NASA TECHNICAL MEMORANDUM

NASA TM X-52404

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EXPLORING IN AEROSPACE ROCKETRY

17. ROCKET TESTING AND EVALUATION IN GROUND FACILITIES

by John H. Povolny
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Presented to Lewis Aerospace Explorers
Cleveland, Ohio
1966-67

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION · WASHINGTON, D.C. · 1968

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17. ROCKET TESTING AND EVALUATION IN GROUND FACILITIES

by John H. Povolny*

Rocket engines and vehicle stages must operate in a variety of environments. Some components need to perform well in space, others must be effective on the launch pad, still others must respond during atmospheric flight, but many need to function satisfactorily under all conditions from launch through orbit. Of these conditions, vibration, pressure, vacuum, temperature, humidity, mechanical stresses, and gravity forces are the most important ones affecting performance. Before NASA will commit any engine or other component to flight, they must be sure that it will perform perfectly. To achieve this, extensive testing is necessary. Ideally, test facilities for this purpose should be able to reproduce many of these environmental factors at the same time, but, practically, this is seldom possible, so the effects of environment are usually examined one or two at a time, and testing is often limited to those considered most significant.

Although the investigations usually range from tests of the smallest component to tests of the complete system in a simulated environment, this discussion ignores the smaller research setups and concentrates on the larger test facilities used by NASA at the Lewis Research Center.

AMBIENT FACILITIES

Back in the early 1940's, when rocketry became a serious study, engine research and development facilities consisted primarily of small (several hundred pounds thrust capacity), horizontal or vertical, sea-level test stands such as the one illustrated in figures 17-1 and 17-2. Then there was so much to learn about the fundamentals of rocket propulsion that these small-scale rigs were satisfactory. In fact, small test stands are still useful for basic research purposes. As the size of the engines increased, larger, vertical, sea-level test stands were built, such as the one illustrated in figure 17-3. This facility, located at the Lewis Research Center, will support experimental rockets having thrusts up to 50 000 pounds and using exotic propellants such as liquid hydrogen and liquid fluorine. The largest test stand built to date for liquid-propellant systems is for the M-1 engine and is located in Sacramento, California; the largest for solid-propulsion systems is for the 260-inch-diameter engine and is located near Homestead, Florida. The stand

*Chief, Engine Research Branch.

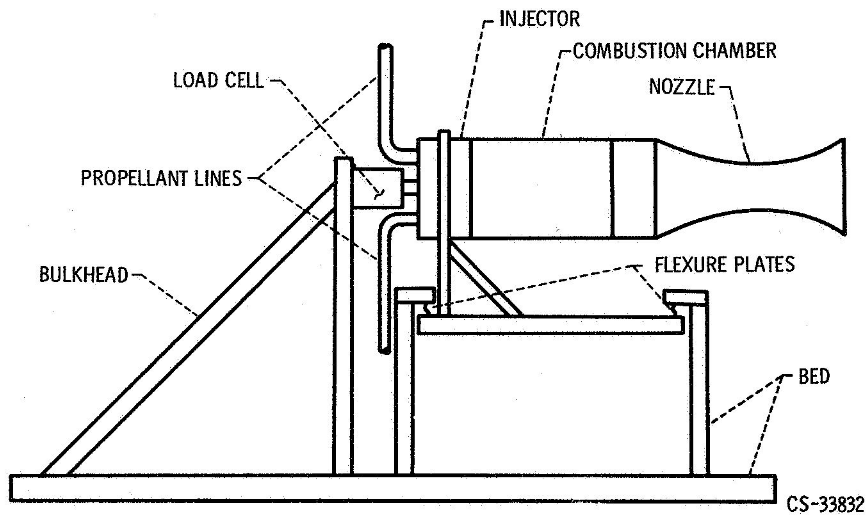


Figure 17-1. - Simple rocket thrust stand.

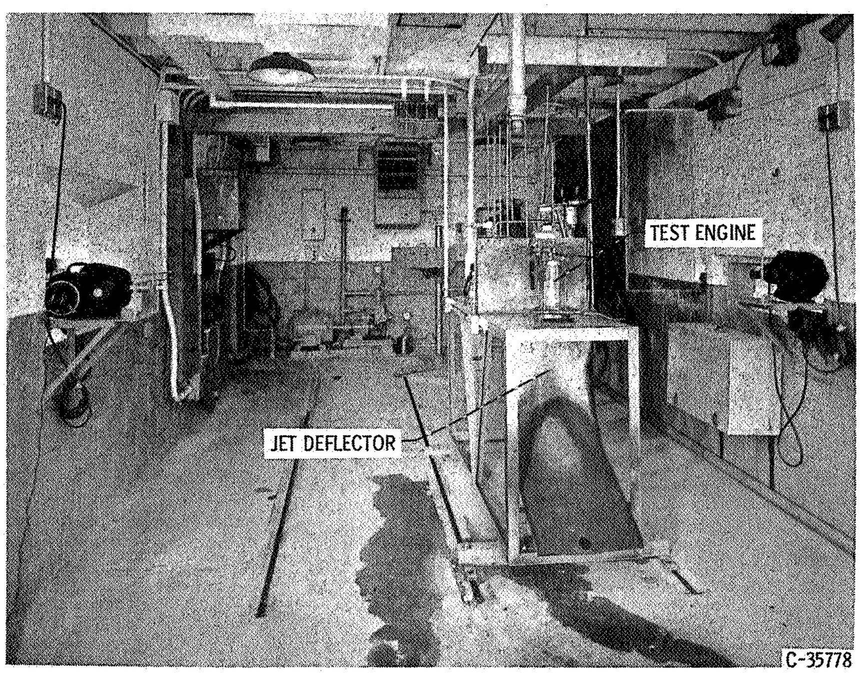


Figure 17-2. - Small sea-level thrust stand.

