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Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at
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E-3460

INTRODUCTION

Nuclear rockets will require many components to function while exposed to an environment of high-intensity nuclear radiation, cryogenic temperature, and hard vacuum. Shielding may be used to reduce the radiation problem, but shield weight must be optimized with payload and vehicle thrust. This optimization requires that shielding be minimized and components be qualified or developed for maximum tolerance to radiation.

Much work has been done on the effects of radiation on materials and components and a considerable amount is in progress dealing with combined environments. The Radiation Effects Information Center of Battelle Memorial Institute reports available results of radiation effects work. Reference 1 lists the latest compilation of Battelle reports. There is, however, a continuing need for research wherein materials and components are functionally tested in a combined environment of nuclear radiation, cryogenic temperature, and vacuum. To provide a test environment for this type of effort, three cryogenic systems exist at the NASA Plum Brook Reactor Facility (PBRF) in Sandusky, Ohio. One closed-loop system, which has been in use for several years, has a 1.1-kW capability and can deliver helium gas at 30° R and 50 psig to an experiment (ref. 2). The second system is a 20-kW closed-loop system capable of delivering helium gas at 50° R and 100 psig (ref. 3). The third system, the subject of this paper, is being installed in support of the Lewis Research Center's radiation effects program. This system is a once-through system and is also unique in that helium can be supplied to large experiments in the $11\frac{3}{4}$-inch-i.d. HT-2 test hole at 100° R and 1000 psig as compared with small experiments and low pressures for the other two systems.

The irradiation system discussed in this paper consists of an experiment capsule assembly for holding experiment packages, an insertion system for placing of the experiment capsule in the PBR, a data acquisition system for recording experiment data and controlling the experiment, and a cryogenic helium system for cooling and actuating experiments. In addition to the irradiation system, a brief description of the PBR is included.

REACTOR FACILITY

The PBR is a 60 MW test reactor with MTR-type fuel elements. It is light-water cooled and moderated with primary beryllium and secondary water reflectors. The reactor complex has been described briefly in a paper presented at the previous conference in this series (ref. 4) and in references 5 and 6.

Figure 1 is a cutaway perspective of the PBR tank assembly, showing the basic configuration and layout of test holes. A number of beam holes and rabbit tubes and two horizontal through holes are used for experiments. Figure 2 shows the orientation of beam holes and through holes around the PBR. The test system described in this paper utilizes horizontal through hole 2 (HT-2), which is located adjacent to the north side of the reactor and traverses the reactor tank from quadrant A to quadrant C. The equipment described herein utilizes the quadrant C end of HT-2.

HT-2 is an aluminum cylinder of $11\frac{3}{4}$-inch inside diameter by about 14 feet long. Small guide rods (1/4-inch aluminum) are installed along the inner surface to aid capsule alinement and to protect the tube from abrasize wear. The tube is cooled inside and outside by circulating reactor primary water.

The fast neutron flux and gamma heating rate along the axial centerline of HT-2 are shown in figure 3. The sketch on this figure indicates the tube's proximity to the fueled region. The curves are calculated for the tube in a voided condition. Fast neutrons of the order of 5×10^{12} n/(cm^2)(sec) ($E > 1$ MeV) and a gamma heating rate of approximately 1.4 W/g are available, based on full reactor power. This gamma rate corresponds to approximately 4.6×10^8 rads/hr. Exposure rates on an experiment are variable by adjustment of the insertion depth into the tube.

IRRADIATION TESTING SYSTEM

The system being installed will provide for the irradiation of experiments functioning in a cryogenic-vacuum environment and for the pre- and post-irradiation handling of the experiments. Figure 4 is a plan sketch of the arrangement of equipment in the quadrant C area. Equipment shown includes the experiment capsule and the insertion and handling system. Except for the hot cave and parts of the service frame, the equipment is located and operated under 20 to 25 feet of water.

Experiment Capsule

The experiment capsule positions the experiment in the HT-2 test hole and provides the following additional capabilities:

(1) Control of the cryogenic coolant and actuation gas flow to the experiment

(2) Connection of the experiment to the data system

(3) A vacuum environment of approximately 2 microns for the experiment

(4) Indexing of the experiment in 60^{o} increments around the axial centerline of HT-2; The indexing is performed remotely in a special hot cave.

Description. - Figure 5 is a cutaway sketch of the experiment capsule. The capsule is constructed from four basic subassemblies, which are the equipment box, the capsule snout, the experiment cap, and the porting plate bulkhead. The equipment box has outside dimensions of approximately 5 by 2 by 4 feet (lwh) and is constructed with two compartments. The front compartment (1) contains the surge chambers and the piping that directs gas to and from the porting plate bulkhead. A vacuum of approximately 130 microns is held in this compartment to reduce heat transfer from the capsule surroundings to the gas piping. The rear compartment (2) contains service equipment for the experiment such as control valves, vacuum pumps, pressure transducers, thermocouple reference junctions, and power supplies. This compartment is purged with clean dry air to remove heat generated by the vacuum pumps and other electrical components.

The capsule snout is constructed from a tube with an 11.25-inch outside diameter, a 10.25-inch inside diameter, and 9 feet 6 inches long. The 9-foot length of the snout allows the experiment package to be positioned close to the fueled region of the reactor. The 11.25-inch outside diameter is a basic limitation for HT-2 experiments. Eighteen vacuum-jacketed gas flow lines traverse the snout from compartment 1 of the equipment box and terminate at a bulkhead located at the front end of the snout. Six of the lines are 1.0-inch outside diameter and contain the electrical wiring for experiment command signals and data. Of the remaining twelve gas flow lines, six are 1/2-inch outside diameter and six are 1/4-inch outside diameter. In addition, one 3-inch vacuum line, two 1/4-inch seal vacuum lines, and one 5/8-inch water supply line are located in the snout. The lines are woven in the snout to reduce radiation streaming.

The experiment cap is 11.25 inches in outside diameter, 10.6 inches in inside diameter, and 40.0 inches long. This cap is constructed of Ti-6Al-4V alloy and weighs 69.5 pounds. It provides the primary containment between the HT-2 coolant water and the vacuum surrounding the experiment. The experiment package contained in the cap includes the experiment, the necessary support tubing, and a special flange that mates with the snout bulkhead. The experiment package is limited to 10 inches in outside diameter and a mass of about 220 pounds. The experiment cap is screwed onto the snout after connection of the experiment to the snout bulkhead. During irradiation, water must be circulated through HT-2 around the cap at a flow rate of at least 24.8 gpm to prevent nucleate boiling. Over 100 gpm is available with the present capsule geometry.

The porting plate bulkhead, while not a major subassembly, is described because of its unique use. The bulkhead is located on top of the equipment box and, when used with a porting plate, directs gas to the proper lines in the snout. When an experiment is indexed, the rotation of this porting plate redirects the gas flow as desired. In addition, the bulkhead provides a convenient area for mounting experiment pressure transducers that are not radiation tolerant.

