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The Pluto Program was established to show the feasibility of a nuclear reactor which would be able to propel a supersonic ramjet missile. Feasibility has been defined as the successful ground operation of a reactor, with the desired characteristics, for short periods of time together with suitable laboratory experiments to allow extrapolation to the desired lifetime. With the exception of the lifetime and the expected missile accelerations the reactor will perform on the ground in the same environment as expected in the missile flight.

Although the nuclear ramjet can be designed for flight at altitudes from sea level to over 100,000 feet, it possesses a unique ability for supersonic flight over long distances at sea level. Overcoming the supersonic missile drag at sea level requires a large amount of energy which can be supplied only by a reactor if flight over significant distances is required. The present Pluto Program is directed toward the design of a reactor for sea-level flight.

The nuclear ramjet consists of an inlet diffuser followed by a single-pass, straight-through heat exchanger (the reactor) and an exhaust nozzle. (Fig. 1) The purpose of the diffuser is to reduce the velocity of the intake air and recover as much of the ram or stagnation pressure as possible. In passing through the reactor, heat is added

*Work done under the auspices of the U. S. Atomic Energy Commission.

to the air. The random heat energy is changed into directed motion in the nozzle, resulting in an increase in air momentum and a net thrust for the missile. The sea-level nuclear ramjet develops a maximum thrust in the vicinity of Mach 3. This is illustrated in Fig. 2 where the thrust is plotted as a function of the flight Mach number for several reactor temperatures. The design has been optimized at each velocity and temperature. It is apparent that the ramjet performance increases rapidly with temperature increase and that a Pluto reactor will be a high-temperature reactor by today's standards.

The choice of materials for the reactor is severely restricted. The material must have reasonable strength and resist oxidation at elevated temperatures. In addition it must be a good moderator and a poor neutron absorber. Moderating ability is required because a fast, unmoderated reactor would be prohibitively expensive in terms of nuclear fuel. The only material that can meet the requirements for the moderator is the ceramic, beryllium oxide. Uranium forms a refractory oxide, UO_2, which unfortunately turns to a volatile oxide at high temperatures in air. Cladding is impractical at these temperatures and thus the fuel is mixed homogeneously with the BeO moderator.

The reactor neutronics must next be considered. The Pluto reactor can be classified as an intermediate-energy reactor, which means that a large fraction of the fissions take place at neutron energies greater than thermal. This is a consequence of the small size of the reactor. The prediction of criticality for such a reactor is difficult and much effort has been expended at the Laboratory in the development of computational methods and in critical experiments which allow the checking and normalization of the computations. Critical experiments have been done at temperatures from room temperature up to 1200°F. Much of this work has already been reported in the literature (1). A homogeneous reactor is by its nature rather slow to respond in temperature to power changes because of the large heat capacity of the fuel elements. However, power and temperature changes must be fast when compared to usual procedures for power reactors. Start-up times of the order of one minute are desired. Thus a considerable effort has been devoted to the reactor controls, kinetics, and automatic control systems.

The reactor radiation creates a problem due to the large gamma and neutron heating in non-nuclear components both in and near the reactor. As an example, power densities in metallic structures in the reactor can be several times larger than the power density in the fuel elements themselves. Also, radiation damage of some materials can have serious consequences. These problems are under investigation by computation and experiment.

The mechanical designer is faced with formidable difficulties. The pressure drop in the direction of the air stream results in a force of several hundreds of thousands of pounds tending to push the reactor out of the nozzle. In addition, accelerations of many g's due to air turbulence in flight must be reacted. The materials for supporting structures are limited in volume and nature because of neutronic requirements and high temperatures. Cooling air has a minimum temperature of 1000°F. The usual weight limitations are also present for structural elements. The fuel elements are ceramic and thus are brittle. Methods of design had to be utilized which did not rely upon ductility to take care of inevitable errors in fabrication and design.

After suitable laboratory experiments and tests it was deemed desirable to attempt the solution of all of these problems — and others unmentioned such as thermodynamics and fluid flow — in a reactor to be tested upon the ground.

For a Mach 3 sea-level ramjet, air is supplied to the reactor at a pressure of approximately 350 psi and a temperature of about 1000°F. Flow rates greater than 2000 pounds per second can be achieved. It is immediately apparent that the ground test facility, in particular the air supply, for such a reactor is large and complex. Also a considerable amount of BeO is required for a full-scale reactor. At the beginning of the program the fabrication of BeO was expensive and time-consuming. Therefore it was decided that the first ground test would be of a small reactor, so that the air supply and BeO requirements would be minimized. The small, high-temperature, fueled core of this reactor would be tested in order to obtain data on the materials, physics, and engineering required for the design of the full-scale reactor. In order to enable the reactor to reach criticality, the core would be surrounded with a thick carbon reflector operating at room temperature. In addition, the reactor controls would be placed in this reflector so that the problem of operating control rods in a reactor at high temperature could be avoided in the first tests. The reflector with controls has no bearing whatsoever upon the missile reactor, since it is present only to satisfy neutronic requirements for the small test core. This reactor concept is called the Tory II-A reactor and is due to undergo initial high-power operation within a few weeks. Two of these reactors of essentially identical construction will be tested. The Tory II-C reactor which will be tested after the II-A series, will be a full-scale, missile-like reactor and is intended to demonstrate the feasibility of the Pluto ramjet reactor.

The test facility located at the Nevada Test Site is now complete. The reactors are tested on unshielded railroad flat cars which can be remotely moved between a test bunker and a disassembly facility. Electrical, air, and water-cooling connections and disconnections to the test bunker can be made remotely. The site layout is shown in Fig. 3. The control room is located approximately two miles from the test bunker. The shielded test bunker contains electronic and air supply equipment which must be located close to the reactor. Access to the bunker can be made while a radioactive reactor is in place, through a 500-ft-long, shielded tunnel. Compressed air at 3600 psi (120,000 lb) is stored in long steel bottles. During a reactor operation the air passes into the bunker, through a stack of previously heated steel, out of the bunker and into the reactor at 350 psi and 1060°F. For the Tory II-A reactor approximately as much heat is added to the air before it reaches the reactor as is added in the reactor itself. This amount of stored air allows full-power operation of the Tory II-A reactor for approximately two minutes. After operation, the air bottles and heater can be recharged in less than two days. The test bunker and air storage cylinders are shown in Fig. 4. Figure 5 shows the Tory II-A test vehicle in place at the bunker face with approximately 700 pounds of air per second at 1060°F passing out of the nozzle. The air storage capacity will be increased to approximately 1,000,000 pounds of air for operation of the Tory II-C reactor.

The main parameters of the Tory II-A reactor are listed below:

Power:	155 megawatts
Flow rate:	708 pounds/sec
Maximum fuel-element wall temperature:	2250°F
Exit gas temperature (tube):	1975°F
Core diameter:	32 inches
Core length:	48 inches
Side reflector thickness (graphite):	24 inches

The core contains approximately 100,000 hexagonal fuel elements 4 inches long, 297 mils across flats with 200-mil-diameter holes for the passage of air. These tubes are arranged in hexagonal bundles about 5 inches across. The bundles are contained in unfueled BeO structural elements as shown in Fig. 6. The fuel elements are not shown in this figure. An air-cooled Hastelloy R-235 tube is placed in each corner of the hexagonal bundles. The R-235 tubes are attached to a massive front support structure. At the exit end of the reactor the R-235 tubes are attached to coated molybdenum base plates. The pressure drop through the fueled tubes appears at these base plates. This load on the base plates is reacted through the R-235 tubes and appears finally at the front support structure. The core is cantilevered from the front support structure by an air-cooled R-235 shroud.

