[redacted]

THE NERVA ENGINE PROGRAM

U

By Lester C. Corrington

Space Nuclear Propulsion Office, Cleveland Extension [redacted]

X65 50153

INTRODUCTION

The objective of the NERVA engine program is the development of a nuclear rocket engine for use in space missions. The letters N E R V A mean Nuclear Engine for Rocket Vehicle Application. NERVA is a long-range program that had its beginning in about 1955 when the Los Alamos Scientific Laboratory began preliminary studies on the feasibility of thermal reactors for rocket application. At about the same time, the Livermore Laboratory began parallel studies, but this dual effort was discontinued about a year later.

Los Alamos investigated metallic and graphite reactors and came to the conclusion that graphite offered more promise for early reactor development. Consequently, they narrowed their studies to graphite reactors, and this work has culminated in the building and testing of several reactors. Two principal types of reactors were built, and they are known as Kiwi A and Kiwi B reactors. The Kiwi A reactors were primarily test reactors for the investigation of fuel elements. The Kiwi B reactor was to be of a concept adaptable for flight, and the NERVA engine is based on the Kiwi B concepts.

In 1960 the NASA made the decision to initiate the development of an engine based on the Kiwi B concepts, and a joint office representing both the NASA and the Atomic Energy Commission was set up for this purpose. This joint AEC-NASA Office is known as the Space Nuclear Propulsion Office and is located at AEC Headquarters in Germantown, Maryland. It is managed by Mr. H. B. Finger.

In 1961 an industrial contractor team, the Aerojet-General Corporation and the Westinghouse Electric Corporation, was selected to carry out the development of the NERVA engine, and their activity began in mid-1961. Aerojet was made the prime contractor with responsibility for the complete engine development program, and Westinghouse was made a principal subcontractor with responsibility for the development of the reactor.

A government field office, the Cleveland Extension of the Space Nuclear Propulsion Office, was set up to manage this development program. This office is located in Cleveland because of the availability of technical backup at the Lewis Research Center.

KIWI REACTORS

Description of Kiwi Reactors

Figure 1 shows a diagrammatic cross section of the Kiwi B reactor. It con-

[redacted]

[redacted]

[redacted]

sists of a homogeneous graphite core surrounded by an insulating graphite shell, a beryllium reflector, and 12 rotating-type control drums located in the reflector. The reactor is contained in an aluminum pressure vessel to which is mounted a propellant-cooled nozzle. In operation, the liquid-hydrogen propellant enters a manifold at the nozzle exit, passes through the coolant passages of the nozzle, through the reflector, through the core where it is heated, and then out through the nozzle to produce thrust.

The core is simply a graphite heat exchanger that is heated by nuclear fission that, in turn, heats the hydrogen that flows through the coolant passages. The diameter of the core is 36 inches and the length is 52 inches. At the design point the core delivers 1120 thermal megawatts to the hydrogen, and the average exit gas temperature from the core is 4090° R. These operating conditions represent a major extension from the current state of the art.

The core is made up of a large number of graphite fuel elements loaded with enriched uranium. Los Alamos investigated several different concepts of fuel elements and the interest is now centered around the concept shown in figure 2. In this concept, known as the Kiwi B-4 concept, the core is made up of simple hexagonal fuel elements, each with 19 coolant holes. In cross section, the hexagon is 0.75 inch across flats, and the coolant holes are approximately 0.095 inch in diameter. In initial experiments, these fuel elements were extruded with a mixture of uranium oxide, graphite flour, and a binder. After extrusion, they were baked by a process which graphitized the entire element and changed the uranium oxide to uranium carbide. Because of problems involving a hydrolysis reaction when uranium carbide is exposed to air containing moisture, a new loading concept has been developed, which is illustrated in figure 3. Small spheres of uranium carbide about 0.002 to 0.005 inch in diameter are coated with pyrolytic graphite to a coating thickness of about 0.001 inch. The pyrolytic graphite provides a very dense and impervious coating that protects the uranium carbide from contact with the atmosphere and thereby prevents the hydrolysis reaction. These small beads are mixed with graphite flour and a binder and are extruded and then graphitized to form the fuel elements.

At the design operating temperature of these fuel elements, there is a reaction between the hydrogen propellant and the graphite. The hydrogen combines with carbon to form volatile hydrocarbons such as methane. To surmount this problem, a coating has been developed for lining each coolant passage. This coating is niobium carbide. It is applied by a vapor-deposition process to a thickness of about 0.002 inch, and in laboratory tests it has performed with reasonable success. This development of a good coating has been a major accomplishment in the program.

The fuel elements are assembled into clusters of seven for installation in the reactor, as illustrated in figure 4. Six uranium-loaded elements are placed around the central element that is made of unfueled graphite. This cluster of elements is supported in the reactor by a metallic tie rod that extends axially through a hole in the central element. This hole in the central element is lined with pyrolytic graphite for insulation purposes and then with a thin stainless-steel tube for retention of the pyrolytic graphite in case of delamination or flaking. Low-temperature hydrogen coolant passes through the annular space be-

[redacted]

[redacted]

tween the stainless-steel tube and the tie rod.

Figure 5 shows a cutaway view of the fuel-element cluster. At the hot end is an unfueled graphite block that has the same external shape as the seven-element cluster. The fuel elements rest on this graphite block, which is supported by the cooled metallic tie rod that extends the entire length of the cluster. This tie rod is in turn supported by a core support plate at the inlet end (cold end) of the reactor core. The fuel elements in the cluster are retained at the cold end by a metallic cluster plate that makes provision for installation of orifices in each of the fuel-element flow passages.

A cross section of a Kiwi B-4 reactor is shown in figure 6. The core consists of about 260 of the seven-element clusters illustrated in figure 5, and these clusters are mounted to the aluminum core support plate by the tie rods as illustrated. The core is surrounded by a graphite barrel, and this barrel provides the mounting for the core lateral support system. This system keeps the fuel elements tightly bundled together to prevent hydrogen from flowing between them and to support the entire core against excessive lateral movement. It consists of a series of graphite strips that run the full length of the core that are faced with a layer of pyrolytic graphite for insulating purposes. These graphite strips are loaded against the core periphery by metallic springs mounted in the graphite barrel.

Also illustrated in figure 6 are the control rods mounted in the beryllium reflector. These control rods are made of beryllium cylinders about 4 inches in diameter with sheets of boral covering about 120° of the circumference. The control rods are rotated by externally mounted actuators.

