressures to determine the actual skin pressure differentials, that is, one of the important parameters in the design of the fairing. Hence, little accountability resulted, and a detailed understanding of the transonic behavior of the external airflow along the PLF and vents was not required.

In contrast to the associate contractor relationship of the T34D program, the TIV U.S. Air Force contract gives LMC prime contractor responsibilities for the entire vehicle, and the role of the PLF design is given to a subcontractor, the McDonnell Douglas Corporation. This distinction is important because it has resulted in a greater understanding of the flow phenomena along the PLF. In the TIV analysis, the progression of the terminal shock is simultaneously incorporated into the external pressures along the PLF, the vent pressures, and consequently the internal PLF compartment pressures.

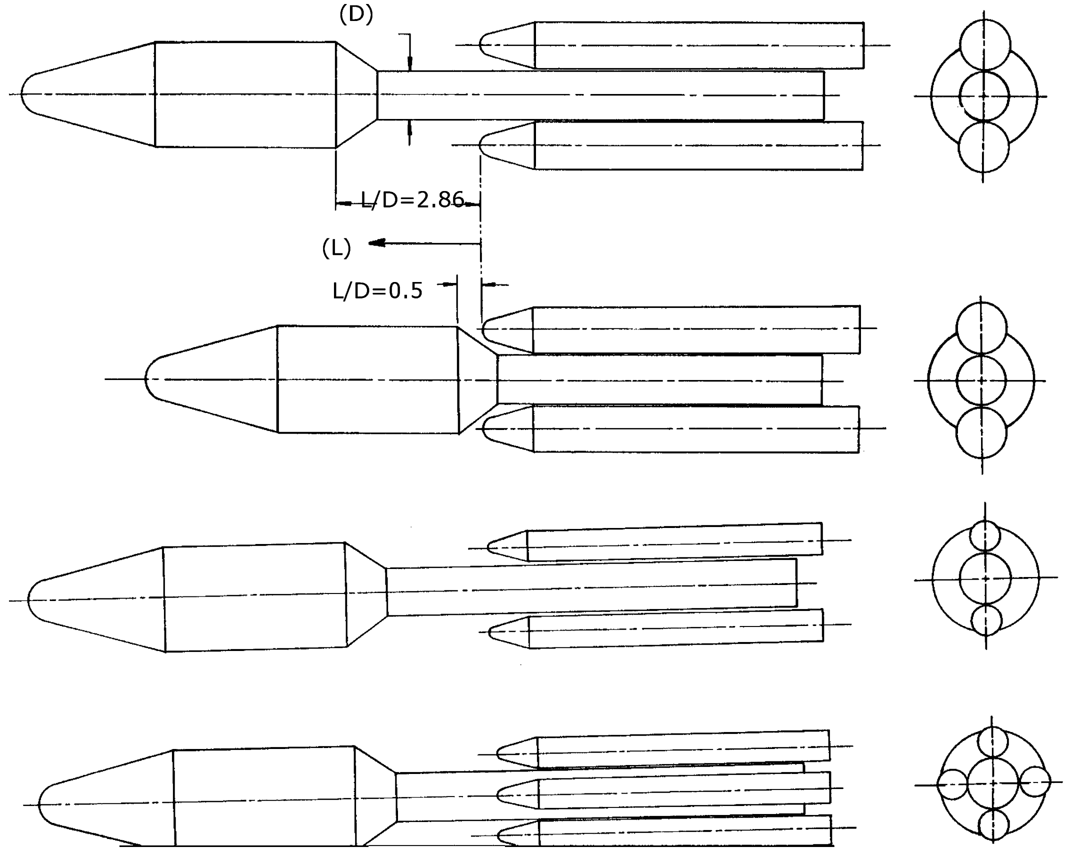


Fig. 10 Multibodied launch vehicle models, solid rocket configurations.[4]

