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ANALYSIS OF STEAM LOOP FOR EXPERIMENTAL GAS-COOLED REACTOR

J. F. Bailey

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ANALYSIS OF STEAM LOOP FOR EXPERIMENTAL GAS-COOLED REACTOR

J. F. Bailey

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J. F. Bailey

Abstract

Several types of steam-cooled experimental loop for operation in the EGCR were considered in order to select the system best suited to the EGCR conditions. The system selected employs a turbine-driven compressor, an open-type heat exchanger, a condenser, and a pump. The comparison of the different systems considered was based on the power required for each, the relative simplicity of the system, and the availability, complexity, and physical size of the components. A startup procedure for the recommended system was outlined.

One of the various possible loop accidents, a leak in the through-tube, was analyzed. It was found that a steam leak would not produce a serious hazard, but it would permit a chemical reaction between the steam and the reactor graphite, which could affect up to 31 lb of the removable graphite sleeves.

Introduction

The Experimental Gas-Cooled Reactor (EGCR), a prototype power reactor which is being constructed on the Clinch River about two miles east of the Oak Ridge National Laboratory, is designed to provide for operation of experimental gas-cooled loops in core through-tubes. Sectional views of the reactor building and the basement floor plan are shown in Figs. 1 and 2. The EGCR will use UO_2 clad in stainless steel as the fuel, graphite as the moderator, and helium at 315 psig as the cooling gas. The reactor is designed to generate approximately 85 Mw of thermal power when operating with gas temperatures of 510°F at the inlet and 1050°F at the outlet. The energy from the reactor will be transferred by the helium to water in two boilers. Steam will be generated at 1250 psia and 900°F and supplied to a turbine-generator, which will produce approximately 25 Mw of electrical power.

Provisions were made for installation of a maximum of four experimental loops in the reactor core at a future date. Two of these loops

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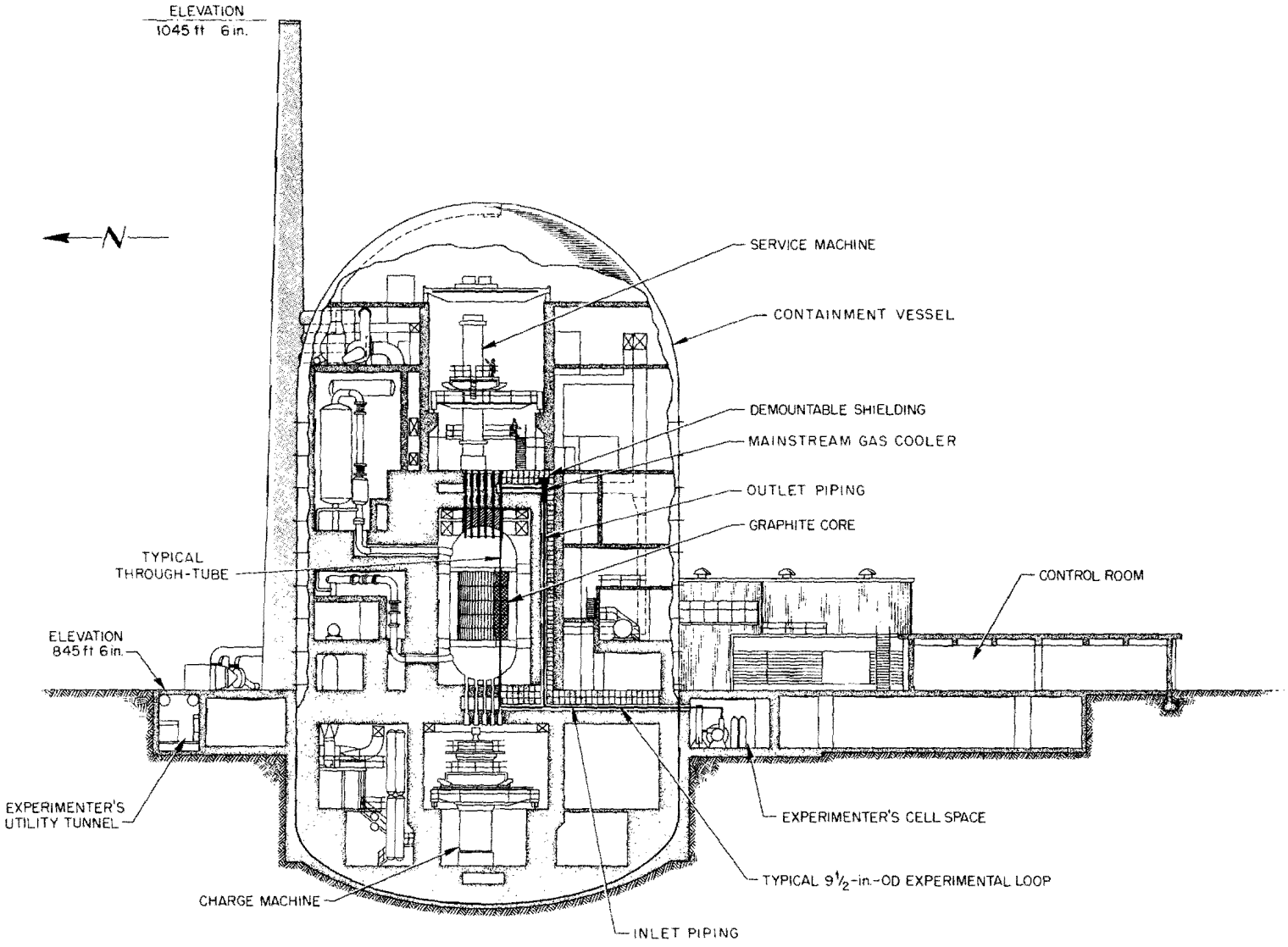

