SPACE SHUTTLE EXTERNAL TANK GASEOUS OXYGEN VENT SYSTEM

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In the summer of 1979, NASA program management was faced with the problem of ice forming on the Space Shuttle External Tank, becoming airborne during launch, and potentially damaging the Orbiter thermal protection tiles. The ice would form during loading of the External Tank propellants as cryogenic gaseous oxygen was vented through the nose cone vent louvers and mixed with the humid and sometimes wet environment at the launch pad. This ice had to be eliminated to ensure the successful launch of the Shuttle without risking damage to the fragile tiles.

To prevent the ice formation would require a system for removing the cryogenic gaseous oxygen (GOX) from the proximity of the Shuttle and venting it a safe distance away without creating ice on the External Tank (ET) or any of the system hardware. The system had to interface with the ET vent louvers at any location within the stacking envelope of the vehicle at the launch pad and provide an adequate seal, preventing the ice-forming leakage of cold gaseous oxygen in the vicinity of the ET, without altering the design of the ET or placing excessive loading on the tank's surface. The system would be required to track and remain interfaced with the ET in winds of up to 25.2 m/sec (49 knots) and be operational for launch in winds of up to 17.7 m/sec (34.4 knots) while allowing for downward tank shrinkage of approximately 6.9 cm (2.7 inches) as loading of the liquid oxygen proceeded. Although these requirements directed the final design concept, the basic success criteria for the system was "no ice formation."

Two problems had to be solved to assure successful elimination of ice on the ET. First, an access/support structure had to be provided from the Launch Complex 39A Fixed Service Structure (FSS) to the vicinity of the nose cone on the ET approximately 82.3 meters (270 feet) above the surface of the pad and 22.9 meters (75 feet) from the face of the FSS. Second, an umbilical had to be designed and tested that would seal around the ET GOX vent louvers and not allow ice to form on the tank or the umbilical. The umbilical would be designed to be mated to the access/support structure. To solve the first problem, a swing arm subsystem had to be designed to provide the support structure for and to allow access to the umbilical. After consideration of several concepts, the final decision was made in September 1979 to proceed with a modified Apollo service arm as the concept for the swing arm subsystem. To solve the second problem, an umbilical had to be designed which could be remotely disconnected or reconnected with the ET. Again several concepts were considered; and the concept chosen by KSC and MSFC for design and testing was an inflatable vent seal subsystem providing a cloth seal around each vent louver with an internal annulus to provide a path for the gaseous oxygen from the ET to a hard duct on the swing arm. The baseline inflatable vent seal subsystem would require no modifications to the ET.

The system description falls into two major parts: the final design of

the swing arm subsystem which provides the access/support structure and the vent seal subsystem which provides interfaces between the swing arm vent pipes and the ET; and the qualification testing required to certify the system for use on the launch pad and to resolve major problems which developed in support of the first Shuttle launch.

FINAL SYSTEM DESIGN

The swing arm subsystem consists of a horizontally rotating, 19.2-m (63-ft) long arm truss hinged at the northeast corner of the FSS, a vent hood with its actuation mechanism, and a hydraulic/pneumatic control console to provide power to retract or extend the arm (see Figure 1). The arm truss, hinges and control console are all modified Apollo/Saturn V service arm hardware.

The arm truss, made of tubular T-1 steel, is a lightweight design supporting the vent hood located at the tip of the arm and providing access to the vent hood for up to six people. The truss and vent hood assembly, longer than any previous cantilevered swing arm used in launch operations, is 24 meters (79 feet) from arm hinge centerline to the tip of the vent hood. The total arm weight is 10,500 kg (23,100 lb) with an additional 5450-kg (12,000-lb) hinge weight. The arm is actuated by two hydraulic cylinders attached at the hinge and supplied with 1.52×10^7 N/m^2 (2200 psig) pressurized hydraulic fluid from the hydraulic/pneumatic control console. Each cylinder develops 364,000 Joules (268,000 foot-pounds) torque to swing the arm about the hinge.

The vent hood, located on the tip of the arm truss, is the carrier for the vent seal subsystem. The aluminum hood is hinged at its connection to the arm truss and is rotated up or down about that hinge line using the vent hood actuation mechanism (a primary or a secondary screw jack operated by vane-type air motors which are driven by a compressed air supply). In operation, the hood is raised at a .84 rad (48^o) angle from horizontal when the arm is extended or retracted to allow it to clear the ET. The hood is then lowered to the horizontal position by the screw jack to allow proper location of the vent seal subsystem. To complete positioning of the vent seal subsystem, the arm extend angle is optically aligned with the centerline of the ET and the vent hood is adjusted in or out axial to the arm truss using two large screw jacks. The vent hood is then leveled by adjusting the secondary screw jack. The arm adjustment of $\pm$ 0.017 rad (1^o) in extend angle and the vent hood axial adjustment of $\pm$ 11.4 cm (4.5 in) takes care of the $\pm$ Y and $\pm$ Z vehicle stacking tolerances. This locates the vent seal subsystem properly for mating with the ET.

The hydraulic/pneumatic control console provides arm and hood operating pressure with a 1.52×10^7 N/m^2 (2200 psig) hydraulic supply to extend or retract the arm and an 8.62×10^5 N/m^2 (125 psig) air supply to raise or lower the vent hood. It utilizes a bank of 4.14×10^7 N/m^2 (6000 psig) gaseous nitrogen accumulators regulated down to 1.52×10^7 N/m^2 (2200 psig) to pressurize the hydraulic accumulators and thereby maintain system operating pressure. The facility supplies hydraulic fluid, compressed air, and gaseous nitrogen at system operating pressures to the console; however, the console

has accumulator capacity so that once charged the arm and hood can be completely cycled (retracted and extended) twice without any fluid or gas replenishment. The control console contains the KSC Launch Processing System (LPS) controlled valving to provide complete redundancy for arm and vent hood extension and retraction with no single failure points.