Figure 6 is a photograph of the completed experiment capsule assembly. The overall assembly is 18 feet long and weighs approximately 4000 pounds.

Capsule flow. - Figure 7 indicates the flow path within the experiment capsule. Two warm and two cold gas streams penetrate the purged region of the equipment box and merge to form two independent pressure, temperature, and flow streams. The two flow streams are passed through final pressure-control valves and then penetrate the wall separating the purged compartment from the vacuum compartment. The two streams then pass through surge chambers, where the pressure and temperature feedback signals are obtained, and enter the porting plate bulkhead. From the porting plate bulkhead, the gas streams are routed through the porting plate, back down through the vacuum compartment, and through the gas lines in the capsule snout to the experiment. Gas exhaust follows a reverse flow path through separate tubes and is exhausted outside of the reactor building. Lines are also included in the capsule for snout coolant water (supply and exhaust), for purge air supply and exhaust for the equipment in the box, and for vacuum exhaust.

Insertion and Handling System

Reference is made to figure 4 for the location of the insertion handling system. The criteria for the design of this system were as follows:

(1) Insertion of the experiment capsule snout into the HT-2 test hole, during reactor operation, against hydraulic forces and friction in excess of 15,000 pounds

(2) Rate of reactivity change less than 0.02 $\Delta K/(K)(\mathrm{sec})$ because of experiment insertion

(3) Separation of the coolant water in the HT-2 test hole from the water in the quadrant

(4) Redundant interlocks and thrust-limiting devices to prevent damage to the HT-2 test hole or the experiment capsule

(5) Operation and handling of the experiment capsule during reactor operation

(6) Removal and replacement of the experiment without removing the experiment capsule from the quadrant.

Insertion table. - The insertion table (fig. 4) is approximately 17 feet long and is constructed of schedule-40 304 stainless steel pipe. A ball screw, center mounted and end fixed, drives a carriage along rails located on the top surface of the table. The experiment capsule is held to the table carriage by means of a rotating C clamp, which engages with a concentric ring on the capsule snout. The table frame and ball screw were tested against thrust loads in excess of 20,000 pounds after fabrication. Limit switches suitable for operation under water for periods in excess of 1 year are mounted in pairs along the side of the table in four places. Additional limit switches, which indicate four approximate capsule insertion depths in HT-2, are located on one side of the table. All limit switches are actuated by a cam arrangement attached to the underside of the table carriage. Located beside the insertion table is the drive motor which, through a gear reducer and chain arrangement, rotates the ball screw to provide capsule movement. The table inserts the capsule at 20 in./min. This rate may be changed to 30 in./min by changing the sprockets on the output of the drive unit.

Gate valve and seal assembly. - The gate valve and seal assembly are attached to the HT-2 test hole nozzle and provide a means of isolating the water in HT-2, which is at 150 psig, from the quadrant water. The seal assembly performs the isolation function during experiment insertion, and the gate valve is used when the capsule snout is not in HT-2.

The seal assembly consists of two independent sealing units. Triple chevron seals made of natural rubber provide a primary seal during capsule movement. Opposed, natural rubber U-cup seals, held in place by a spacer ring and water pressurized, provide a static or secondary seal when the capsule is not in motion. The seal assembly is separated from the gate valve by a bellows unit that provides for ±0.5° of misalinement and allows the seal assembly to float on the outside diameter of the capsule snout. Because of radiation damage, the seals used in this equipment require replacement, at 9-month intervals based on a 70% operating time for the reactor.

Capsule service frame. - The service frame is located directly behind and above the insertion table and is used when indexing of the porting plate or routine maintenance of the equipment in the experiment capsule is required. The frame provides a means for tilting the capsule snout down at angles of 0° to 40° from horizontal and for use of the reactor building crane to raise the equipment box portion of the capsule above water level. When the capsule equipment box is above water, the experiment is shielded with 6 feet of water.

Hot cave subsystem. - The hot cave subsystem consists of an insertion table located in quadrant C and a hot cave located outside the quadrant. The hot cave contains two 12-inch penetrations for capsule snout insertion and experiment transfer, a disassembly table and related tools, two master-slave manipulators, a viewing window, and an access door for maintenance of disassembly equipment. The cave is suitable to hold an experiment equivalent to a point source of the order of 20 Kilocuries located in the center of the cave. This source will result in a radiation level of about 2.5 mr/hr at the outside surface of the cave wall.

Reactivity

The reactivity worth of a typical experiment was measured in the PBR mockup reactor. The results of this testing and the corresponding PBR limits are listed in table I.

TABLE I. - REACTIVITY EFFECTS

Reactor reactivity effect	PBR limit for one experiment	Typical HT-2 experiment
Maximum decrease	0.75% $\Delta K/K$	0.13% $\Delta K/K$
Maximum step increase by experiment failure	.15% $\Delta K/K$	.04% $\Delta K/K$
Maximum planned change rate	.02% $\Delta K/(K)(sec)$	.0015% $\Delta K/(K)(sec)$
Maximum planned change with reactor at power	.25% $\Delta K/K$	.13% $\Delta K/K$

Instrumentation

The instrumentation complex is located outside the containment vessel, in the experiment control room, approximately 100 feet from the experiment package. The complex was designed primarily for support of dynamic testing of control components. Equipment is available, however, for recording thermocouple or other related signals such as flow or pressure.

For dynamic data acquisition, the console contains 44 channels. The 44 channels consist of an 8-channel direct writing oscillograph, a 12-channel recording oscillograph, a 14-channel FM tape recorder, and a 10-channel strip chart recorder.

For data conditioning, the console includes a 15-amplifier analog computer, a transfer function analyzer, a low-frequency oscillator, a frequency changer, and other equipment such as amplifiers, power supplies, etc.

The experiment safety equipment consists of 48 channels for monitoring critical parameters. A total of 24 channels are reserved for experiment support equipment and 24 channels for thermocouples. Each channel of the system provides both visual and audible alarms and can also be used to initiate an automatic withdrawal of the experiment if the particular parameter approaches an unsafe condition.

A control panel to operate devices in the experiment capsule and a control console, which will contain operating equipment required for an individual experiment, are included in the complex.

The entire complex is tied together through a master plugboard. Transition from one experiment to another requires programing the master plugboard, connecting the appropriate safety channels, and placing in the control console the operating equipment required for the particular experiment.

CRYOGENIC HELIUM SYSTEM

Some experiments planned for this irradiation system require helium gas in two separate flow streams called coolant gas and drive gas. Additional design criteria for this system include the following:

(1) Each of the two gas streams is variable in temperature from about 100° to 600° R.

(2) The coolant gas stream is variable in pressure from 600 to 1,000 psig and is capable of delivering 0.5 pound of helium gas per second.

(3) The drive gas stream is variable in pressure from 150 to 250 psig and is capable of delivering 0.04 pound of helium gas per second.

(4) The experiment exhaust back pressure is controllable to about 35 psig.