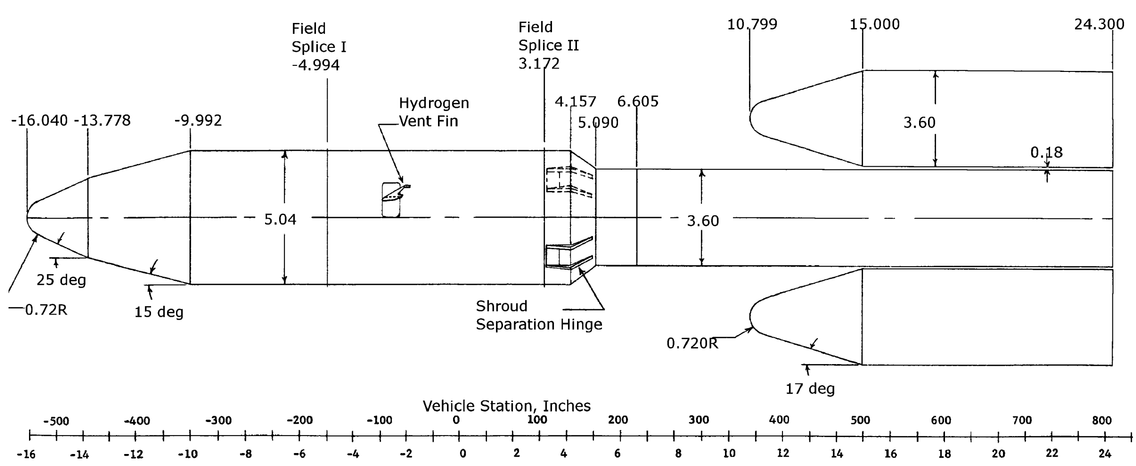


Fig. 11 TIII/Centaur (TIIIE) wind-tunnel vehicle configuration.[10]

The second reason for not accounting for the terminal shock in early Titan analyses is that the skin/stringer design of early PLF's resulted in large load margins. However, the PLF of the TIV is of a lighter isogrid construction, and its design was always on the "ragged edge" as far as load margins were concerned. Low margins necessitate a finer analysis and, consequently, a more exact understanding of the transonic flow behavior generating the pressure environment.

## III. TIV Wind-Tunnel Test Summary

### A. 2.8%-Scale Model in the Arnold Engineering Development Center 4-Foot Transonic/Supersonic Wind Tunnel[11]

The first actual TIV configuration test is described in Ref. 11 and was conducted in the early 1984 time frame. At that time in the proposal effort, the TIV was named Improved Expendable Launch Vehicle (IELV). This force and moment test was conducted to verify the stability characteristics of the IELV. Its results showed that the total vehicle center of pressure was $\frac{1}{2}$–1 diameter forward of the estimated position. A more forward c.p. (less stability) identified here, late in the proposal effort, was the first indication of some of the problems that the TIV program would encounter throughout its design.

The oil-flow photographs obtained during testing in the boattail and SRM nose region are excellent. These photographs clearly show that the flow stagnates adjacent to the nose of the solid on the core, flows radially outward, and then streams forward toward the boattail. This creates a circulating eddy aft of the boattail and helps to explain the high fluctuating pressures in compartment 2A (TIV

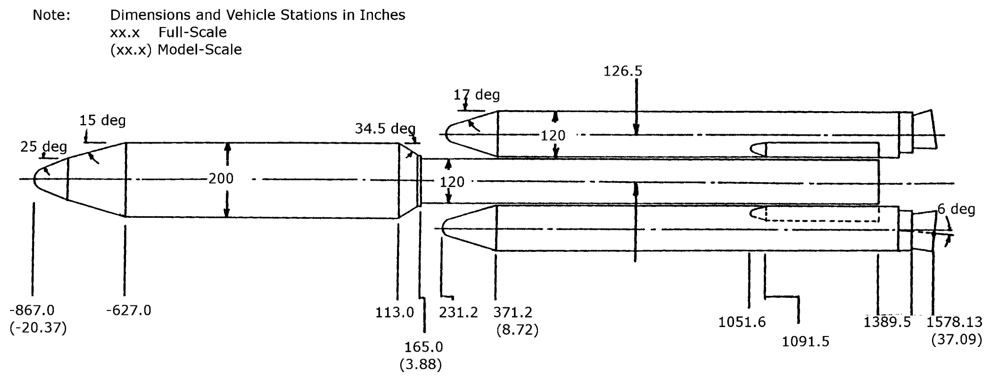


Fig. 12 IELV 2.8%-scale model test configuration (early TIV/SRM).[11]