Fig. 1. Sectional View of EGCR Reactor Building.

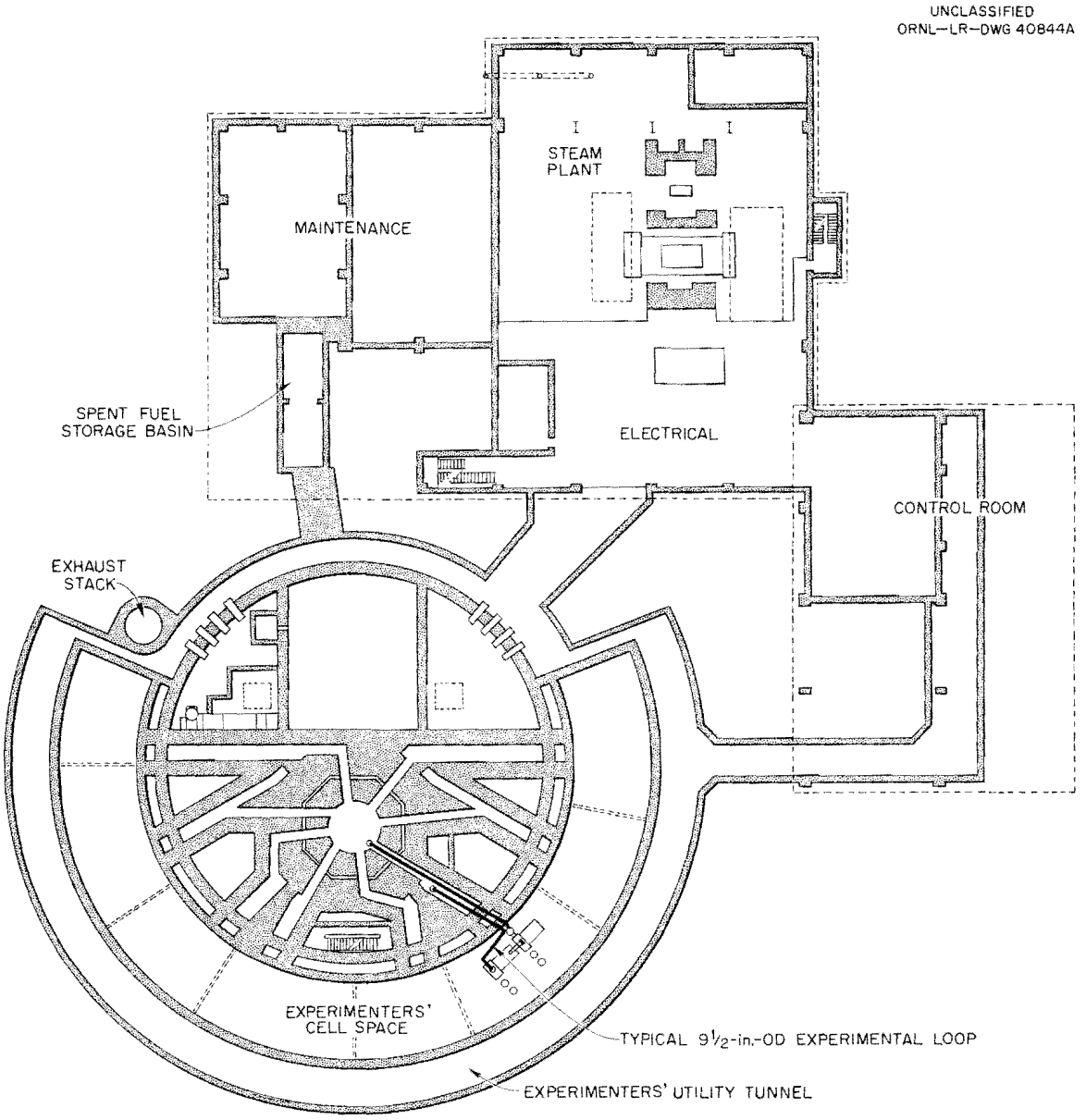

Fig. 2. EGCR Basement Floor Plan at an Elevation of 841 ft.

will utilize 5 1/2-in.-OD stainless steel tubes passing through the core along an axis that is approximately 17 in. from the central axis of the core. The other two loops will utilize 9 1/2-in.-OD through-tubes located approximately 68 in. from the central axis.

The experimental loops that will utilize the smaller through-tubes (designated TS-2 and TS-3) were designed[1] for operation with helium or carbon dioxide as the cooling gas. At present it is not known what gases will serve as the coolants for the loops that will utilize the larger through-tubes (designated as TL-1 and TL-4). It has been assumed, however, that the most likely choices are hydrogen and steam (water vapor), and the preliminary design[2] of a hydrogen-cooled loop to be located in through-tube TL-4 has been prepared. The status of the analysis and design of a steam-cooled loop suitable for installation in through-tube TL-1 is presented here.

The reactor core is a vertical right-circular cylinder made up of 16-in.-square graphite columns that are 19 ft 4 in. high. Vertical channels through the graphite columns accommodate the fuel elements, control rods, and experimental loops. The reactor core is housed inside a cylindrical pressure vessel with an inside diameter of 20 ft and an inside height of 46 ft. The reactor containment vessel is a cylinder 114 ft in diameter with a hemispherical top and bottom. Its overall height is 216 ft. Access to the containment vessel is through a personnel airlock and an equipment airlock.

The EGCR is designed for fuel charging and discharging while operating at full power. A charge machine located beneath the reactor will load and unload the reactor fuel elements. A service machine above the reactor will handle the control rods and the loop experimental equipment.

