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# COMPACT 30 KW CIRCULATING HELIUM CAPSULE FOR FUEL ELEMENT TESTS IN NASA PLUM BROOK REACTOR


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TECHNICAL PAPER proposed for presentation at National Symposium on Developments in Irradiation Testing Technology sponsored by the U.S. Atomic Energy Commission and the National Aeronautics and Space Administration
Sandusky, Ohio, September 9-11, 1969


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## ABSTRACT

A capsule has been endurance tested out of pile and two capsules have been run in the Plum Brook Reactor. The capsule operates at pressures to 2500 psi, motor speed to 3000 rpm, flow rates to 0.09 lb He/sec, capsule wall temperatures to 1000°F, specimen powers to 30 kw with 180°F cooling water. Demonstrated out-of-pile life is at least 3000 hours. Fuel specimen surface heat fluxes of 2 kw/in$^2$ have been obtained in pile. The capsule is 18 feet long with 4.3 inch maximum O.D. and 2.875 O.D. in the test section. It is composed of a variable speed electric motor driven vane pump, concentric tube heat exchanger, and a fuel element test section. The capsule is made of modified commercially available parts. Provisions are made for 15 thermocouples. Pressure leads used for filling are also used to measure gas flow rate and monitor coolant gas for fission product leaks. A loss of coolant accident can be contained without reactor scram for specimen powers of 30 kw or less. Capsules are relatively inexpensive and can be discarded when the test is completed.

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## SUMMARY

The Lewis Research Center is conducting gas cooled fuel specimen tests in the Plum Brook Reactor. This report describes the capsule used to test the specimens. A capsule has been endurance tested out of pile and two capsules have been run in the Plum Brook Reactor.

The capsule operates at pressures to 2500 psi, motor speeds to 3000 rpm, flow rates to 0.09 lb He/sec, capsule wall temperatures to 1000°F, and specimen powers to 30 kw with 180°F cooling water. Demonstrated out-of-pile life is at least 3000 hours. The capsule is 18 feet long and 4.3 inch maximum O.D. and is composed of a variable speed electric motor driven vane pump, concentric tube heat exchanger, and a fuel element test section. The capsule outside diameter is 4.3 inches in the motor-compressor section and 2.875 inches in the heat exchanger and fuel element test section. The capsule is made of schedule 80 SS pipe, and uses a modified commercially available motor and pump. Provisions are made for 15 thermocouples. Pressure leads used for filling are also used to measure gas flow rate and monitor coolant gas for fission product leaks. A loss of gas coolant accident can be contained without resort to reactor scram for specimen powers of 30 kw or less. Capsules are relatively inexpensive and can be discarded when the test is completed.

The first in-pile capsule ran for 294 hours in the Plum Brook Reactor and was stopped due to a bearing failure for reasons which have been corrected. The total operating time at the end of the test was 632 hours. The second in-pile test was terminated due to a fuel specimen fission product leak after only eight hours of operation. The capsule had, however, operated satisfactorily for more than 600 hours prior to irradiation and has continued to operate for 200 hours since fuel specimen failure. Fuel specimen surface heat fluxes of 2 kw/in$^2$ were obtained in pile.

The out-of-pile endurance tests are continuing and demonstrated lifetime is above 3000 hours. The endurance test is at 2400 rpm, 1550 psi, 6 psi pressure drop, and 0.049 lb/sec helium flow rate. Bench test capsules are being fabricated for endurance tests at higher flow rates and pressure drops.

## INTRODUCTION

The Lewis Research Center is studying gas cooled reactors for mobile nuclear power application. One important problem is establishing the probable fuel element lifetime and burnup at the contemplated reactor operating conditions. Specimens of candidate fuel elements are being tested in the PBR (Plum Brook Reactor). This paper describes the design characteristics and the performance capability of the circulating gas capsule in which the tests are conducted. A circulating capsule was required because the fuel specimen surface heat flux was greater than 2 $kw/in^2$ which was higher than could be obtained in a natural convection capsule. The capsule has been endurance tested out of pile and two capsules have been operated in the Plum Brook Reactor.

The capsule is composed of an electric motor driven vane pump, concentric tube heat exchanger, and a fuel element test section. The capsule is made of standard pipe and uses a modified commercially available motor and pump. As a result the capsules are relatively inexpensive and can be discarded when the test is complete.