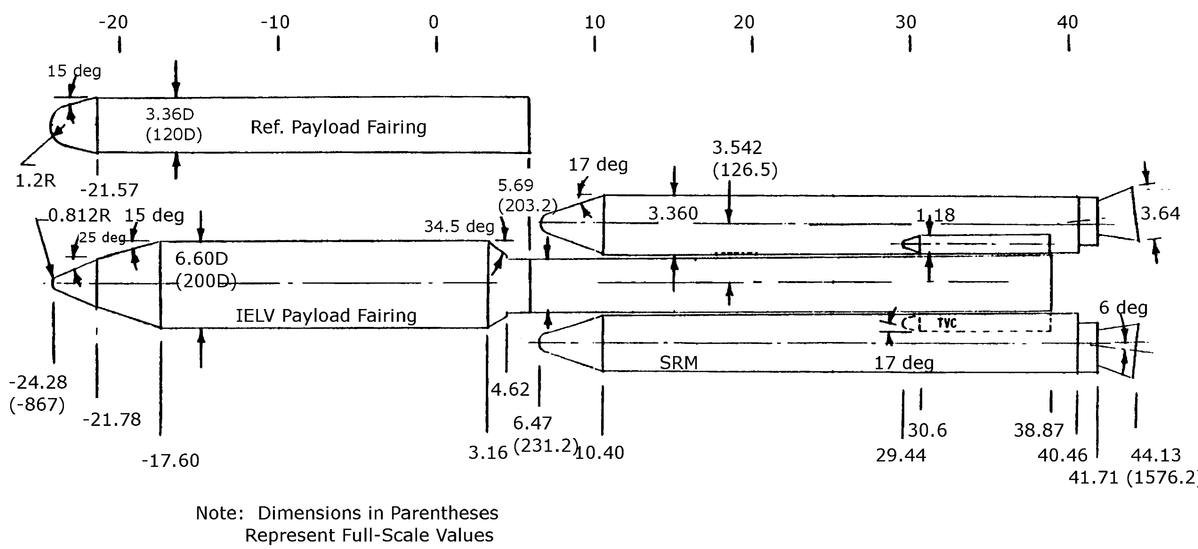


Fig. 13 Titan 34D7/CELV wind-tunnel vehicle configuration.[12]

vehicle station 163–283, a sensitive instruments location). See the vehicle configuration used during this test in Fig. 12.

### B. T34D7/CELV Wind-Tunnel Test[12]

After the TIV contract was awarded to the Martin Marietta Corporation, a more comprehensive test program was undertaken to measure the aerodynamic loads on the TIV [complementary expendable launch vehicle (CELV)] vehicle. In late 1985, a 2.8% force and moment model and a 2.35% pressure and acoustic model were tested in the 4-ft transonic wind tunnel at the Arnold Engineering Development Center (AEDC). Static pressure taps extended forward to vehicle station 197 (approximately $1\frac{1}{2}$ diameters forward of the boattail). The full description of static pressures along the PLF was then obtained by splicing these data with that of Ref. 10, the TIIIE test. Additionally, one SRM was instrumented with static pressure taps. See Fig. 13 for the configuration tested in the wind tunnel.

The data obtained in this test along with that of Ref. 10 are the primary sources for all TIV/SRM venting analyses. Integration of the external pressures obtained in these tests at angle of attack/side slip are used to determine the running airloads. The balance data and pressure data are merged into a description of the forces, moments, and c.p. that act on the vehicle during ascent. These data in the form of coefficients are used in the vehicle trajectory simulation analyses. A unique feature of this test was that one TVC was instrumented with a force balance. An analysis of the TIV/SRM TVC tank loads are given in Ref. 13.

### C. TIV Buffet Test[14]

The effect that large-diameter/thin-skinned PLFs have on lightweight spacecraft during ascent was not (and still is not) well understood. To investigate the aerodynamic buffet phenomenon and provide qualitative dynamic pressure data to calculate buffet forcing functions, the buffet test was conducted in August 1988. A 7.9%-scale model of the TIV, truncated $4\frac{1}{2}$ diameters aft of the SRM shoulder, was tested in the 16-ft transonic wind tunnel at AEDC.

Model configurations consisted of a TIV 86-ft PLF with a SRM, TIV 86-ft PLF with a SRMU, TIV 56-ft PLF with a SRM, and TIIIC and TIIIE vehicle configurations. The TIIIC and TIIIE models were used to correlate existing flight data to wind-tunnel buffet results. The SRMU configuration was modeled by moving the nose of the solids forward 10 in. relative to the core, that is, no SRMU diameter change occurred. See Fig. 14 for the vehicle configurations tested. More than 180 dynamic pressure transducers were distributed over critically deemed surfaces of the PLF, core, and SRM. To monitor model motion, 10 accelerometers were mounted inside the model.

In an effort to identify the Mach number at which maximum buffeting occurs, fine Mach number wind-tunnel runs in increments of 0.02 were conducted for each configuration. In addition to the dynamic pressure taps on the model, selected static taps were placed on the PLF aft cylinder [vehicle stations (VS) 147–113], the PLF boat tail (VS 113–165), and aft of the boattail (VS 165–330). Because of the fine Mach number sweeps conducted during the test, an excellent definition of the progression of the terminal shock was acquired.

These data were used to supplement the static pressures of the Ref. 10 and 12 wind-tunnel tests, particularly at the PLF vent location (generic VS 17, approximately one-half diameter forward of the boattail). The dynamic pressures obtained during testing were reduced to a static equivalent using a 3-sigma representation assuming a Rayleigh or Gaussian distribution.