The core is separated from the reflector by a water-cooled aluminum pressure shell. The graphite reflector is in two sections which can be separated horizontally so that the aluminum pressure shell can be removed from the reflector. The reflector contains 8 graphite cylinders with boron steel at the outer edge of one quadrant of each. These cylinders rotate and control the reactor by increasing or decreasing the effective size of the reflector. Additional fast control is obtained from four linear rods placed near the inner wall of the reflector. All control elements are moved by hydraulic actuators and can be operated singly or in unison. The reflector is water-cooled.

The core during assembly is shown in Fig. 7. The BeO structural elements and R-235 tubes can be seen. Figure 8 shows the outside of the core. A few of the outside structural elements are in place. The dark tubes are fueled. The painted dots are a code system to indicate the percent uranium content. Strain gauges and thermocouples are in place. The front (upstream end) of the core is shown in Fig. 9. The front support structure and R-235 tubes can be clearly seen. The fully assembled core in the pressure vessel is shown in Fig. 10.

A side view of the Tory II-A test vehicle is shown in Fig. 11 and a view from above, Fig. 12, shows the hydraulic actuators.

The Tory II-A reactor was taken critical at Livermore in November of 1960. Since a mockup reactor was not available for criticality experiments, the fuel-element loadings were specified from calculation. The calculations were normalized to simple critical configurations having the shape of rectangular parallelepipeds. The calculations overestimated the criticality by about 6% in reactivity. An adequate amount of reactivity was regained by cooling the reflector with D_2O rather than H_2O. The reactor was taken critical at the Nevada Test Site in December of 1960. Flow rates without nuclear power of up to 300 pounds per second were also achieved in December. From January to April, efforts have been devoted to obtaining completely satisfactory hot piping for the bunker and to improving the reactor front support structure and the clamps for the test vehicle piping. It is expected that a high-power run will take place in a few weeks.

The Tory II-C design is essentially complete and fabrication of some parts has begun. A drawing of the test vehicle and ducting is shown in Fig. 13. There will be no water-cooling on the test vehicle. The nozzle and reactor duct will be air-cooled. The reactor will be controlled by linear rods in the hot core which are moved by pneumatic actuators. The actuators are located in front of the reactor in the 1060°F inlet air stream. These actuators together with servo valves and motors have been successfully operated at temperatures of 1200°F for periods of several hours. A facility for the fabrication of the Tory II-C fuel elements has been completed and manufacture of these elements will begin shortly.

Although solutions have been found for many of the major problems in the design of the ramjet reactor, it is expected that further problems will become evident with the operation of the Tory reactors.

Reference

1 Reynolds, H. L., "High Temperature Critical Systems," ARS Journal, vol. 30, 1960, pp. 772-775.

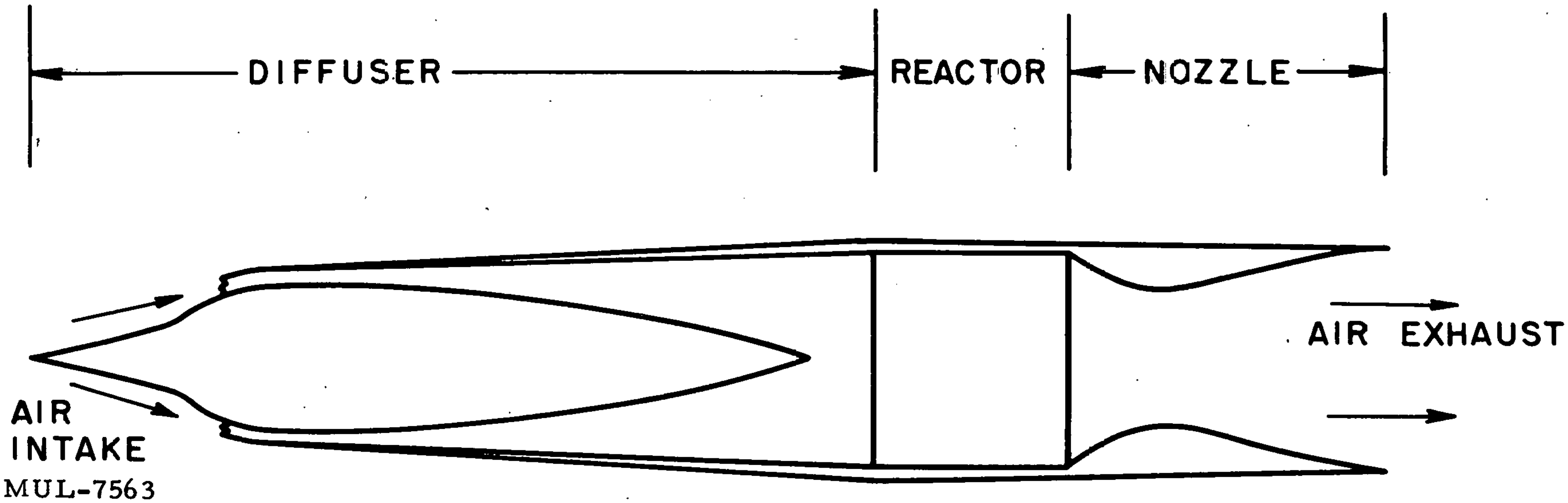

Fig. 1. Conceptual arrangement of a nuclear ramjet.