Kiwi Reactor Tests to Date

A total of six Kiwi reactors have been tested up to the present time by Los Alamos at the test site in Nevada. The first three were of the Kiwi A type and were run primarily for the investigation of fuel-element concepts. The fuel elements were operated at near the design point temperature but at a power level of only about 100 megawatts. The propellant (coolant) used in these initial tests was ambient-temperature gaseous hydrogen.

The next two reactor tests were of a Kiwi B-1 design that had a fuel-element concept substantially different from the one illustrated in figure 2. The first of the Kiwi B-1 reactors was operated at near the design-point temperature and at a power level of about 250 megawatts and was also cooled with gaseous hydrogen. The second of the Kiwi B-1 series represented the first reactor test in which liquid hydrogen was used as the propellant. Serious flow instabilities were encountered in the two-phase flow regime during the startup. The reactor attained temperatures and power levels near the design point for a very brief period of time, but the core was damaged extensively during the run.

The first and so far the only test of the Kiwi B-4 type reactor (the type that appears to be of most interest for the NERVA engine) was run in December of 1962. The propellant used for this test was liquid hydrogen, as in the last Kiwi

[redacted]

[redacted]

B-1 test. Through prior modifications to the propellant system, the hydrogen instability problem that had been experienced previously was overcome, and the hydrogen flow during the Kiwi B-4 test appeared to be very smooth and steady throughout the entire test.

During the Kiwi B-4 test, the reactor power was brought up to a level of about 250 megawatts at which point it was held for about a minute for calibration of nuclear instrumentation. The core temperature at this hold point was about 2500° R. Following this hold, an attempt was made to go up to the design-point temperature and power level, but indications of core damage resulted in the reactor being shut down considerably short of its design-point goals. Disassembly of the core revealed substantial breakage of fuel elements, although the tie rod support system was essentially intact. Analysis of the failure has indicated that the probable cause was a lack of adequate lateral support of the core by the lateral support system. Loads resulting from core vibration apparently caused considerable breakage of fuel elements. The lateral support system has since been redesigned in an attempt to overcome this vibration problem.

NERVA ENGINE

Description of NERVA Reactor

The reactor for the NERVA engine is based on the concept of the Kiwi B-4 reactor, but with a number of changes in design to make it suitable for withstanding flight loads and to incorporate a shield for the protection of engine components and the propellant in the stage tank against nuclear radiation. Figure 7 shows a cross section of the major elements of the NERVA engine reactor design as it exists at the present time. The core is composed of the seven-element clusters supported in the same manner as in the Kiwi B-4 reactor. The lateral support system has been redesigned to overcome the core-vibration problem experienced in Kiwi B-4 and to support the core against lateral accelerations of up to 4 g's that may be experienced in ground handling and in flight.

The shield in the NERVA reactor is contained entirely within the reactor pressure vessel. It is designed for an overall energy attenuation of about 10, and centerline measurements show a gamma-flux attenuation of about 20 and a neutron-flux attenuation of about 140. The shield consists essentially of a large number of stainless-steel tubular capsules mounted axially very closely together and filled with lithium hydride and borated stainless steel. The propellant flow path for this reactor is similar to that of the Kiwi B-4 reactor except that the full propellant flow passes through the shield for cooling purposes before it enters the reactor core.

The NERVA reactor program is strongly oriented toward research and development testing of components prior to full-scale reactor tests. This component development program is underway at the present time, and the first full-scale hot test of a NERVA reactor is scheduled for early next year. Fabrication of the long-lead-time parts for this reactor is now underway at Westinghouse. This test will be followed with tests of additional reactors at about 3-month intervals.

[redacted]

[redacted]

Description of NERVA Engine

A schematic representation of the flow system for the NERVA engine is shown in figure 8. This engine is based on the so-called "hot-bleed" cycle. In this cycle, liquid hydrogen flows from the propellant tank into the pump where the pressure is raised to about 1000 pounds per square inch. It then flows through the coolant passages in the nozzle, through the reflector, through the radiation shield, through the reactor core, and out through the nozzle. A small portion of the hot hydrogen is bled off at the inlet to the nozzle, is mixed with cold hydrogen from the nozzle coolant tubes to reduce its temperature to a safe level for the turbine, and is then ducted to the turbine that drives the pump. The discharge from the turbine is ducted to two swivelable nozzles that are used for vehicle roll control.

A full-scale mock-up of the NERVA engine is shown in figure 9. The turbopump is mounted within the thrust structure just above the reactor. Liquid hydrogen flows from the propellant tank down through the inlet line to the turbopump, through an external line to the nozzle, through the nozzle coolant tubes, and then through the internal parts of the reactor and out through the nozzle. A hot-gas bleed line leads from the nozzle inlet to the turbine, and the exit gas from the turbine flows out through the two roll-control nozzles.

The entire engine is gimbaled about a point in the inlet line to the pump. One of the gimbal actuators is visible in the photograph. The spheres near the top of the engine contain high-pressure hydrogen gas for actuation of various devices prior to and during the bootstrap start of the engine. Also visible are the 12 control-drum actuators at the top end of the reactor. The overall length of the engine, as illustrated, is about 23 feet.

Performance Goals

The following design-point operating conditions have been established as the initial goal:

Reactor thermal power delivered to propellant, Mw	1120
Average reactor-exit gas temperature, °R	4090
Reactor-core-exit pressure, lb/sq in.	550
Hydrogen flow rate, lb/sec	75
Thrust, lb	55,600
Overall system specific impulse, sec	750
Operating time at full power (with two restarts)[a], min	20
Engine weight, lb	14,500

[a]The operating time goal for development engines is 60 min to permit the testing of each engine several times.

Development Program

A program is now underway for the initial development for feasibility evalua-

[redacted]

[redacted]

tion purposes of all the principal components of this engine. The reactor represents the main component and probably the most difficult development problem in the entire engine. Other components that appear to present major problems are the turbopump, the nozzle, and the control system.

The turbopump will consist of a single-stage centrifugal pump driven by a two-stage axial-flow turbine. The bearings will not be lubricated but will be cooled by liquid hydrogen. Axial loads on the bearings will be limited by a thrust-balancing piston. A significant problem in the turbopump is the development of hydrogen-cooled bearings that are resistant to nuclear radiation.

The nozzle will be of the conventional tubular construction, but because it has a very high contraction ratio from the point of attachment to the pressure vessel down to the throat, it incorporates a heavy pressure shell. Significant problems in the nozzle are the high heat-flux rates in the nozzle throat (twice as high as in chemical rocket engines) and a difficult fabrication problem because of the requirement of a heavy pressure shell.