## GENERAL DESCRIPTION OF CAPSULE

The capsule system, shown schematically in figure 1, consists of the capsule and its control console. The capsule, with its most important components identified, is shown in a water-cooled reactor test hole. A capsule assembly drawing is presented in figure 2. The capsule assembly consists of the sealed pressure vessel with the fuel element test section at the reactor end, the gas circulator at the shield end, and the helium-to-water heat exchanger connecting these ends. The long heat exchanger keeps the motor-compressor in the low radiation region when the test section is in the high flux region. The capsule length is 18 feet and is the maximum that can be handled in the water quadrant surrounding the PBR test hole. The capsule diameters were determined by the requirement that two capsules could be inserted into a nine inch I.D. water-cooled test hole. Helium is used as the gas coolant; however, any inert gas could be used.

The capsule operates in the following manner. High pressure helium is pumped through the center tube of the concentric tube heat exchanger to the fuel element, where it removes the nuclear heat and then flows back through the annular passage of the heat exchanger where this heat is transferred to the reactor facility water system. Helium pumping power is provided by a circulator consisting of a vane type pump driven by a variable speed electric motor. A wide range of helium flow rates for fuel element temperature control can be obtained by varying helium pressure and motor speed. The capsule operation is monitored and controlled from a console which contains the variable frequency motor power supply, coolant flow rate controls, radiation monitor controls, pressure and temperature recorders , and alarms.

The circulator end of the capsule is located outside the reactor shield in the quadrant water sufficiently far from the reactor core to assure low radiation levels and minimize radiation damage to the circulator components (see fig. 3). The heat exchanger diameter is kept to a minimum to reduce streaming. To detect specimen fission product leak, a small amount of specimen coolant is circulated past a radiation monitor.

Personnel safety is provided by the reactor quadrant water. The quadrants are kept full during fuel element testing, and permit safe charging or withdrawal of the capsule from the reactor core with the reactor at full power. The sealed capsule design together with the quadrant water shield permits testing to fuel specimen fission product leakage, in which case the capsule gas lines are closed and the capsule is withdrawn from the reactor core.

Damage to the capsule pressure shell in event of fuel element meltdown, resulting from accidental loss of helium flow at full capsule power was regarded as the major safety problem. This problem was further complicated by an experiment ground rule that reactor scram not be used as a primary safety operation. This problem was solved by designing a graphite tray wrapped with tungsten sheet to catch materials that may melt in the event of helium flow loss, and to safely redistribute the nuclear heat without damage to the capsule pressure shell (see fig. 4). At present the catch tray can disipate 30 kw. This established the maximum allowable capsule power rating. However, the pump and the heat exchanger have the capability to go to higher powers.

Instrumentation has been provided to protect the experiment data. When high fuel element and/or gas temperatures are detected, alarms sound. Higher temperatures cause the capsule to automatically withdraw from the reactor. Still higher temperatures cause the reactor to scram. This instrumentation was not used for safety purposes because in-pile tests of several thousand hours were contemplated and thermocouple reliability for this time in the test environment could not be established prior to the test.

## DESIGN CHARACTERISTICS

The following figures give an overall view of the capsule system. Capsule system layout and dimensions are presented in figures 1, 2 and 3. Figure 4 shows the graphite catch tray and tungsten wrapper. Figure 5 is a photograph of the motor-compressor parts. The thermal-hydraulic characteristics are described in figures 6 and 7. The design and operating characteristics are summarized below. The capsule is still being out-of-pile tested and its performance may be uprated as more experience is obtained.

## General

1. Out-of-pile demonstrated lifetime is at least 3000 hours at 0.049 lbs/sec flow rate, with 6 psi pressure differential across the pump.

2. Alarms, table abort, and reactor scram protect experiment data in case of motor-circulator malfunction.

3. The capsule can be safely operated without thermocouple monitoring after operating conditions for test have been established.

## Nuclear

1. Maximum fission and gamma power in fuel specimen and holder is 30 kw.

2. Maximum allowable radiation dose in motor compressor section is $10^6$ rads to grease and motor insulation.

## Safety

1. Specimen coolant is continuously monitored for fission product leaks.

2. Fuel specimens can be tested until a fission product leak occurs without exceeding safe radiation levels in the working area above the quadrant.

