-6-62

ENGINEERING PAPER NO. 1400

VIII: 2

DOUGLAS

Facility Design for Handling Liquid Hydrogen for Space Vehicle Applications

JUNE 20-23, 1962

Prepared by:
T. D. SMITH
Chief Engineer Space Systems

E. L. WILSON
Assistant Chief, Space Propulsion Section

E. J. SCULLY
Group Engineer Facilities and VSE
Space Propulsion Section

Presented to:
German Society for Rocket Technology & Astronautics
Braunschweig, Germany

Facility Design for Handling Liquid Hydrogen for Space Vehicle Applications

T. D. Smith[1], E. L. Wilson[2], E. J. Scully[3]

The performance capabilities of liquid hydrogen as a fuel, in combination with oxidizers such as liquid oxygen or liquid fluorine, indicates its desirability for use in large space vehicle propulsion systems. The theoretical vacuum specific impulse, at a chamber pressure of 1000 psia (70.32 kilograms per square centimeter) and a nozzle area ratio of 40, is 460 for hydrogen and oxygen, and 484 for hydrogen and fluorine. This represents a 30% and a 37% increase respectively over a specific impulse of 354 for the oxygen and kerosene presently used for space boosters. Currently this fuel is being used in combination with the liquid oxygen on such space programs as Centaur, three stages of the Saturn vehicle, and is to be used on Nova and nuclear propulsion systems of the future. The purpose of this paper is to present the philosophies used by the Douglas Aircraft Company in designing static and flight test facilities for handling large quantities of liquid hydrogen at high flow rates as applied in the development of large space vehicles. These philosophies have been applied in the design, construction and operation of a test facility which has been safely and successfully operated in support of the Saturn space program for the past year.

The development of large space vehicles and their propulsion systems is usually conducted initially at a remotely located static firing test facility. The static test facility maintained by the Douglas Aircraft Company, Figures 1 and 2 is located near Sacramento, California and consists of two static firing test

---

[1] Chief Engineer, Space Systems, Douglas Aircraft Company, Santa Monica, California

[2] Assistant Chief, Space Propulsion Section, Douglas Aircraft Company, Santa Monica, California

[3] Group Engineer, Facilities and VSE, Space Propulsion Section, Douglas Aircraft Company, Santa Monica, California

stands and a component test area. The first vehicle system tests are conducted on a tank and engine combination which has become known as a battleship installation, Figures 3 and 4, due to the heavy steel wall construction used in the tank. This practice allows testing of the propulsion systems to be scheduled without regard to the development schedule of the flight tankage. In addition, the heavy construction provides a certain amount of protection in case of accidental fires or detonations on the test stand. Further static firing tests are then conducted on flight vehicles. This static test program is followed by a flight test program at Cape Canaveral, Florida to prove the integrity of the vehicle design under actual operating conditions.

A battleship tank, Figure 5, designed by Douglas and currently being used in a space vehicle test program, is constructed of American Iron and Steel Institute type 304 low carbon stainless steel plate. The tank is divided into two compartments by a single membrane, or common bulkhead, to contain the liquid oxygen and liquid hydrogen which are used in the static engine firing test program. In order to simulate the actual vehicle operation as nearly as possible, the tanks conform in size and internal shape to the propellant tanks of the actual flight vehicle. The tank shell is 9/16 inch (14.288 mm) plate, the upper hemispherical head is 3/8 inch (9.5 mm) plate, the lower torispherical head is 3/4 inch (19 mm) plate. To reduce heat transfer from the atmosphere to the liquid hydrogen during test, a 3/4 inch (19 mm) balsa wood insulation is applied internally to the walls of the liquid hydrogen tank. The balsa wood is applied to the tank walls in sections and is bonded with an epoxy resin. The inner surface of the insulation is sealed by cementing a layer of fiberglas cloth to the balsa wood and then coating the fiberglas with a resin which is applied in layers. The common bulkhead is also insulated with balsa wood to reduce heat transfer from the liquid oxygen to the liquid hydrogen. All inlets and outlets on the tank, such as propellant fill valves, propellant gas vent and relief valves, engine feed line connections and gas pressurization ports are located in the same places on the battleship tank as on the actual flight vehicles. The engines, propellant feed lines, pneumatic system components and all ancillary parts of the propulsion system are flight hardware. This design philosophy provides a reliable means of determining vehicle tank pressures during propellant loading and for checking the operation of the propellant tank pressurization systems, the propellant tank outlet and anti-vortex devices and for demonstrating proper feeding of the engines through the propellant feed lines. The battleship tank is designed in accordance with the requirements of the American Society of Mechanical Engineers Code for unfired pressure vessels which requires a burst pressure of 4 times the working pressure. It is hydrostatically tested to a pressure of 1 1/2 times the maximum working pressure. The maximum working pressure of the hydrogen portion of the tank is 50 psig (3.51 kg per square cm) and the maximum working pressure of the oxygen portion is 65 psig (4.57 kg per square cm). All seams and joints are radiographically examined for weld integrity; the completed assembly is leak tested by pressurizing the tanks to the working pressure with a mixture containing 95% nitrogen and 5% helium and all joints are checked by using a helium mass-spectrometer. Instrumentation ports, light windows and camera windows and included in the tank to provide for the necessary recording of factual and visual test information.

The flight vehicle liquid hydrogen tank walls are internally insulated with a Douglas developed insulation material. The common bulkhead due to its unique construction, requires no additional insulation. Two complete hemispherical membranes of 2014-T6 aluminum alloy are bonded to either side of a one inch (25.4 mm) thick fiberglas honeycomb core with an epoxy resin. No outlets, bosses or other penetration of any kind are permitted in the bulkhead to preclude accidental mixing of fuel and oxidizer. This design provides a bulkhead which has the capability of resisting reverse pressure (pressure in the hydrogen tank at a higher level than in the oxygen tank) which might result in the event of a tank pressurization system failure. This concept provides an important margin of safety during test operations and in flight.