In the engine control system, the reactor power will be controlled by neutron flux sensors with a reactor-exit temperature trim. The propellant flow will be controlled by pressure sensors that measure the reactor-exit pressure. Significant problems in the control system include the development of temperature sensors that will operate above 4000° R, the development of adequate neutron detectors, and the development of pressure sensors, wiring harnesses, and other components to operate reliably in a high flux radiation field.

Another significant problem in the design of the NERVA engine and its supporting equipment arises from the fact that once an engine has been run it is highly radioactive. The engine must be designed in such a way that maintenance, disassembly, and reassembly operations can be done remotely, and remote-handling equipment must be designed to perform these functions. Although this does not represent a problem for flight engines, because these engines will not be operated prior to flight, it represents a major problem for development engines because of the requirement for repeated tests on each engine.

The date for the first test of the engine assembly will depend on the rate at which success is achieved in the reactor program. For planning purposes, it is assumed that the first engine test will take place in late 1965 or early 1966. This test will probably be followed by subsequent tests at about 3-month intervals during the first year and at closer intervals during subsequent years.

NERVA ENGINE DEVELOPMENT FACILITIES

In the NERVA program, the reactor testing and the engine testing will all be done in Nevada in a remote desert area called Jackass Flats, about 95 miles northwest of Las Vegas. The test site has been initially developed by Los Alamos Scientific Laboratory for Kiwi reactor testing and is now known as NRDS, the Nuclear Rocket Development Station. It is located in a remote area because of the possibility of radioactive fallout during testing. Figure 10 shows a portion of the Jackass Flats area. Some of the existing reactor test facilities are

[redacted]

[redacted]

shown but are difficult to see because of the great distances involved. The engine test facilities will be in an area near the left side of this photograph.

The facilities layout at the test site is shown in figure 11. Test cell A is the test cell in which all of the reactor testing to date has been done. Test cell C is also a reactor test cell and is now in its final stages of activation. These two reactor test cells are operated from a control point about 2 miles away.

The reactor MAD (maintenance, assembly, and disassembly) building consists essentially of two cold assembly bays, one large hot disassembly bay, and a number of small hot cells. The disassembly bay is a heavily shielded room equipped with the necessary remote-handling equipment to carry out complete disassembly operations on the reactor.

One engine test stand, ETS-1, is well along in construction and another engine test stand, ETS-2, is in the advanced planning stage. These two test stands will be operated from an underground control point located about 1000 feet away. An engine MAD building for maintenance, disassembly, and reassembly operations is now in the early stages of construction.

Facilities for the ground testing of complete nuclear stages are shown near the left side of figure 11. These facilities are now in the early planning stages. One of them is planned to be suitable for either engine or stage testing.

All of the test stands and the two MAD buildings are interconnected by a railroad system. Reactors and engines are moved to and from the test stands on these railroads by remotely controlled locomotives. Figure 12 shows a reactor on its test cart being moved to the test stand. In this particular case, the nozzle had not yet been installed on the reactor. The stepped plug on the forward end of the test cart fits into an opening in a heavy shield wall at the test stand, and the test connections are made on the far side of this shield.

Test cell A is shown in figure 13. The two cylindrical tanks at the upper right are liquid-hydrogen Dewars with a capacity of 28,000 gallons each. The shed mounted on tracks is for the protection of the reactor and personnel from the weather during test-stand operations. During testing, this shed is moved well away from the test stand.

Figure 14 shows a reactor at the test stand ready for test. These reactors are tested in an up-firing position for simplicity in the disposal of the exit hydrogen gas. The test cart carries a heavy shield just below the reactor, and the control-drum actuators are located below this shield. Hydraulic actuators are used for reactor test purposes but will not be suitable for use on the engine because of radiation effects. It is planned that electropneumatic actuators will be used on the engine.

An aerial view of test cell C is shown in figure 15. The two spheres are liquid-hydrogen Dewars with a capacity of 50,000 gallons each. The long cylindrical tanks are high-pressure gas bottles. This facility also contains a high-

[redacted]

capacity liquid-hydrogen flow loop for component test purposes.

The reactor MAD building is shown in figure 16. This building contains two assembly bays and one large shielded disassembly bay. It also contains a number of small hot cells for use in post-mortem examination of reactor components.

Figure 17 is an artist's sketch of the first engine test stand, ETS-1. The run tank on this stand has a capacity of about 70,000 gallons, and this is augmented by a spherical storage Dewar with a capacity of about 250,000 gallons. The engine is installed on the test stand by a rail-mounted vehicle operated from a heavily shielded cab. During operation, two halves of a cylindrical shield are brought together to form an enclosure around the engine that can be made inert. The engine fires downward into an exhaust duct that diffuses the jet and turns it through an angle of about 120°. This diffuser is water cooled. The entire test stand with the exception of the exhaust duct is made of aluminum because of neutron activation considerations. The exhaust duct, however, will remain highly radioactive and must be shielded before personnel can approach the test stand. This shielding is accomplished by movable shield doors over the exhaust-duct vault.

The present appearance of ETS-1 is shown in figure 18. This test stand is well along in construction and will be ready for operation about the middle of 1965.

GROWTH CAPABILITY OF NERVA

The reactor power is limited primarily by thermal gradients in the core, by temperature levels, and by structural strength. Reactor temperature levels are limited by the high-temperature capability of the fuel matrix in the graphite and by coatings for the prevention of fuel-element corrosion. Operating time is limited primarily by corrosion and is therefore to some extent a trade-off with temperature level.

Design analyses of the NERVA engine indicate that the growth of power level will probably be limited by nonreactor components such as the turbopump and nozzle. These components have been designed for growth to about 1500 megawatts, whereas the reactor appears capable of ultimate growth to significantly higher power levels.

If the operating time of 20 minutes is maintained, it appears that the ultimate propellant temperature will be limited by the reactor to about 4500° R.

With these increases in power and temperature levels, the engine should have a thrust of about 74,000 pounds and an overall system specific impulse of about 830 seconds. Any increases in power beyond this level will require major redesign and development of engine components and systems, and there is currently no engine development activity in this direction. However, the advanced engine program is investigating ways and means of advancing the technology for the eventual design and development of higher power nuclear rocket engines.