Flow and Control

Figure 9 is a simplified flow diagram of the cryogenic helium system. Helium gas flows from a high pressure storage bank through a main pressure control valve (PCV). The flow is split into two streams, which are called hot and cold. The hot line is routed through a heater where the temperature is controllable. The cold line is routed through a liquid-nitrogen bath-type heat exchanger and through a similar liquid-hydrogen heat exchanger.

The hot and cold lines are each split into two flow lines and routed through flow control valves called temperature control valves (TCV). One cold and one hot stream are blended and routed through a final pressure control valve to from the coolant supply for the experiment. The temperature of this coolant gas is sensed near the experiment and controlled by cycling the two appropriate temperature control valves. The other hot and cold lines are likewise blended and controlled to form a second gas supply for driving the experiment equipment.

As the coolant and drive gas exit from the experiment, they combine to form a common exhaust. Exhaust gas is routed through a final pressure control valve to maintain the desired back pressure on the experiment.

The helium exhaust gas may be treated in several ways. Clean gas may be routed directly to a vent stack or reheated and stored in a low-pressure bag. Gas of unknown activity may be reheated, passed through a radiation monitor and then either vented or stored. Stored helium will later be recompressed, purified, and returned to the high-pressure storage bank.

Helium flow duration through this system is related to total flow rate and the final source pressure head available from the helium supply. As indicated in figure 10, an experiment that requires 0.1 pound of helium per second and a source pressure of 1000 psi can be operated continuously for 3 hours. Likewise, if a high flow rate such as 0.5 pound per second and a 1250 psi head are required, the experiment can be operated for about 1/2 hour. (At a flow rate of 0.5 pound per second, the cold helium gas will experience a pressure drop between the gas storage area and the reactor building of about 240 psi.)

Description

The physical layout of the cryogenic helium system is shown in figure 11. Major pieces of equipment are grouped in the functional areas that will now be discussed.

Gas and cryogen storage. - This area is about 500 feet north of the reactor and includes the following equipment:

(1) The high-pressure helium storage bank has a capacity of 200,000 SCF of gas at 2200 psi; this is equivalent to about 2100 pounds of helium gas at 60° F.

(2) A nitrogen gas cylinder bank stores purge gas and gas for valve operators; this bank stores about 39,000 SCF of nitrogen at 2200 psi.

(3) A liquid-nitrogen bath-type heat exchanger consists of a 4000-gallon Dewar containing 3/4-inch stainless steel cooling coils equivalent to about 2000 lineal feet. This heat exchanger is capable of cooling helium gas at 0.5 pound per second from 520° R down to about 150° R.

(4) A 4000-gallon liquid-hydrogen heat exchanger is similar to the nitrogen Dewar, with 3/4-inch stainless steel cooling coils equivalent to 1500 lineal feet. A 25-foot vent stack is provided to dissipate hydrogen boiloff gas above ground level. Under full flow conditions, hydrogen boiloff rate will be about 0.5 pound per second. This heat exchanger will be capable of cooling the 150° R gas further to below 100° R. Hazards associated with the storage and use of this liquid hydrogen are primarily responsible for the remote location of this area.

(5) A sand-filled blast barrier protects the reactor complex from line-of-sight blast damage in the event of a hydrogen explosion or deflagration.

(6) Control and miscellaneous valving, piping, transducers, and other equipment provide for the safety and functional control of this area.

(7) A 4-inch stainless steel helium vent stack, 61 feet high, discharges used or purge gas. The radioactivity of the effluent from this stack is limited to a continuous gaseous release of 4.6 microcuries per minute. Higher short-time release rates are permissible.

Piping trench. - A concrete walled trench extends from the gas storage area to the north basement wall of the reactor building. The necessary piping and conduit connecting the main functional areas are located in this trench.

Reactor building basement. - The helium gas lines run from the piping trench across the reactor building basement to an equipment area just outside the containment vessel. The heater for the hot gas stream is located here. Just prior to penetrating the containment vessel, each gas line passes through an emergency shutoff valve. These valves are remotely operable from the helium system control console and the reactor operation console and serve to preserve containment vessel integrity when necessary.

Containment vessel. - Located on the inside containment vessel wall is an assembly of valves, surge chambers, and associated equipment called the valve package. Principal components of this package are the temperature and back pressure control valves, a purge vacuum pump, and an air compressor that supplies operator air to all valves inside the containment vessel.

From the valve package, the helium lines are routed through the quadrant C wall and via flex lines to the experiment capsule. Final supply-pressure control valves and pressure and temperature transducers are located inside the capsule. Exhaust gas from the capsule is routed back along the same route as the supply gas.

Low-pressure storage and recompression area. - Helium exhaust gas is routed first to the low-pressure storage area. From here, it may be routed directly to the vent stack or stored and later recompressed and returned to the helium storage bank. The equipment for low-pressure storage and reprocessing is located about 200 feet from the reactor building adjacent to the piping trench. Major items of equipment are described as follows:

(1) The pebble bed heater consists of a steel cylinder, 6 feet in diameter and 14 feet high, which contains 20 tons of quartz pebbles. This heater is designed to warm helium gas from 150° to about 510° R (suitable for storage in the low-pressure bag) at a maximum flow rate of 0.5 pound per second.

(2) The hemispherical helium storage bag is 92 feet in diameter and 46 feet high and is capable of storing 200,000 SCF of helium at a gage pressure of about 2 inches of water. The bag is a double envelope type with the inner bag containing the helium and the outer bag pressurized by air blowers to maintain its shape and rigidity. The fabric material for the inner envelope is a laminate of hypalon-coated nylon bonded to a Mylar and aluminum foil laminate. The outer bag is a vinyl-coated nylon fabric. The ground cloth is of a material similar to the inner bag.

(3) A compressor and purification system are located in the compressor building adjacent to the storage bag. The compressor is a four-stage unit with a rated delivery of 71 SCFM at 2400 psi. The purification system consists of an oil and moisture adsorber bank and a liquid-nitrogen-cooled charcoal adsorber box for the removal of gaseous contaminants. This system is designed to recompress and purify helium gas at a rate greater than 100,000 SCF per day.

Control room. - All remotely operable equipment in the helium supply portion of the system is controlled from a central console located in the experiment control room. This console is separate from the experiment control console described previously and comprises three standard racks of equipment. The temperature and pressure of the coolant and drive gas streams, the exhaust pressure, the hot heat exchanger temperature, and associated normal flow valves and equipment are all controlled from this console.

All operations dealing with the low-pressure storage and recompression of the used gas are controlled from separate equipment located in the Compressor Building.