The test facility storage and transfer systems must be capable of providing propellant to the battleship tank and static and flight vehicles in the desired quantities and flow rates at a reasonable expenditure of money. The propellant storage required is dependent upon:

1. Vehicle tankage requirements.
2. Test schedule and firing duration.
3. Losses due to boil-off during storage, transfer system chilldown and boil-off after tanking the test vehicle.
4. Propellant logistics.

Two types of tanks are normally used for storage of cryogenics: spherical and cylindrical. For liquid hydrogen storage tanks having capacities exceeding 30,000 gallons (113,550 liters) and requiring high internal storage or transfer pressures, the weight savings and resultant cost savings made possible by the spherical shape together with the somewhat greater surface area to volume ratio and resultant high boil-off rate of a cylindrical tank favor the selection of a spherical rather than a cylindrical tank. Based on these considerations, each test stand at Sacramento is supplied with liquid hydrogen from a field constructed 90,000 gallon, (340,650 liter) column mounted, dewar type spherical tank, Figures 6 and 7. The inner sphere, approximately 29 feet (8.84 meters) in diameter, is constructed of welded aluminum alloy and the outer sphere, approximately 34 feet

(10.36 meters) in diameter, is made of carbon steel. The space between the two spheres is filled with perlite insulation and evacuated to an absolute pressure of 10 microns of mercury (10^{-2} torr) when the tank is warm. After the tank is filled with liquid hydrogen, the annulus pressure decreases to less than one micron (10^{-3} torr) due to condensation of the interstitial gases. The selection of evacuated perlite as an insulating media was based on the following considerations:

1. Application of powder insulation in the field is easily controlled and inexpensive when compared to multilayer radiation shield insulation.
2. Powders do not require a high vacuum for effectiveness and mechanical vacuum pumps are capable of evacuating the insulating annulus.
3. Powders are effective adsorbents and will adsorb gases which result from a minor leak in the tank outer vessel, thus maintaining a vacuum for long periods of time without repumping.
4. When a substantial thickness of powder is used, there is no significant advantage in providing low emissivity type insulation.
5. Installed cost of perlite is very favorable when compared to other powder insulations or to multiple layer insulations.

Since conductive heat transfer is a direct function of cross sectional area and varies inversely with length of the heat path, all tank supports and piping connections were designed to minimize the cross sectional area and to provide long heat transfer paths. In an effort to reduce the size and quantity of supports required between the inner and outer tank, the completed inner sphere was proof tested pneumatically rather than hydrostatically. This method of testing eliminated the necessity for designing the support structure to support the weight of water during the test. The tank is designed so that the maximum liquid hydrogen evaporation loss rate is .12% by weight per day. Lines connecting to the inner vessel are designed so as to be flexible in order to accommodate thermal expansion and contraction of the lines and of the inner and outer tank shells.

Selection of a method of transferring propellants is a function of the flow rate desired and the availability of hardware to do the job. The two common methods of transferring cryogenic propellant are pumping and pressure transfer. At the time this facility was designed, there were no fully developed and tested ground facility type pumps that could be used to transfer liquid hydrogen at flow rates of 2000 gallons per minute, so pressure transfer was selected as the method to be used for the static firing test facilities at Sacramento. The only media which can be used for pressurized transfer of liquid hydrogen because of the freeze-out problem are gaseous hydrogen or gaseous helium. Consideration was given to the on-site or delivered cost and the availability of the two gases. Since the U. S. Bureau of Mines recommends the use of a suitable substitute for helium where possible and due to the higher cost of helium, hydrogen gas was selected as the pressurizing medium. Hydrogen gas is also used as a purging medium to reduce the quantity of air or nitrogen present in the battleship or flight vehicle liquid hydrogen tanks to a safe level prior to loading liquid hydrogen. The hydrogen gas required for these operations is obtained by vaporizing liquid hydrogen through a pump-vaporizer, Figures 8 and 9, which converts the liquid hydrogen to gaseous hydrogen and boosts the pressure to 2500 psig. The gaseous hydrogen is then stored at this pressure in 300 actual cubic foot cylindrical storage vessels until required during the test program.

Liquid hydrogen is transferred from the storage sphere to the test vehicle through two vacuum jacketed, stainless steel transfer lines approximately 300 feet in length. A four inch diameter line is used to transfer the bulk of the liquid to the vehicle at 2000 gallons per minute under a storage tank pressure of 40 psig. The final portion is transferred at 500 gallons per minute through a topping or replenishing line which is 2 inches in diameter. This method of transfer was used because:

1. The quality and heat content of the liquid hydrogen entering the vehicle is critical.
2. Propellant must be loaded on board the vehicle with a tolerance of ± 1/2% of total propellant mass. In order to allow the capacitance type probe to control the load within this tolerance, low final transfer rates are required.
3. Due to safety considerations, the liquid hydrogen storage sphere is located remotely from the test stand resulting in long transfer lines.
4. Transfer of small quantities of hydrogen through a large line would result in an undesirable amount of heat gain in transit.