Eight cells are provided around the periphery of the reactor containment vessel to house loop equipment. Each cell is approximately 24 ft wide, 15 ft deep, and 36 ft long. The cells are located below ground level

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[1]C. Michelson and F. H. Neill, "EGCR Experimental Loops Preliminary Design Report," USAEC Report ORNL-TM-134, Oak Ridge National Laboratory, March 27, 1962.

[2]A. W. Culp, C. Michelson, and F. H. Neill, "Preliminary Design of a Hydrogen-Cooled Loop for the EGCR," USAEC Report ORNL-CF-61-9-3, Oak Ridge National Laboratory.

with the top of their roof plugs at ground level. Adjacent cells are separated by a removable gastight metal bulkhead that is 18 in. thick and can be filled with metal punchings for shielding. The cells are lined with gastight carbon steel liners. A rupture disk is provided between each cell and the reactor containment vessel to protect the cell against overpressure. Personnel access to each cell is provided by a portable airlock that can be positioned over a special hatchway built into the cell roof. Access to the cell during major maintenance is provided by removing several roof plugs and cutting out a section of the cell liner. The resulting opening is 11 1/2 ft wide by 26 ft long.

Loop piping between the experimenters' cells and the reactor through-tubes runs through pipe chases in the reactor biological shield. The inlet piping to a given through-tube runs horizontally through the upper biological shield to a vertical pipe chase near the external face of the reactor biological shield. Space is provided in the vertical chase for a loop cooler. From the bottom of the vertical chase the piping runs horizontally to the experimenters' cell.