[redacted]

DIAGRAMMATIC CROSS SECTION OF KIWI B REACTOR. POWER, 1120 Mw; GAS EXIT TEMPERATURE, 4090° R

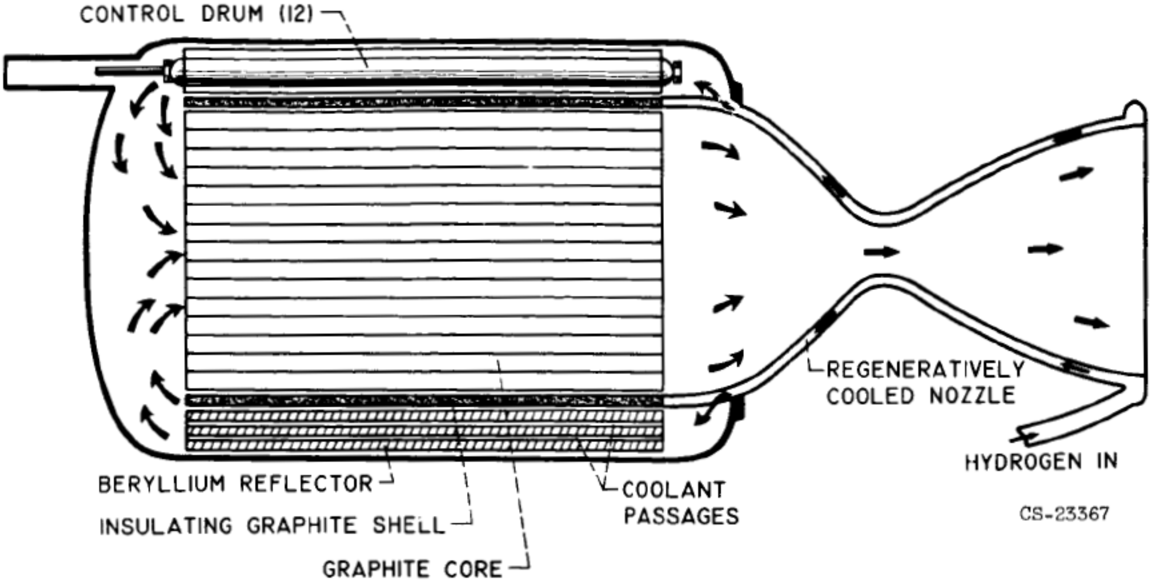

Figure 1

KIWI B-4 AND NERVA FUEL ELEMENTS SHOWING 19 COOLANT PASSAGES APPROX. 0.095 IN. IN DIAMETER COATED WITH NIOBIUM CARBIDE

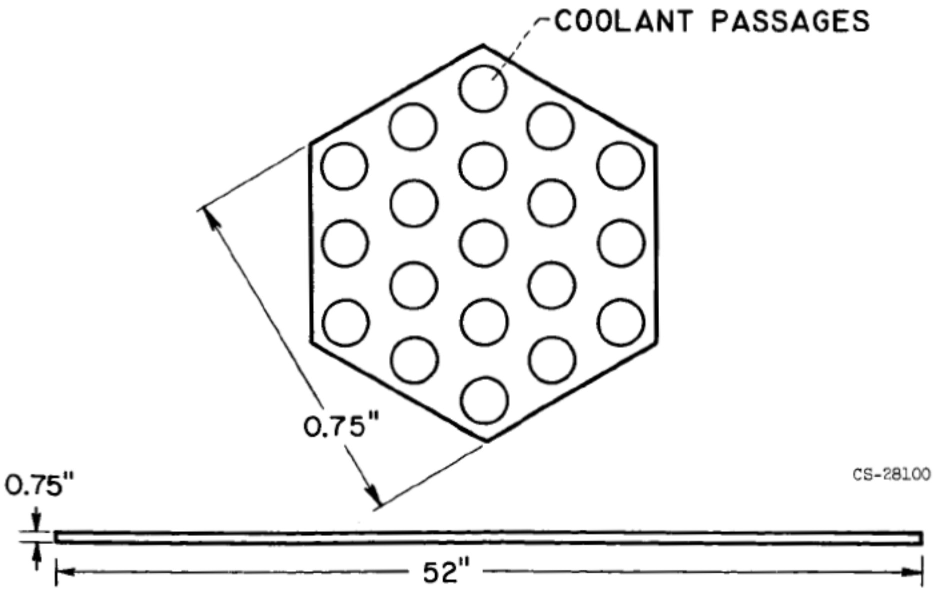

Figure 2

[redacted]

[redacted]

FUEL PARTICLES USED IN MANUFACTURE OF FUEL ELEMENTS
URANIUM CARBIDE SPHERES; 0.002- TO 0.005-INCH DIAMETER;
COATED WITH PYROLYTIC GRAPHITE 0.001 INCH THICK

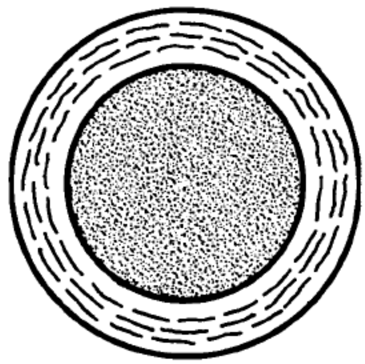

Figure 3

KIWI B-4 AND NERVA FUEL ELEMENT CLUSTERS

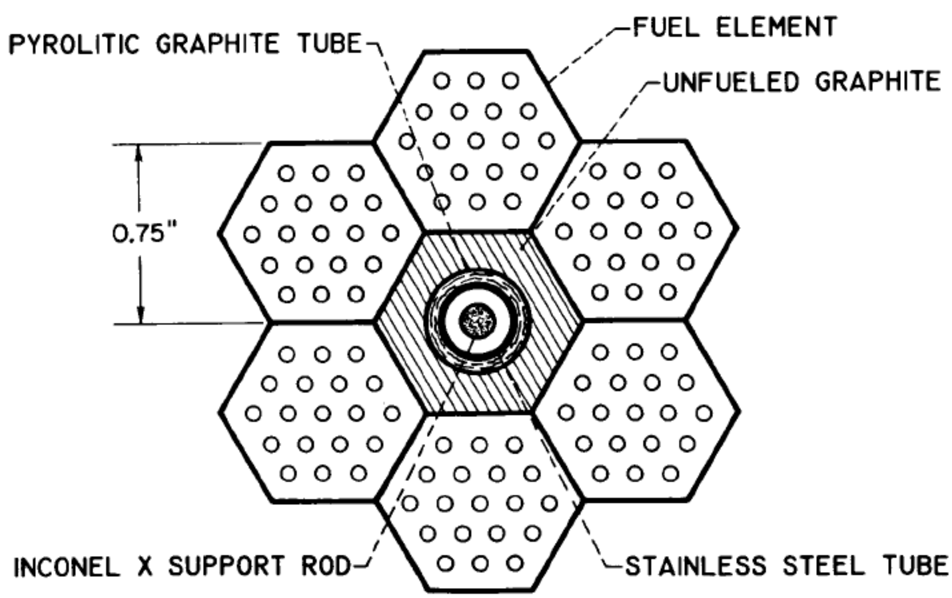

Figure 4

[redacted]