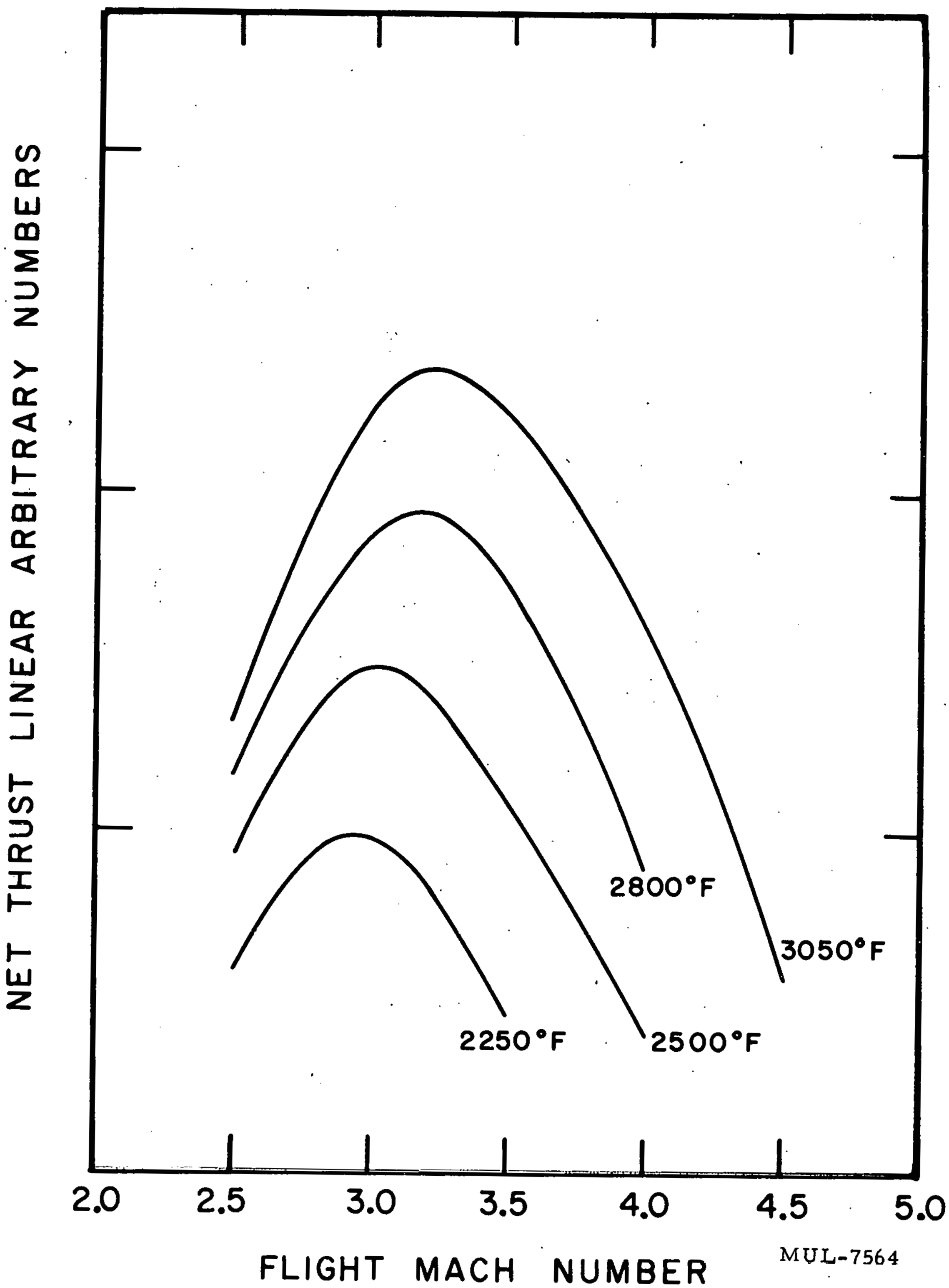

Fig. 2. Typical relations between flight Mach number, heat-exchanger wall temperature, and a number proportional to net thrust coefficient, for a duct containing a reasonable reactor.

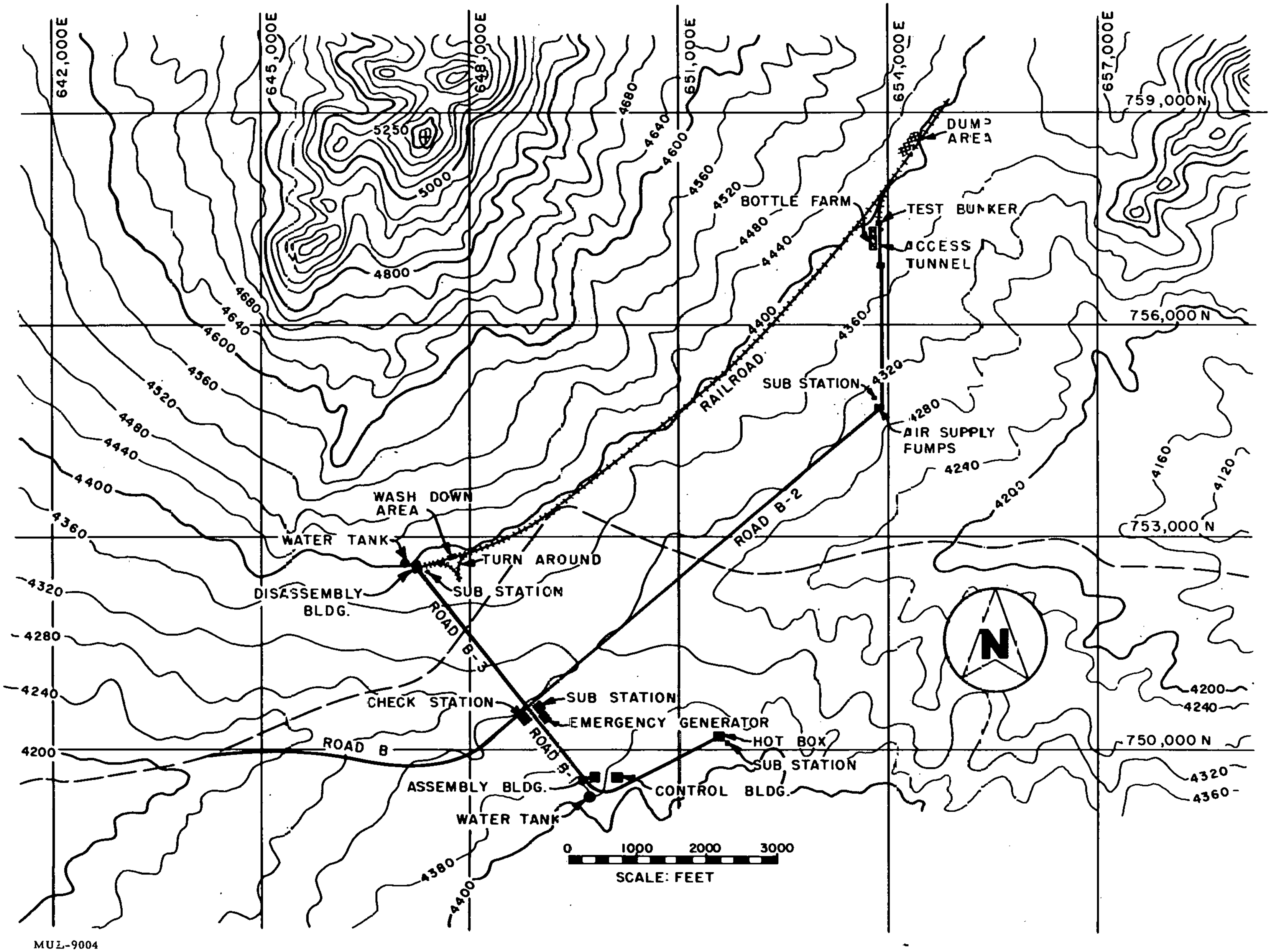

Fig. 3. Test site layout.