CONCLUDING REMARKS

An irradiation system has been described that is suitable for certain experiments planned for the Plum Brook Reactor in support of the nuclear rocket effort. This system consists of an experiment capsule, an insertion assembly for horizontal through hole 2 in the NASA Plum Brook Reactor, and a cryogenic helium system to service the test items. The testing system was designed primarily for the dynamic testing of components in a combined environment. This testing is a determination of how well a component follows a given command under various environmental conditions. The command signal may be either electric or pneumatic. Standard dynamic tests will include frequency response, threshold response, linearity, step response, and dynamic resolution. Both command and feedback signals are measured and recorded for evaluation of the component performance. Some of the basic capabilities of this system are restated as follows:

(1) A fast neutron flux of the order of 5.6×10^{12} n/(cm^2)(sec) ($E > 1$ MeV) and a gamma heating rate of the order of 1.4 W/g may be obtained.

(2) Helium gas flow to an experiment is controllable to about 0.5 pound per second, up to 1,000 psi, and at temperatures from 100° to 600° R. Run time is dependent on helium flow rate and the pressure required for the particular experiment.

(3) A vacuum environment may be provided for the experiment. The vacuum is estimated at approximately 2 microns without cryopumping.

(4) Experiments up to 10 inches in diameter and 31 inches long with a mass of approximately 220 pounds may be irradiated.

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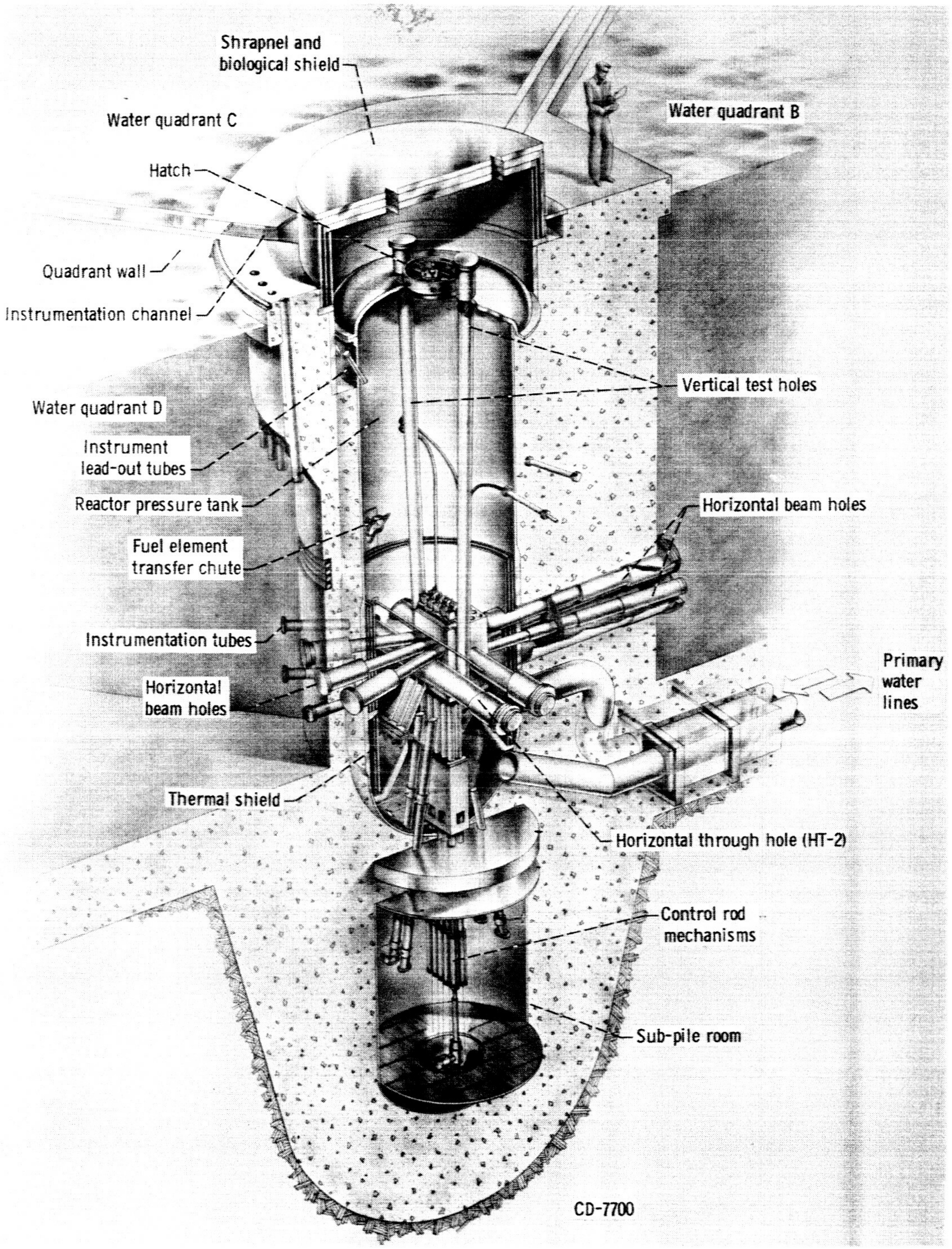

Figure 1. - Cutaway perspective drawing of reactor tank assembly.