[redacted]

CUTAWAY VIEW OF KIWI B-4 AND NERVA FUEL ELEMENT CLUSTER

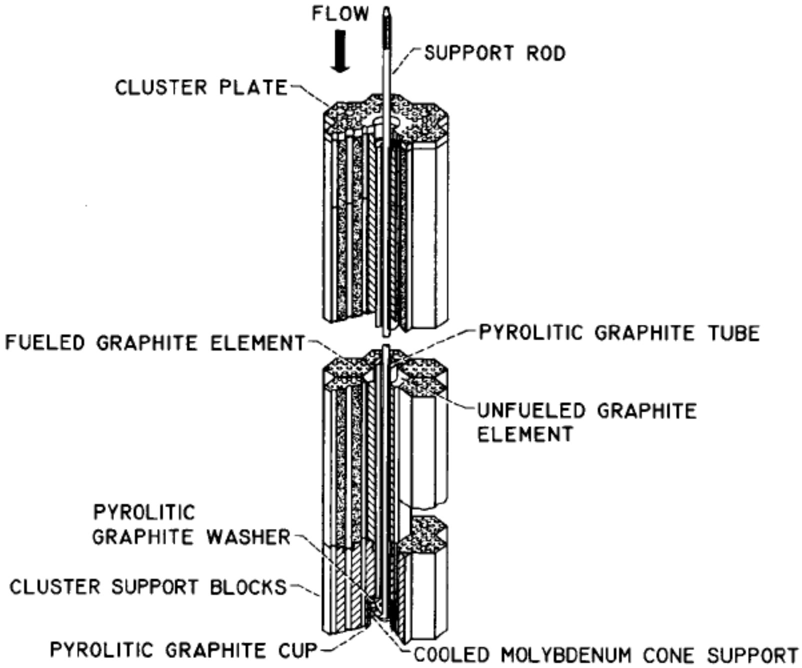

Figure 5

CROSS SECTION OF KIWI B-4 REACTOR

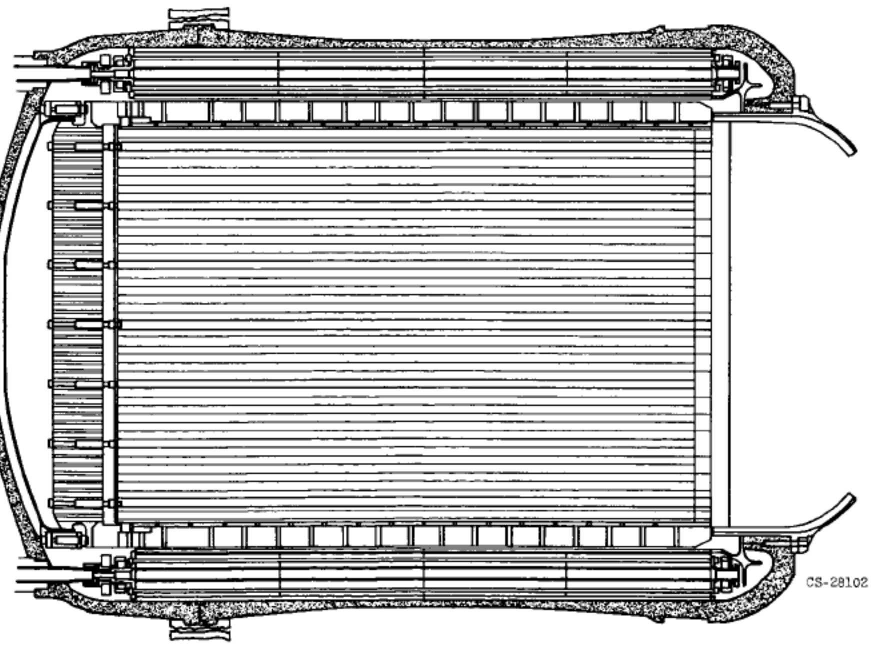

Figure 6

[redacted]

[redacted]

CROSS SECTION OF NERVA REACTOR

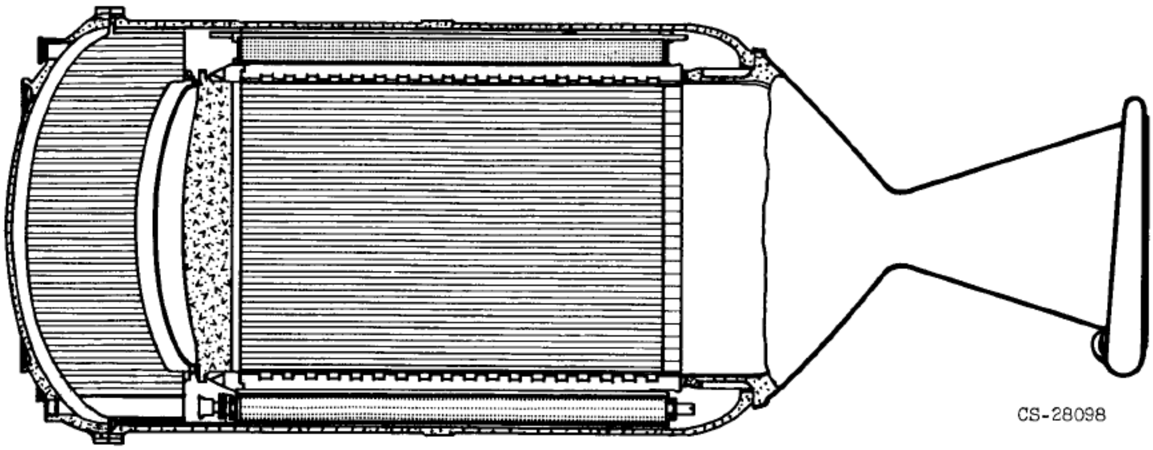

Figure 7

SCHEMATIC DIAGRAM OF NERVA ENGINE FLOW SYSTEM

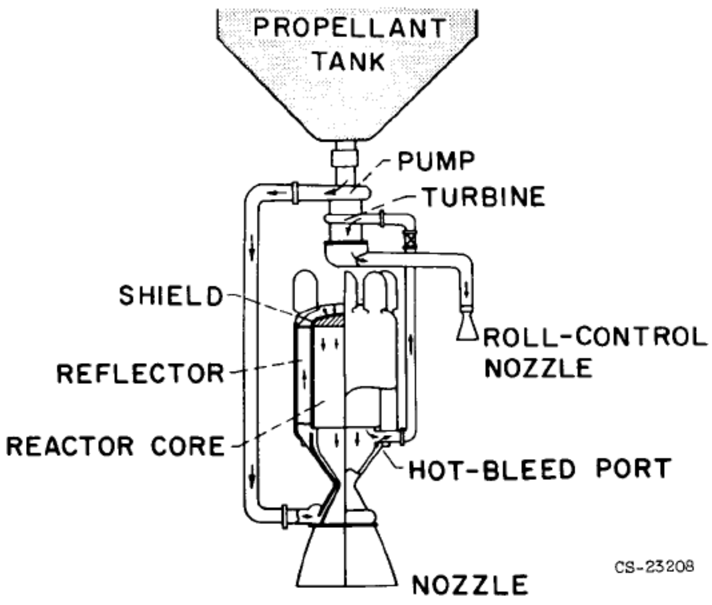

Figure 8

[redacted]