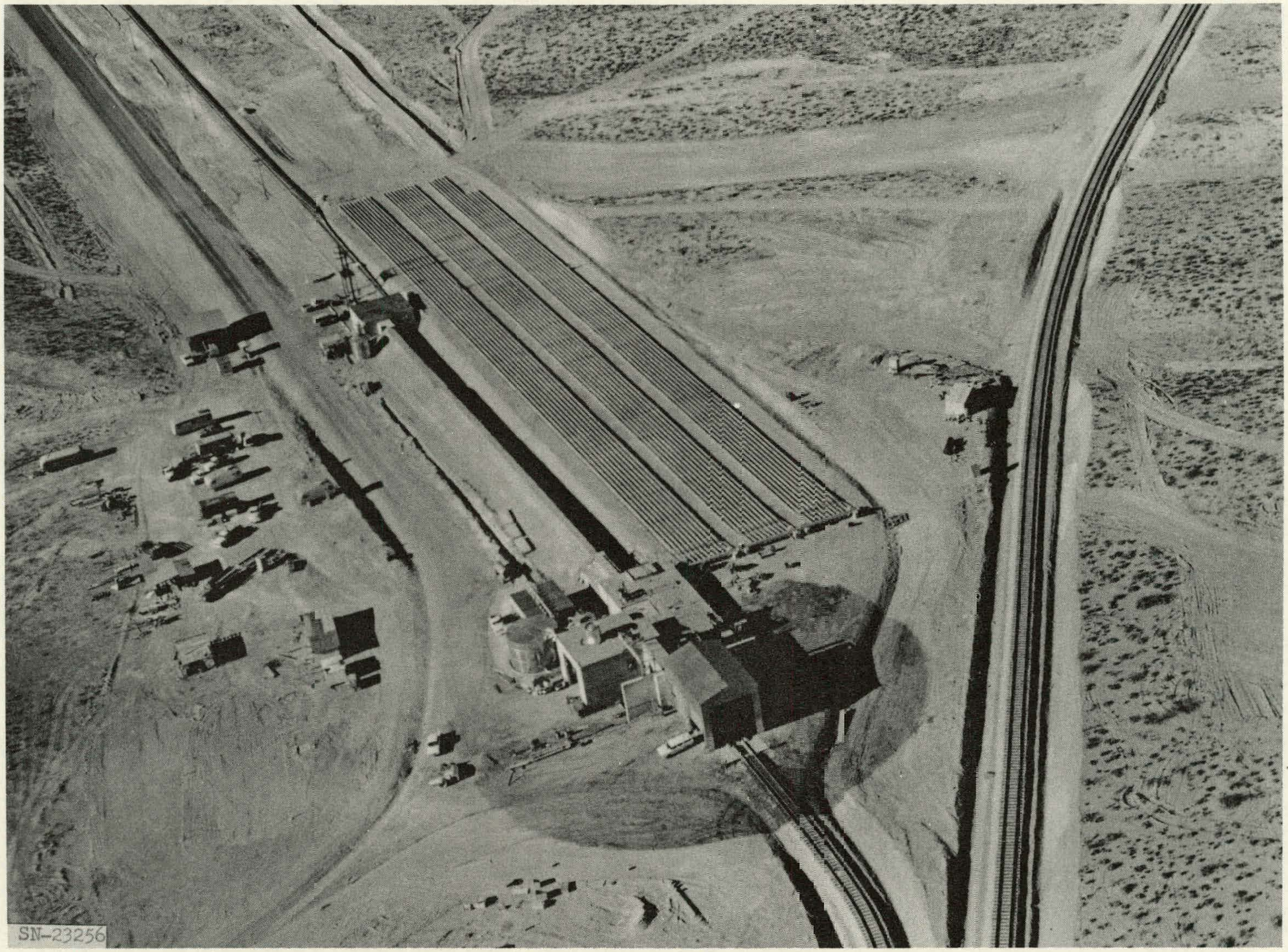

Fig. 4. Test bunker and air storage cylinders.

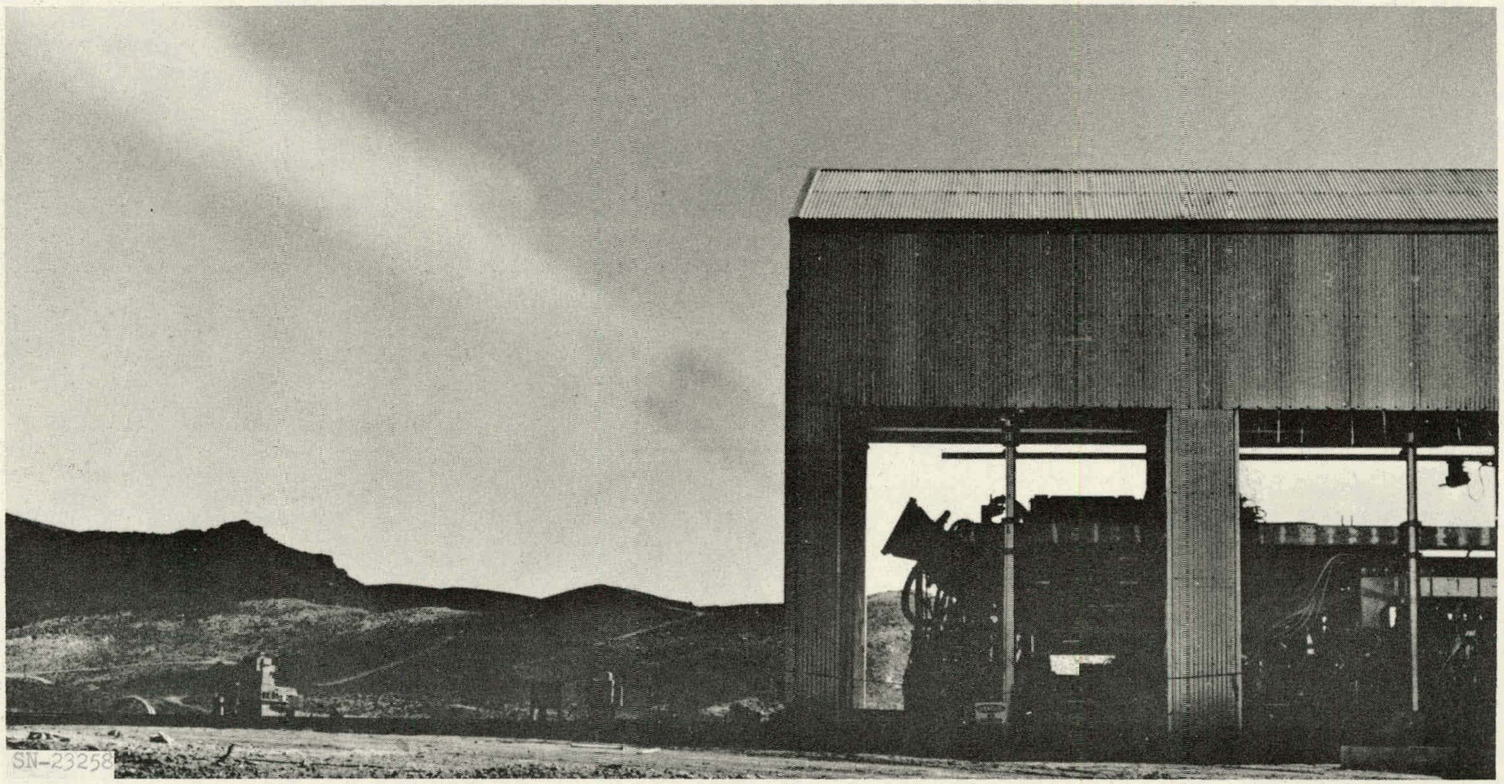

Fig. 5. Tory II-A test vehicle at the bunker face.