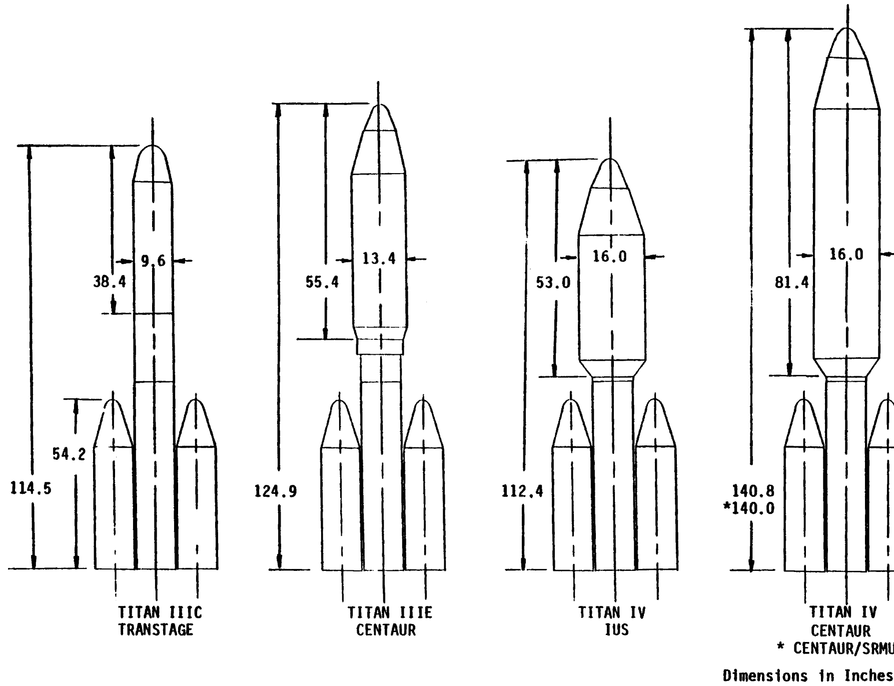


Fig. 14 Titan IV buffet test vehicle configuration.[14]

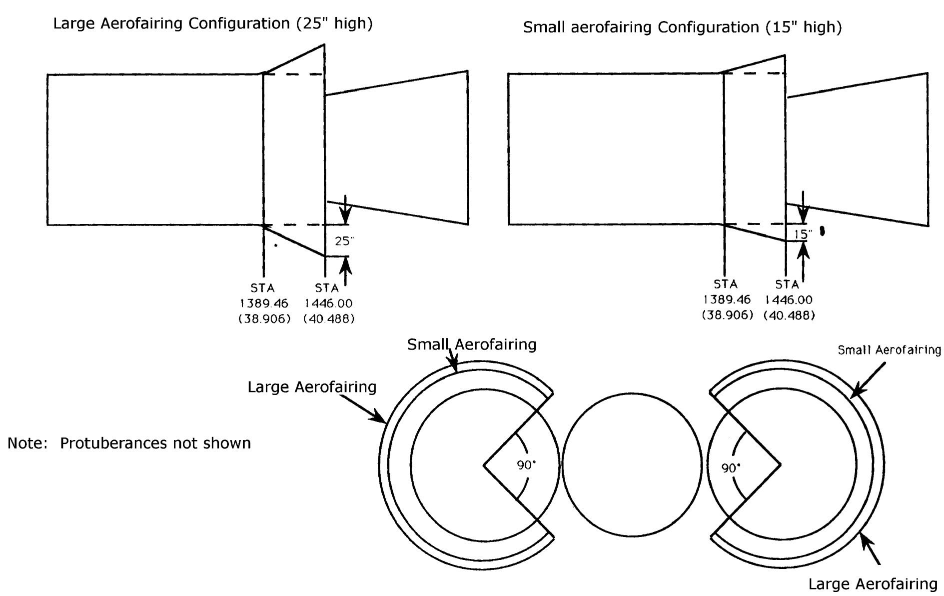


Fig. 15 Titan IV SRMU force and moment wind-tunnel aerofairing configuration.[15]

The primary data from this test were incorporated into a forcing function used in loads analyses. Secondary use of the static pressures and equivalent dynamic pressures are used in venting analyses and aided in describing the pressure differentials predicted along the PLF. See the venting analysis[35] leading up to the first TIV launch for a complete description of how the dynamic and static pressures were combined in determining the skin-pressure differentials given to McDonnell Douglas for the design of the PLF.

## D. TIV SRMU Force and Moment Wind-Tunnel Test[15]

The force and moment test described in Ref. 15 was conducted in the 16T transonic wind tunnel at AEDC. It was the first wind-tunnel investigation of the full TIV/SRMU, that is, a TIV with SRMUs. Included in the model were 56- and 86-ft PLFs and two seven-segment SRMs. In anticipation of the expected large aerodynamic hinge moments on the SRMU nozzles, two aerofairings (15 and 25 in.) were part of the model. The aerofairings were intended to deflect the freestream flow away from the SRMU nozzles, as shown in Fig. 15. The outboard profile of the entire 86-ft PLF model used in the Ref. 15 test is shown in Fig. 16.

Three six-component balances measured the forces and moments on the total vehicle and individually on the PLF and one of the solids. Fortunately, data were also taken for the no-aerofairing configuration. The nozzle hinge-moment test described in Ref. 36 showed that the aerofairing design does not decrease the hinge moment on the SRMU nozzles.