The fluid carrying inner line, Figure 10, is light-weight austenitic stainless steel with as low a mass as is possible to reduce the chilldown time, reduce the hydrogen vaporization losses, and to reduce the amount of two-phase fluid flow. Each section of transfer piping is enclosed on the ends by a thin steel conical diaphram welded to the inner and outer pipe thereby providing a vacuum annulus. Each vacuum annulus is inspected in the fabricator's shop with a helium leak detector and is vacuum pumped to a pressure of 10 microns of mercury (10^{-2} torr) prior to acceptance and delivery to the field. The fact that each section of pipe has an integral vacuum annulus eliminates the possibility of one leak destroying the vacuum in the entire transfer system and provides a means of delivering a completely tested unit to the field for installation. Each section of transfer lines includes a vacuum gage probe and a vacuum valve which allows for periodic check and repumping of the lines as necessary. The differential contraction between the inner and outer shells of the transfer line is offset by the use of metal bellows placed in the inner line. Each bellows is guided and restrained by the use of tie-rods with stops on the ends. Heat transfer due to radiation is reduced by the inclusion in the vacuum jacketed annulus of a low-emissivity, multi-layer type insulation. This insulation is wrapped around all portions of the transfer line including the expansion joints and fittings. Since the inner line must be supported inside the outer jacket, consideration must be given to the problem of heat transfer by conduction through these supports. The material selected for these supports is a laminated plastic with an epoxy binder which has a low thermal conductivity, good strength characteristics and a low "out-gassing" tendency.

To reduce the possibility of leakage, all pipe sections are joined by welding rather than with bolted flanges. All components are likewise joined to the system by welding. All weld joints are then enclosed by a thin cylindrical stainless steel jacket which is welded between the outer portions of each vacuum jacket section of the transfer line. The resulting annulus is then filled with polyurethane foam and the pour hole sealed with a thin metal disc attached to the jacket with a self-curing adhesive. The calculated heat transfer through this joint is approximately 75 BTU per hour (18.9 kg. cal. per hour). All welding, either in the field or in the shop, is performed using an inert gas shielded tungsten arc welding process and all field joints are made with an inert gas purge flowing through the inner line. Ten percent of all typical shop welds are checked by radiographic inspection. All joints are proof tested to 1-1/2 times the design working pressure, and leak tested at the design working pressure using a helium mass-spectrometer. Where it is mandatory that a joint be installed with the capability for easy removal or replacement, a Douglas designed bayonet type joint, Figure 11 is utilized. This joint consists of a double wall vacuum jacketed probe and a double wall vacuum jacketed receptacle which are joined together and retained with a "V" band type clamp. Consideration was given to the heat transfer due to conduction and all direct heat transfer paths are as long as is possible. The primary seal is an "O" ring included on the probe half of the coupling and a secondary metallic seal is used between the mating halfs of the clamp flanges.

The selection of flow system components was made based on:

1. Heat transfer characteristics.
2. Reliability of design.
3. Minimum mass for quick chilldown.
4. Compatibility of materials with the flowing medium.
5. Capability of being cleaned for liquid hydrogen service.
6. Capability of being serviced without removal from the welded system.

A review of the commercially available flow control valves did not provide a component which met these design requirements and indicated the need for a special design. A local valve manufacturer proposed to design a valve to our requirements (Figure 12). The normal commercial stainless steel "Y" type globe valve body was reduced in mass to reduce the heat capacity, the valve actuation stem and yoke were extended to lengthen the heat transfer path, and the entire valve body was surrounded by a stainless steel jacket filled with polyurethane foam insulation. The valve seat is made from a tetrafluoroethylene resin and all gaskets or seals which may come in contact with the flowing medium are made from a tetrafluoroethylene resin or a trifluorochloroethylene ploymer. A 72 micron (.072 mm) filter is incorporated in the fill line to protect the vehicle from contamination and it likewise has a low heat capacity body and a foam filled stainless steel jacket. The storage tank fill line includes a 40 micron (.04 mm) foam jacketed filter to preclude contamination of the storage tank during loading operations from the transporter. Foam insulated components were selected over vacuum jacketed components because they provide an integral factory complete component which may be certified in the factory by functional and leak testing, and because they result in a reduction of field maintenance since they require no vacuum maintenance or repumping. The heat transfer rate through a 4 inch foam jacketed valve is approximately 300 BTU per hour (75.6 kg-cal. per hr.) while the heat transfer rate through a similar vacuum jacketed valve is approximately 220 BTU per hour (55.4 kg-cal. per hr.). For a 2 inch valve the heat transfer rates are 170 BTU per hour (42.8 kg-cal. per hr.) and 130 BTU per hour (32.8 kg-cal. per hr.) respectively.

In designing a liquid hydrogen transfer system, consideration must be given to safety. The most serious hazard with hydrogen is the danger of fire or explosion. Liquid hydrogen is very volatile, the limits of flammability or detonability of gaseous mixtures with air or oxygen are wide and the potential energy release per pound of reactants is very large. Fortunately, it is extremely difficult to obtain detonations of hydrogen-air mixtures in free space and radiation damage due to hydrogen fires is very small. The hazards associated with the handling and storage of liquid hydrogen are therefore considered to be less than those encountered with the hydrocarbon fuels.

Consideration must be given to the safe disposal of hydrogen gases which are used during the test run or are generated in the storage tank due to boil-off in the transfer line and vehicle tank during tanking and in the gas cooler during test operations. Since the storage tank and test area are remotely located, two gaseous hydrogen vent stacks are provided. The vent stack for the the storage area disposes of the tank boil-off gases during standby and disposes of the pressurizing gas which is released when depressurizing the storage tank after transfer. The test stand vent stack disposes of the hydrogen gases generated in the transfer line and vehicle tank during chilldown and also disposes of the hydrogen gas which is used to purge air or nitrogen from the vehicle tank prior to transfer. After completion of the static test firing the vehicle tank is also vented through the stand vent and the hydrogen gas remaining in the vehicle tank is purged from the tank by replacing it with gaseous nitrogen.