FULL-SCALE MOCKUP OF NERVA ENGINE

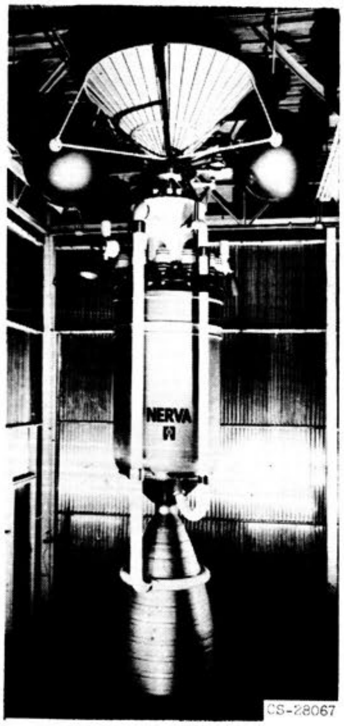

Figure 9

PORTION OF NUCLEAR ROCKET DEVELOPMENT STATION AT JACKASS FLATS, NEVADA

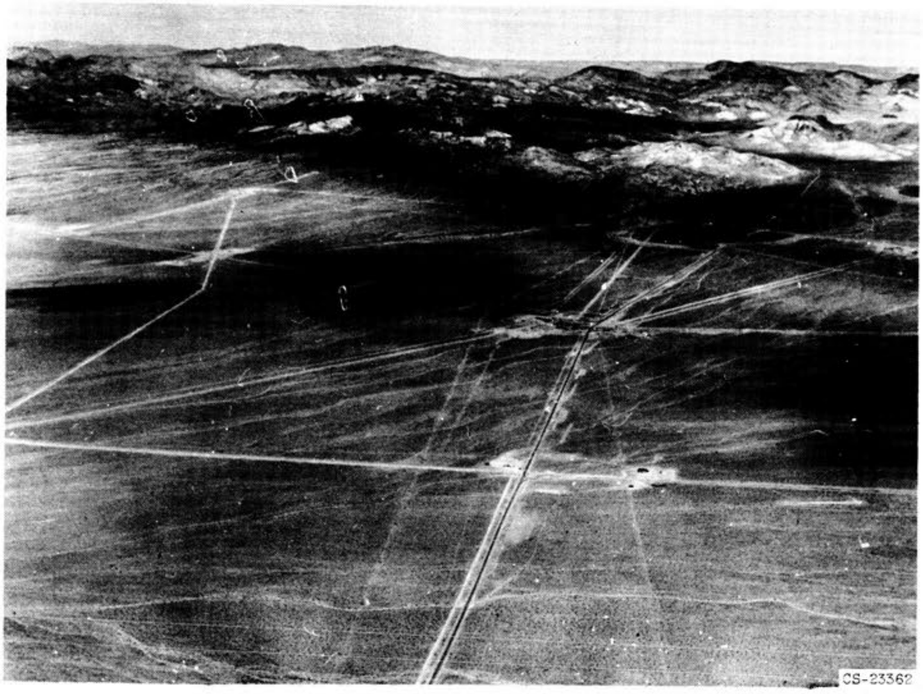

Figure 10

FACILITIES LAYOUT AT NUCLEAR ROCKET DEVELOPMENT STATION

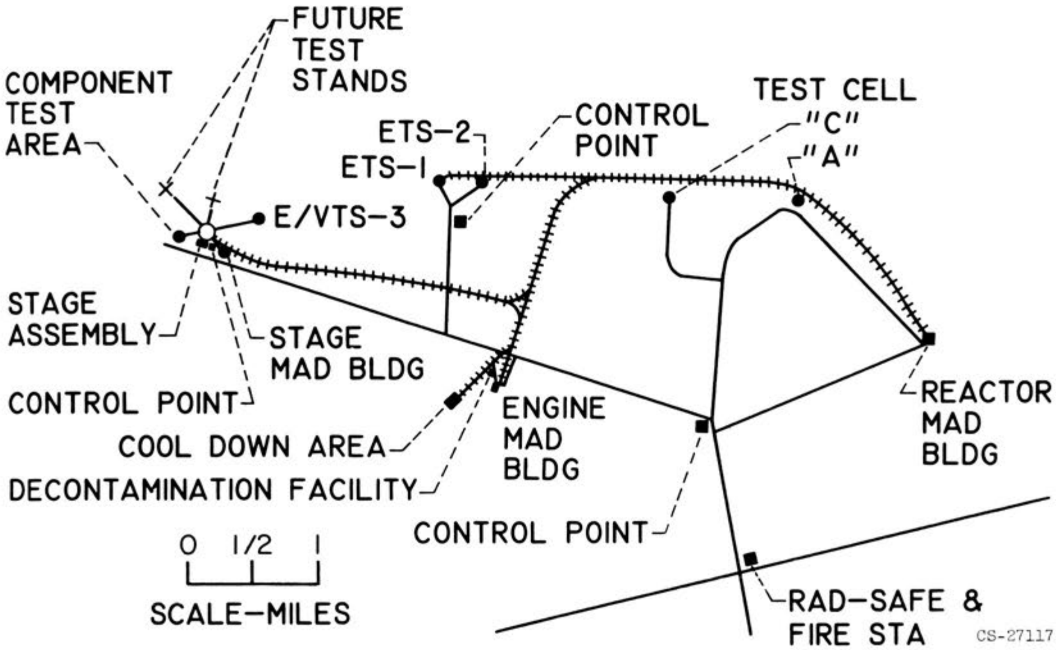

Figure 11

REACTOR IN TRANSIT TO TEST STAND (NOZZLE NOT YET MOUNTED)