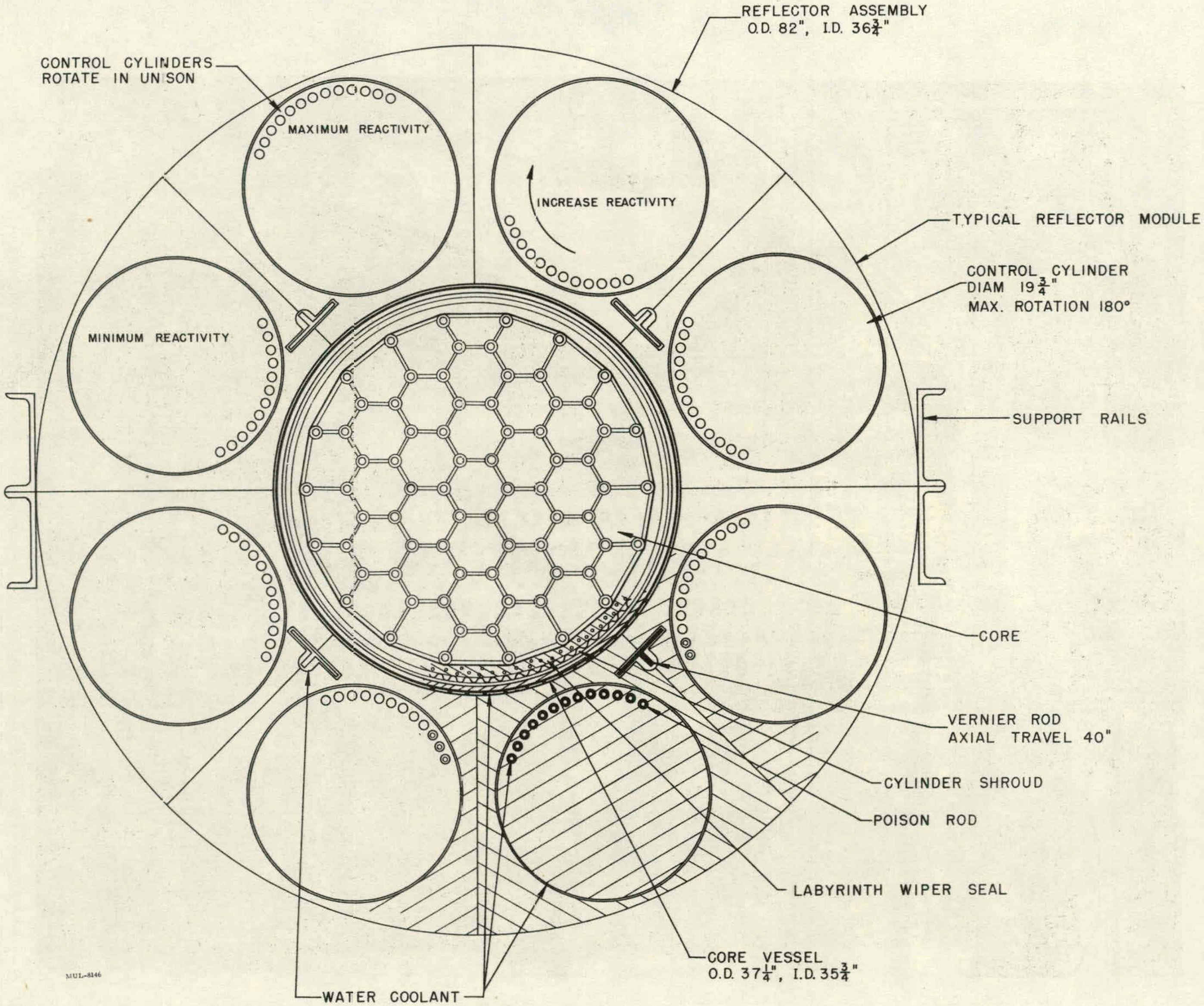

Fig. 6. Cross section of Tory II-A core and reflectors.

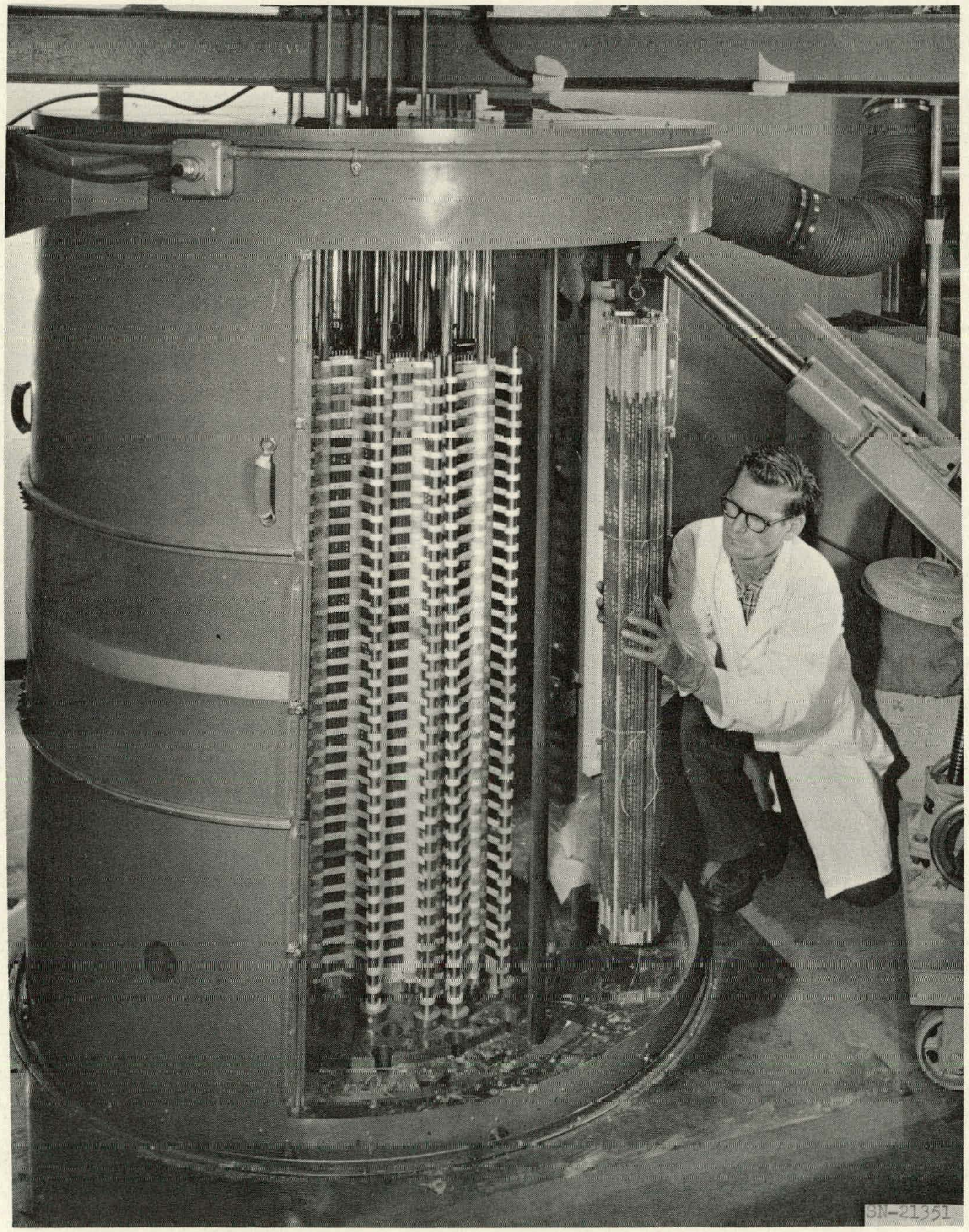

Fig. 7. Tory II-A core during assembly.