A utility tunnel is provided next to the experimenters' cells to accommodate various cell services. This tunnel is approximately 12 ft wide, 17 ft deep, and 388 ft long and is situated adjacent to the outer periphery of the experimenters' cells. The top of the utility tunnel roof is at ground level. Personnel access to the tunnel is through corridors from the turbine building and the control building.

A crane bay is provided in the space directly above the experimenters' cells and the utility tunnel. This space is closed by corrugated transite siding and a built-up roof that abuts the reactor containment vessel. The bay is serviced by a 20-ton traveling-bridge crane for removing the cell roof plugs and components from the experimenters' cells.

The experimenters are provided with a control room, which is located in the EGCR control building. Two experimental fuel assembly storage holes are provided for storage of irradiated loop experiments. These storage holes are located in the reactor biological shield at the west end of the service machine room.

System Selection

The use of steam as a coolant introduces at least one major difference between the steam-cooled loop and all other gas-cooled loops considered. This difference is that the coolant may appear as a vapor, a liquid, or a mixture of these phases. Because of this possibility, there exists a greater selection of types of systems that may be employed with steam than with the other gases. Before beginning the design of a steam-cooled loop, it was necessary to determine which type of system appeared most promising. Six different systems or loop arrangements were considered. They are identified as

I. Motor-Compressor System
II. Turbine-Compressor-Cooler System
III. Turbine-Compressor-Exchanger-Cooler System
IV. Turbine-Compressor-Exchanger System
V. Condensing System
VI. Jet-Pump System

System I, which is shown schematically in Fig. 3, consists of a motor-driven compressor, the test section, and a cooler. Only major items of equipment are shown, since the auxiliary equipment was not considered in this initial analysis. Systems II (Fig. 4), III (Fig. 5), and IV (Fig. 6) employ turbine-driven compressors, condensers, and pumps, and in this respect they are similar. Basically they differ from one another in the means of cooling the gas flowing from the test section to the compressor. System II uses a cooler that is a gas-to-liquid heat exchanger; system III uses an open-type heat exchanger and a cooler; and system IV uses only an open heat exchanger. In addition, system II requires a boiler for normal operation. It is anticipated that all systems will require a small boiler for startup.

System V, which is shown in Fig. 7, does not employ a compressor but provides for condensing the vapor and circulating the fluid by pumping it as a liquid. The closed heat exchanger, condenser, pump, heater, and test section are the major components. System VI (Fig. 8) uses a jet pump to assist in circulating the fluid. In addition to the jet pump,