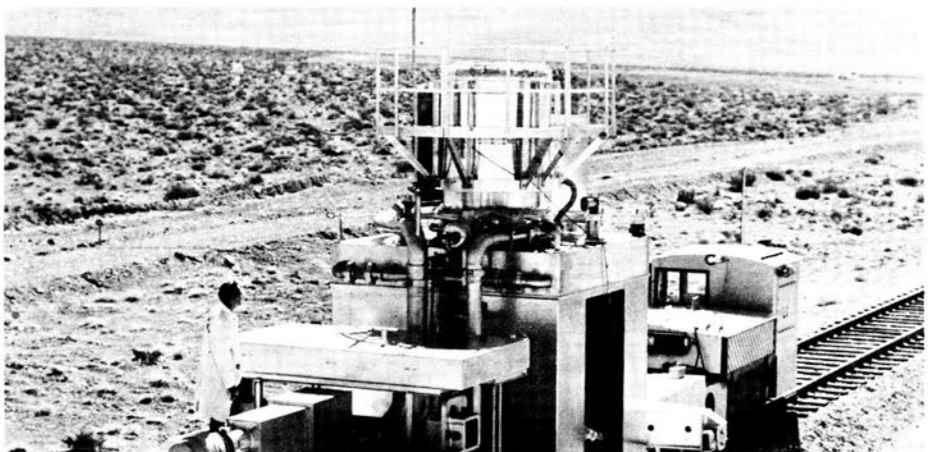

Figure 12

TEST CELL A

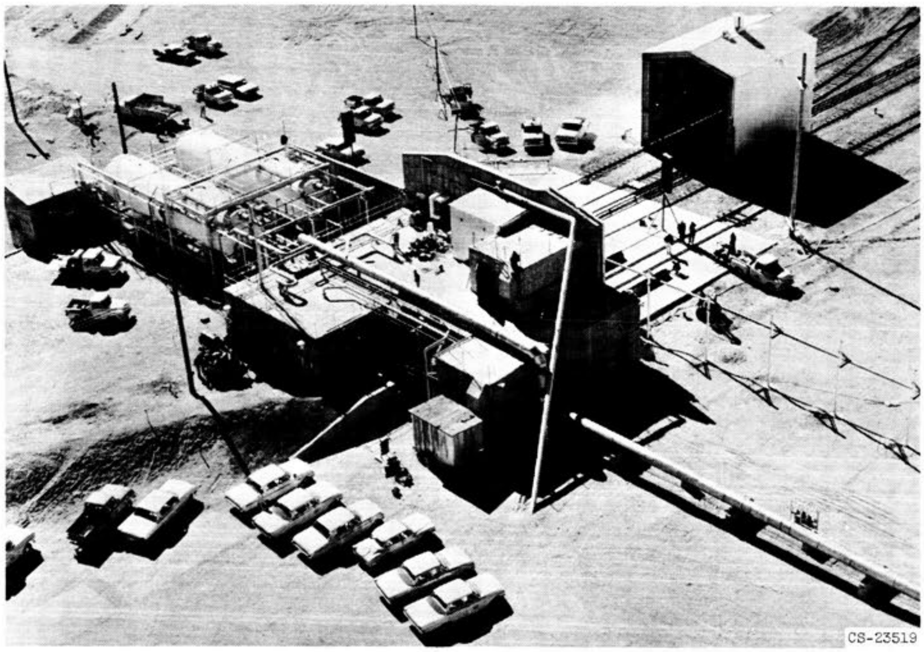

Figure 13

REACTOR AT TEST CELL A

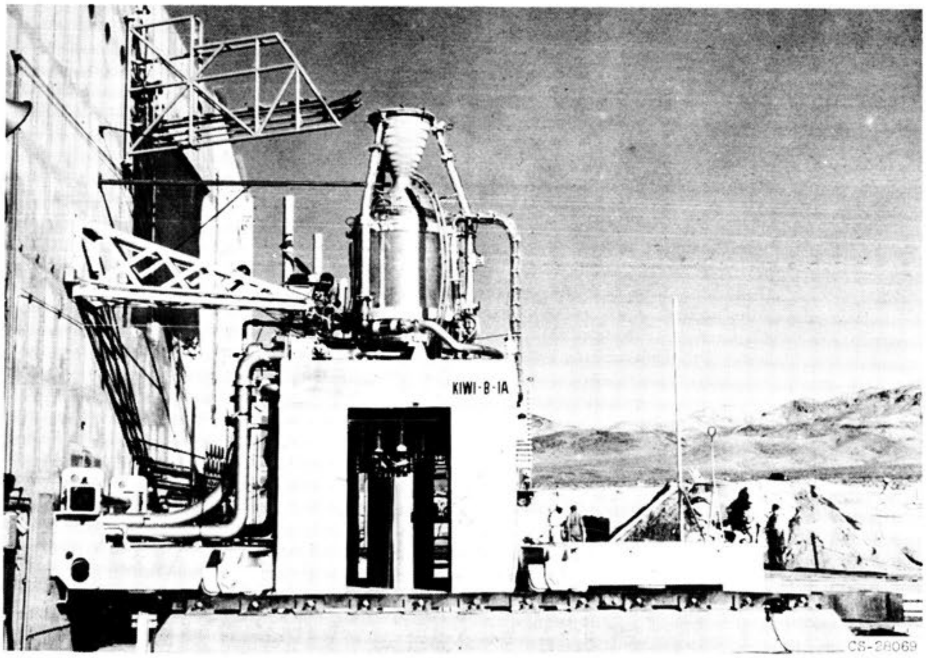

Figure 14

TEST CELL C

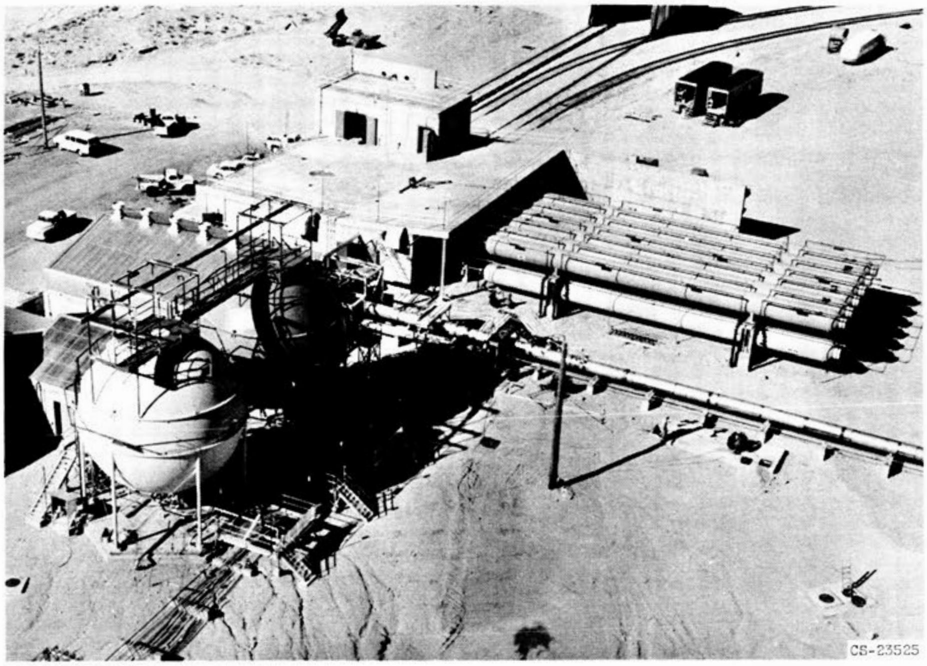

Figure 15

REACTOR MAINTENANCE, ASSEMBLY, AND DIS-