3. Loss of coolant accident including fuel specimen meltdown can be contained without resort to reactor scram for power levels of 30 kw or less. The catch tray used to contain drippings from melted fuel element is shown in figure 4.

## Mechanical Design

1. System layout and dimensions are shown in figures 1, 2, and 3. Figure 4 is a schematic of the catch tray and tungsten wrapper. Figure 5 is a photograph of motor compressor parts prior to assembly.

2. Motor speed range, 1500 - 5000 rpm.

3. Present maximum motor operating speed is 3000 rpm.

4. Maximum coolant pressure is 2500 psi at 1000°F wall temperature based on ASME pressure vessel code.

5. Compressor displacement is 3.5 $in^3$/revolution.

6. Present maximum pumping capacity is .09 lbs/sec helium at 2500 psi, 3000 rpm, and 12.5 psi pressure drop. (Determined with a typical fuel specimen installed in the capsule.)

7. Maximum allowable grease temperature is 475°F. Grease is GE Versilube G-300.

8. Maximum allowable motor temperature is 350°F (Class H insulation).

9. Maximum allowable coolant temperature into pump is 250°F. Temperature restricted to minimize temperature gradients. Individual parts can operate to 350°F.

10. Coolant flow can be monitored during test.

11. Up to 15 thermocouples can be used in the capsule.

12. Motor capacity is 2 hp at 10,000 rpm (maximum rated hp) and 3/4 hp at 3000 rpm.

13. Motor speed is measured by a rotating magnet tachometer in the motor-compressor shaft.

14. Catch tray has sufficient volume to contain melted test specimen and holder.

15 Catch tray surface area is sufficient to redistribute 30 kw of nuclear heat without damage to the tray or to the capsule wall. Maximum tray temperature equals 4500°F (assuming radiation cooling only) which is within the strength capability of both graphite and tungsten.

16. Compressor vanes are made of Graphitar No. 2751 graphite. Wear rate was very sensitive to type of graphite and each batch of material must be tested for wear rate prior to use in a capsule. Wear rate is about one percent in 1500 hours at 2400 rpm.

Thermal - Hydraulics

1. Present maximum coolant temperature is 1000°F with potential for higher temperatures.

2. Coolant temperature into pump at 30 kw is about 50°F above water temperature. Maximum allowable temperature into pump is 250°F.

3. Maximum gas to water heat flux is about 140,000 Btu/ft$^2$ hr at 30 kw and 1000°F outlet gas temperature. Assumes gas side heat transfer coefficient increased by a factor of 2 at the heat exchanger inlet.

4. Maximum wall temperature at 30 kw and 1000°F gas temperature is about 500°F. Maximum wall temperature gradient is about 1200°F/in. Assumes water temperature is 150°F and gas side heat transfer coefficient is increased by a factor of two at the heat exchanger inlet.

5. The calculated heat exchanger pressure drop and the gas temperature at pump inlet and at test section inlet and outlet are shown in figure 6 for 30 kw.

6. The measured flow rate and loop pressure drop as a function of pressure and motor speed is shown in figure 7.

## INSTRUMENTATION AND CONTROL

Figure 8 shows the instrumentation and flow control diagram. All instrumentation and control apparatus, including the solid-state variable frequency motor power supply, is contained in a three-bay console as shown in figure 9. Instrumentation can be divided into three groups with sometimes overlapping functions. These are control, data gathering, and experiment safety.

### Control Apparatus and Instrumentation

Coolant flow rate is manually controlled by adjusting coolant pressure and motor speed. Motor speed is set via a multi-turn potentiometer which is connected to the variable frequency power supply. The flow rate is measured by a venturi. The pressure, motor speed, motor current, and venturi pressure differential are recorded. Meters show motor voltage, current, and frequency. Alarms are provided to signal motor overcurrent and gas pressure too high or too low. Alarm conditions are displayed on a resettable alarm panel.

### Experiment Data Instrumentation

Experiment data instrumentation consists of temperature, pressure, venturi $\Delta P$, and coolant radiation recorders. Provision is made for a maximum of 15 thermocouples. As a minimum, gas temperatures are measured at compressor inlet and fuel specimen inlet and outlet. Fuel specimen temperatures are measured at the hot and cold ends of the specimens and these temperatures are used in the maximum clad temperature calculations. The remaining thermocouples can be used to measure either gas or metal temperatures. The radiation monitor is used to detect pin failure. All of the above data is recorded and in addition, pressure, venturi $\Delta P$, and coolant radiation level are also shown on meters.