Hydrogen gas can be discharged from the vent stack directly into the atmosphere or can be ignited at discharge by a flame or hot wire. No clear cut criteria is available to determine which of these is the better method. Since it seemed safer not having a fire of any type at the test site, a "non-burning" vent system was selected. A continuous wire electrical resistance type fire detector is located at each vent outlet and a gaseous nitrogen spray device is also included at each outlet. In the event that discharging hydrogen gas is ignited, the detector system will indicate a fire and the vent outlet area will then be saturated with gaseous nitrogen. This method of operation has been checked out and operates very satisfactorily. Additional safeguards which are employed in the vent stack include a check valve to preclude the entrance of air into the stack, a gaseous nitrogen purge which is used to cleanse the vent stack piping before and after every test run, a vent outlet which is screened to prevent the nesting of birds and a vent outlet shape which precludes the admittance of rain or snow.

Additional safeguards throughout the facility include the following:

1. All electrical wiring and fixtures are of the totally enclosed or "explosion proof" type.
2. Continuous wire resistance type fire detectors are located in all areas where gross hydrogen leakage could exist.
3. Explosion proof enclosures surrounding electrical equipment within 25 feet (7.6 meters) of propellant containers, lines or storage vessels are purged with nitrogen gas.

4. All electrical systems and fluid systems are grounded to prevent sparking.

5. Television cameras are located throughout the test stand areas which present a fire hazard and are monitored from the blockhouse.

6. Many water deluge outlet nozzles are placed in the areas where fire could be present.

7. Portable hydrogen detectors are available for personnel to use when entering the test area after a static firing test.

8. The hydrogen storage tanks are surrounded by earthen dikes to contain hydrogen spillage and the diked area is covered with gravel to accelerate vaporization of any spilled hydrogen.

Experience to date with the liquid hydrogen storage and transfer system at the Douglas Aircraft Company test facility has been very good. Facility checkout and certification began last year with a series of individual propellant loading tests. First the liquid oxygen system was tested at various loading flow rates. Following the satisfactory completion of the liquid oxygen loading, a series of liquid hydrogen loading tests was conducted. After each propellant system had been operated separately, a series of combined liquid oxygen and liquid hydrogen loadings was performed. During these loading tests no major problems occurred either mechanically or electrically. The test facility is now performing as designed and fulfilling its primary purpose in providing a means for testing the space vehicle and its components. Operating experience at the test facility has shown:

1. Liquid hydrogen can be transferred at 2000 gpm using gaseous hydrogen as the motivating force.

2. Discharge of gaseous hydrogen through a non-burning vent stack to the atmosphere is a satisfactory means of disposal. Fires which have

occurred at the vent stack outlet have been detected by the fire detection system and extinguished by purging the outlet area with gaseous nitrogen.

3. Purging of the battleship tank with gaseous hydrogen to eliminate the gaseous nitrogen inerting blanket is most effective when the hydrogen gas is introduced at the top of the tank and discharged at the tank bottom. The method of continuous purging proved to be less time consuming and required less gas than the method of alternately pressurizing the tank to operaterating pressure and depressurizing to ambient pressure.
4. When repairs are required on a transfer system which has previously contained hydrogen, an inert gas purge, such as helium, is required and the purge gas must flow away from area being repaired toward the hydrogen storage tank. Gas flow from the storage tank toward the repair area could contain entrained hydrogen gas or force pure hydrogen gas through the opening and present a fire hazard.

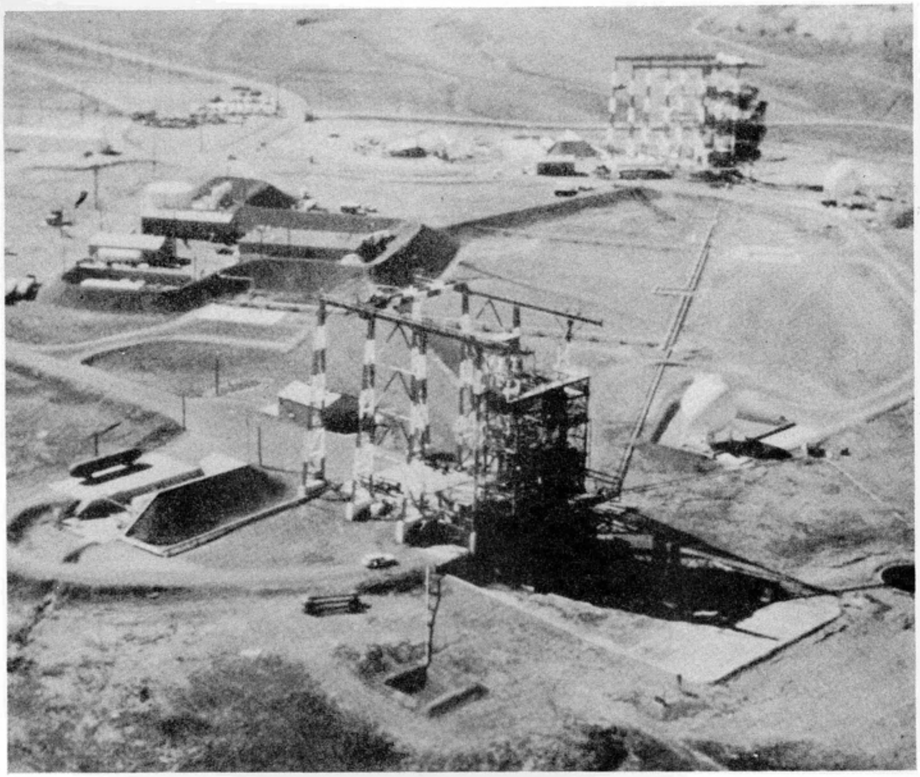
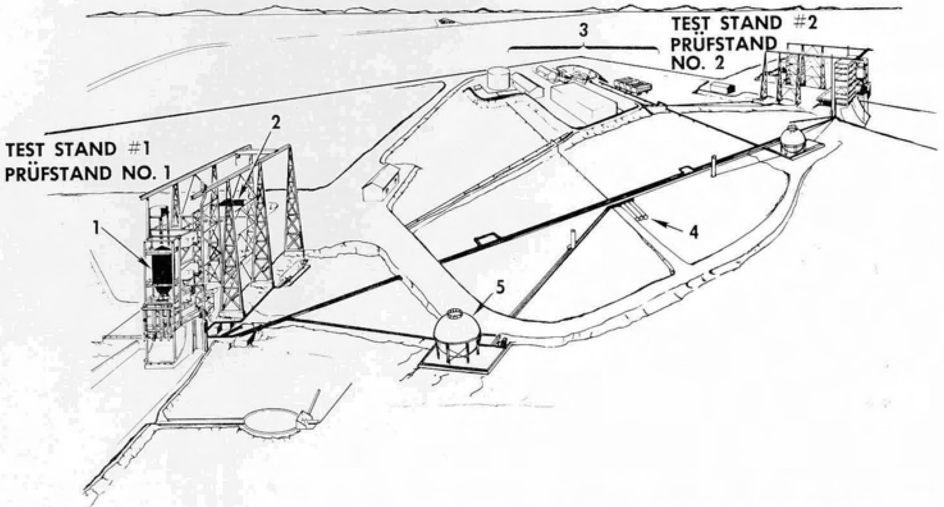