## E. Titan IV SRMU Nozzle Hinge-Moment Wind-Tunnel Test[36]

The 4%-scale model TIV/SRMU nozzle hinge-moment test described in Ref. 36 was conducted in the 16T transonic wind tunnel at AEDC in August 1989. Exhaust flow of the two SRMUs was simulated by cold air entering the model through a floor-mounted strut. Test data were measured at vehicle angles of attack/side slip

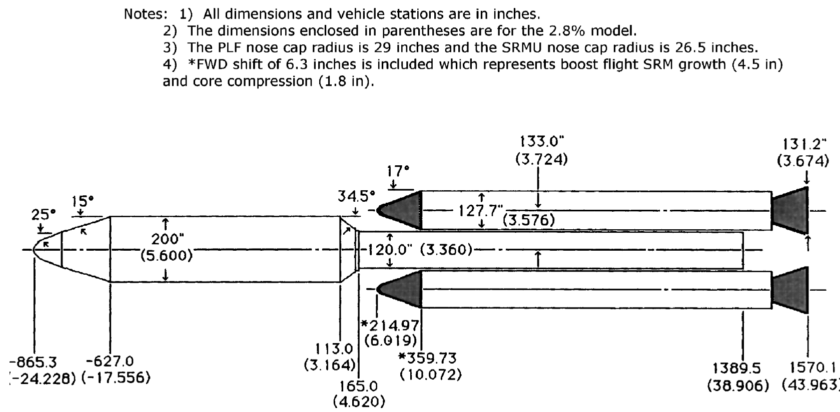


**Fig. 16 Titan IV SRMU force and moment wind-tunnel test vehicle configuration.[15]**

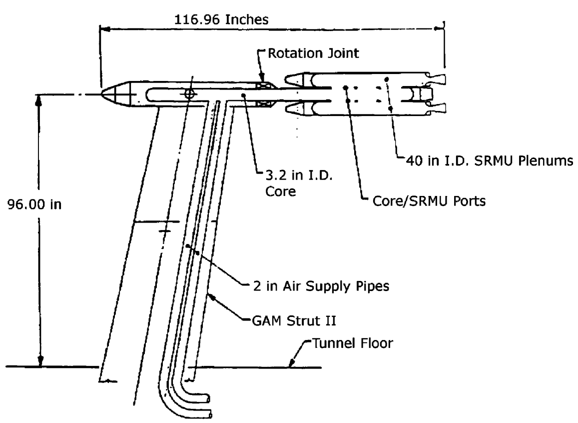


**Fig. 17 TIV hinge-moment wind-tunnel test configuration, strut mount.[36]**

of ±8 deg and gimbal angles, that is, SRMU nozzle deflections up to 5 deg. The primary purpose of the test was to measure the aerodynamic hinge moments acting on the SRMU nozzles during transonic flight. Each nozzle was instrumented with 96 static pressure taps. Instantaneous integration of the pressures during a test run allowed for comparisons of the individual hinge moment of each configuration. To accommodate the strut mount and keep the nozzles at least three diameters aft of the strut, the PLF was extended 20 in. (model scale) relative to an actual 86-ft PLF length. This was determined to not affect the quality of the data taken on the SRMU nozzles. However, the data obtained at Mach numbers over the range 1.0–1.2 show somewhat questionable behavior.

Compensation for the degradation in the test data from Mach 1.0 to 1.2 is accomplished by smoothing the data over all Mach numbers. A detailed account of the methodology used to smooth the data is given in Refs. 5 and 16.

Before the test, the design of the SRMU included an aerofairing mounted to the aft end of the SRMU to deflect the flow that streams down the solid. After testing several aerofairing configurations, it became clear that the no-aerofairing configuration produced the smallest hinge moments. It turns out that an inboard to outboard force results from the core freestream flow, increasing the pressure on the inboard nozzle surface. Hence, an aerofairing that deflects the outboard freestream flow causing lower outboard pressures only magnifies the hinge moment.

Soon after the test and a comprehensive review of the data, it was determined to not use an aerofairing for the TIV/SRMU vehicle. The strut mounting and total model length for the hinge moment test is shown in Fig. 17. Data from this test not only define a maximum hinge moment, they also characterize the nozzle contribution to the 6-degree-of-freedom aerodynamics of the vehicle. This contribution to the vehicle aerodynamics is called aeroruddering and usually acts to stabilize the vehicle. However, in Ref. 37 a combination of angle of attack/side slip and nozzle gimbal angle is described that actually moves the vehicle c.p. forward, a less stable condition.

The wind-tunnel investigation described in Ref. 15 was with a fixed-nozzle configuration at zero cant angle. In the hinge-moment test described in Ref. 36 jetoff data, that is, no nozzle flow, were taken and subtracted from the fixed nozzle forces and moments. Consequently, the actual forces and moments with the jeton effects were added to the total vehicle forces and moments. See Ref. 38 for the methodology used to incorporate the hinge-moment results with total vehicle aerodynamics.