The experiment data is protected by alarm, table abort, and reactor scram instrumentation. These systems receive their input from the thermocouple circuits. Should the thermocouples deterioriate with time in the irradiation environment, motor rpm and/or current can be used as input. Alarms are displayed on a resettable alarm panel.

### Safety Instrumentation

Safety instrumentation consists of a pressure relief valve to assure capsule cannot be overpressured, a coolant radiation monitor to detect release of fission products into the coolant gas, and a alarm on the radiation monitoring gas flow to assure there is a satisfactory amount of gas being circulated past the radiation monitor.

## PRODUCTION MODEL TESTS

Prior to capsule fabrication, the motor-compressor is assembled and run-in for at least 50 hours in a bench test capsule at the Lewis Research Center. When the run-in test is complete, the capsule flow rate, current and voltage are measured over the full pressure and rpm operating range and ground (HYPOT) and resistance tests are performed on motor and tachometer leads. The motor-compressor is then shipped to the capsule fabricator.

Each test capsule undergoes the following test sequence following completion of fabrication.

1. Radiography of all pressure vessel welds.

2. Pneumatic pressure test under collision mats to 3750 psig ($2.16 \times 10^7$ N/m$^2$).

3. Helium mass spectrometer leak test at 1500 psig ($1.04 \times 10^7$ N/m$^2$).

4. Ground (HYPOT) and resistance tests on all motor and tachometer leads.

5. Ground and resistance tests of all thermocouples.

6. Bake-out and simultaneous evacuation of the assembly for ten hours to 180°F (360°K) and 50 microns (6.6 N/m$^2$) absolute pressure. This is the minimum pressure to prevent the bearing lubricant from boiling.

7. Operation of the motor at fixed speed from three-phase 60 $H_Z$ supply. Stethoscopy for unusual noise.

Following these tests the assembly is backfilled with pure helium to approximately 25 psig, crated and shipped to Lewis.

The capsule is returned to Lewis and is run-in for at least 50 hours at contemplated in-pile operating conditions. The capsule is then calibrated and shipped to Plum Brook. Calibration consists of measuring motor current and flow rate as a function of capsule pressure and rpm over the full operating range of the capsule.

## CONCLUDING REMARKS

Two capsules have been operated in the Plum Brook Reactor. The first in-pile capsule ran for 294 hours in pile. The test was stopped due to a bearing failure for reasons which have been corrected. Total operating time on the first capsule at the end of the test was 632 hours. The second in-pile capsule test was terminated due to a fuel specimen fission product leak after only eight hours of operation. The second capsule had, however, operated satisfactorily for more than 600 hours during preirradiation checkout and has continued to operate satisfactorily for more than 200 hours since fuel pin failure. Specimen surface heat fluxes of 2 kw/in$^2$ were obtained in the in-pile test. The out-of-pile endurance tests are continuing and demonstrated lifetime is above 3000 hours. The endurance test is at 2400 rpm, 1550 psi, 6 psi pressure drop, and 0.049 lbs/sec helium flow rate. Bench test capsules are being fabricated for endurance tests at higher flow rates and pressure drops.