The vent seal subsystem consists of two soft, inflatable seals supplied with heated gaseous nitrogen (GN_2) from a pressure regulation panel and heater bank which is ducted across the arm truss for distribution to the vent hood. The inflatable seals are the interface of the ground ET GOX Vent System with the Shuttle External Tank. They provide a flexible pipe able to withstand the 92°K (-294°F) temperature (GOX) venting from the ET vent louvers while ducting the GOX to the hard vent pipes on the vent hood, along the arm truss and away from the ET (see Figures 1 and 2).

The vent seals are inflated with the heated GN_2 from the pressure regulation panel and heater located on the 83.8-meter (275-ft) level of the FSS. The panel is supplied with 1.03×10^6 N/m^2 (150 psig) GN_2 and regulates it down to 5170 N/m^2 (0.75 psig) with two redundant, dome-loaded pressure regulators operating in parallel. The regulators sense the vent hood plenum (seal supply) pressure to maintain the inflatable seals with the 2758 ± 690 N/m^2 ($0.4 \pm .1$ psig) tolerance required for proper seal function. The seals are protected from overpressurization by four relief valves located at the regulation panel outlet. The pressure regulation panel is capable of flowing 68 kg/min (150 lb/min) of GN_2 to the heater. The 156-kW heater operating at one-quarter capacity heats the GN_2 to approximately 389°K (240°F). The heat losses in the ducting reduce this to 355°K (180°F) maximum by the time the GN_2 reaches the vent hood plenum and the seals. A temperature-sensing probe is located in the plenum which is routed to the heater controller, maintaining the plenum (seal supply) temperature between 350°K and 355°K (170°F and 180°F) by varying the heater temperature. After exiting the heater the heated GN_2 flows through the main GN_2 shutoff valve (which is controlled by LPS) and to the ducting on the arm truss. The ducting distributes the approximately 45.4 kg/min (100 lb/min) total GN_2 heated flow to three areas: the vent hood plenum at 27.4 kg/min (60 lb/min); the two flexible vent ducts located at the arm truss/vent hood hinge line at 4.5 kg/min (10 lb/min) each; and the two exhaust tips of the GOX vent pipes at 4.5 kg/min (10 lb/min) each.

The vent hood plenum supplies the heated GN_2 to the inflatable seals. Ideally in operation, the inflatable seals are pressurized to approximately 3103 N/m^2 (0.45 psig) with a GN_2 supply temperature of 355°K (180°F) at a flow rate of 10.5 kg/min (23 lb/min) maximum to each seal with an additional 6.4 kg/min (14 lb/min) being dumped to inert the hood annulus. The inflatable seals are constructed of a vinyl-impregnated nylon cloth (Herculite 20 manufactured by Herculite Products) and Beta cloth (a Teflon-coated fiberglass cloth used in making the astronauts' suits during the Apollo Program). The vinyl-impregnated nylon cloth (called nylon cloth for simplicity) is stitched into a segmented column to provide the structural strength to hold the seal shape when inflated. When the seal is inflated against the tank, the nylon cloth is the contact surface of the seal with the ET. The Beta cloth, used as

an inner liner to the seal, protects the nylon cloth from the GOX by maintaining its flexibility under the cryogenic flow conditions and insulating the seal (see Figure 3). The use of the Beta cloth was required since the nylon cloth becomes stiff at temperatures below 239°K (-30°F) and cracks when subjected to motion. The Beta cloth, which remains relatively flexible down to 89°K (-300°F), insulates the nylon cloth from the cryogenic gas by using the heated GN_2 flowing through each seal at 10.5 kg/min as a captive boundary layer between the two fabrics. The heated GN_2 passes through an even distribution of .64-cm (.25-in) holes in the nylon cloth, into the boundary layer between the two materials and through a smaller quantity of .64-cm holes in the Beta cloth. The heated GN_2 is then exhausted into the vent pipe providing a limited boundary layer effect on the outside surface of the Beta cloth. Pictures of the inflated vent seals are shown in Figures 4 and 5. When the vent seals are inflated around the two ET vent louvers they provide a complete flexible pipe from the GOX vents to the vent pipe on the hood (see Figure 3 for the shape of the sealing surface with the ET) which is able to track vehicle motion during cryogenic propellant loading and operating winds.

When the cold GOX has been exhausted through the seals, it travels through the vent pipes and is dumped approximately 6.7 m (22 ft) from the ET. The GOX from each vent seal flows through an insulated 0.46-m (1.5-ft) diameter vent pipe on the hood to the flexible vent ducts. The flexible vent ducts provide a lightweight, flexible pipe to allow the vent hood to raise and lower while the arm and hood vent pipes remain connected. The 1.83-m (6-ft) long flexible vent ducts are cylindrical versions of the inflatable vent seals and are clamped to both the vent hood and arm truss vent pipes. From the inflatable vent ducts the GOX travels down two 0.61-m (2-ft) diameter, 8.2-m (27-ft) long insulated vent pipes before being dumped to the atmosphere. On the exhaust tip of each GOX vent pipe is a 0.3-m (1-ft) long, heated annular section which is designed to prevent ice formation on the vent pipe.

SYSTEM QUALIFICATION TESTING

Shuttle Program testing of the vent seal subsystem was conducted in four parts: concept verification tests to determine if the system concept would perform under the required conditions, qualification testing to certify the performance of the designed hardware, pad validation testing to verify system installation and marriage with the pad systems, and system requalification testing required due to the failure of the system to function as designed in support of the first Space Shuttle launch (STS-1).