Figure 1

DSV-4-198

SATURN S-IV SACRAMENTO FACILITY
SATURN S-IV ANLAGEN IN SACRAMENTO



1 BATTLESHIP TANK	"BATTLESHIP TANK"	4 GH_2 STORAGE TANK	WASSERSTOFF-AUFBEWAHRUNGSTANK (GASFÖRMIG)
2 LO_2 STORAGE AREA	GEBIET FÜR FLÜSSIG-SAUERSTOFF-AUFBEWAHRUNG	5 LH_2 STORAGE TANK	WASSERSTOFF-AUFBEWAHRUNGSTANK (FLÜSSIG)
3 GAS STORAGE AREA	GEBIET FÜR AUFBEWAHRUNG VON GASEN		

Figure 2

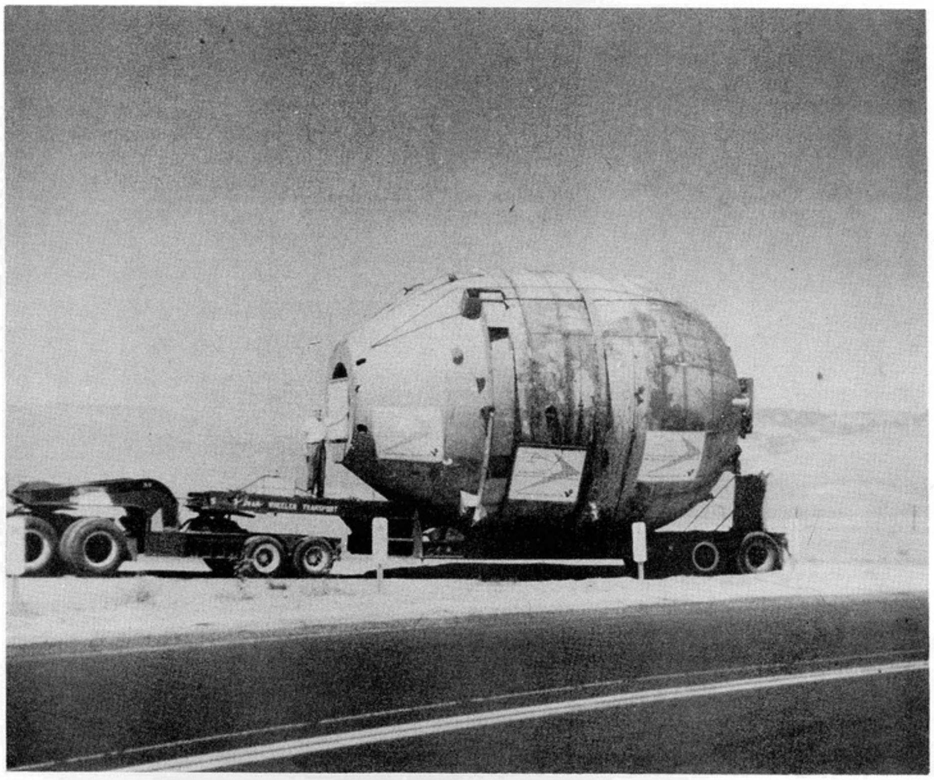


Figure 3

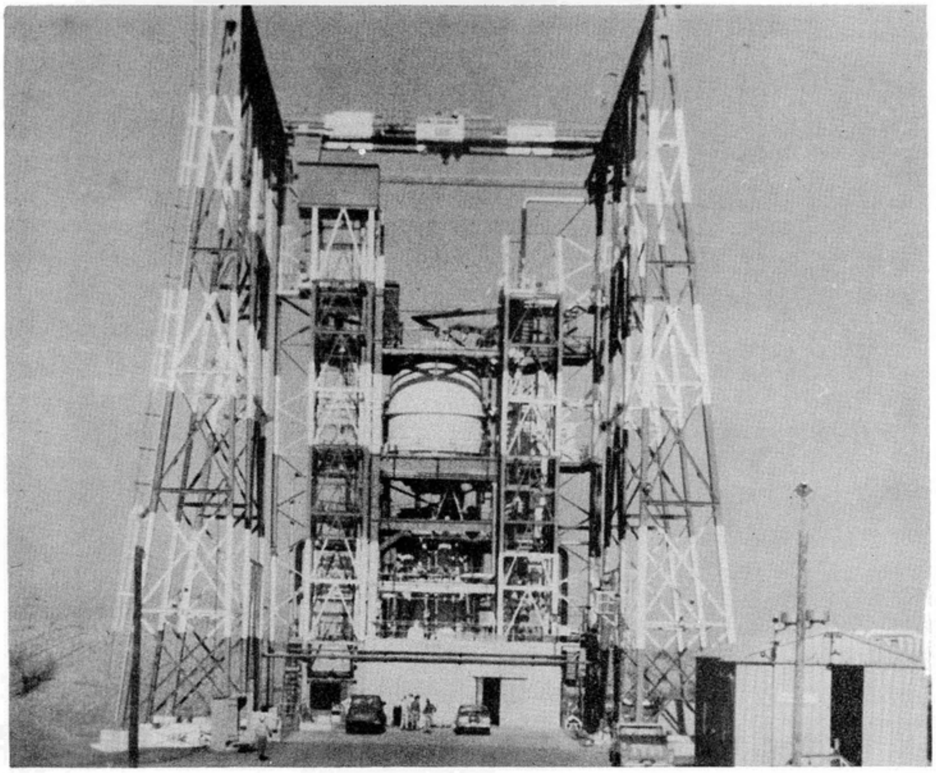


Figure 4

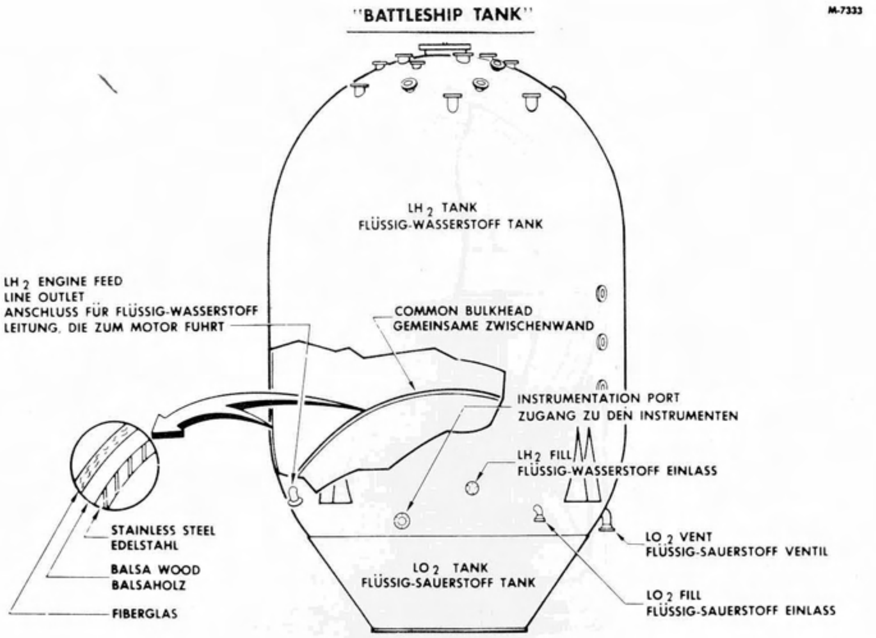


Figure 5

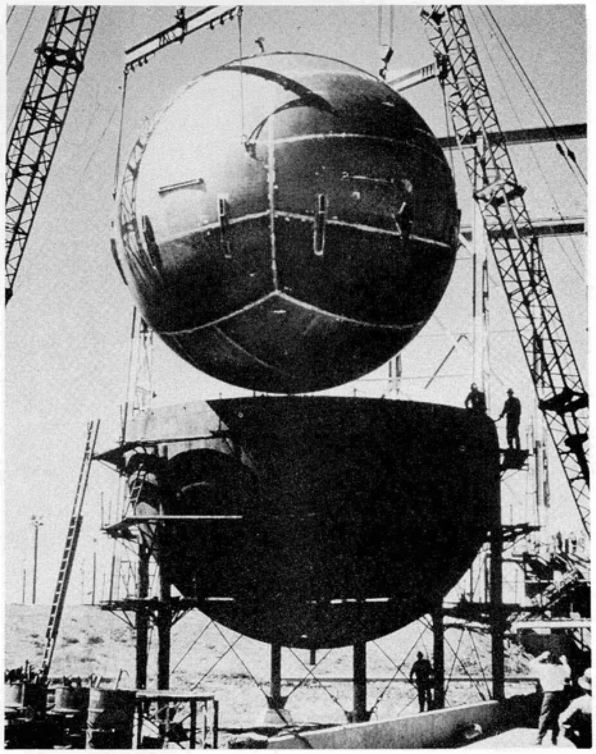


Figure 6

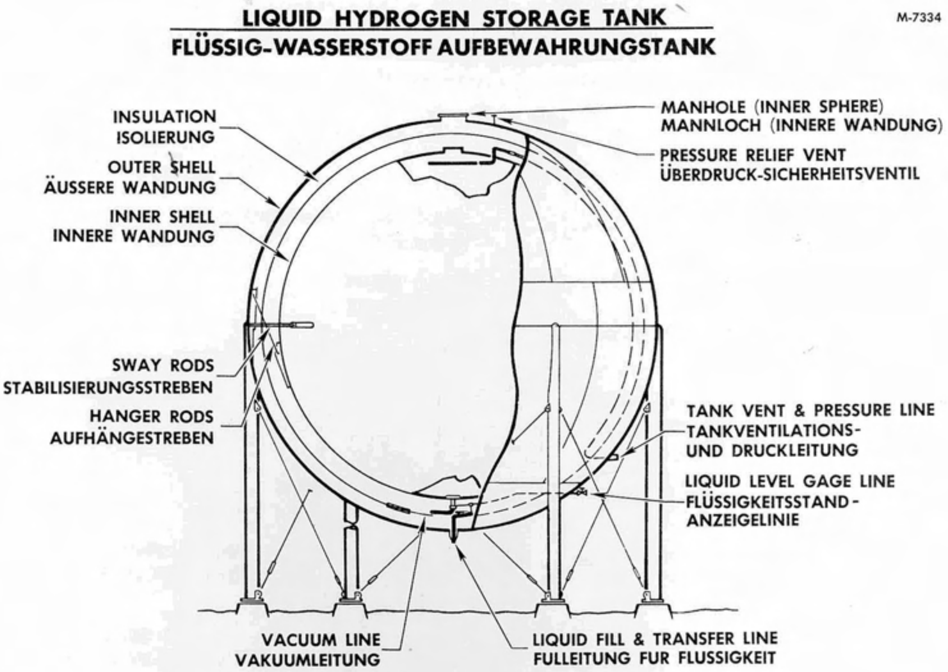


Figure 7