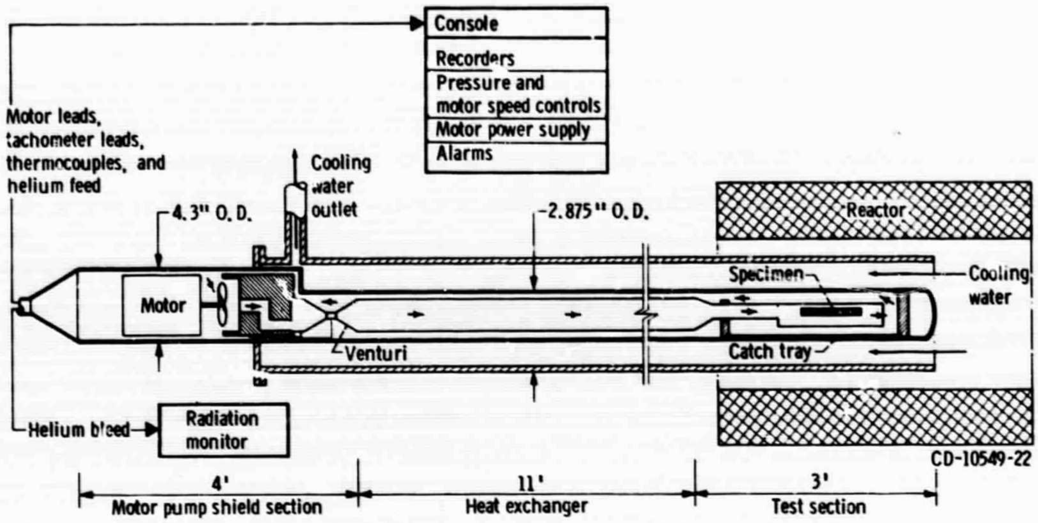



Figure 1. - Circulating capsule schematic.

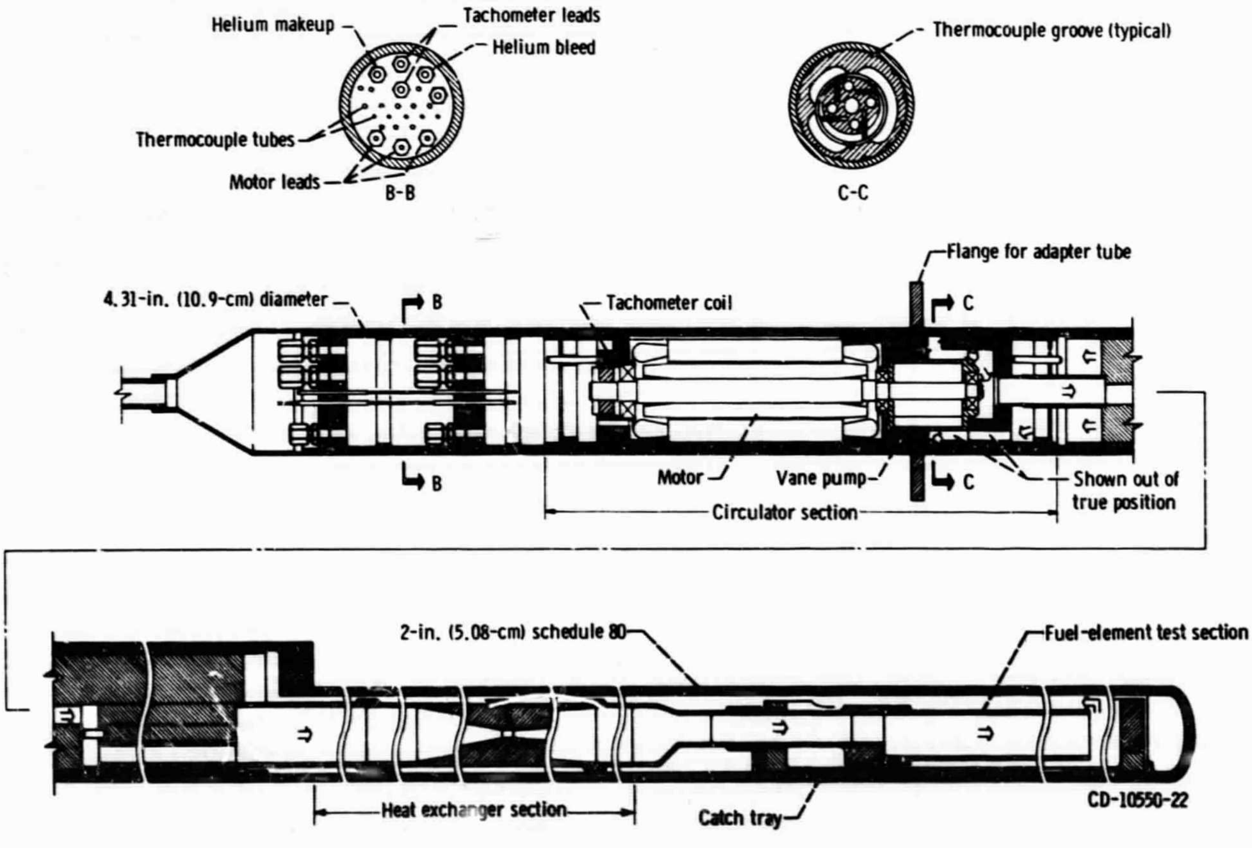



Figure 2. - Capsule assembly.