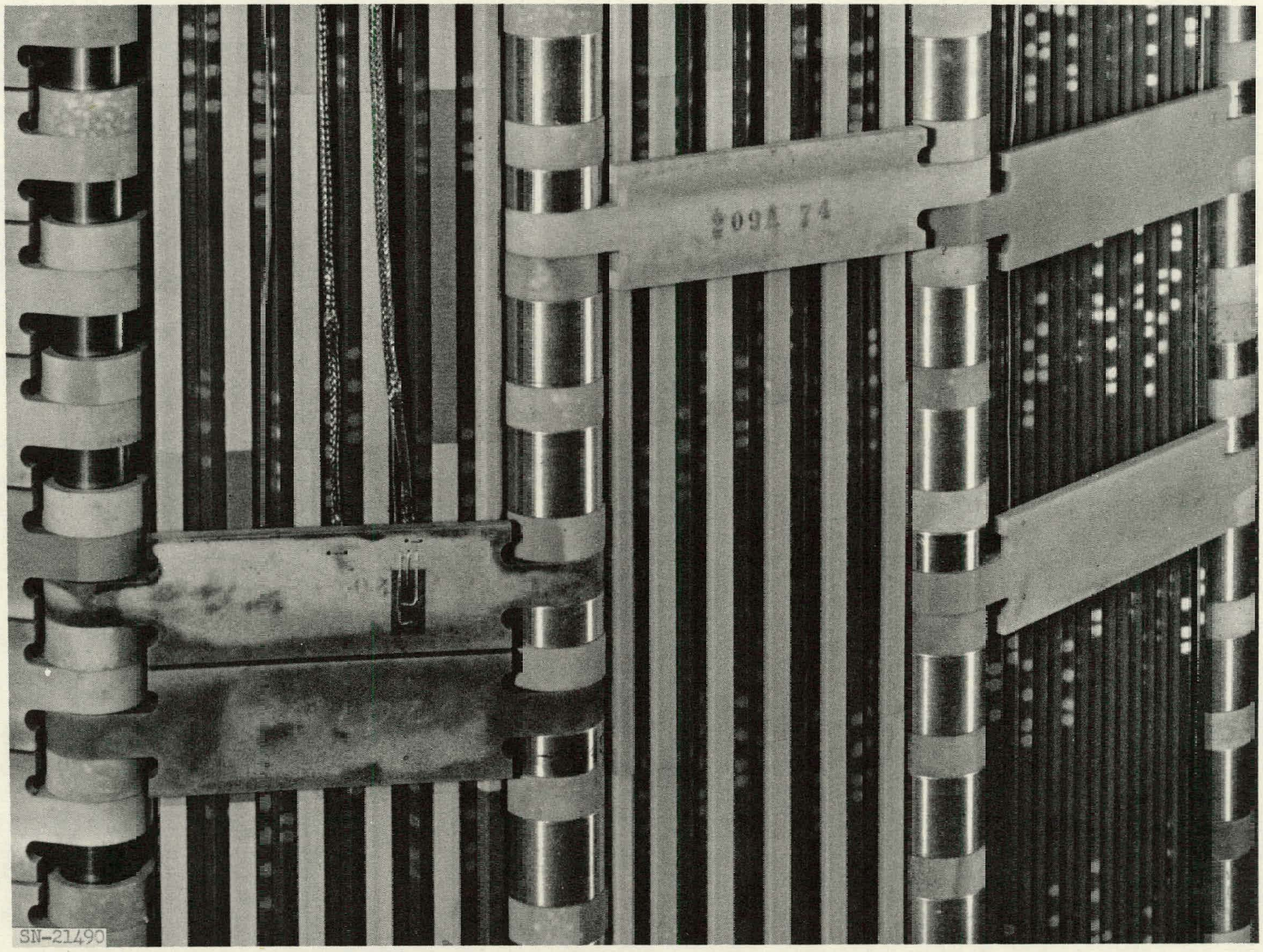

Fig. 8. View of outside of Tory II-A core.

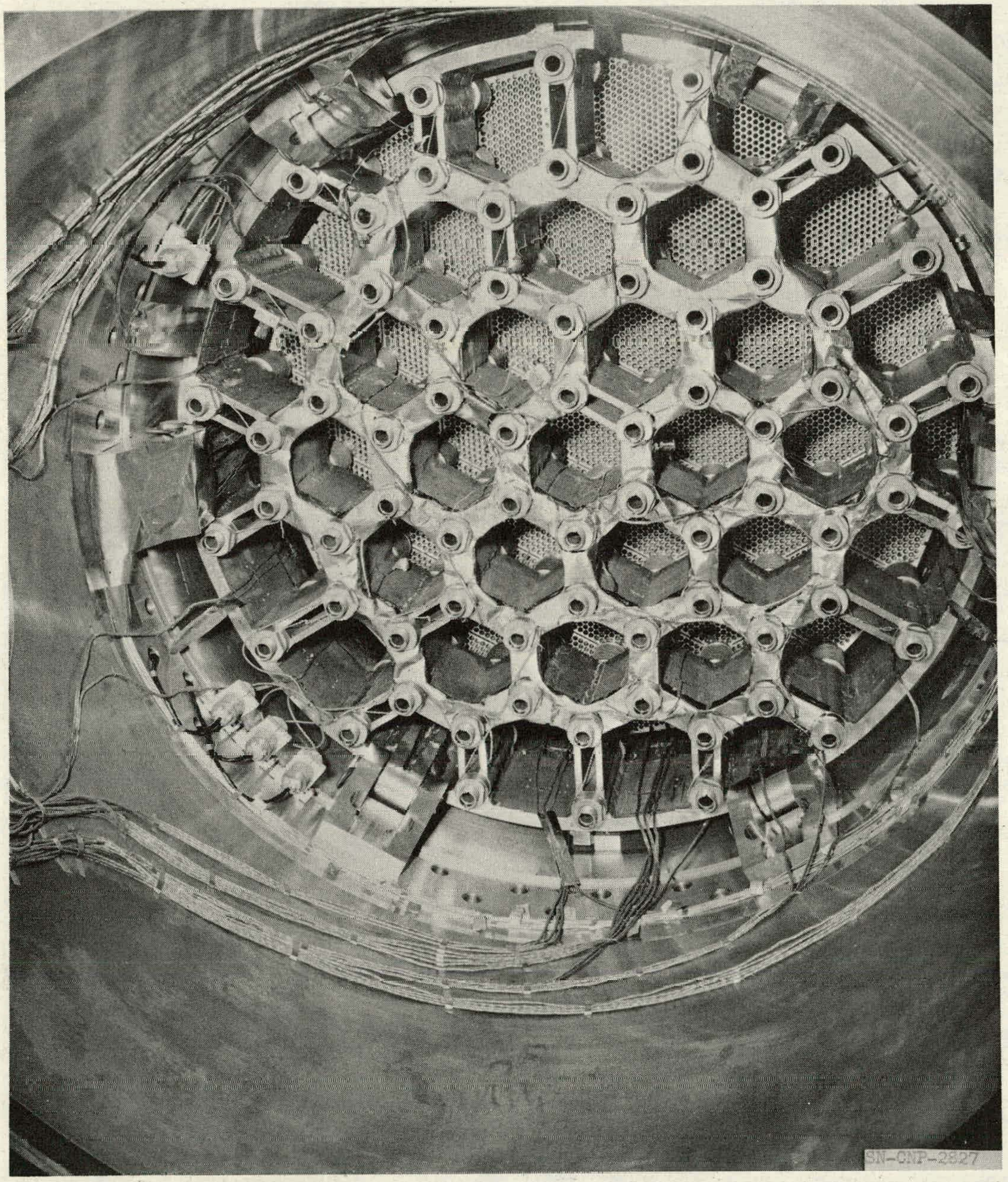

Fig. 9. Front of Tory II-A core.