The concept verification testing (CVT) was conducted in September and October 1979. The prototype vent seal configuration was tested to determine its capability and performance in sealing against the ET under the required vehicle stacking and tracking parameters. To accomplish this test program, a test nose cone was outfitted by MSFC and installed in the KSC Launch Equipment Test Facility (LETF) on an existing vehicle random motion simulator. Liquid nitrogen tanker trucks were connected to the ET nose cone vent valve plumbing to provide cryogenic GOX simulation, and a gaseous nitrogen supply

was connected to an existing heater to provide the heated GN_2 for the inflatable vent seals. The test vent seals were installed on a prototype vent hood structure which provided the plumbing for the heated GN_2 supply. Simulations of worst-case venting conditions and all vehicle stacking and tracking parameters were successfully completed. As a result of the successful concept verification testing, the system design was baselined for use on STS-1.

The qualification testing was conducted from April to September 1980 in the LETF. For this test program the pad vent hood, vent seals, hood retract mechanism, and a 1.8-m (6-ft) section of the arm truss (support structure for the vent hood and hood retract mechanism) were installed in the LETF on the test stand about the nose cone simulator. This hardware is called the tip assembly. The pad GN_2 regulation panel was also installed, mated with the heater (used during the CVT program and identical to the pad heater), and the ducting routed to the tip assembly. The pad arm truss GOX vent pipes which for STS-1 were 20.4 m (67 ft) long and 0.3 m (1 ft) in diameter were not installed but were simulated with shorter 4.5-m (15-ft), smaller 0.15-m (.5-ft) diameter vent pipes due to the short test program initially scheduled to meet a September 1980 launch. The cryogenic GOX simulation was the same as for the CVT program.

During the qualification testing a number of minor problems occurred, related to heated GN_2 flow to the inflatable vent seals and flexible vent ducts, which required minor modifications to the hardware and operating procedure. Most notable of these problems was the sensitivity of nylon cloth and stitching to pressure and temperature. The material, originally thought to be structurally sound when supplied with 4137-N/m^2 (.6-psig) GN_2 at 380°K (225°F), became severely damaged. Modifications were made to the seams to add adhesive to minimize stress concentrations at the stitch holes. The seal operating pressure was reduced to 3447 N/m^2 (.5 psig) maximum and the seal supply temperature was reduced to 366°K (200°F) maximum resulting in a maximum seal temperature of 355°K (180°F). Modifications were also made to the hood retract mechanism to install a gear reducer between the air motor and jack screw drive shafts. This was required to meet the hood retract time requirement of 25 ± 5 seconds and the hood extend time requirement of 35 ± 5 seconds.

By the completion of the qualification testing, all Shuttle Program requirements were successfully tested, and all known problems had been resolved. The ET stacking and motion tracking envelopes were successfully tested. ET cyclic venting with the vent valve open for two minutes and closed for three minutes and an opening pressure of 5.5×10^4 N/m^2 (8 psig) quickly dropping off to 1.4×10^4 N/m^2 (2 psig) was tested at temperatures ranging from 273°K (32°F) to 88.5°K (-300°F). ET constant venting was simulated for 5½ hours with the vent valve remaining open and the tank venting from 5.5×10^4 to 1.4×10^4 N/m^2 during that time span. Vent hood retraction and re-extension tests were completed with successful seal disconnect and reconnect, simulating remating with the ET in the event of a launch scrub/abort after the vent hood and arm had been retracted. Following the final qualification tests, the tip assembly and GN_2 regulation panel were removed from the LETF, refurbished and installed at the launch pad.

The pad validation testing was conducted in two phases to allow for parallel testing of the arm and its control system on the FSS at the pad while the critical tip assembly and heated GN_2 supply hardware were being tested in the LETF. Phase I testing (starting in June 1980) verified operation of all arm and control console hardware except the LETF test hardware. A weight cage was constructed and installed on the arm tip to simulate the tip assembly weight and C.G. This allowed arm proofloading and timing tests to be completed to control the arm swing time, allowing the arm to swing as quickly as possible without excessively loading the arm truss chord members. An arm retract time of 45 $\pm$ 5 seconds was selected after reviewing strain gauge data and possible failure modes which could increase/decrease arm retract time. This time was minimized due to the vent hood retract sequence starting at T-2 minutes and 35 seconds with arm retraction required by T-30 seconds. After similar analysis an arm extend time of 65 $\pm$ 5 seconds was selected. Complete checkout of the control console and verification of the operation and control of all LPS-operated valves was also accomplished. Phase II testing (conducted from October to December 1980) verified the end-to-end operation of the installed pad system as operated by the LPS console in the Launch Control Center (LCC). Following validation of the installed GN_2 regulation panel and tip assembly, the complete system was qualified with LPS; and the system operation times and conditions verified as those required to support a launch. Testing was completed prior to rollout of STS-1 to the launch pad on December 29, 1980.

The ET GOX vent system was supporting the STS-1 LOX tanking test on January 24, 1981, when the first in a series of failures occurred. The vent seal over the southwest ET vent louver leaked at the seal/ET interface, damaging the ET insulation below the louver. Investigation of the failure revealed several factors: when the ET vent valve was opened, the vent hood/arm truss bounced up approximately 2.5 cm (1 in) and the seal pressure increased from 3310 N/m^2 (0.48 psig) to 4000 N/m^2 (0.58 psig) indicating a sudden loading of the vent seal due to blast pressure from the ET vent or backpressure in the vent pipe; the vent seal moved 10 cm away from the louver at the initial vent valve opening; the failure occurred at a stage during LOX tanking which was not simulated in the LETF due to a lack of ullage capacity in the facility system; the ET surface in the seal contact area was rougher than specified; another contributing factor to the failure may have been arm truss/vent hood misalignment with the ET. After reviewing these factors, the following modifications were made to the system prior to STS-1. Flight Readiness Firing (FRF): the vent seal pressure was increased to 0.039 kg/cm^2 (0.55 psig) to force the seal to conform to the ET surface; the vent seal supply temperature was increased to 377^{o}K (220^{o}F) to heat the seal footprint; a fiberglass seal support frame was attached to the vent hood to prevent seal movement; the ET surface was repaired and smoothed as much as possible; seal vent cavity backpressure transducers were added with data recorded in the LCC and a film camera arranged to monitor the seals during venting.