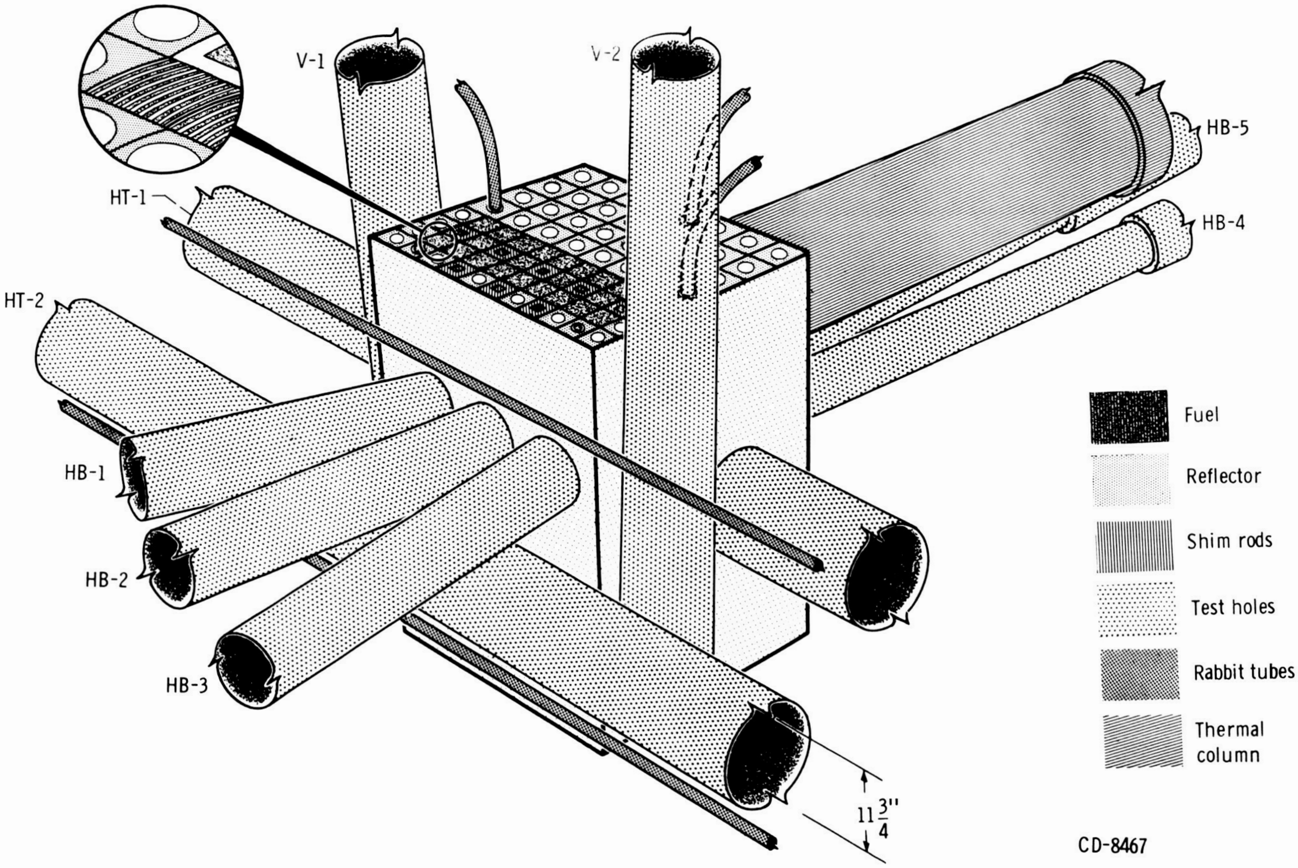

Figure 2. - Plum Brook Reactor.

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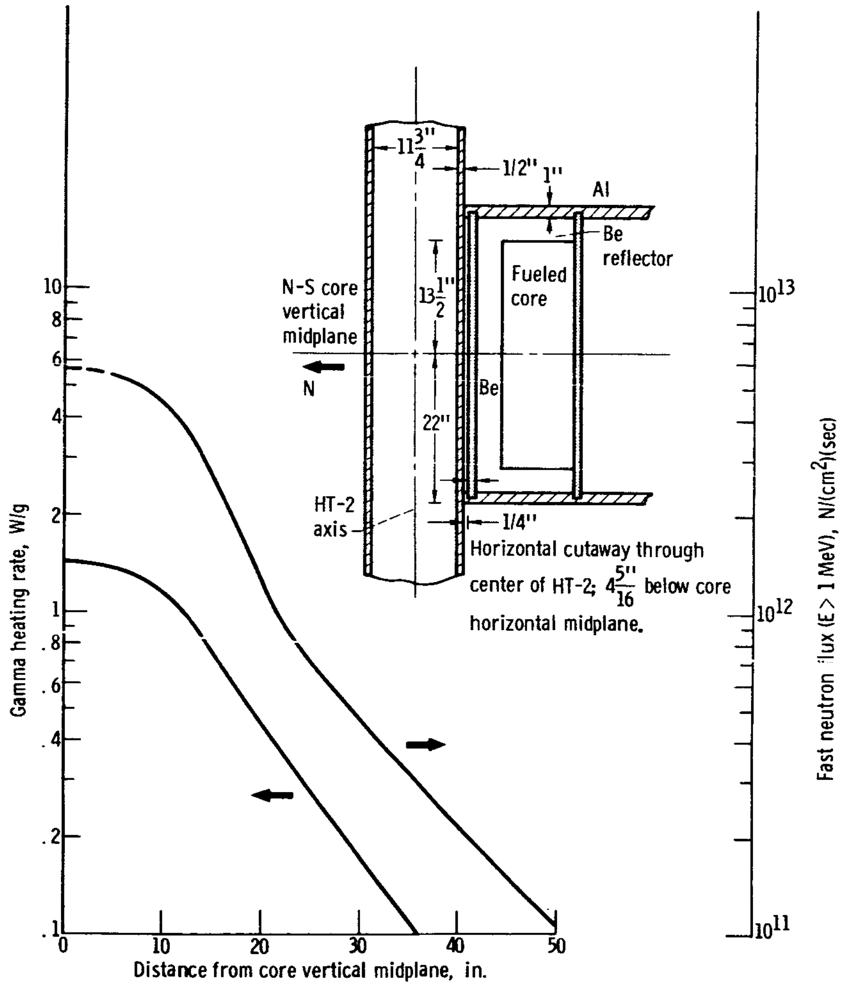

Figure 3. - Radiation along centerline of voided HT-2 for full reactor power.

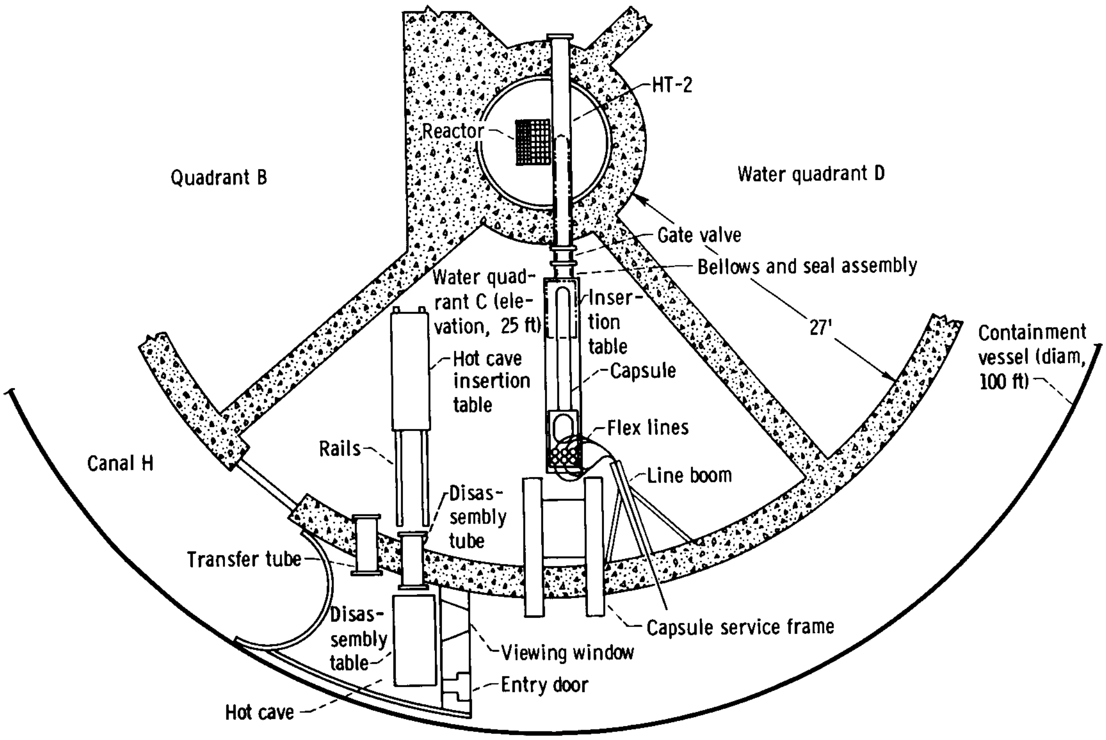

Figure 4. - Capsule insertion and handling system.