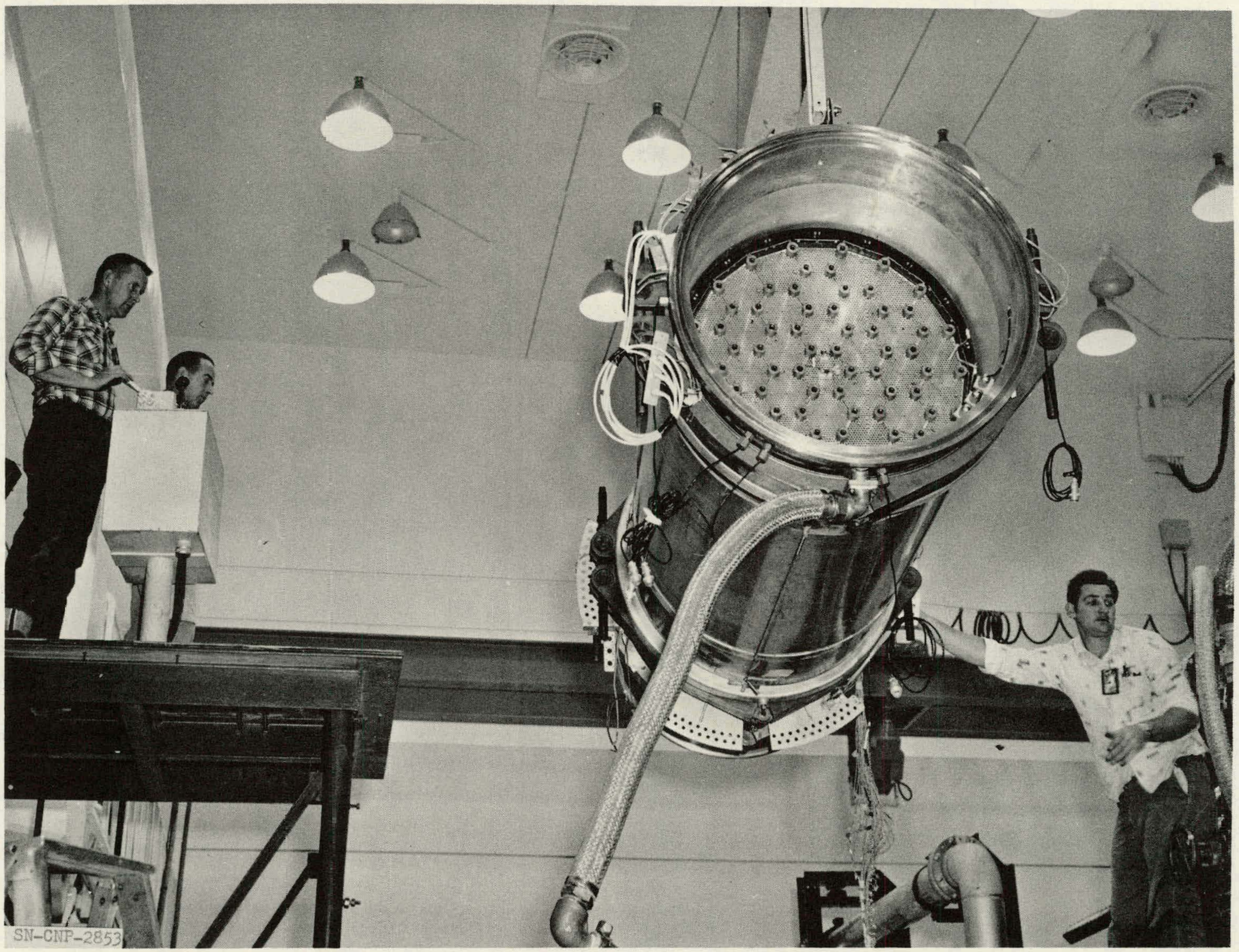

Fig. 10. Fully assembled Tory II-A core in pressure vessel.

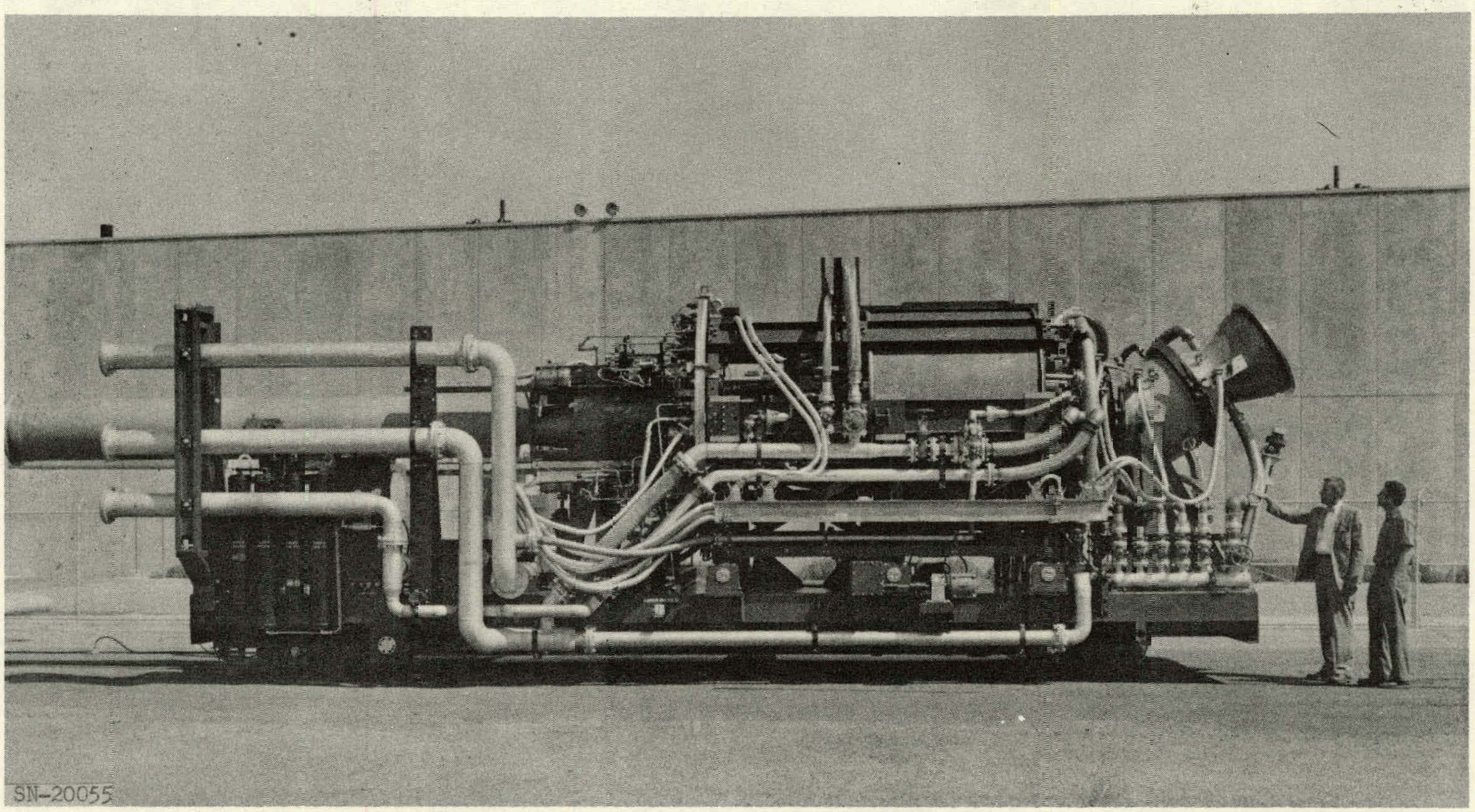

Fig. 11. Tory II-A test vehicle.