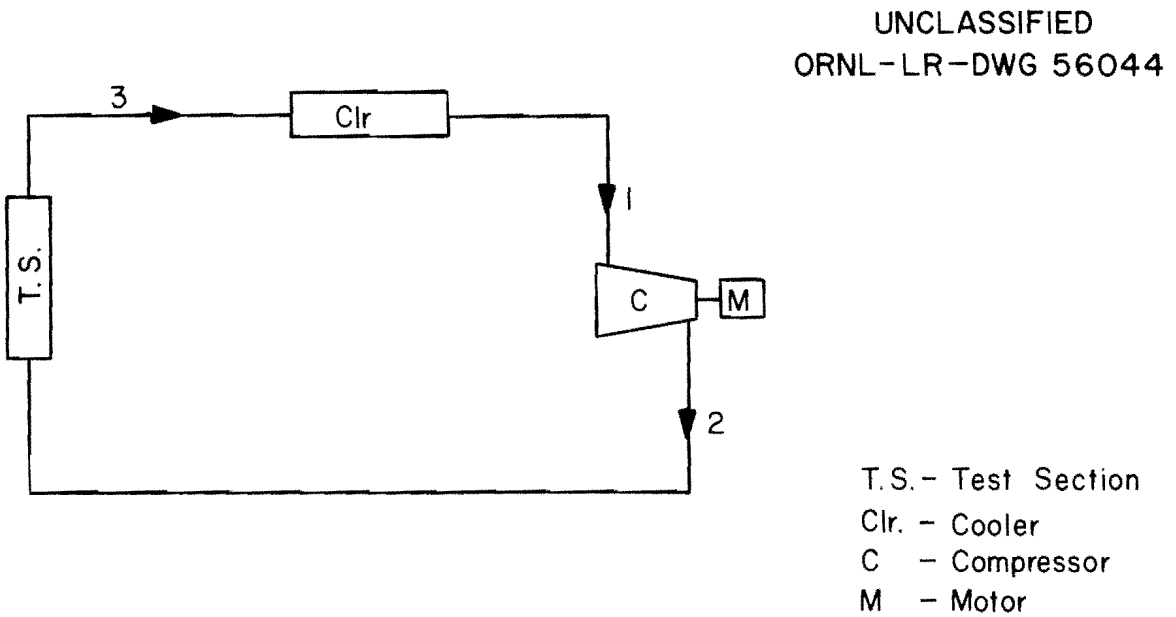

Fig. 3. Motor-Compressor System.

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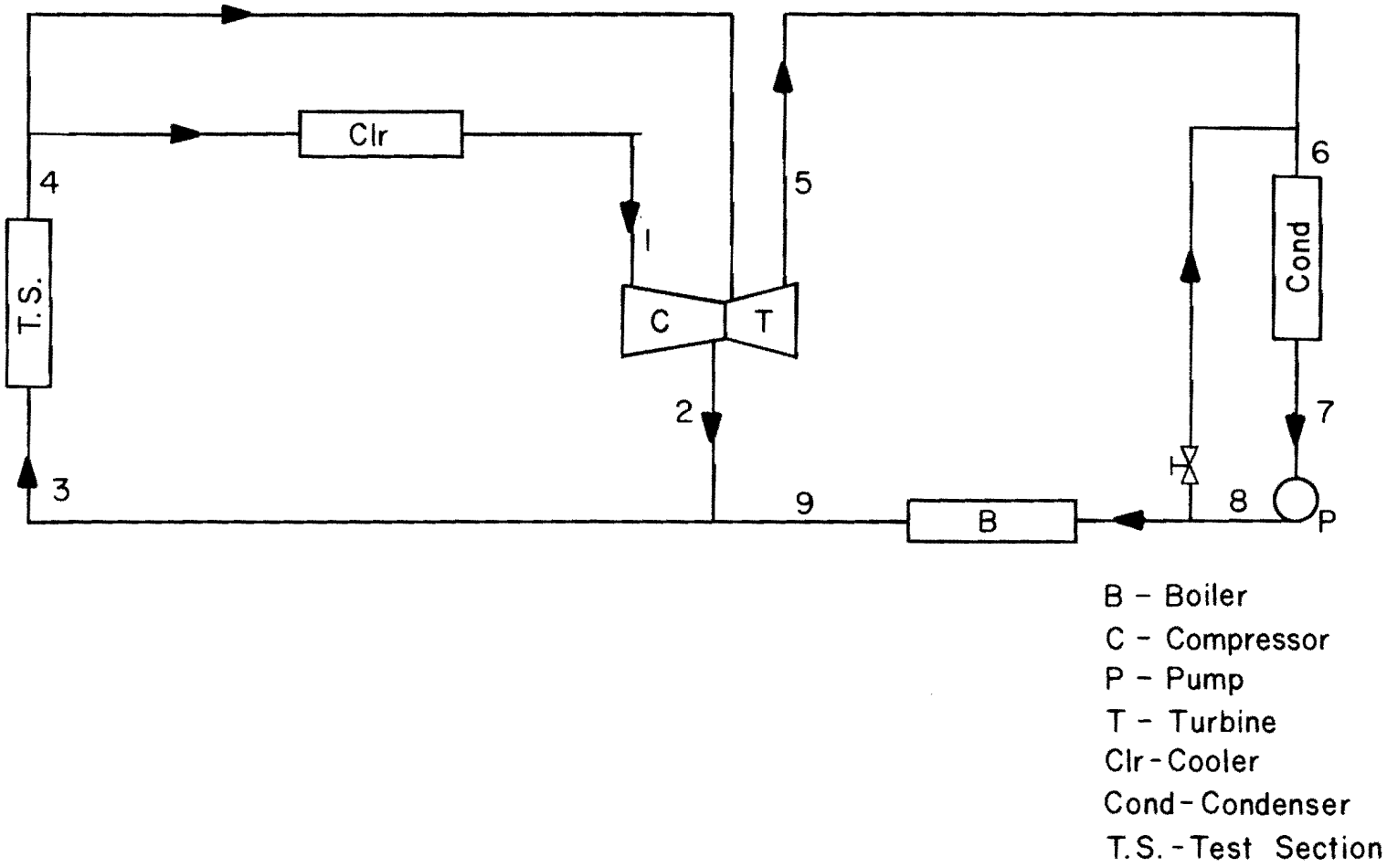

Fig. 4. Turbine-Compressor-Cooler System.