### F. TIV Wind-in-the-Vents: Scale Model Test[17]

In the late 1980s, ground wind contamination became an important issue due to the sensitive surfaces of spacecraft. It was hypothesized that a given ground wind that impinges on the PLF primary vent location could overcome the positive air conditioning flow exiting the PLF. As a result, salt, dust, bugs, etc., could enter the vehicle skin and possibly contaminate the spacecraft. The solution was to assure that there was always positive flow out of the vents. Vent covers and ground wind placards were the solution method for TIV vehicles.

A 1.5% test of the TIV PLF was conducted at the Colorado State University Thermophysics Laboratory Water Tunnel to model the interaction between the PLF vents, the air conditioning flow exiting the vents, and the impingement of various ground wind speeds on the PLF. The purpose of the test was to confirm the prediction methodology described in Ref. 39 associated with the ingestion of ambient air into the PLF before launch.

Pressure distributions around the PLF were measured, flow rates of water representing the air conditioning flow were measured, and orifice flow coefficients were calculated. Important experimental observations from the test included that 1) inflow occurred only at the most windward vent and 2) the low-speed jet created by the inflow extended well within the cylinder before dispersing.

The observation that only inflow occurred at the windward vent was as predicted. However, the extent of the encroachment of this inflow toward the center of the vehicle was unexpected. This justified the use of the vent blocking system for contamination control that was later implemented. Refer to the model, the velocity profile, and model dimensions in Fig. 18.

### G. Scale Model Ground Wind Tests[18–25]

The wind-tunnel tests presented in, Refs. 18–25 describe ground wind investigations of the TIV SRM and SRMU at Launch Complex (LC)-40 and LC-41 at ETR and Space Launch Complex 4 East (SLC-4E) at WTR. Testing was conducted at the Cermak Peterka Peterson (CPP) low-speed wind tunnels in Fort Collins, Colorado, over a 10-year time frame from 1986 to 1996. These tests used 1:100-scale models of the TIV launch vehicle in its prelaunch configuration. All ground launch complex structures including the umbilical tower, the mobile service tower, and all significant facilities and ground features within a radius of about 500–600 ft of the vehicle launch pad were accounted for in the scale model.

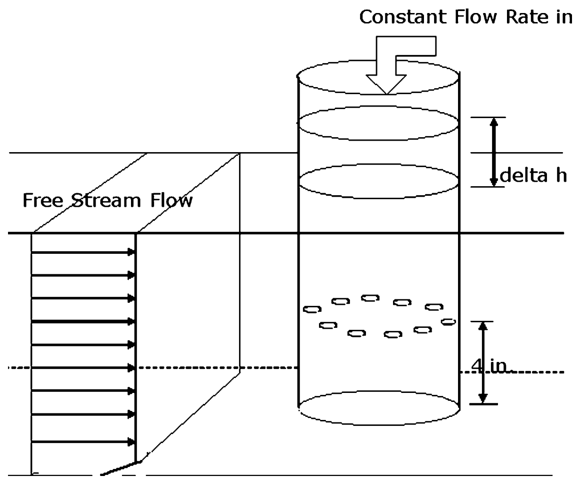


**Fig. 18 Wind-in-the-vents water-tunnel test setup.**[17]

The model was placed in a simulated atmospheric boundary layer, and measurements of the mean and fluctuating aerodynamic load and vehicle response were obtained under various combinations of vehicle configuration and wind direction.

The ground wind profile used in testing was described by the equation

$$V_x = V_{\mathrm{ref}} \times (x/x_{\mathrm{ref}})^{\exp}$$

where $V_x$ is the wind velocity at a distance $x$ above the ground and $V_{\mathrm{ref}}$ is the wind velocity at the reference height $x_{\mathrm{ref}}$. The exponent was taken to be $\exp = 0.14$. This exponent was recommended by the CCP tunnel personnel as the most representative of a wind profile across level ground. However, when using these data, note that the U.S. Air Force requires the TIV program to use an exponent of 0.2 and that the complex at WTR is not on level ground. See Ref. 39 for a discussion on the latter concern.

The data from these tests are primarily utilized to define the forcing functions and to predict the load placards on the different vehicle lengths for day of launch. Secondary use of the data is to define the 90 deg, that is, the orientation of the vehicle in its prelaunch configuration, force and c.p. description for launch aerodynamics. The methodology used to determine launch aerodynamics is given in Ref. 27.

## IV. Summary

The major aerodynamic wind-tunnel tests that span the time frame from the early Titan I vehicle developed in 1955 to the most recent Titan family vehicle, the TIV SRMU are summarized. These tests cover all aspects of single- and multibodied aerodynamics including nozzle hinge moments, fire-in-the-hole staging, SRM staging, total vehicle and SRM/SRMU forces and moments, dynamic and static pressures, and launch facility impingement pressures. Additionally, various ground wind tests were conducted to address contamination concerns and loads on the vehicle at liftoff.