FRF occurred on February 20, 1981, with the vent seals again failing to perform. The southwest vent seal ruptured and damaged the ET during the fourth ET vent valve open cycle with the LOX tank approximately 50% full. Analysis of the failure revealed the following: visible signs of stress in the

failed seal (stretch marks, elongated stitch holes) indicated that the higher seal pressure and temperature were contributors to the seal failure; the vent seal pressure increased from 3585 N/m^2 (0.52 psig) to 4690 N/m^2 (0.68 psig) and the vent hood bounced approximately 4.6 cm (1.8 in) when the vent valve opened; backpressure in the seal vent cavity increased to approximately 6895 N/m^2 (1 psig) accounting for the vent seal pressure increase and the hood bounce by the sudden dynamic loading; the fiberglass seal support appeared to pinch the vent seal against the ET as the seal attempted to track the shrinking tank; the vent seal appeared to be too closely confined for its designed length which created a bunching action and may have contributed to the problem. Any or all of these factors may have caused the second failure; however, it was apparent that the blast from the southwest vent louver (the northeast seal had never leaked) and the vent cavity backpressure (coupled with the vent hood bounce) were the major contributors to both seal failures. After FRF the system was returned to the baseline configuration (tanking test configuration) pressures and temperatures with the fiberglass seal support removed. The vent seal inflated length was changed from 0.61 m (24 in) to 0.508 m (20 in) to minimize bunching. The ET was also modified to configure the vent orifice located 8 cm (3 in) inside the vent louver to attempt to break up the blast pressure of the venting gas impinging on the vent seal.

These modifications were all accomplished prior to the third ET tanking test which resulted in a third failure of the vent seal. The vent seal leaked with the ET approximately 70% full. The vent seals were removed from the vent hood following completion of the third tanking test, and the vent hood used in the "umbrella" mode as a cover providing a heated nitrogen purge to the ET for STS-1 launch on April 12, 1981. Some ice or heavy frost was formed on the louver area of the ET in spite of the heated GN_2.

A requalification test program of the GOX Vent System was conducted in the summer of 1981. The GN_2 regulation panel and the tip assembly with the full-length vent pipes were returned to the LETF which was upgraded by the addition of a 106-m^3 (28,000-gal.) dewar to the cryogenic simulation system and by other minor modifications to improve the simulation of the ET cryogenic shrinkage, vent hood bounce, ET vent valve, and ET surface smoothness. The test program started by investigating the STS-1 failures to determine their most probable cause. This testing revealed these problems:

1. The blast pressure from the vent valve on the southwest vent seal was approximately ten times that on the northeast seal resulting in an increased load over a concentrated area.

2. The backpressure in the seal vent cavity at vent valve opening was caused by undersized vent pipes, which at 6895 N/m^2 was five times greater than tested one year before. This resulted in a partial internal collapse of the vent seal which was pressurized to less than one-half that amount.

3. The alignment of the arm/vent hood was critical due to the vent seal proximity to the vent louver and may have been as much as 10 cm (4 in) off for STS-1 first tanking test.

To resolve these problems modifications were made to the ET vent valve, the GOX vent pipes and the vent hood. The ET vent valve, a poppet valve, was modified to limit the stroke of the poppet to 42% of the original stroke, thereby reducing the flow through the valve; and the orifices downstream of the vent valve were removed to allow greater expansion of the GOX prior to exiting the vent louvers and impinging on the vent seals. The existing GOX vent pipes were removed and new ones installed which were twice as large in diameter (0.61 m vs 0.3 m) and less than half as long (8.2 m vs 20.4 m). The vent hood was modified to provide an improved optical alignment capability to assure that the vent seals were centered about the ET vent louvers. After the modifications, the retest of the system was performed with the following results:

1. The blast pressure on the southwest vent seal was reduced by 90% to approximately that of the north vent seal on STS-1 (which did not leak).

2. The backpressure in the seal vent cavity at vent valve opening was reduced by 85% to less than 1034 N/m^2 (0.15 psig).

3. The alignment of the arm/vent hood with the ET could be consistently made within 1.25 cm (0.5 in).

4. The LETF cryogenic system could successfully simulate the predicted STS-2 vent valve cyclings and pressure curves.

The retest program successfully requalified the GOX Vent System tip assembly and GN_2 regulation panel which were reinstalled at the pad and checked out prior to STS-2 rollout.

In support of STS-2 the system performance was excellent (see Figure 6). On September 15, 1981, the system successfully supported the tanking and detanking of the ET with no problems. Prior to launch a new seal set was installed. The system successfully supported the STS-2 launch scrub on November 4, 1981, and the launch on November 12, 1981, with the same set (pair) of inflatable vent seals which were under operating pressure and temperature for a total of 30 hours and cryogenic flow for 16 hours (the longest operational usage for one inflatable vent seal set).

The system is now operational at the launch pad. Although the quality of the vent seal manufacturing is still a minor problem, most of the major problems have been solved. The vent seal was a significant factor in the ability of the system to meet program requirements due to its flexibility in tracking vehicle motions and its ability to conform to the contour of the ET and not allow any leakage of GOX. A significant lesson learned in the testing of the ET GOX Vent System is to "simulate as little as possible and when you have to simulate make sure that it adequately meets the requirements and predicted capability of the system you are simulating".