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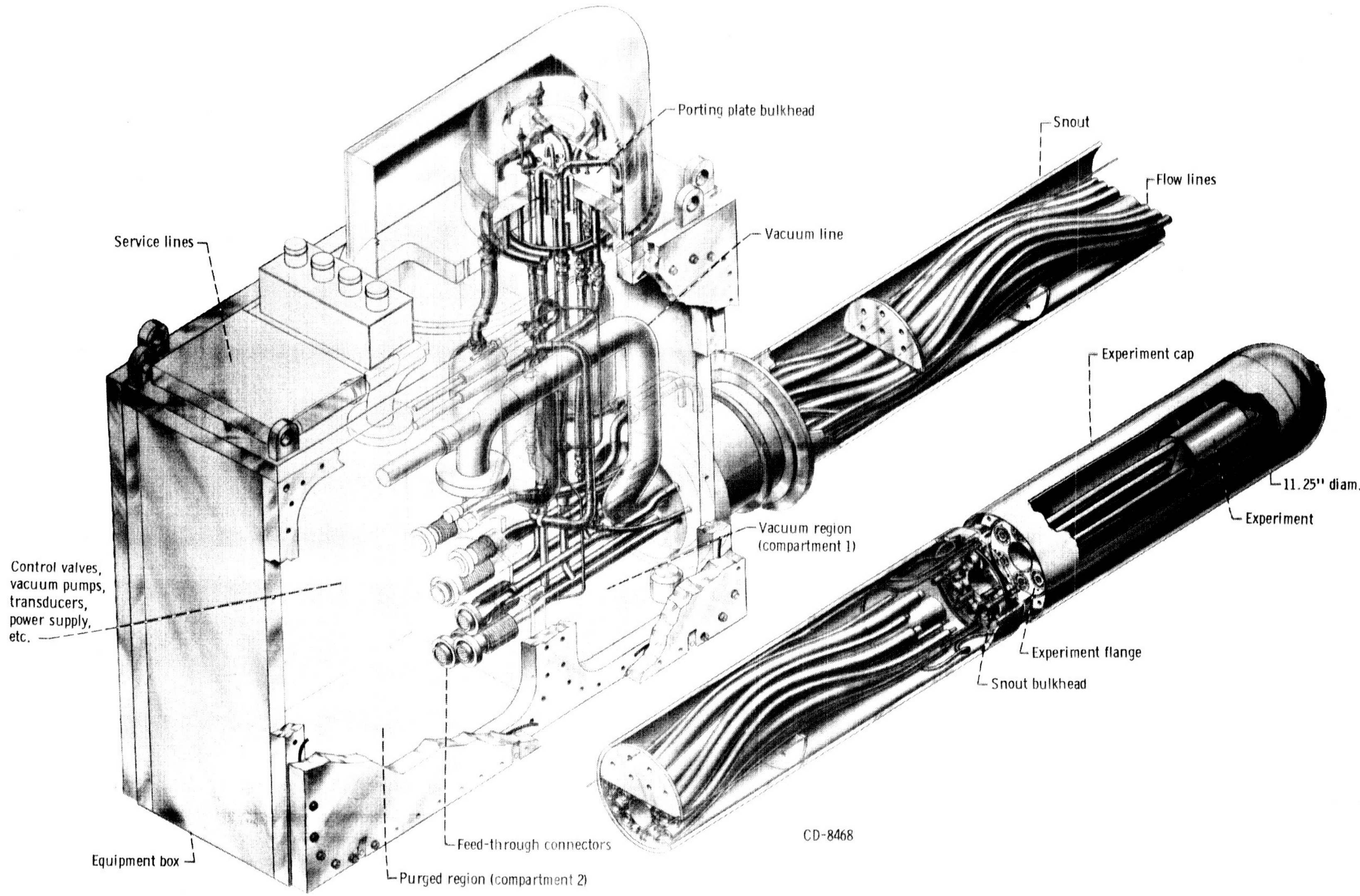

Figure 5. - Experiment capsule assembly.

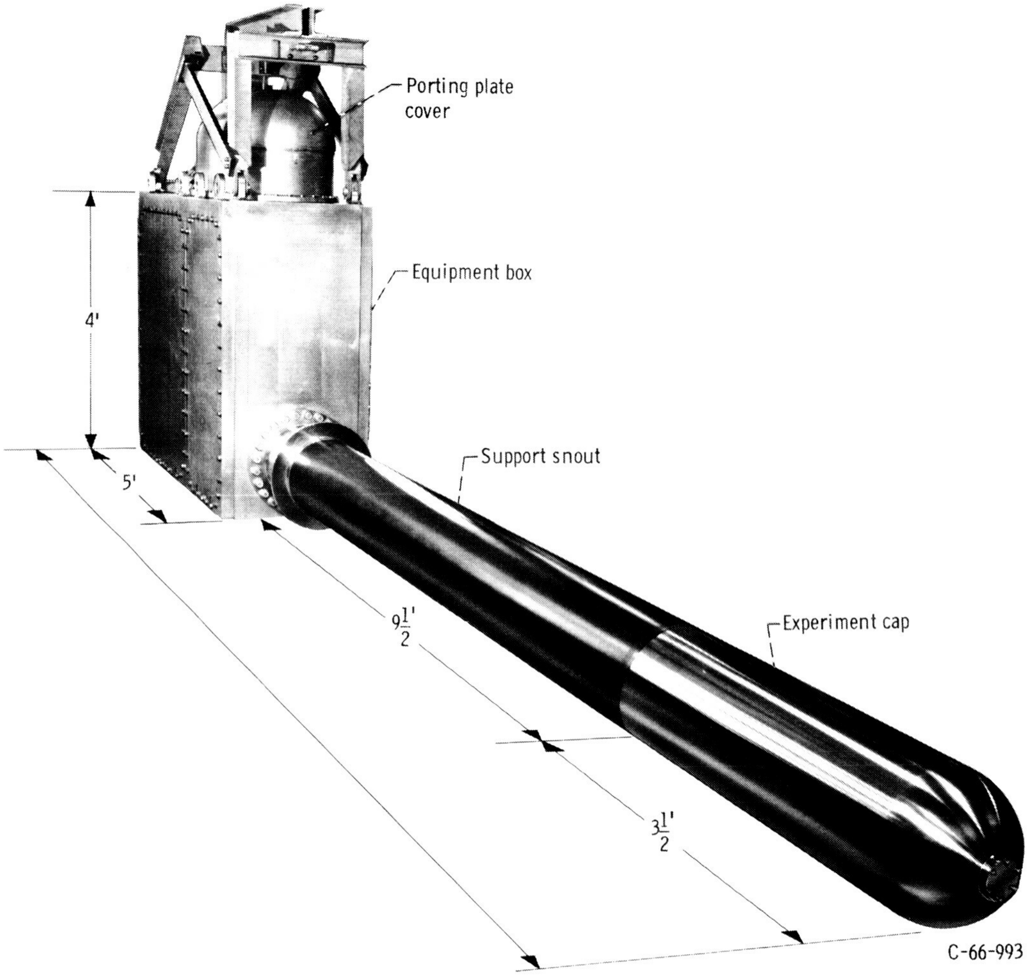

Figure 6. - Experiment capsule.