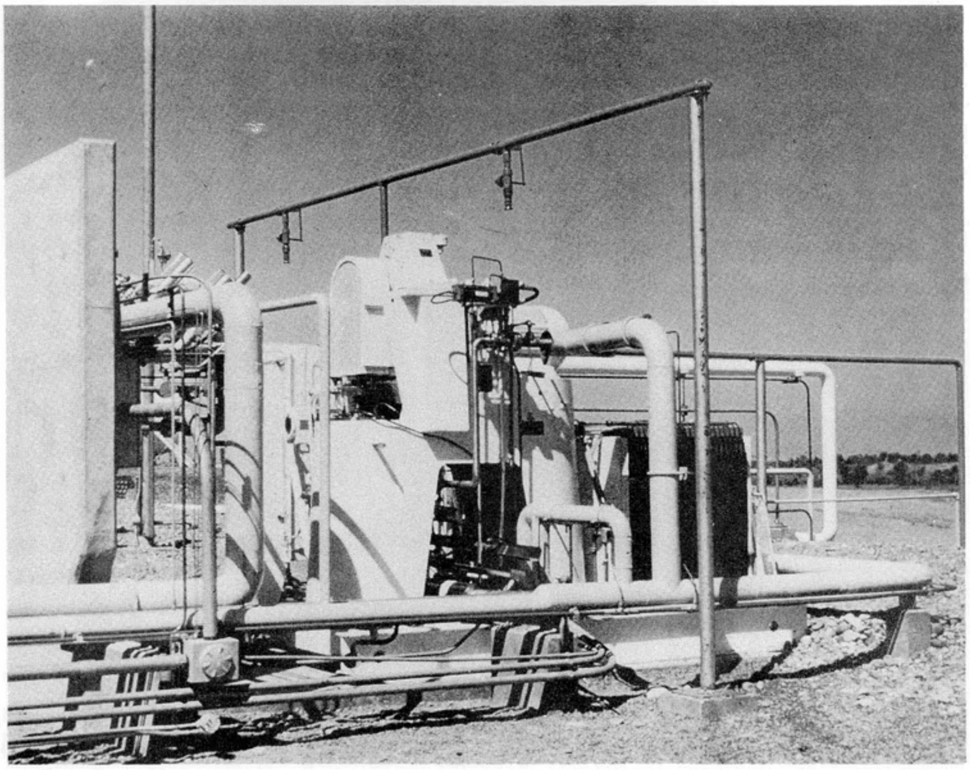


Figure 8

SCHEMATIC - LH_2 PUMP, VAPORIZER

SCHEMATISCHER UMRISS-VERDAMPFER FÜR WASSERSTOFFPUMPE

M-7331

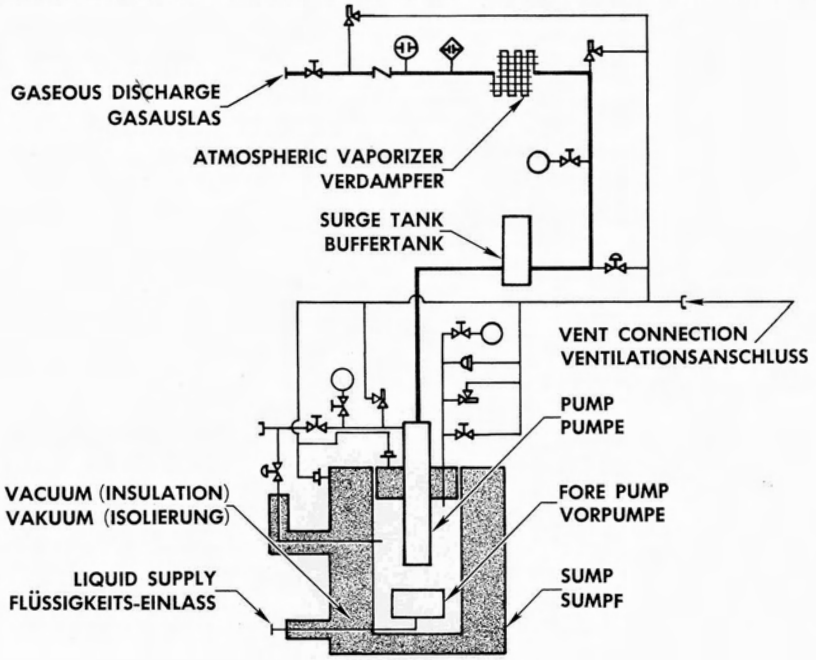


Figure 9

WELD CONNECTIONS
VACUUM JACKETED TRANSFER LINES

SCHWEISSVERBINDUNGEN
VAKUUM-ISOLIERTE LEITUNGEN

M-7330

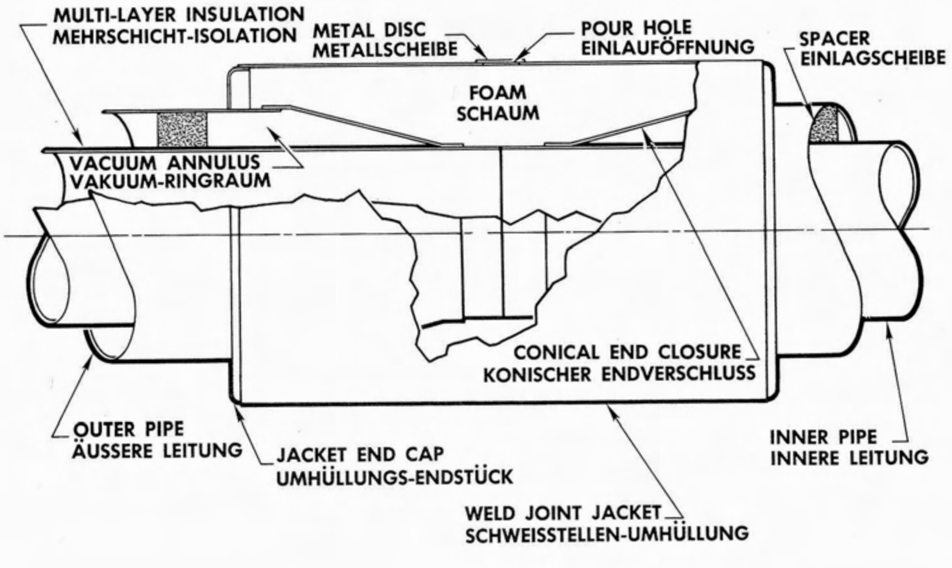