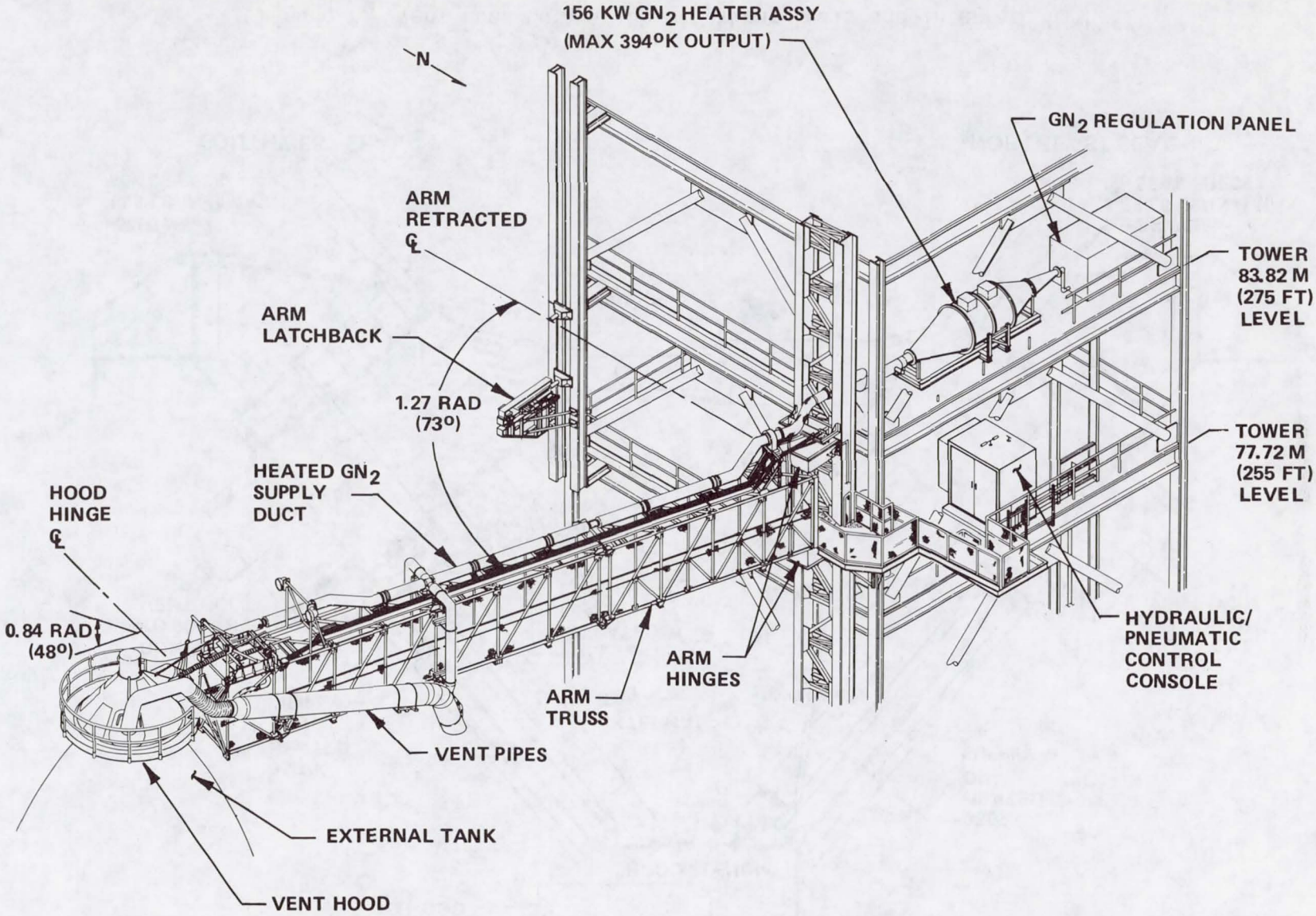

Figure 1. ET GOX Vent System Installation at Launch Complex 39A

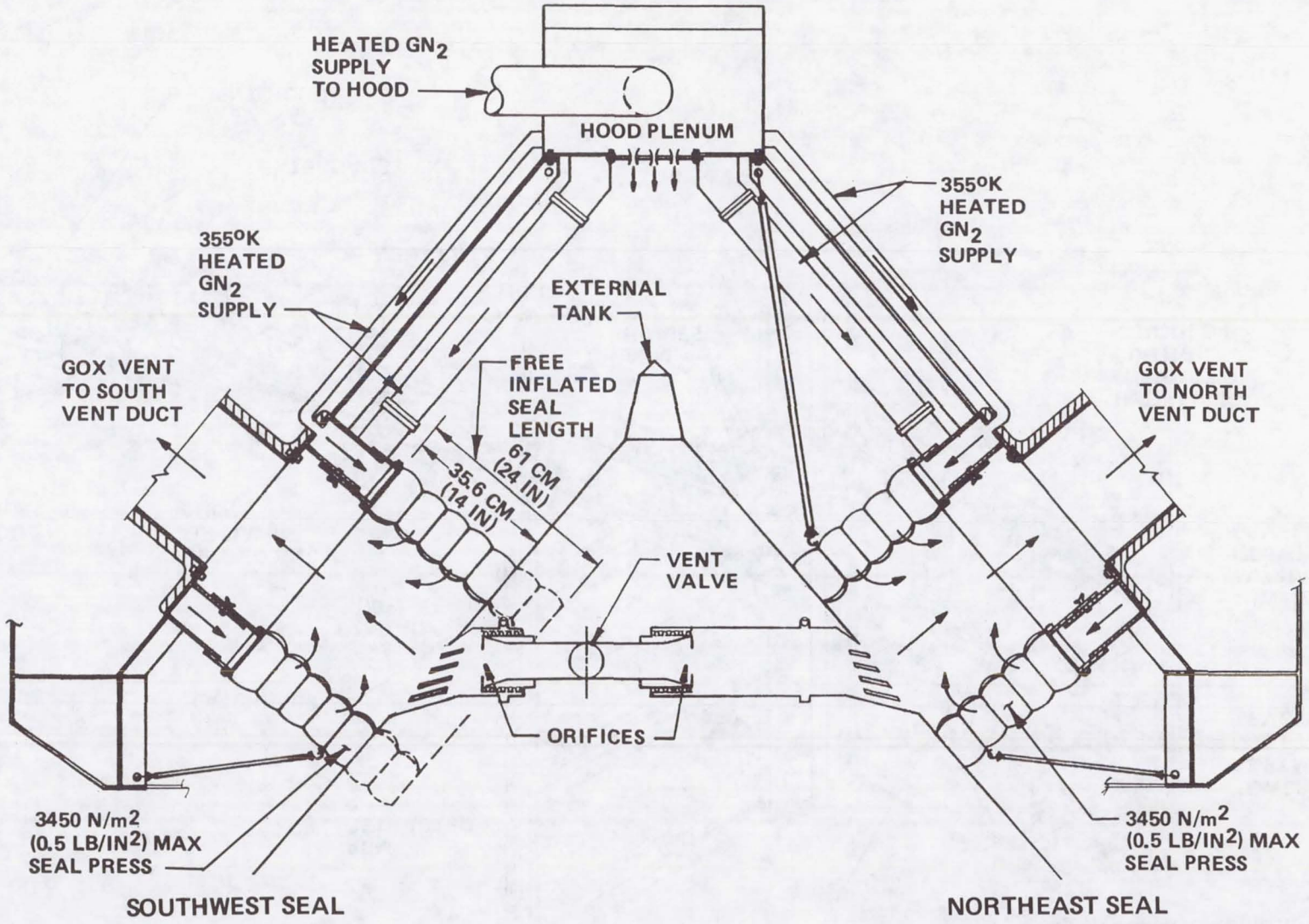

Figure 2. Vent Hood Cutaway Showing Vent Seals and Interface With ET

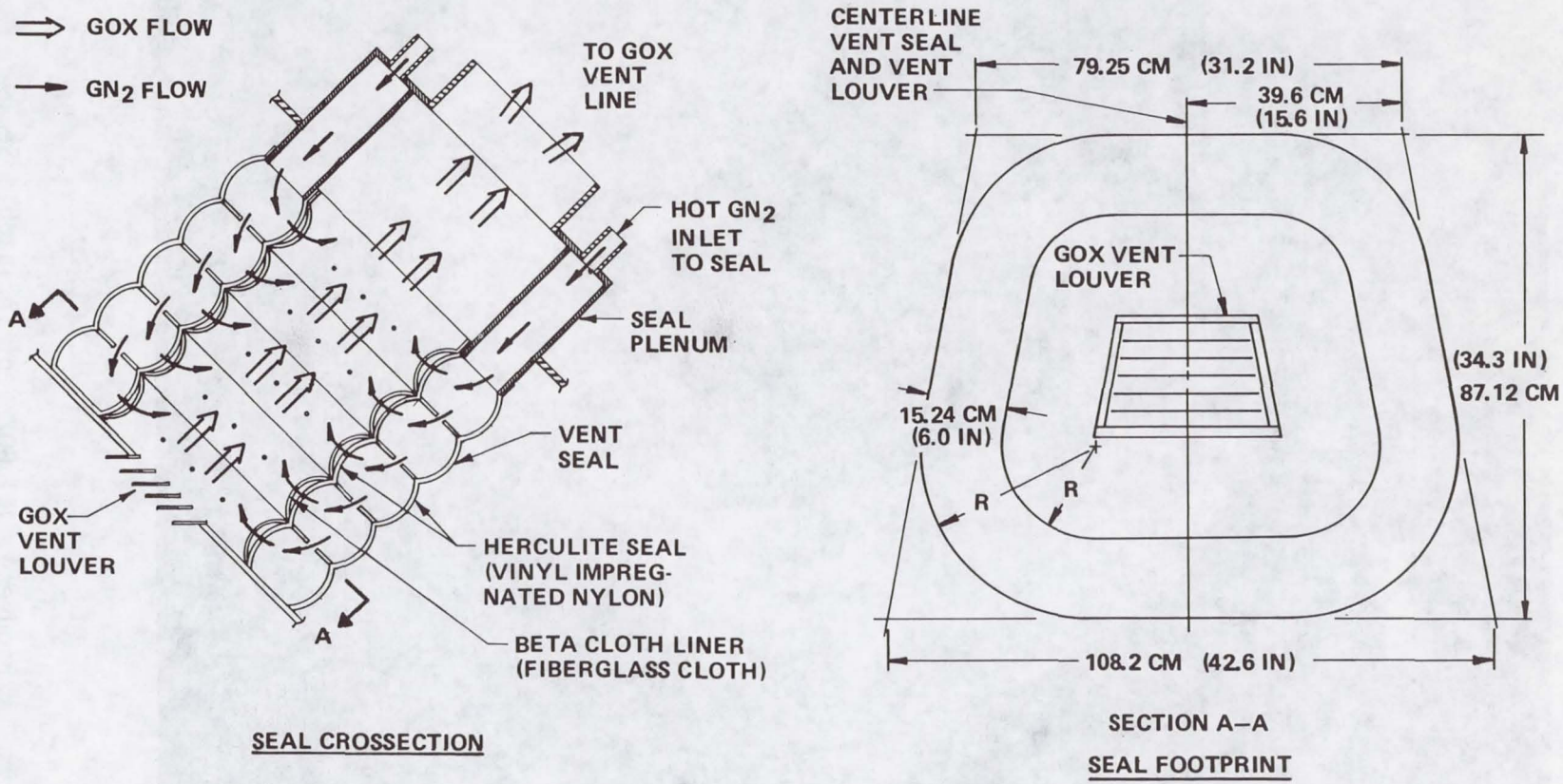

Figure 3. ET GOX Vent Seal