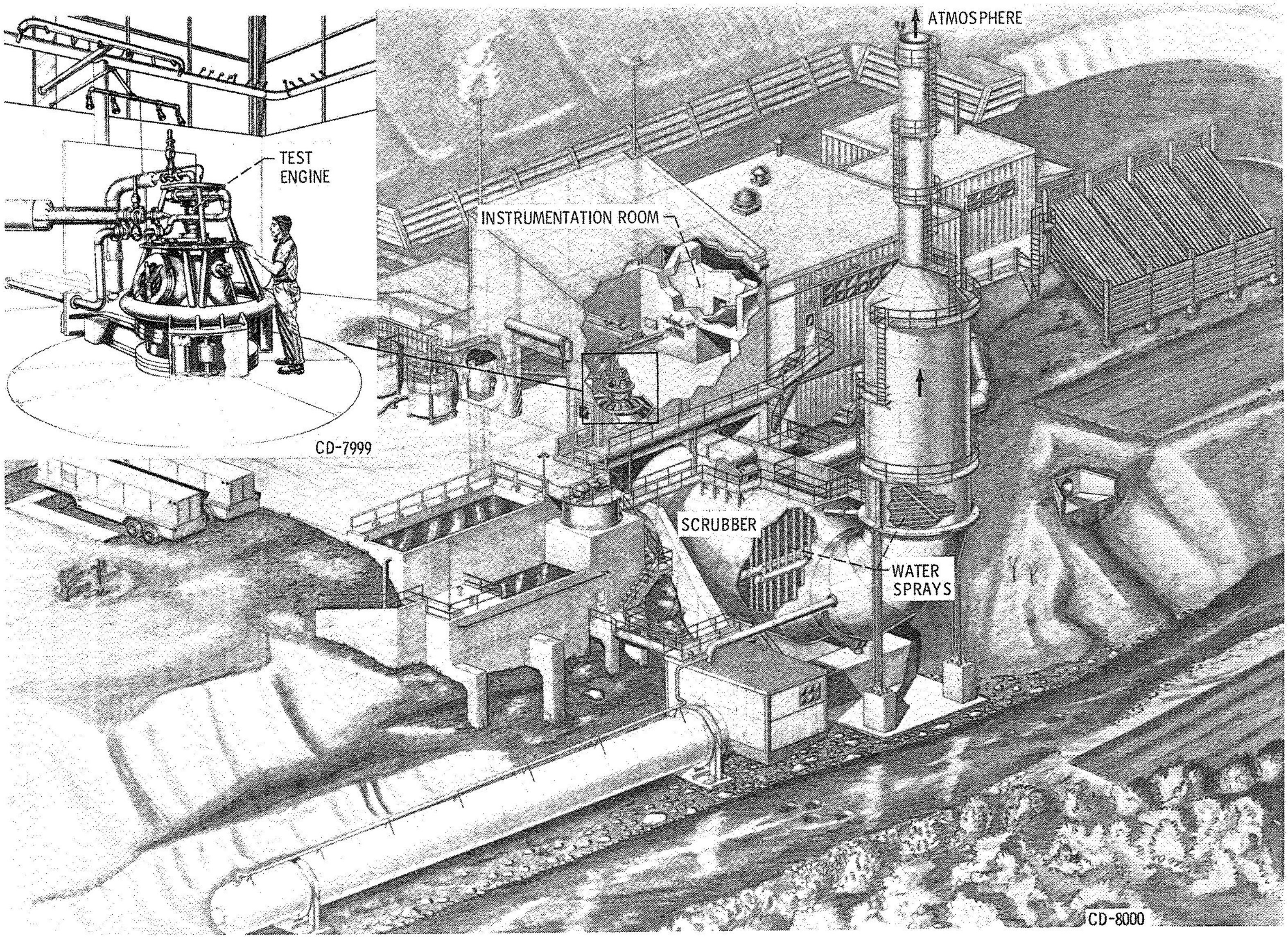


Figure 17-3. - High-energy rocket test stand with closeup of engine installation.

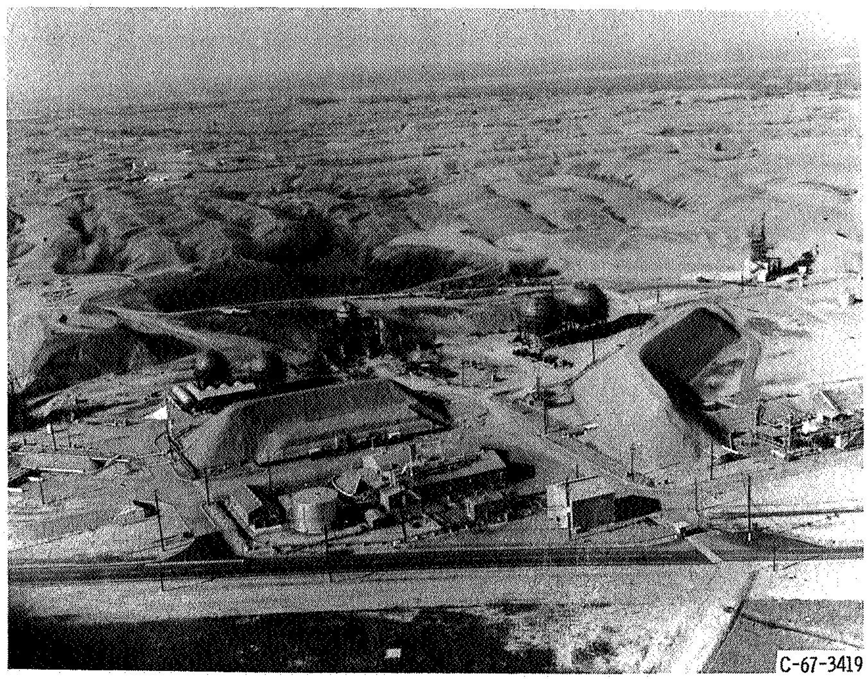


Figure 17-4. - M-1 rocket test complex.

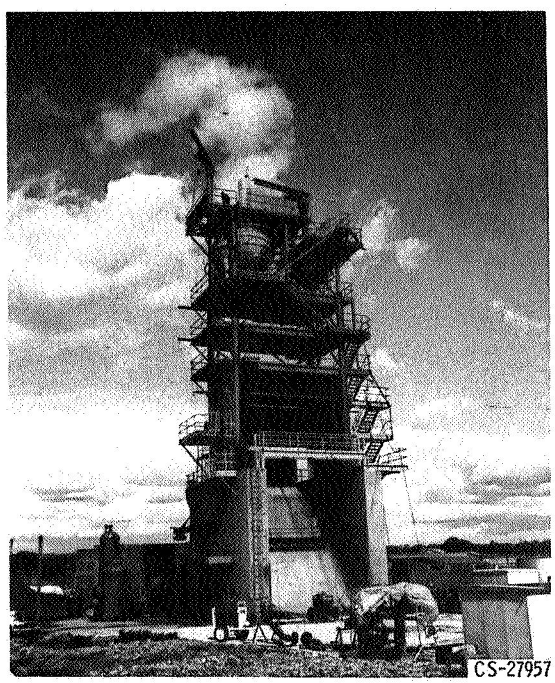


Figure 17-5. - M-1 rocket test stand.

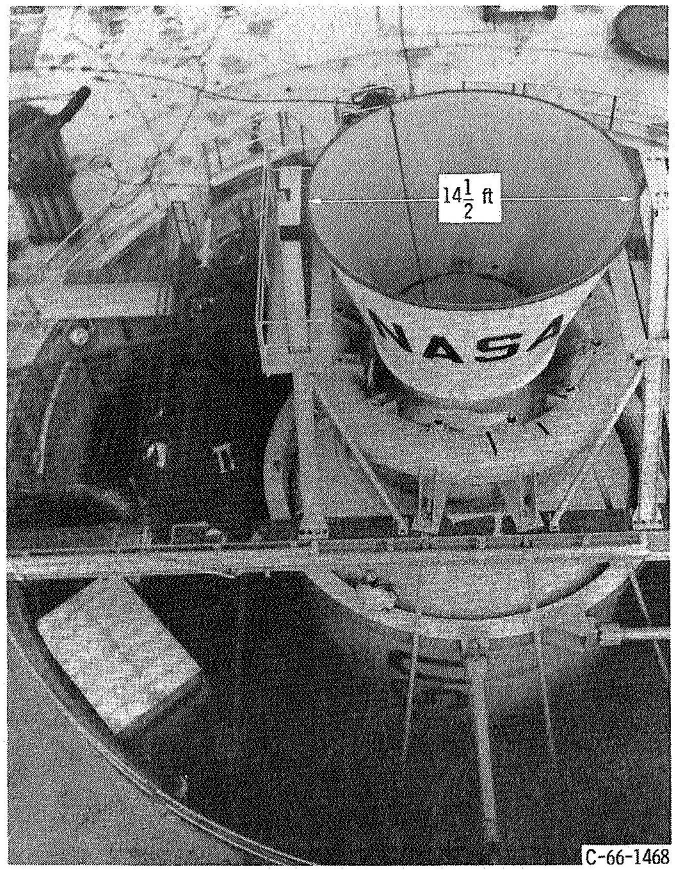
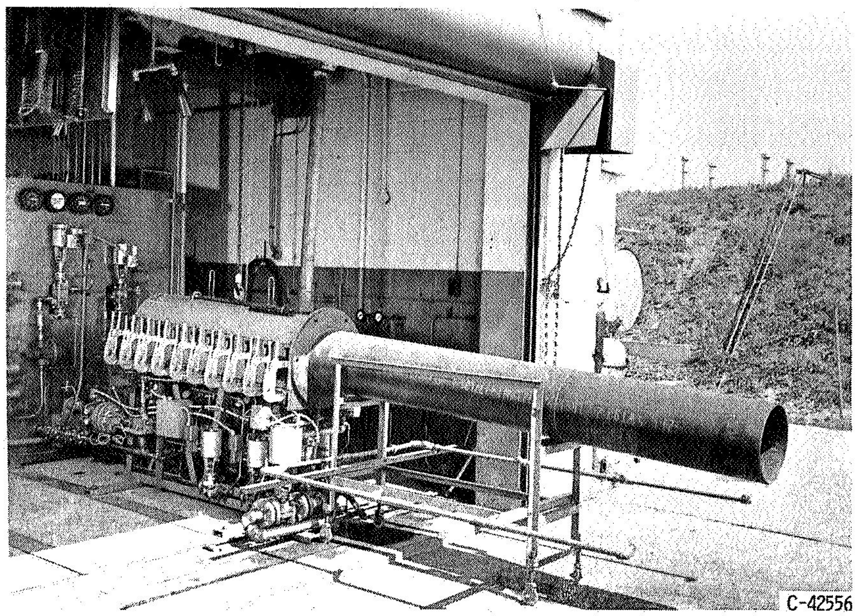