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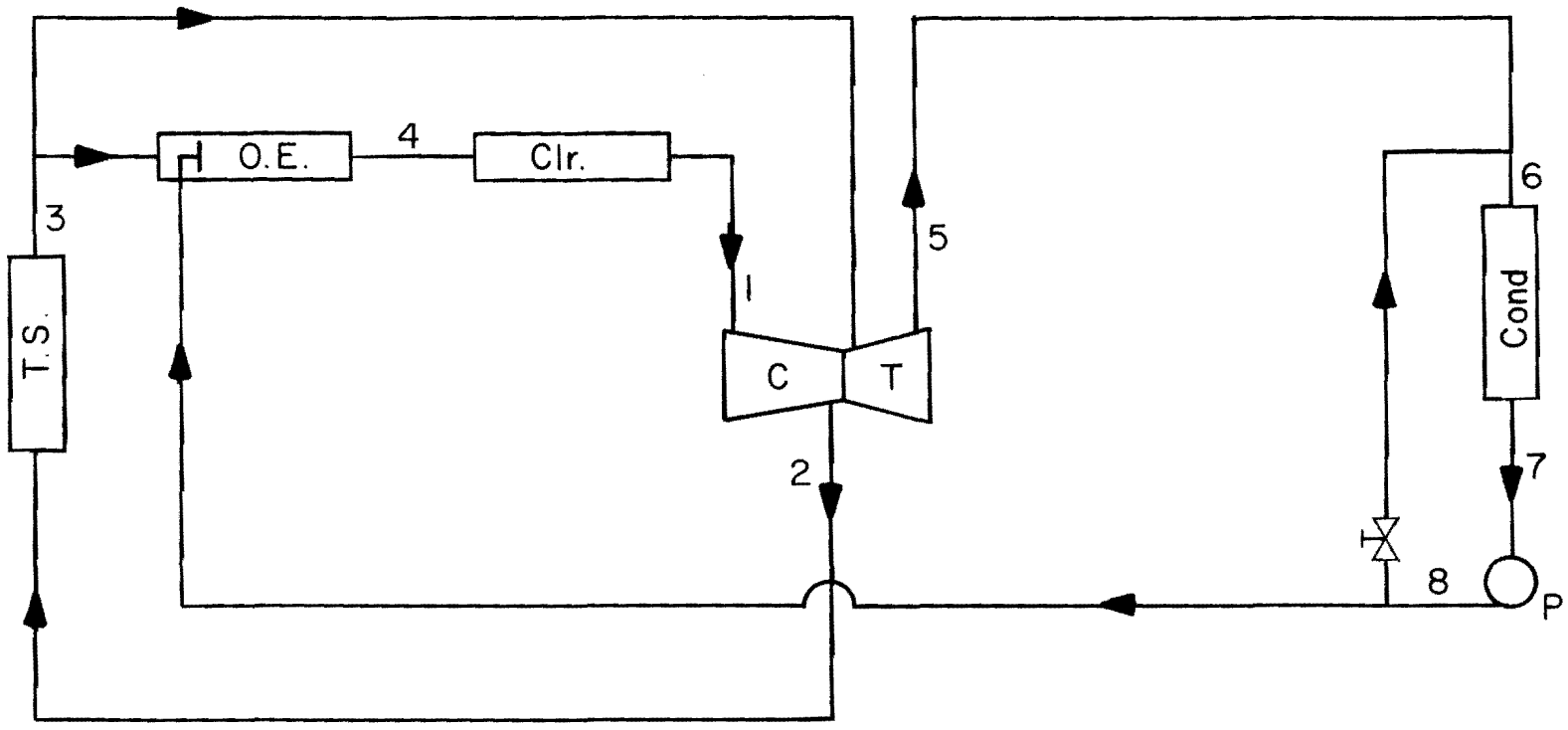

P - Pump
C - Compressor
T - Turbine
T.S.- Test Section
O.E. - Open Type Exchanger
Clr - Cooler
Cond - Condenser

Fig. 5. Turbine-Compressor-Exchanger-Cooler System.