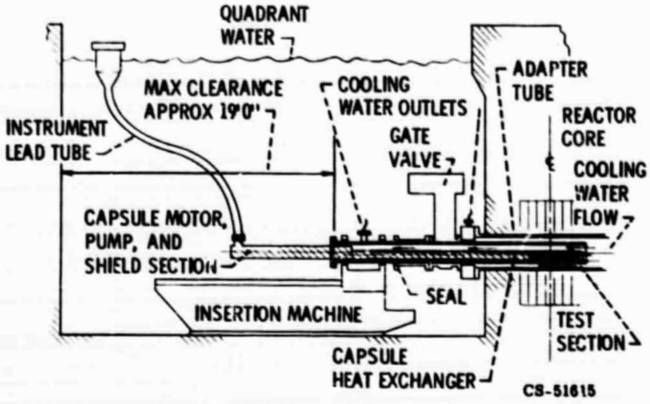



Figure 3. - Capsule in adapter tube on reactor insertion machine.

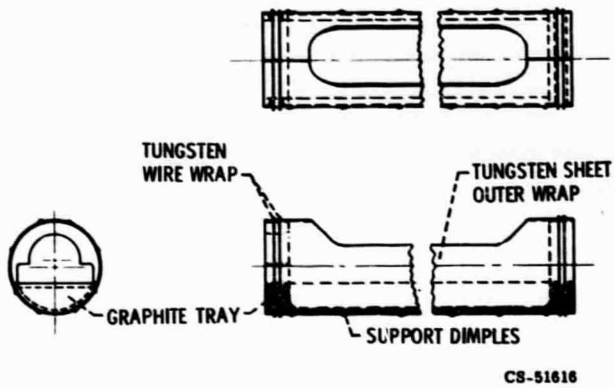



Figure 4. - Graphite catch tray with tungsten wrap.

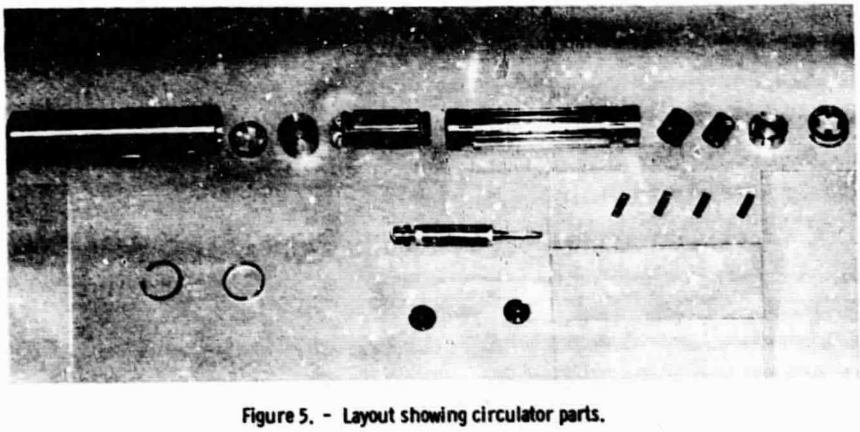


Figure 5. - Layout showing circulator parts.