Figure 17-6. - 260-Inch-solid-rocket test stand.

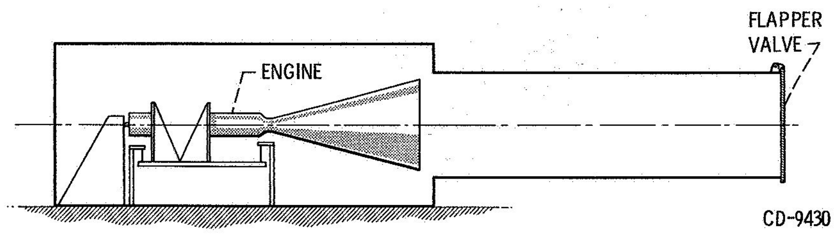
and complex for the M-1 engine, which develops 1.5 million pounds of thrust, is illustrated in figures 17-4 and 17-5, and the stand for the 260-inch engine, which will develop 5.0 million pounds of thrust, in figure 17-6. The two stands are basically different in that the liquid-rocket stand consists of a tower from which the engines are fired downward, while the solid-rocket stand is a hole in the ground from which the engines are fired upward. The reason for this is that the solid engine performance is not influenced by gravity, and thus it can be fired in any attitude; furthermore, it is cheaper to dig a hole in the ground than to build a tower.

ALTITUDE FACILITIES

The facilities discussed so far are only useful for first-stage engines or engines which operate where altitude or space effects are not significant. Where this is not true, as in the case of upper-stage engines or engines with large-expansion-ratio exhaust nozzles, then high-altitude facilities are required. There are various ways of simulating



(a) Without flapper valve.

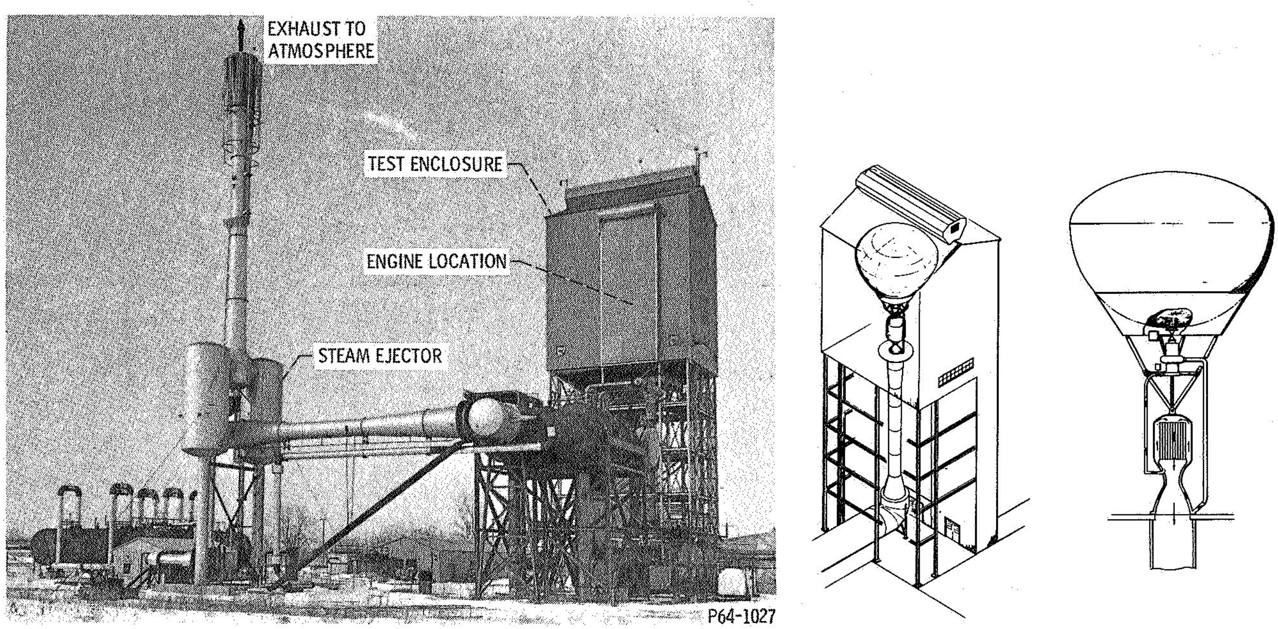


(b) With flapper valve.

Figure 17-7. - Rocket-exhaust ejector.

the desired altitudes; one of the simplest and least expensive is illustrated in figure 17-7. In this case, the entire test stand is enclosed in a tank which has one end left open so that the rocket exhaust can escape. The opening is fitted with a cylindrical tube called an ejector, which utilizes the energy of the exhausting gases to reduce the pressure in the tank. Pressures approaching 1 pound per square inch absolute, corresponding to an altitude slightly over 70 000 feet, have been obtained by this method. Although this technique provides altitude simulation once the engine is operating, it cannot simulate a high altitude for testing engine starting characteristics. This can easily be remedied, however, by adding a flapper valve to the exit end of the ejector tube and evacuating the system. When a high-altitude start is to be made, the vacuum pump is turned on and the pressure in the tank and ejector tube is thereby reduced, while the higher atmospheric pressure pushes on the outside of the flapper valve and gives a tight seal. When the desired pressure condition is achieved, the engine is ignited; exhaust from the engine forces the flapper valve open and the operation is the same as before. If higher altitudes are required during engine operation, they are made possible by the addition of a steam ejector pump or by the installation of the entire engine and rocket exhaust ejector assembly inside a vacuum chamber.

The steam ejector pump is the method used at the B-1 facility located at the NASA Plum Brook Station (fig. 17-8). This installation has a vertical test stand, 135 feet high, currently capable of testing hydrogen-fluorine rockets with thrusts up to about 6000 pounds;



(a) Overall view of test facility. (b) Test enclosure. (c) Engine cross section.

Figure 17-8. - B-1 test facility.

with some modification, it can accommodate engines with thrusts up to 75 000 pounds. The test engine is installed with the exhaust discharging down at about the 68-foot level, leaving a space above the engine for a 20 000-gallon propellant tank. This arrangement allows testing the propulsion system of a complete stage. Run time is limited to several minutes by the capacity of the propellant tanks or by the capacity of the storage system that supplies steam to the ejectors. The B-1 facility has no vacuum chamber for completely enclosing the rocket engine.