ASSEMBLY (R-MAD) BUILDING

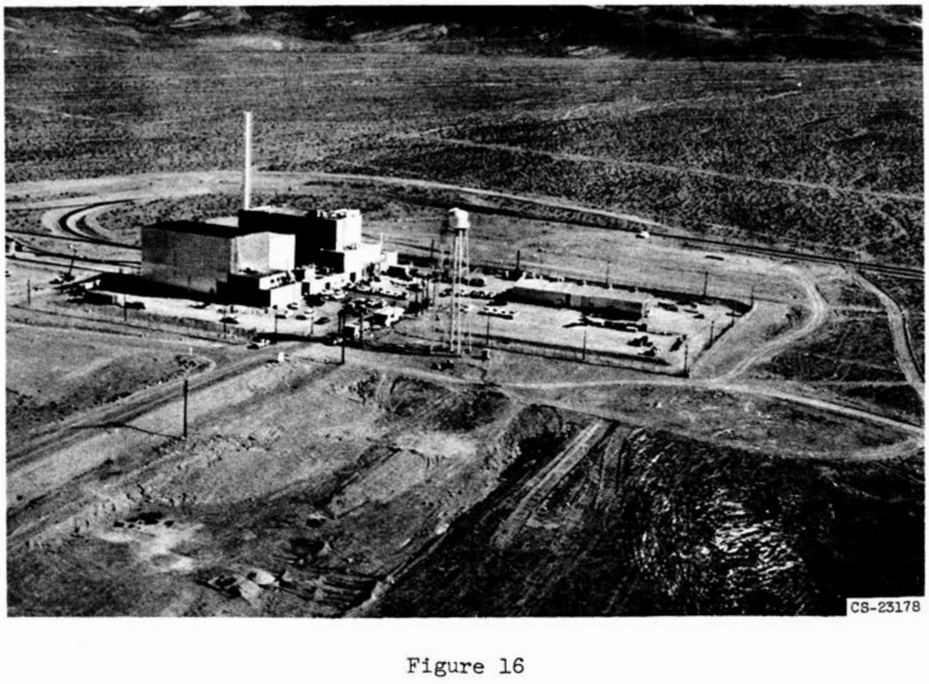

Figure 16

ARTIST'S SKETCH OF ENGINE TEST STAND (ETS-1)

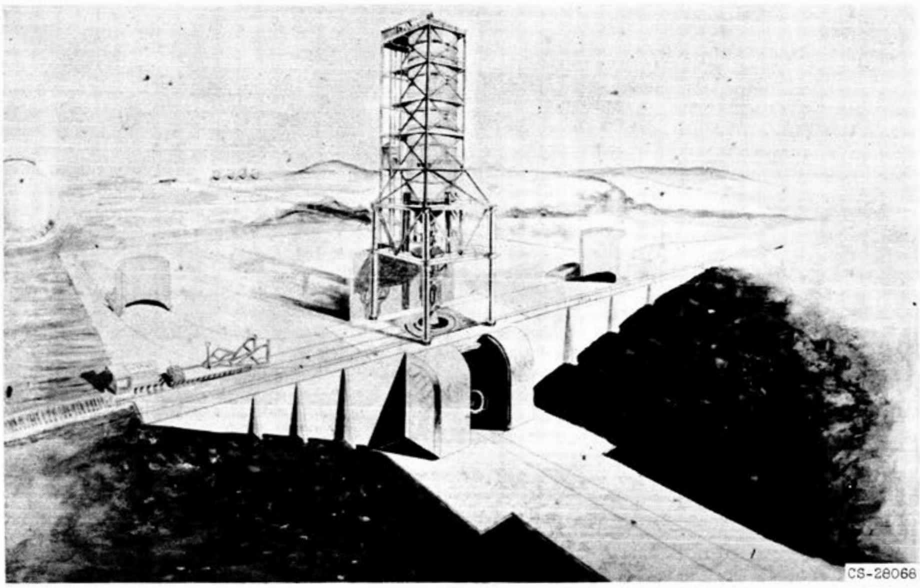

Figure 17

ENGINE TEST STAND 1 (ETS-1) AT PRESENT

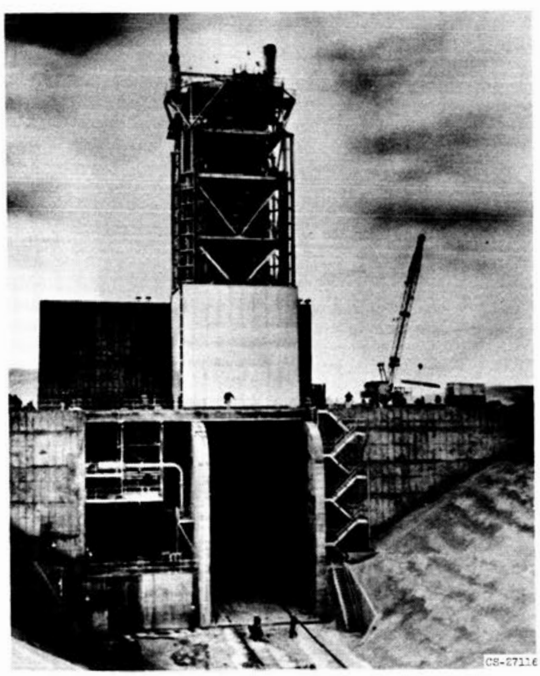

Figure 18