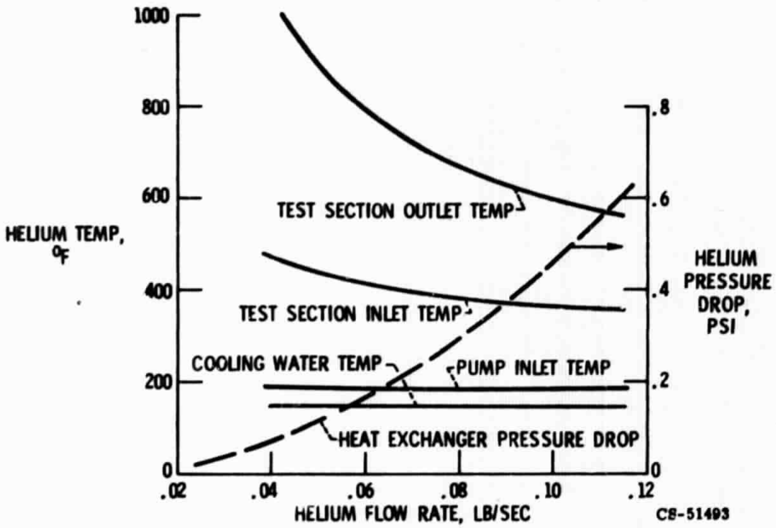
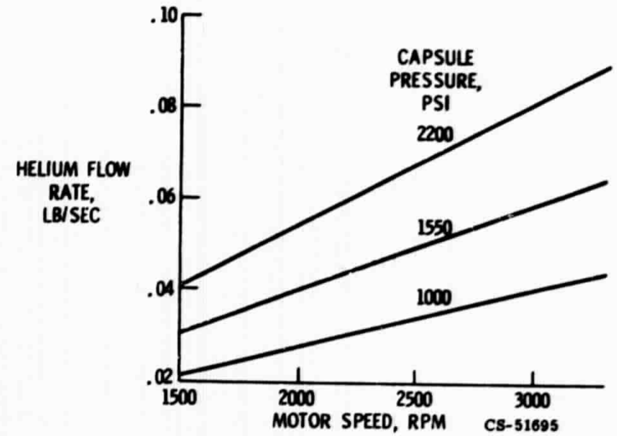
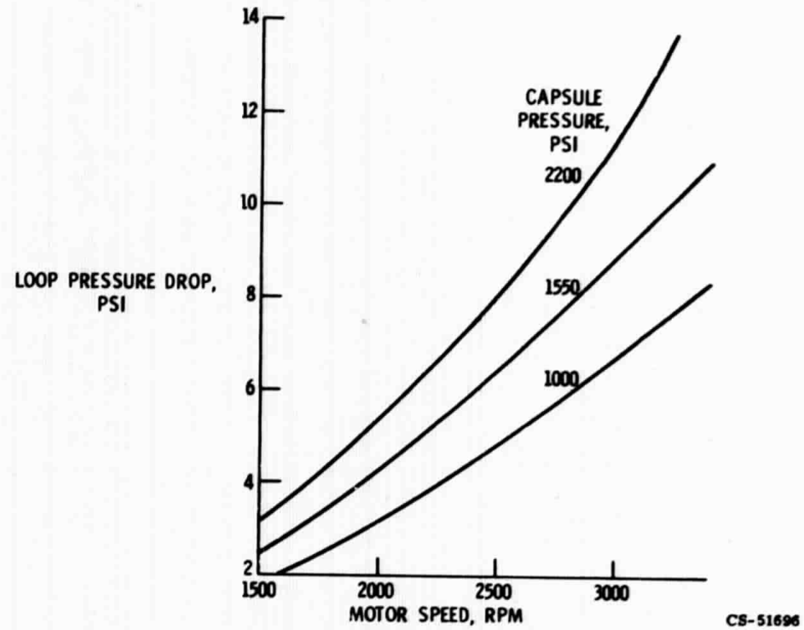



Figure 6. - Helium temperature and pressure drop in heat exchanger for various flow rates. Power, 30 kW; pressure, 1500 psi.




(a) Flow rate versus motor speed and pressure with typical fuel specimen in capsule.