The vacuum chamber is used to simulate altitude at the Propulsion Systems Laboratory (PSL) at Lewis. Rocket engines installed in the PSL are illustrated in figures 17-9 to 17-11. The Centaur engine shown in figure 17-9 is using the PSL tank itself as the vacuum chamber and the flame tube as the exhaust ejector. The hot gases leaving the

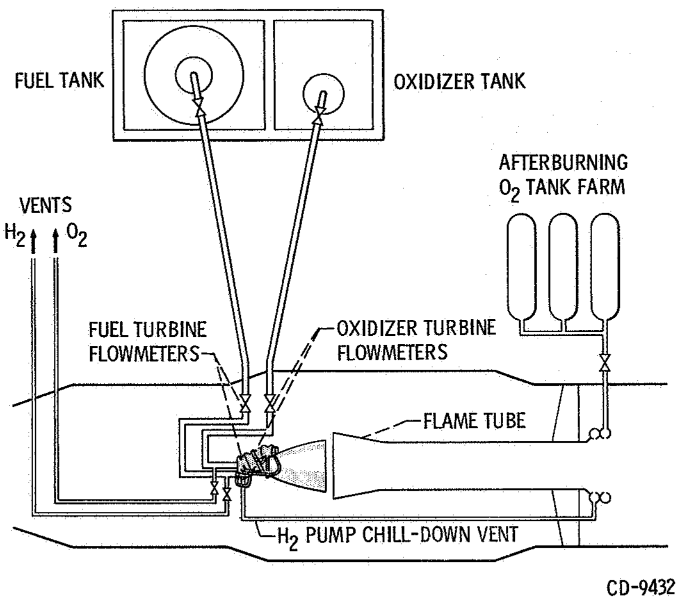


Figure 17-9. - Sketch of Centaur engine installed in Propulsion Systems Laboratory.

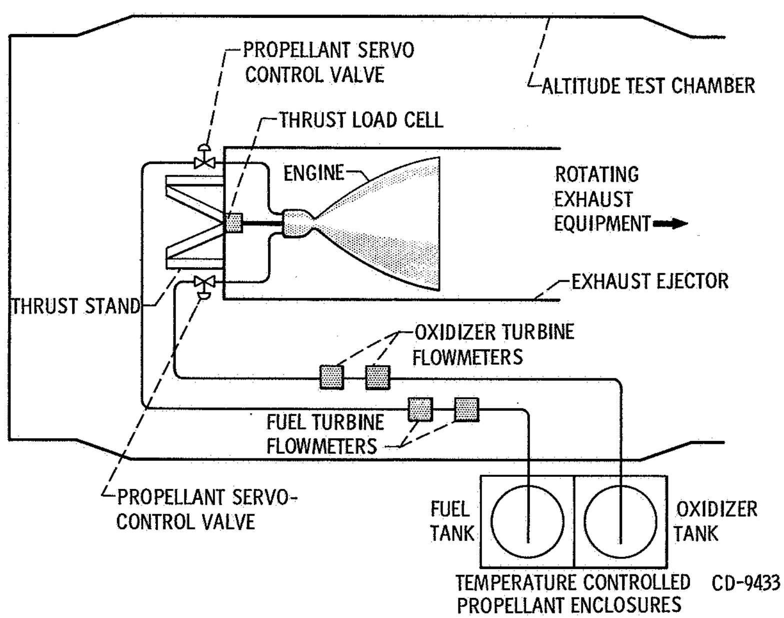


Figure 17-10. - Sketch of engine with exhaust ejector.

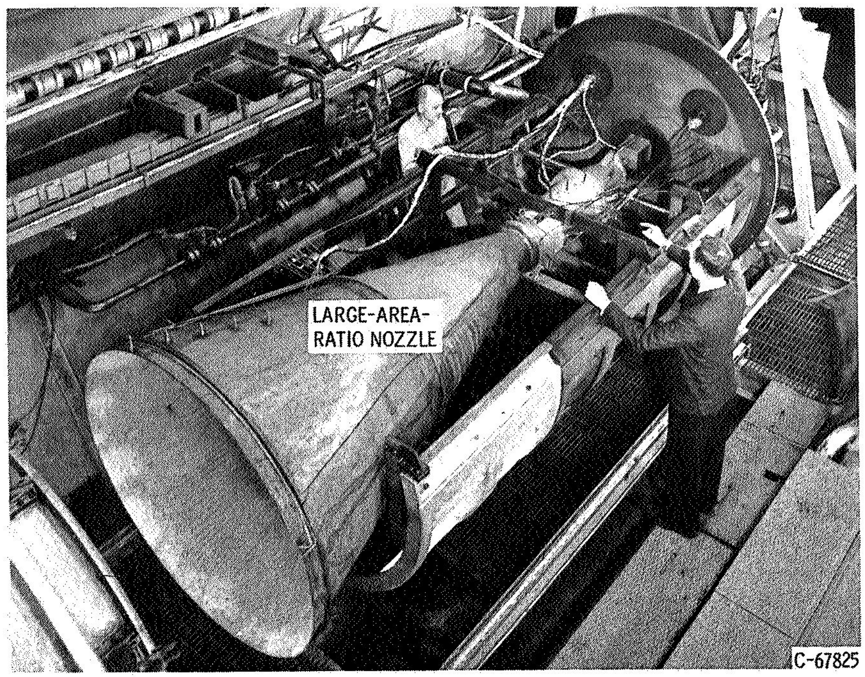


Figure 17-11. - Engine being installed in exhaust ejector in Propulsion Systems Laboratory.

flame tube are discharged into an evacuated system where they are first cooled and then removed by several banks of high-capacity pumps. Although satisfactory for many investigations, the vacuum obtainable by this method is limited by leakage through the PSL tank hatch. When the ultimate in vacuum is desired, as for a large-expansion-ratio rocket nozzle program, the engine is completely enclosed within an exhaust ejector as well (figs. 17-10 and 17-11). Engines having up to about 40 000 pounds thrust can be investigated in this facility.

COMBINED ENVIRONMENTS

Engine Testing

Testing rocket engines under a vacuum is significant because the thrust and efficiency of the rocket is determined as much by the pressure acting outside the engine as by what is going on inside. The latter, of course, is determined by how well the complete propulsion system (consisting of valves, meters, pumps, controls, tanks, etc.) functions, and this, in turn, is affected by other factors such as the thermal balance (and ultimately the temperature) of the various components and how long they have been in space. Obviously, this is of much greater concern for an upper stage that has to

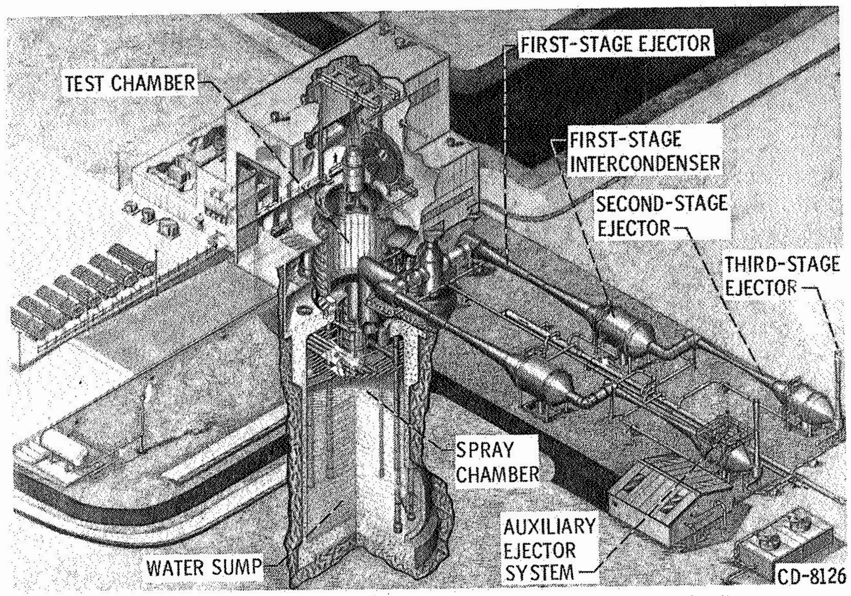


Figure 17-12. - Cross section of B-2 test facility.

function after being in space for some time than it is for the lower stages of a booster. With this in mind a new facility was designed with the capability of investigating the effects of thermal factors as well. This facility, which is approaching completion, is designated as the B-2 Spacecraft Propulsion Research Facility and is located at the NASA Plum Brook Station. Cutaway illustrations of this facility are presented in figures 17-12 and 17-13. Resembling the B-1 facility in that it is downward firing with the engine gases being pumped by both exhaust and steam ejector, the B-2 differs in having the exhaust ejector and cooling systems below ground; however the principal difference between the two facilities is that in the B-2, the complete stage, including the engines, can be exposed to a space environment for as long as desired before firing, whereas the B-1 installation can only produce a vacuum while the engine is running.