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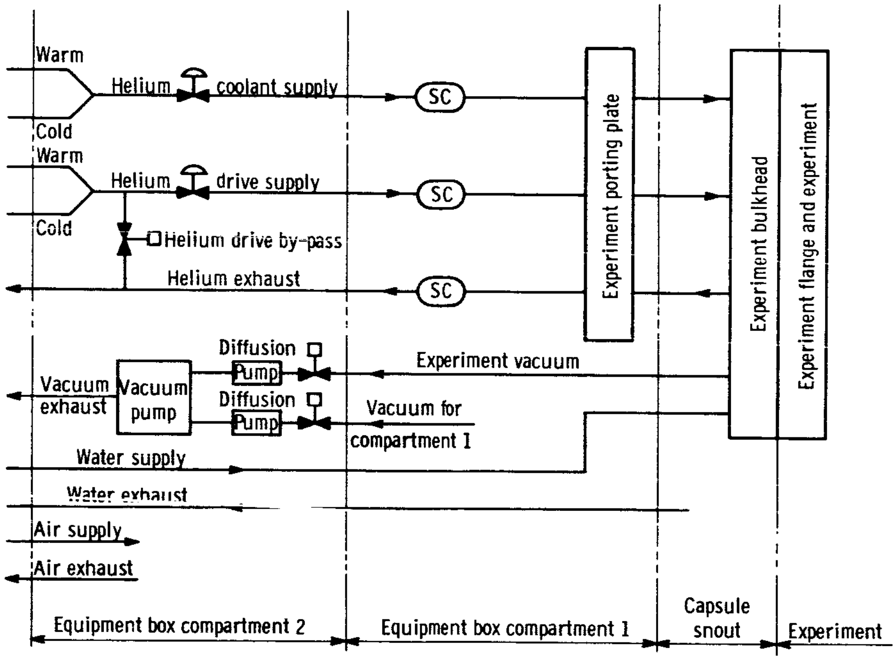

Figure 7. - Capsule flow schematic.

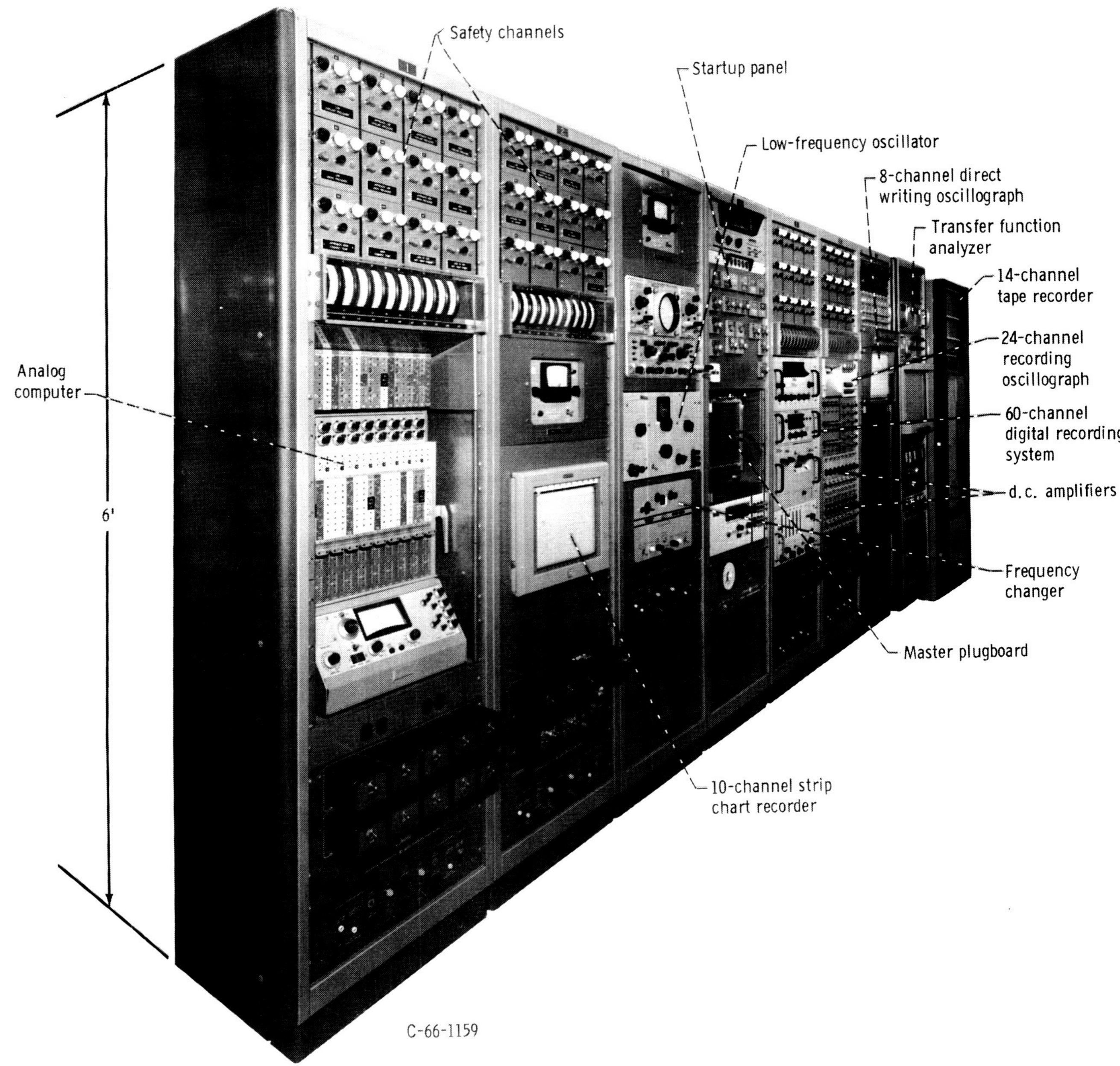

Figure 8. - Instrumentation complex.