Principal aerodynamic observations derived from the various tests and subsequent analyses on the TIV launch vehicle include the following:

1) For vehicle stability, a more forward shift in the TIV c.p. location was based on vehicle unique wind-tunnel tests. Initial predictions were based on earlier Titan family test data.

2) For vehicle staging, nose-in stage O/I worse-case scenario resulted with a SRMU. Initial predictions suggested a nose-out worst case.

3) For vehicle aerodynamics, there was more refined understanding of the significance of the terminal shock in venting analyses and PLF skin-pressure differential definitions.

4) No-aerofairing configuration results in minimizing hinge moments on SRMU nozzles contrary to initial predictions.

5) Vent blocking system was incorporated to preclude ground winds from entering the PLF during pre-launch activities. This concern was never addressed in previous vehicle analyses.

## Note Added in Proof

For the 368th and last time, the United States launched a Titan rocket into space on 19 October 2005 from WTR at Vandenberg Air Force Base in California. The last launch of a Titan rocket from ETR at Cape Canaveral occurred on 30 April 2005.

## Acknowledgments

The author thanks Peter Huseman and William Kelly from the Lockheed Martin Corporation for their help in getting Department of Defense approval to publish this work.

## References

[1]"One-Percent Scale Model Cold Flow Staging Tests," Martin Co., Rept. CR-60-163, Denver, CO, Jan. 1961.

[2]"SM-68 Cold Jet Staging Model Force and Pressure Test," Martin Co., Rept. CR-61-25, Denver, CO, March 1961.

[3]"Titan IIIM Aerodynamic Model Test Report (1.5% Scale Model) Staging Post-Test Report," Martin Marietta Corp., Rept. MCR-67-392, Denver, CO, Nov. 1967.

[4]"Wind Tunnel Tests on Multi-Bodied Launch Vehicle Models with Bulbous Payloads," Martin Marietta Corp., Rept. R-71-48678-003, Denver, CO, May 1971.

[5]Brower, T., "Stage O 6D Aerodynamic Coefficients w/Nozzle Aero Coefficients for All Vehicles," Martin Marietta, Corp., Rept. IOM 5462/CE-90-2736, Denver, CO, Feb. 1990.

[6]"Low Speed Wind Tunnel Cross-Flow Tests of a 0.04 Scale Model of the Martin 624A Standardized Space Launch Vehicle System," Cornell Aeronautical Lab., Inc., Rept. AA-1718-W-1, Buffalo, NY, Oct. 1962.

[7]"4% Scale 624A Force and Pressure Test Phase I Post Test Report NASA-Ames Unitary Plan Wind Tunnel," Martin Co., Rept. SSD-CR-63-36, Denver, CO, Aug. 1963.

[8]"Aerodynamic Test, Post Test Report (Wind Tunnel Test Data, Final)," Martin Marietta Corp., Rept. SSD-CR-65-230, Denver, CO, Jan. 1966.

[9]"Final Post-Test Report on 7% Transonic Buffet Model Test for Various Titan III Configurations," Martin Marietta Corp., Rept. SSD-CR-66-563, Denver, CO, Jan. 1967.

[10]"Titan III/Centaur Wind Tunnel Test Report," Martin Marietta Corp., Rept. MCR-71-276, Denver, CO, Sept. 1971.

[11]"Improved Expendable Launch Vehicle 2.8% Scale Model in the AEDC 4-Foot Transonic/Supersonic Wind Tunnel," Martin Marietta Corp., Rept. MMC-3522/A-84-0001, Denver, CO, May 1984.

[12]DiMicco, R., "Titan 34D7/CELV Wind Tunnel Test Report," Martin Marietta Corp., Rept. MCR-86-2516, Denver, CO, March 1986.

[13]Brower, T., "TIV/SRM TVC Tank Loads," Lockheed Martin Corp., Rept. IOM 3325/CE-96-3372A, Denver, CO, Feb. 1996.

[14]Schoonmaker, M., "Titan IV Buffet Test Report," Martin Marietta Astronautics Group, Rept. MCR-88-2632, Denver, CO, Dec. 1988.

[15]Chavez, G., "Titan IV SRMU Force and Moment Wind Tunnel Test Post-Test Report," Martin Marietta Corp., Rept. MCR-89-2604, Denver, CO, Aug. 1989.

[16]Brower, T., "Preliminary Aero-Moments on SRMU Nozzle," Martin Marietta, Corp., Rept. IOM 5462/CE-90-2696, Denver, CO, Jan. 1990.

[17]Brower, T., "Titan IV Wind-in-the-Vents: A Scale Model Test," Martin Marietta Corp., Rept. IOM-3325/CE-92-2982, Denver, CO, Aug. 1989.