The space environment in the B-2 is simulated in a 38-foot-diameter chamber that surrounds the test vehicle. The inner wall of this chamber is lined with liquid-nitrogen panels (-320° F) that simulate the cold of space. Mounted near the inside wall is an array of quartz, infrared lamps that can be used to simulate solar heating. Proper coordination of these heaters with the liquid-nitrogen system will provide a satisfactory model of the space thermal environment. The space-vacuum environment that is required during testing is provided by a four-stage vacuum system that is connected to the chamber. This system will reduce the chamber pressure to 5×10^{-8} millimeter of mercury (equivalent to an altitude of about 200 miles) as long as the engines are not operating. Starting the engines destroys the vacuum and increases the pressure to an equiva-

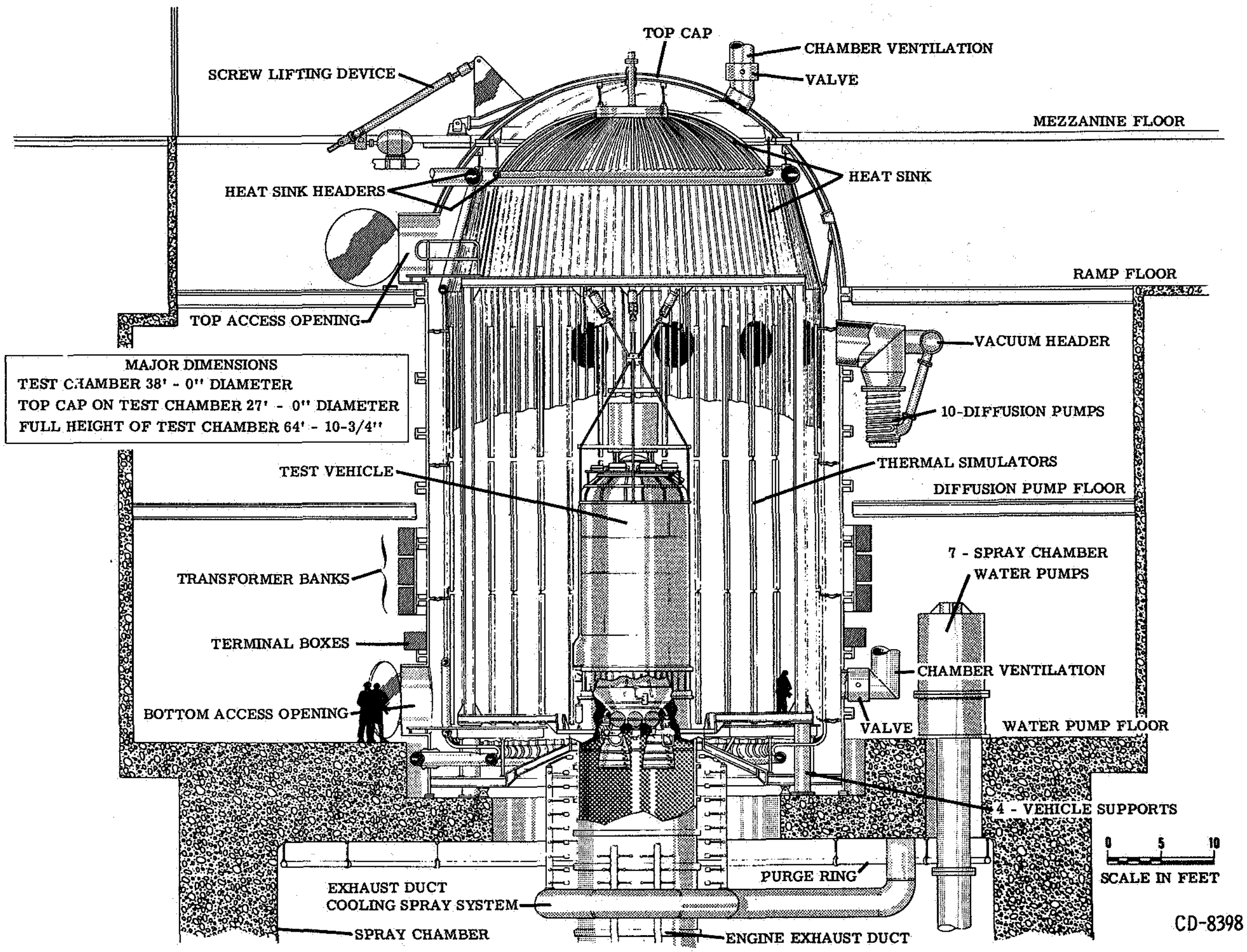


Figure 17-13. - Cross section of B-2 test chamber.

lent altitude of slightly less than 100 000 feet (about 20 miles); this is sufficient, however, for engine performance evaluation. The actual value of the equivalent altitude obtained during this phase is a function of engine size and becomes lower as the engines become bigger. The exhaust system is capable of handling total engine thrusts up to about 100 000 pounds for periods as long as 6 minutes.

Component Testing

In addition to rocket engine testing, space facilities in which the engines are not fired can be useful in many ways, such as determining the operating temperatures of

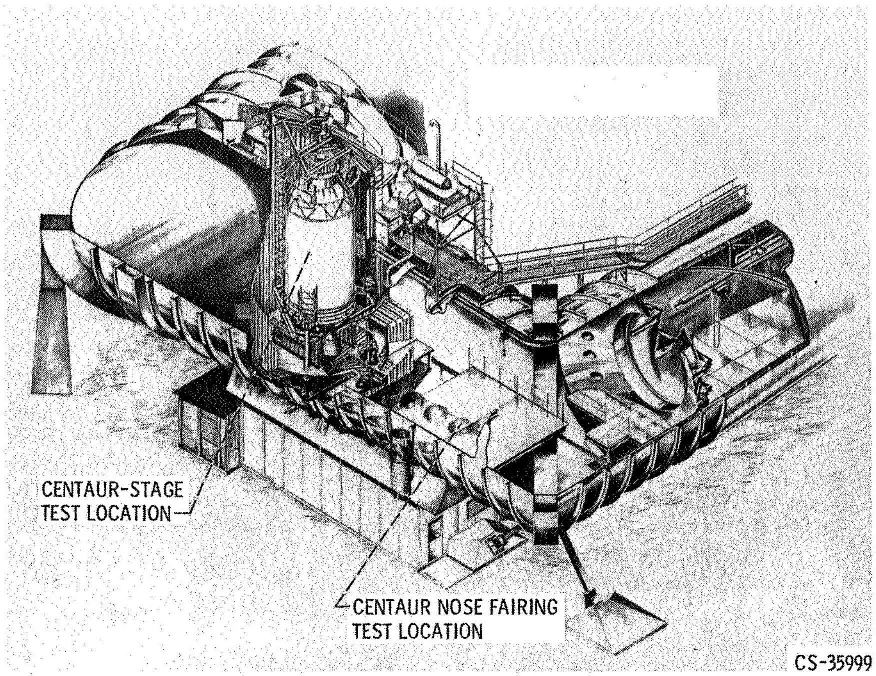


Figure 17-14. - Cross section of Space Power Chamber.

various components after a period of exposure or checking the function of electrical or mechanical components such as a power generating system, a guidance system, or the separation of a nose cone or insulation panels. One such facility that has been useful to the Centaur Project is known as the Space Power Chamber (SPC). This facility (fig. 17-14) was created by partitioning off and modifying a section of an old altitude wind tunnel and by installing liquid-nitrogen panels, solar heat simulators, and high-vacuum pumping equipment.