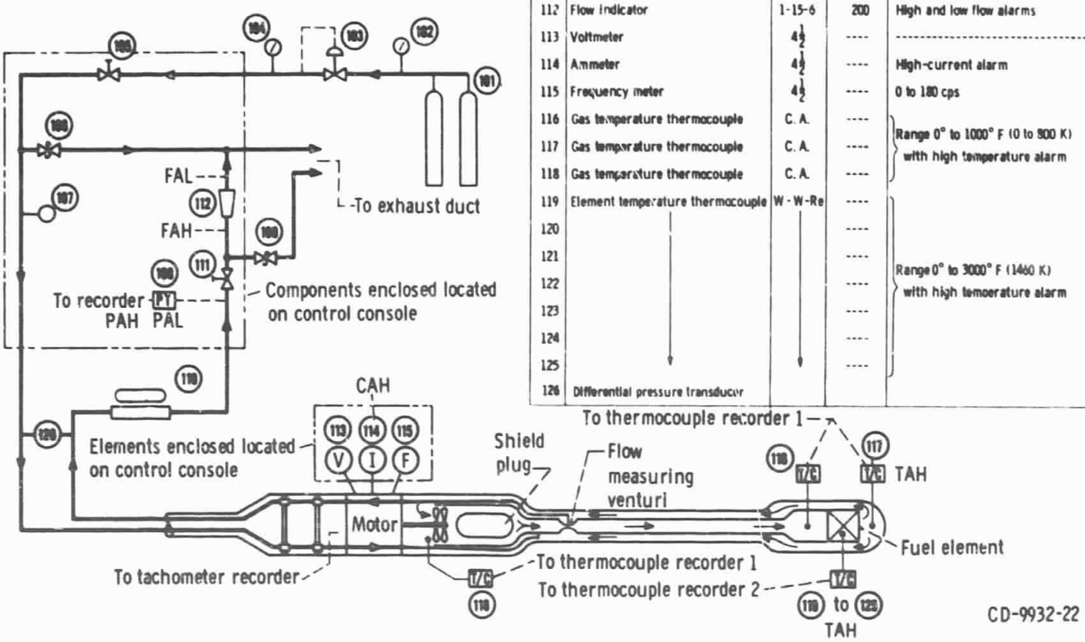



(b) Loop pressure drop versus motor speed and pressure with typical fuel specimen in capsule.

Figure 7

CAH High current alarm
FAH High flow alarm
FAL Low flow alarm
PAH High pressure alarm
PAL Low pressure alarm
TAH High temperature alarm

F Frequency
I Current
PT Pressure transducer
T/C Thermocouple
V Voltage




| Item | Item | Type and size | Working pressure, psia | Remarks |
|---|---|---|---|---|
| 101 | Helium manifold | ------ | 3000 | At reactor |
| 102 | Helium manifold pressure gage | ------ | 4000 | On regulator 103 |
| 103 | Helium supply regulator | 1/4 NPT | 6000 | In line |
| 104 | Helium supply pressure gage | ------ | 4000 | On regulator 103 |
| 105 | Helium supply shutoff valve | ------ | 3000 | ------------------------------ |
| 106 | Helium pressure relief valve | ------ | 3000 | Set 110 percent of capsule pressure |
| 107 | Helium pressure gage | 1/4 NPT | 5000 | ------------------------------ |
| 108 | Helium pressure transducer | ------ | 6000 | High and low pressure alarms |
| 109 | Relief valve | ------ | 3000 | Set at 25 psig ($2.75 \times 10^5$ N/m$^2$) |
| 110 | Radiation monitor | ------ | ---- | At reactor |
| 111 | Flow-control valve | ------ | 3000 | Micrometer adjustment |
| 112 | Flow indicator | 1-15-6 | 200 | High and low flow alarms |
| 113 | Voltmeter | 4 1/2 | ---- | ------------------------------ |
| 114 | Ammeter | 4 1/2 | ---- | High-current alarm |
| 115 | Frequency meter | 4 1/2 | ---- | 0 to 180 cps |
| 116 | Gas temperature thermocouple | C. A. | ---- | |
| 117 | Gas temperature thermocouple | C. A. | ---- | Range 0° to 1000° F (0 to 800 K) with high temperature alarm |
| 118 | Gas temperature thermocouple | C. A. | ---- | |
| 119 | Element temperature thermocouple | W - W-Re | ---- | |
| 120 | | | ---- | |
| 121 | | | ---- | |
| 122 | | | ---- | Range 0° to 3000° F (1460 K) with high temperature alarm |
| 123 | | | ---- | |
| 124 | | | ---- | |
| 125 | | | ---- | |
| 126 | Differential pressure transducer | | | |

Figure 8. - Instrumentation and flow schematic.

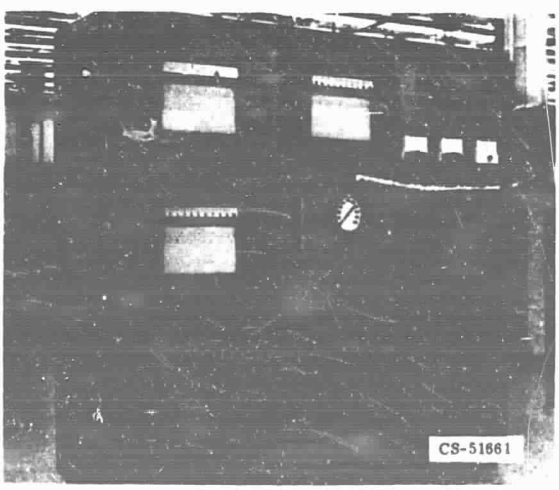



Figure 9. - Control console.