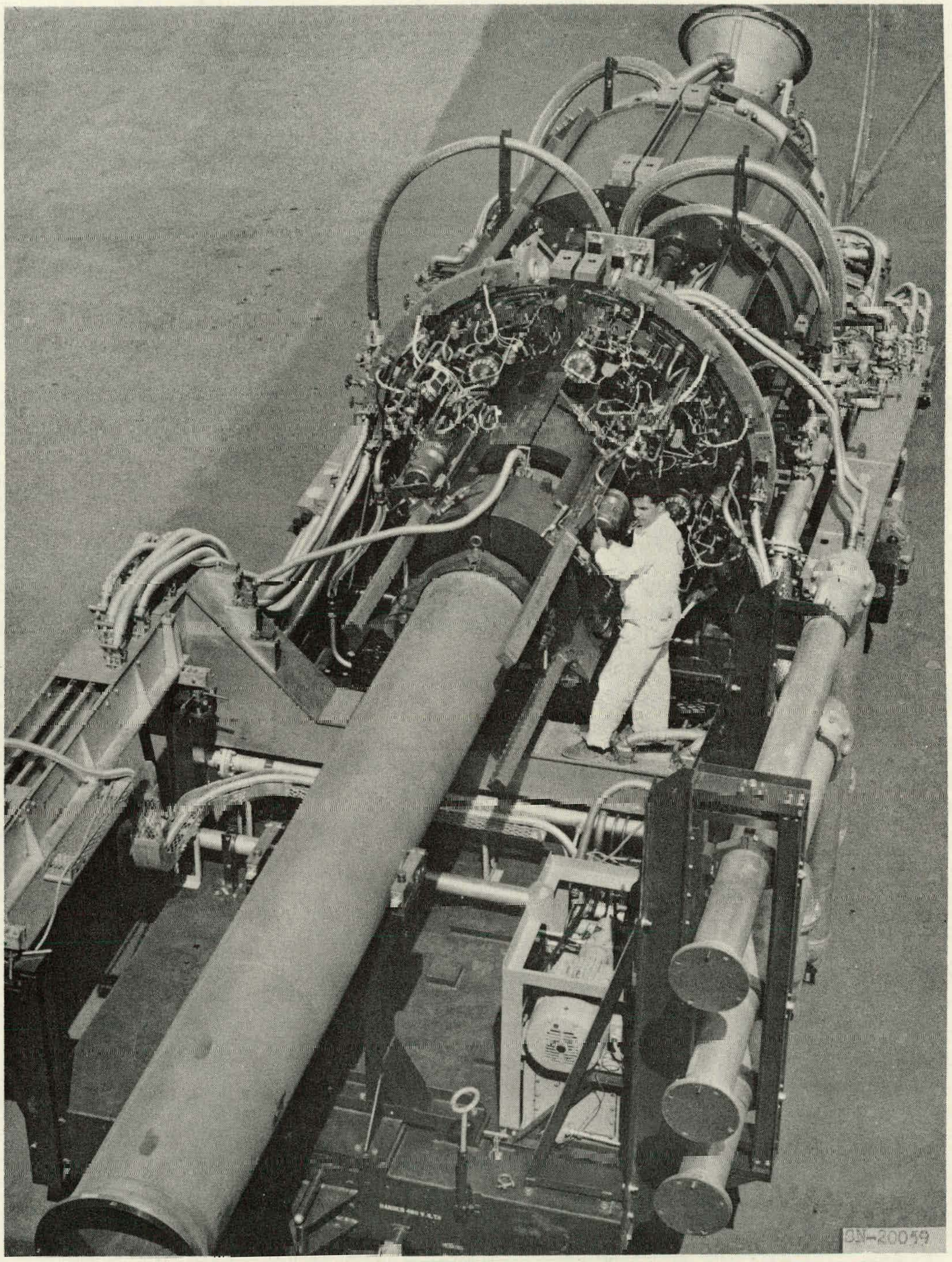

Fig. 12. Tory II-A test vehicle viewed from above.

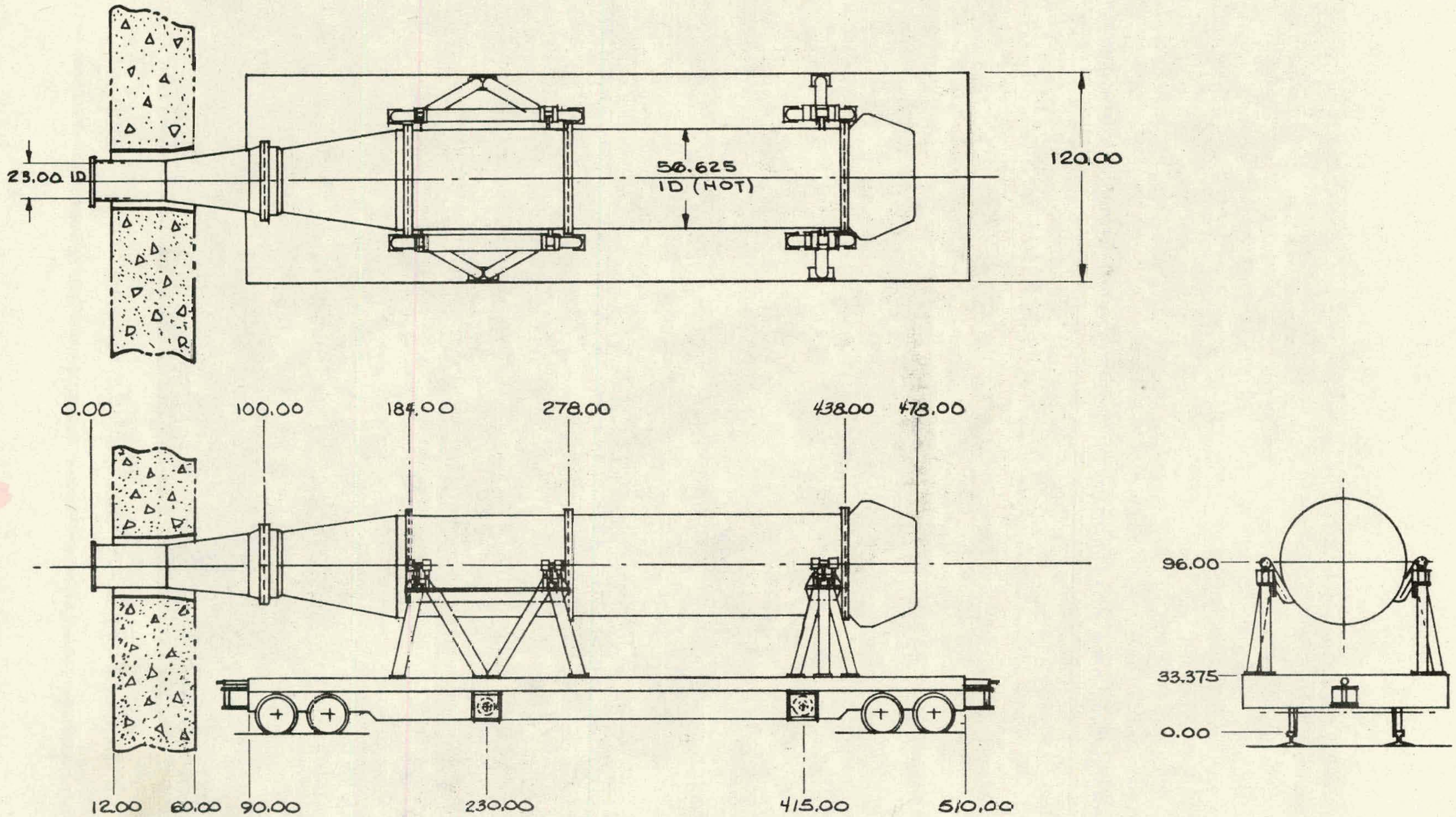

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Fig. 13. Tory II-C test vehicle.