During space environment tests conducted on a complete Centaur stage in one end of this chamber, all the systems were actuated except for firing of the engines. Even the telemetry system was exercised, with data being transmitted to the Lewis telemetry station located in another building. A subsequent comparison of flight thermal data with that obtained in the test chamber showed excellent correspondence.

This chamber was also used for jettison tests of the Centaur nose fairing. In this case a real Centaur nose fairing with all its flight systems was installed in the opposite end of the chamber. During these tests an altitude of 100 miles was simulated, and although the nose cone had been successfully tested a number of times at sea-level pressure, it was not able to take the higher forces that were generated when the separation occurred in a vacuum. Needless to say, a redesign was required. When the redesigned nose cone was finally flown, a comparison of the flight data with that obtained in the vacuum chamber again showed good correspondence.

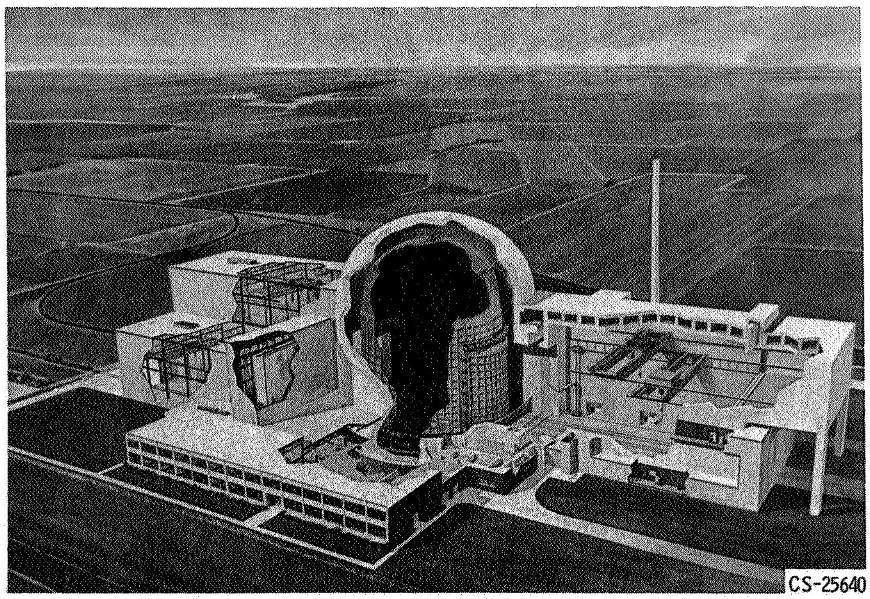


Figure 17-15. - Cross section of Space Propulsion Facility.

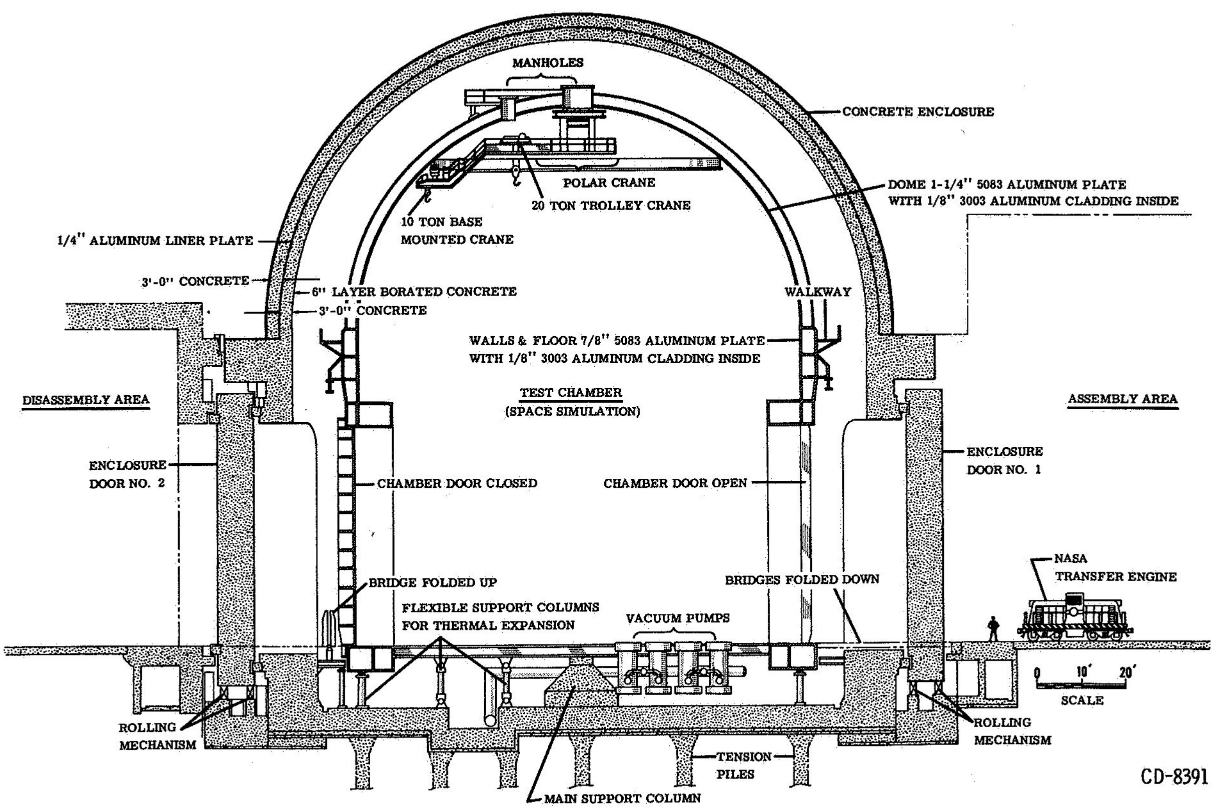


Figure 17-16. - Cross section of Space Propulsion Facility test chamber.

Another Lewis space environmental facility of note is known as the Space Propulsion Facility (SPF), which is under construction at the Plum Brook Station and will be put into operation in early 1968. This facility, which is illustrated in figures 17-15 and 17-16, differs from the preceding one in that it will be used to test nuclear power generation and propulsion systems as well as larger, chemically propelled vehicles and spacecraft. The SPF will have an aluminum test chamber (fig. 17-16), 100 feet in diameter and $121\frac{1}{2}$ feet high, surrounded by a heavy concrete enclosure for nuclear shielding and containment. It will have facilities for assembly and disassembly of experiments and will be able to vibrate the system within a vacuum environment (ultimate capacity 6×10^{-8} mm Hg). It will also have experiment-control and data-acquisition systems. Rather than building in a thermal simulation system of heaters and cryogenic panels, these systems will be built for the particular experiment being conducted. The facility, of course, is designed to comply with all the AEC safety regulations applicable to reactors as large as 15 megawatts. The concrete shielding walls are approximately 6 feet thick so that the radiation levels experienced by people working nearby will be less than the levels specified by AEC. This is one of the most advanced space environmental chambers under construction and should be useful in future investigations.