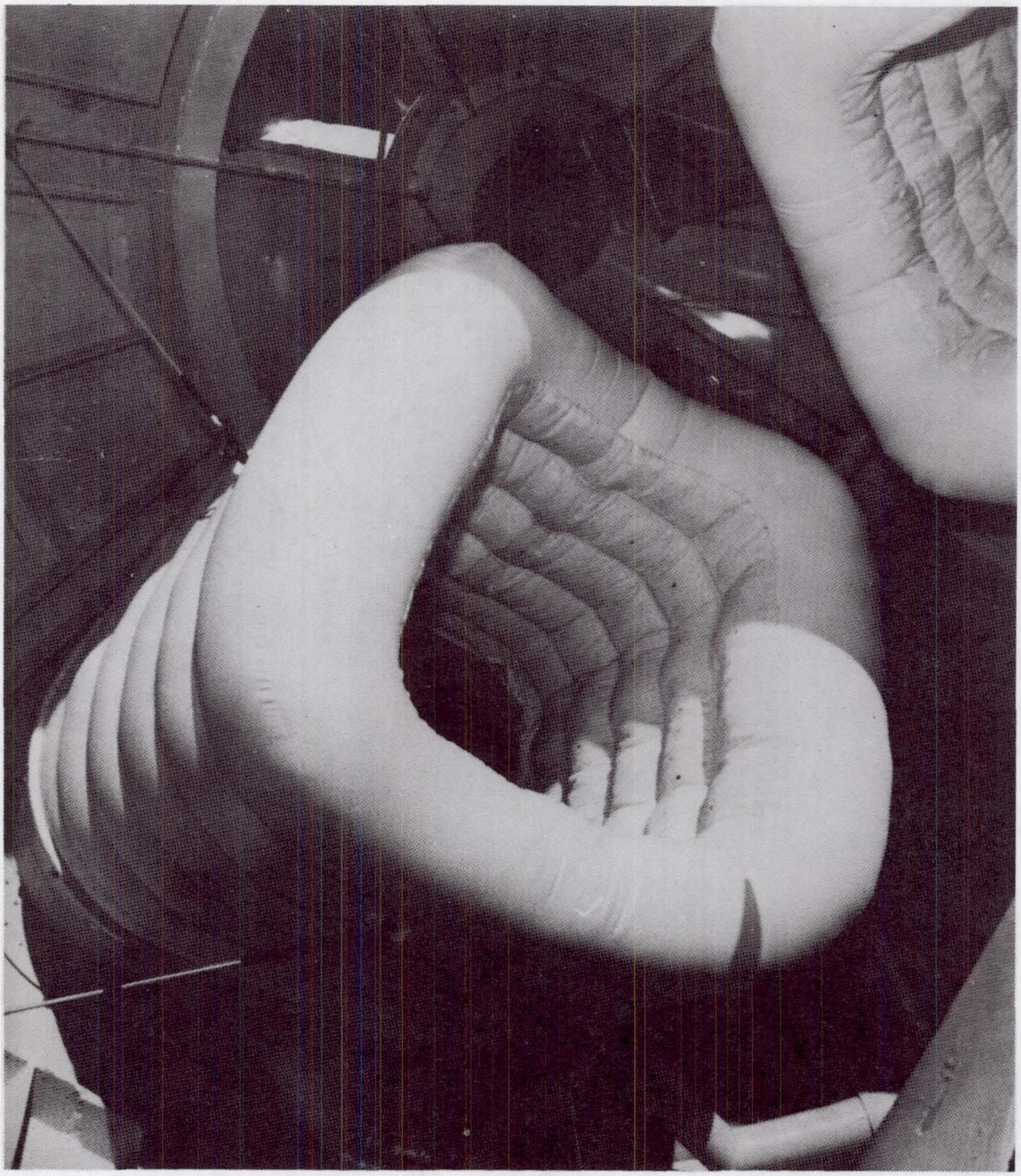

Figure 4. ET GOX Vent Inflatable Seals

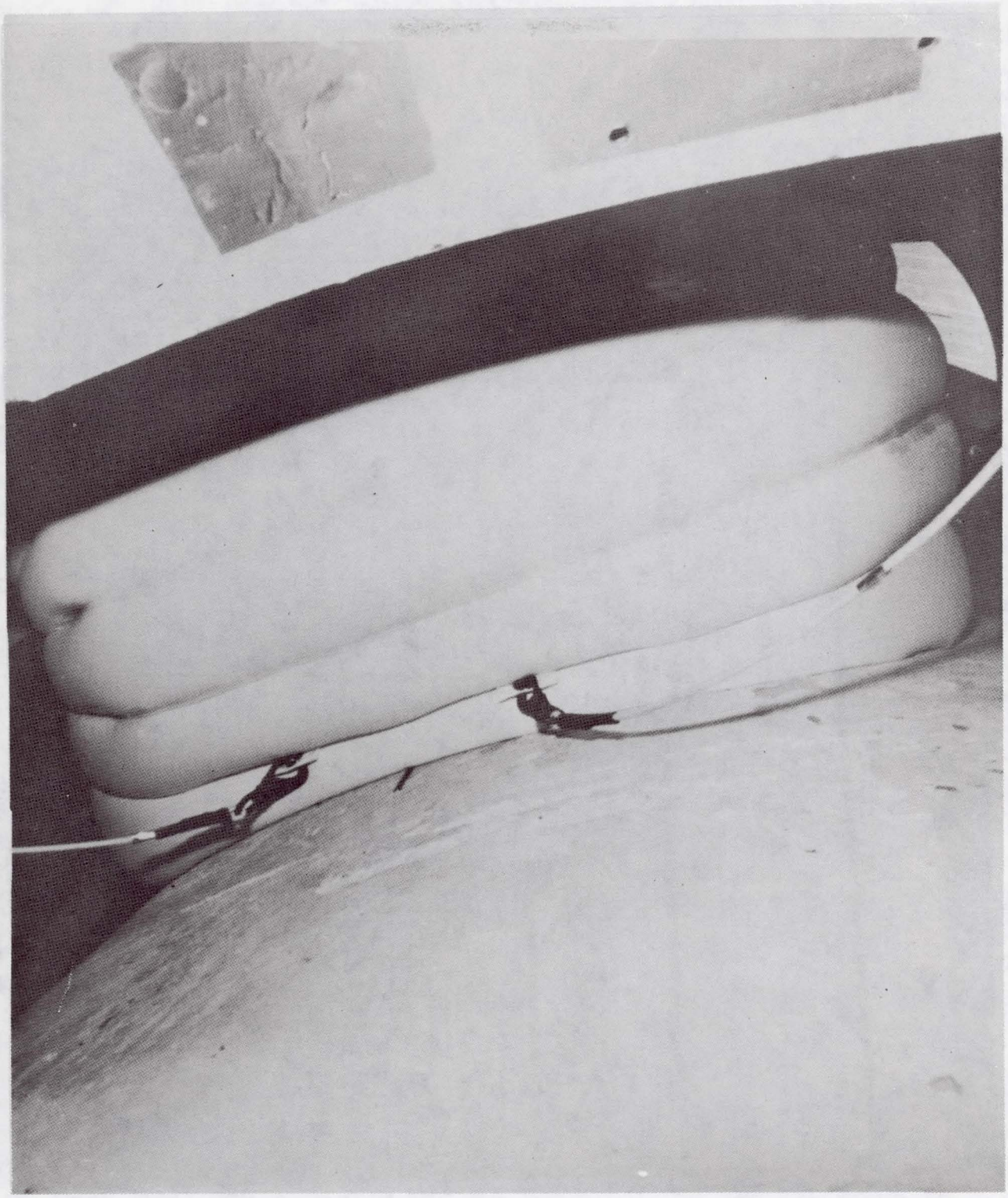

Figure 5. ET GOX Vent Seal Inflated Around ET Vent Louver

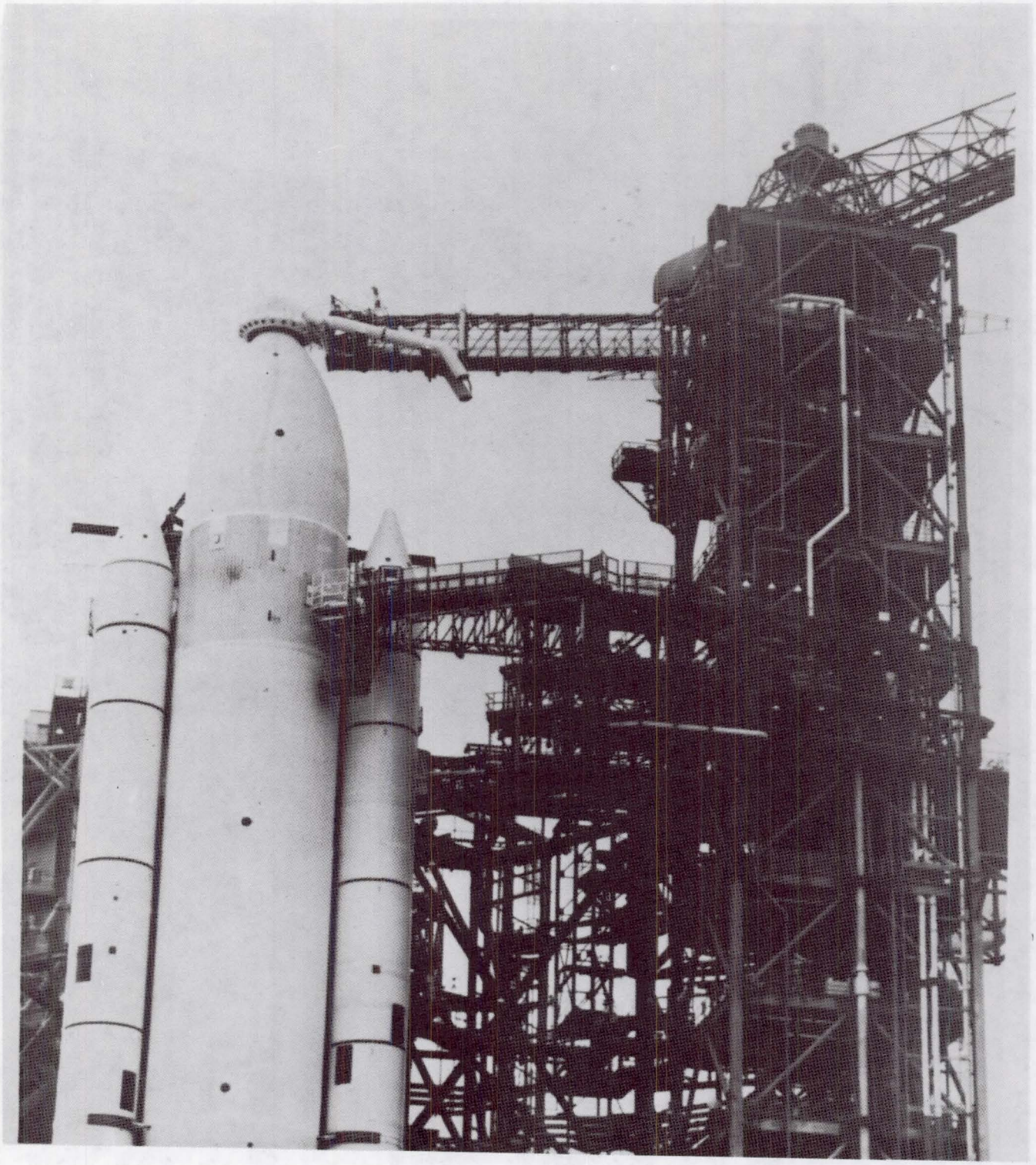

Figure 6. ET GOX Vent System Installed at Pad 39A for STS-2 Launch

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Mr. Franklin has been lead design engineer of the ET GOX vent system for NASA since 1979. Since joining NASA in 1969, he has worked in the Advanced Studies Group and the Launch Accessories Branch of the Design Engineering Directorate. He has been a member of the American Institute of Aeronautics and Astronautics (AIAA) since 1973, serving as chairman of the Cape Canaveral Section from 1978 to 1979. Mr. Franklin received his B.S. degree in Aerospace Engineering from Auburn University in 1973.