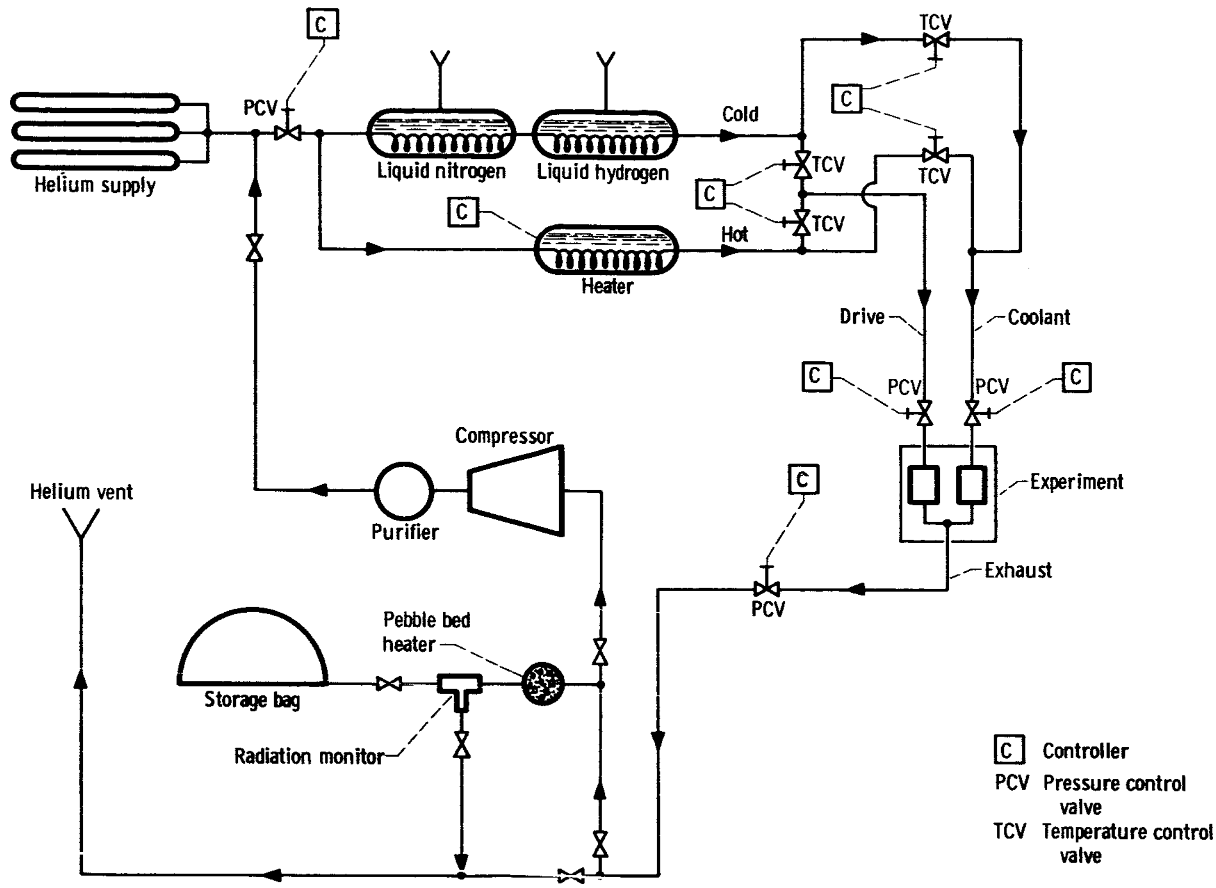

Figure 9. - Simplified flow schematic of cryogenic helium system.

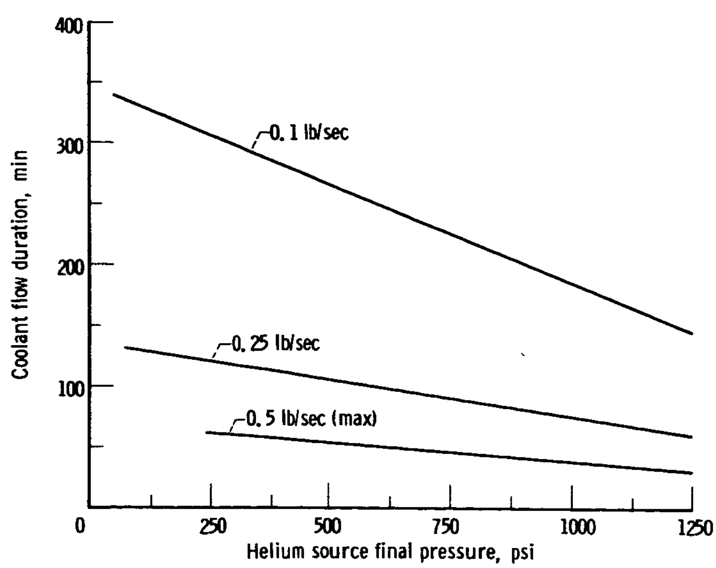

Figure 10. - Flow duration of cryogenic helium system. Initial source, 2100 pounds helium at 2200 pounds per square inch.

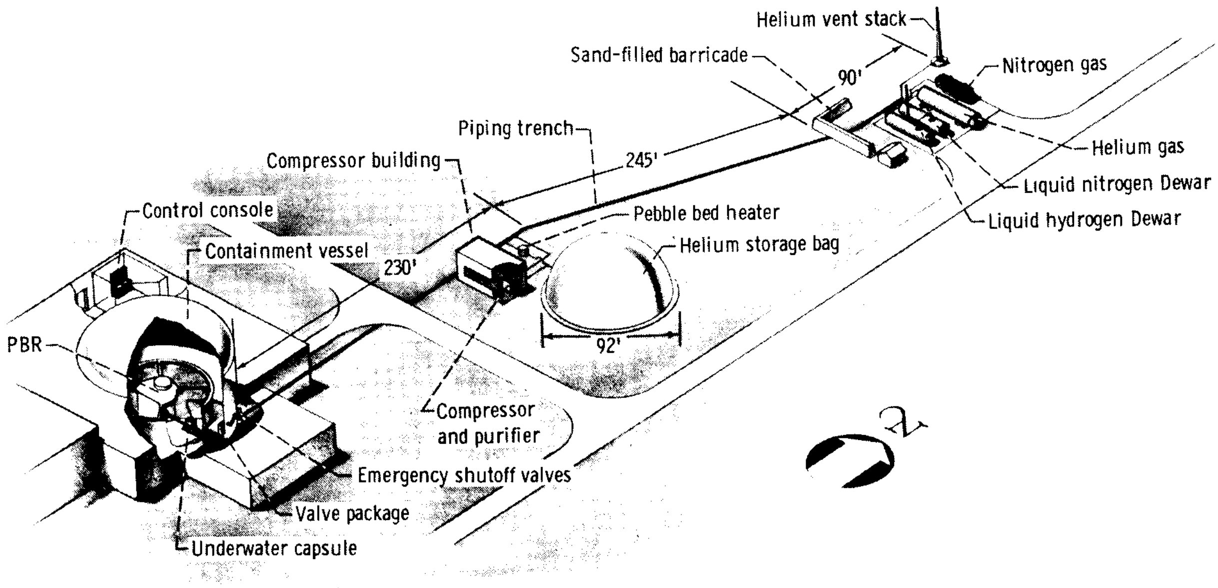

Figure 11. - Cryogenic helium system.