Figure 10

BAYONET TYPE JOINT
VACUUM JACKETED TRANSFER LINES
BAJONETTVERSCHLUSS
VAKUUM-ISOLIERTE LEITUNGEN

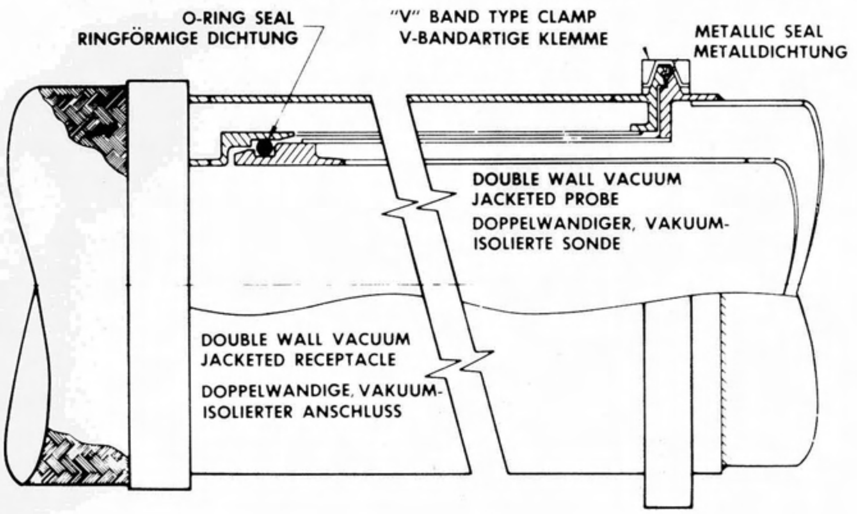


Figure 11

LIQUID HYDROGEN GLOBE VALVE FOAM JACKETED
FLÜSSIG-WASSERSTOFF KUGELVENTIL
MIT SCHAUMVERKLEIDUNG

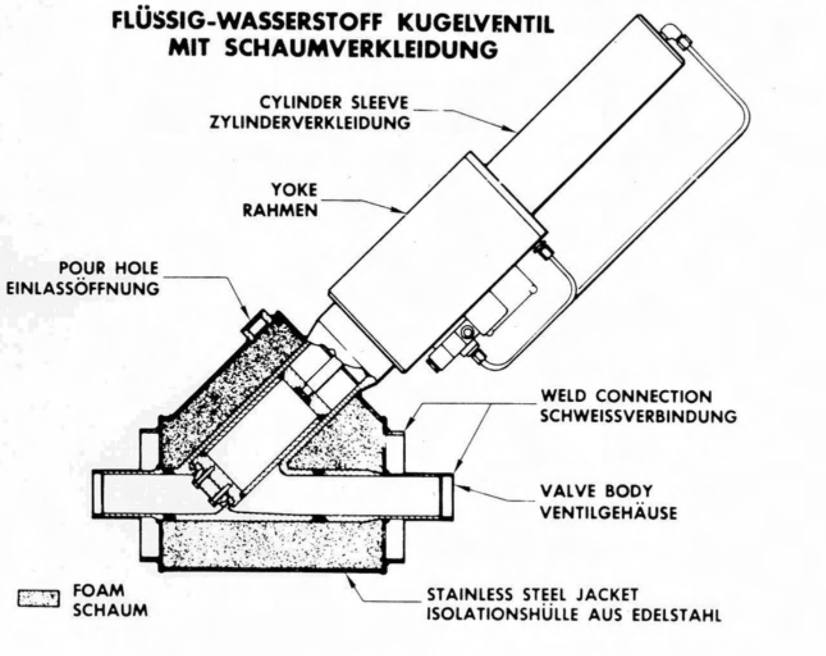


Figure 12