[18]"CELV Launch Loads," Cermak/Peterka and Associates, Inc., Rept. C/PA Project 86-0326, Fort Collins, CO, June 1986.

[19]"Wind Tunnel Tests for Mobile Service Tower—Space Launch Complex 4 East Vandenberg Air Force Base, California," Cermak/Peterka and Associates, Inc., Rept. C/PA Project 86-0365, Fort Collins, CO, Dec. 1986.

[20]"Wind Tunnel Tests: Mobile Service Tower—Space Launch Complex 4 East Vandenberg Air Force Base, California, Revised October 1987," Cermak/Peterka and Associates, Inc., Rept. C/PA Project 86-0365, Fort Collins, CO, Oct. 1986.

[21]"Wind Tunnel Tests: Titan IV Launch Vehicle Loads, Launch Complex 41 Cape Canaveral, Florida," Cermak Peterka Peterson, Inc., Rept. CPP Project 87-0403, Fort Collins, CO, Oct. 1988.

[22]"Wind Tunnel Tests: Dynamic Wind Loads on Titan IV Launch Vehicle, SLC-4E, Vandenberg Air Force Base," Cermak Peterka Peterson, Inc., Rept. CPP Project 89-0553, Fort Collins, CO, July 1989.

[23]"Preliminary Report Aerodynamic Wind Loading on the Titan IV During Launch," Cermak Peterka Peterson, Inc., Rept. CPP Project No. 94-1094, Fort Collins, CO, 13 Jan. 1995.

[24]"Interim Report, Task 5: Launch Loads Study," Cermak Peterka Peterson, Inc., Rept. CPP Project 95-1256, Fort Collins, CO, 16 Sept. 1996.

[25]"Wind-Tunnel Test to Determine Effects of MST Interaction on Titan IV ETR Ground Wind Loads," Cermak Peterka Peterson, Inc., Rept. CPP Project 95-1256, Fort Collins, CO, Nov. 1996.

[26]Huseman, P., "Titan IV I/II Staging Gas Dynamics Analysis," Martin Marietta Corp., Rept. IOM 3325/CE-92-2978, Denver, CO, July 1992.

[27]Brower, T., "TIV Launch Aero Coeff. @ SLC-4E," Lockheed Martin Corp., Rept. IOM 3325/CE-95-3342, Denver, CO, Aug. 1995.

[28]Brower, T., "Titan 34D-7 Stage O-Stage I Aerodynamic Staging Coefficients," Martin Marietta Corp., Rept. IOM 0484/CE-85-2200, Denver, CO, Nov. 1985.

[29]Brower, T., "Review of SRMU Stage I/O Aerodynamic Staging Coefficients," Martin Marietta Corp., Rept. IOM 3325/CE-92-3011, Denver, CO, Dec. 1992.

[30]Brower, T., "Review of SRMU Stage I/O Aerodynamic Staging Coefficients," Martin Marietta Corp., Rept. IOM 3325/CE-92-3011A, Denver, CO, June 1993.

[31]Brower, T., "Review of SRMU Stage I/O Aerodynamic Staging Coefficients," Martin Marietta Corp., Rept. IOM 3325/CE-92-3011B, Denver, CO, Sept. 1995.

[32]Brower, T., "TIV SRM/SRMU Stage O/I Aerodynamic Staging Coefficient Limits," Lockheed Martin Corp., Rept. IOM 3325/CE-97-3448, Denver, CO, Feb. 1997.

[33]"Category A Studies, 12:1 Stage I Nozzle Hinge Moment Test Final Post-Test Report," Martin Marietta Corp., Rept. MCR-68-33, Denver, CO, Jan. 1968.

[34]"SLC-4E Umbilical Tower Impingement Test," Martin Marietta Corp., Rept. MCR-69-402, Denver, CO, Sept. 1969.

[35]Brower, T., "Titan/IUS (56 FT PLF) Compartment Venting Analysis," Martin Marietta Corp., Rept. MCR-86-2566, Denver, CO, Nov. 1986.

[36]Brower, T., "Titan IV SRMU Nozzle Hinge Moment Wind Tunnel Test Report," Martin Marietta Corp., Rept. MCR-89-2643, Denver, CO, Aug. 1989.

[37]Brower, T., "Fwd Shift in Vehicle CP Due to SRMU Aero-Ruddering," Martin Marietta Corp., Rept. IOM 3325/CE-94-3163A, Denver, CO, July 1994.

[38]Brower, T., "Revision to the Titan IV SRMU Point Loads," Lockheed Martin Corp., Rept. IOM 3325/CE-95-3330, Denver, CO, May 1995.

[39]Brower, T., "Ground Wind Contamination Constraint Methodology," Martin Marietta Corp., Rept. IOM 5462/CE-91-2861, Denver, CO, Aug. 1991.

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