STRUCTURAL DYNAMICS

In addition to the large facilities for evaluating the effects of the space environment on upper stage and propulsion system performance, large facilities are also necessary for determining the structural characteristics and capabilities of complete boosters. The reason for this is that, although it is generally possible to calculate the natural frequencies of the first and second bending modes of a complete launch vehicle as well as the dynamic loads that would be encountered at these frequencies, it is impossible to calculate these for the higher modes. Calculating the damping of the vehicle is also impossible. Further, there are additional factors such as the interplay between the propellant system and the structure which cannot be computed and which have a significant effect. Thus, the surest way to assess the structural capabilities of a vehicle is to test it on a dynamic test stand like that which has been successfully used for the Atlas-Centaur-Surveyor vehicle. This stand (fig. 17-17) is known as the E-stand and is located at the Plum Brook Station. As illustrated in figure 17-18, the method of installation is to suspend and position the complete vehicle by means of springs with natural frequencies (in combination with the masses involved) lower than those of the vehicle so that it can respond to the electrodynamic shaker without being influenced by the suspension and positioning systems. No environmental factor is simulated in these tests other than the dynamic force inputs.

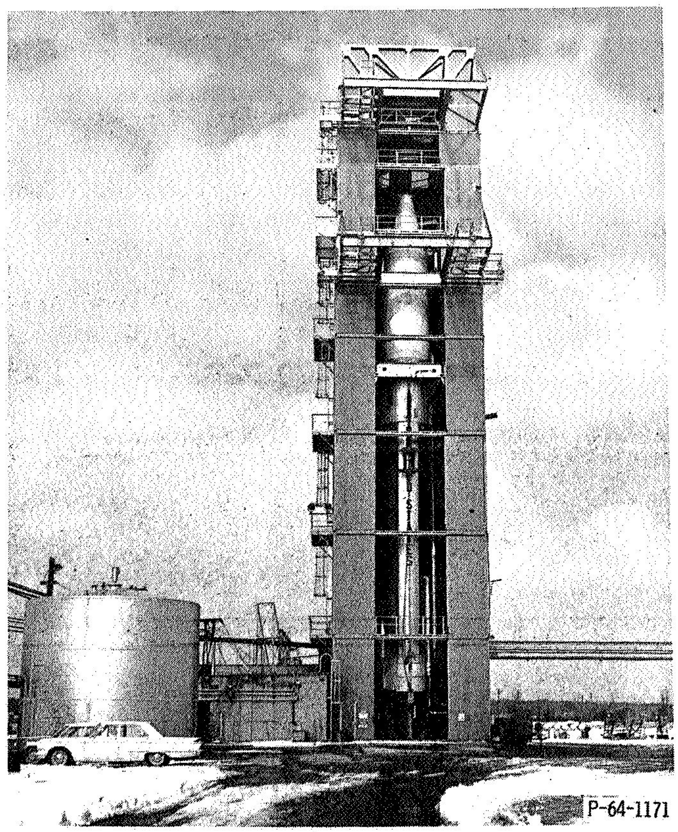


Figure 17-17. - E-stand.

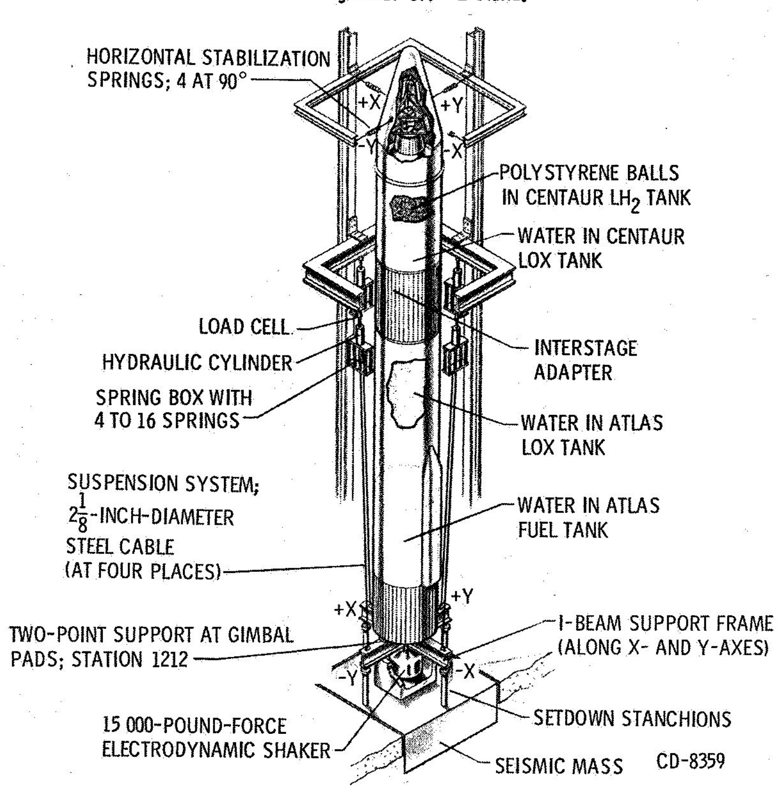


Figure 17-18. - Atlas-Centaur installed in E-stand.

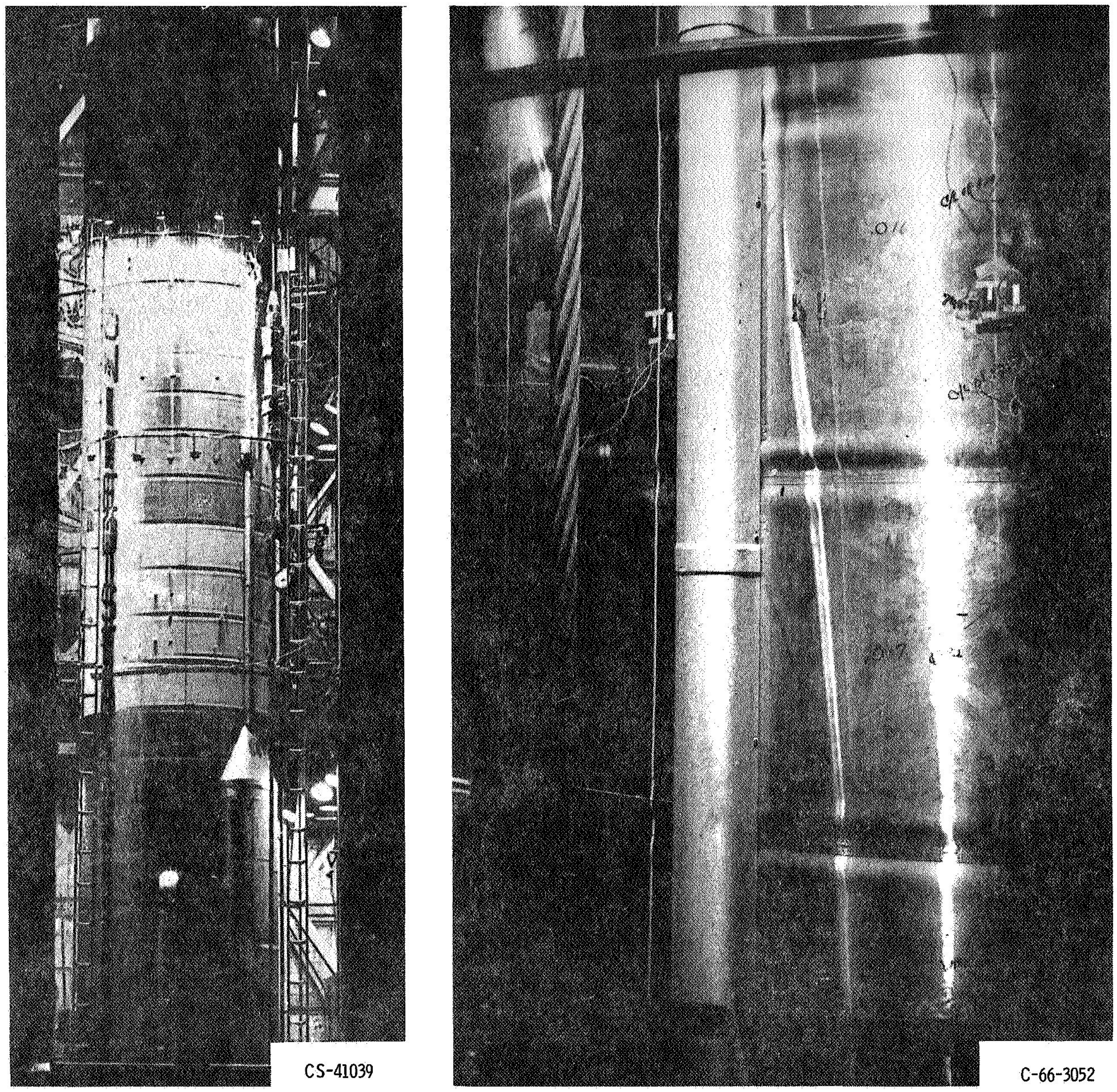
Perhaps the following brief discussion will explain the nature of the problem better. Chapter 11 mentioned that the performance of a booster system is highly dependent on its weight, with the lighter systems having superior performance. Accordingly, structural weight is kept to a minimum and usually ranges between 6 and 10 percent of the total launch weight for the better systems. In addition, minimum drag requirements for the flight path through the atmosphere dictate a long slender vehicle. The result is a highly elastic vehicle with a continually changing natural frequency that is caused by the mass change due to propellant consumption and varying G-forces during flight. The problem is further complicated by the many different disturbances and forces that can be encountered:

(a) During engine ignition
(b) By the sudden launcher release at lift-off
(c) By the ground winds
(d) By the high altitude gusts (jetstream)
(e) By vectoring the engines
(f) As a result of coupling between the engine, propellant system, and structure
(g) By sloshing of the propellants
(h) During engine shutdown
(i) During separation of the stages
(j) During insulation-panel or nose-cone separation
(k) As a result of the aerodynamic and shock wave pressures generated during flight through the atmosphere
(l) By the firing of attitude control engines

These forces, acting singly or in combination, can produce one or more of the following types of deflection of the vehicle:

(a) Lateral - where the vehicle is deflecting normal to its centerline axis (bending)
(b) Longitudinal - where the vehicle is deflecting parallel to its centerline axis (becoming alternately shorter and longer); this can be either a nonreinforced or a reinforced oscillation which is augmented by the engine and propellant systems (called pogo) which results in much greater deflections
(c) Torsional - where the vehicle is rotating about its centerline axis in alternately opposite directions

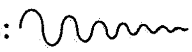
Generally one or more modes of each type of deflection may develop during a flight, so the vehicle should be tested through at least the third mode, if possible. Inasmuch as a vehicle in flight is in free-free condition (no restraint at any point), the characteristic free-free deflection curves are used to define the modes of oscillation. Thus, a vehicle deflection curve that looks like  defines the first mode, one that looks like  the second mode, and one like  the third.



(a) Overall view following test.

(b) Closeup of wrinkle patterns.

Figure 17-19. - Atlas tested to ultimate load capacity.

In addition to the mode and type of deflection, another factor that must be considered is the amount of damping inherent in the vehicle. If it is equal to or greater than the critical damping, then a single, suddenly applied load will not make the vehicle oscillate at any of its natural frequencies. If it is less than critical, then the vehicle will oscillate at one of its natural frequencies but with a decreasing amplitude as follows: 
Vehicle damping is a difficult thing to predict and is best revealed by a full-scale experiment or by comparison with similar vehicles for which it is known.

A complete determination of the structural characteristics of a rocket booster in flight is a complex affair. The engineering approach that is generally employed is as follows: First, the structural equations defining the vehicle deflection modes at any point in time are derived (with the use of the spring-mass method), then the damping is estimated, and finally the effects of all the various disturbances are calculated. The vehicle is then tested in a stand similar to the E-Stand, and the experimental results are compared with those predicted. If they are the same, that is fine, but if not, then the equations must be modified until they represent the actual event. Once agreement is obtained, then flight performance can be reliably predicted.

In addition to dynamic response, the E-Stand is also valuable for determining the ultimate load capability of a launch vehicle. An experiment of this type was conducted on an Atlas booster (fig. 17-19) which revealed that the ultimate load capability of the Atlas was about 50 percent greater than had been previously assumed. This is a significant result because it means that the Atlas still has a substantial growth potential for future space missions.

RELIABILITY AND QUALITY ASSURANCE

All the foregoing discussion of facilities and environmental testing is concerned primarily with the performance evaluation of complete propulsion systems and stages. Every stage, of course, is made up of thousands of parts (over 300 000 in the Atlas), and it is difficult to ascertain that all these parts will satisfactorily function at one time, so that the intended mission will be successful. This was recognized as a problem area in the aerospace industry in the early 1950's, and it was then that reliability and quality assurance engineering, as known today, began. It combines the elements of engineering, statistics, and good sense for evaluating the probability that a given system, subsystem, or part will perform its intended function for a specified time under specified conditions.

The reliability field can be broken down into two basic areas: (1) design goal reliability and (2) use or operational reliability. During the design of a component an estimate can be made of its reliability if the reliabilities of the individual parts are known. This can be calculated from the mathematical expression for individual reliability,

$$R = e^{-t/MTBF}$$

where R is the reliability (or probability of success), e is a constant, t is the mission time, and MTBF is the mean time between failures or operating hours divided by numbers of failures. For the more complex case where the failure of any one part will cause failure of the entire component, the total reliability equation is

$$R_{system} = R_1 \times R_2 \times R_3 \times \ldots R_N$$

It is thus evident that for high system reliability it is necessary to have extremely high part reliability.

Once the component has been built, it is still necessary to evaluate its reliability experimentally because manufacturing and assembly processes vary and also because the environment that the parts experience in this component may be somewhat different than that for which they were designed. This is usually done in a series of design evaluation and proof tests. If the failure rates from these tests are plotted against total operating time (for all components) a curve similar to the one in figure 17-20 is usually obtained.

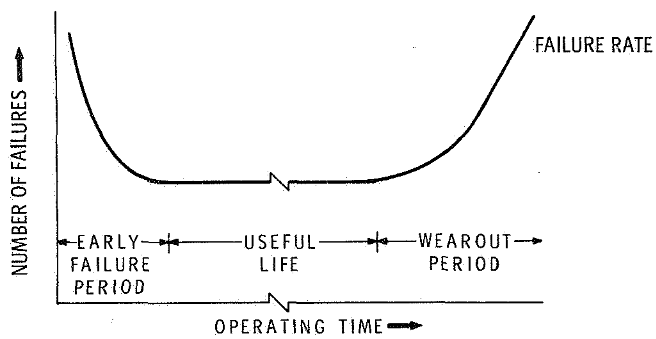


Figure 17-20. - Idealized failure rate curve.

The high failure rate that usually occurs in the early period is generally a result of initially poor parts, marginal design, or both. The high rate that is obtained in the later period is usually a result of wearing out. The fairly low, constant rate that falls between the two high rates is defined as the useful life. For a high reliability, the useful life should be long compared with the time a part has to operate, and the failure rate during the useful life should be as low as possible. Inasmuch as testing is the primary indicator of reliability, the more tests that are run and the more data that are obtained, the more confidence there will be in the results. Confidence can be reduced to a statistical value which reflects the degree of probability that a given statement of reliability is correct. Of course, in order to achieve and maintain a given reliability, it is necessary to originate designs with sufficient operating margins, provide specifications for the processes as well as the finished parts, and enforce a comprehensive system of quality control or assurance. Constant vigilance and attention to detail is the price of high reliability.

NASA-CLEVELAND, OHIO E-3364-17