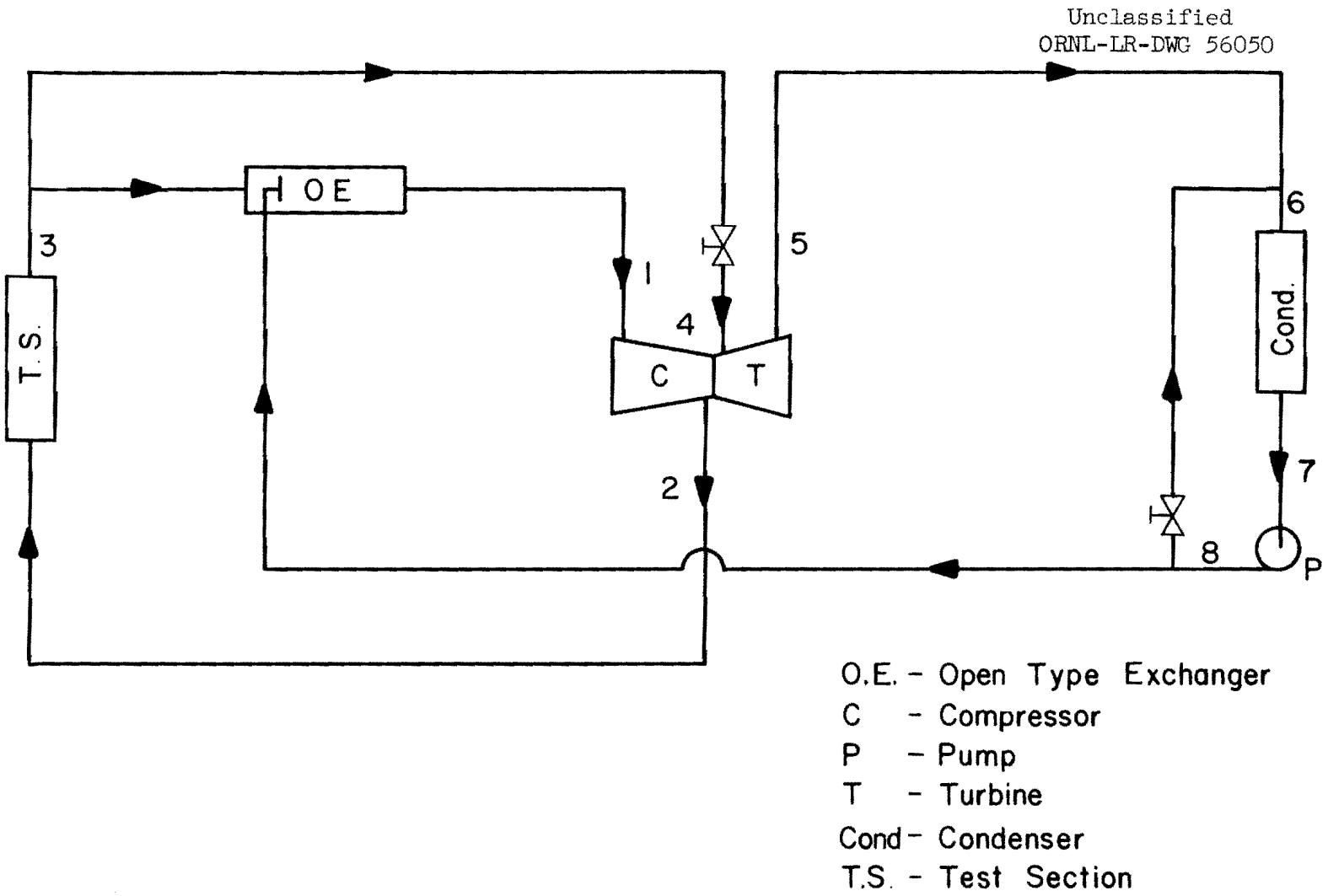

Fig. 6. Turbine-Compressor-Exchanger System.

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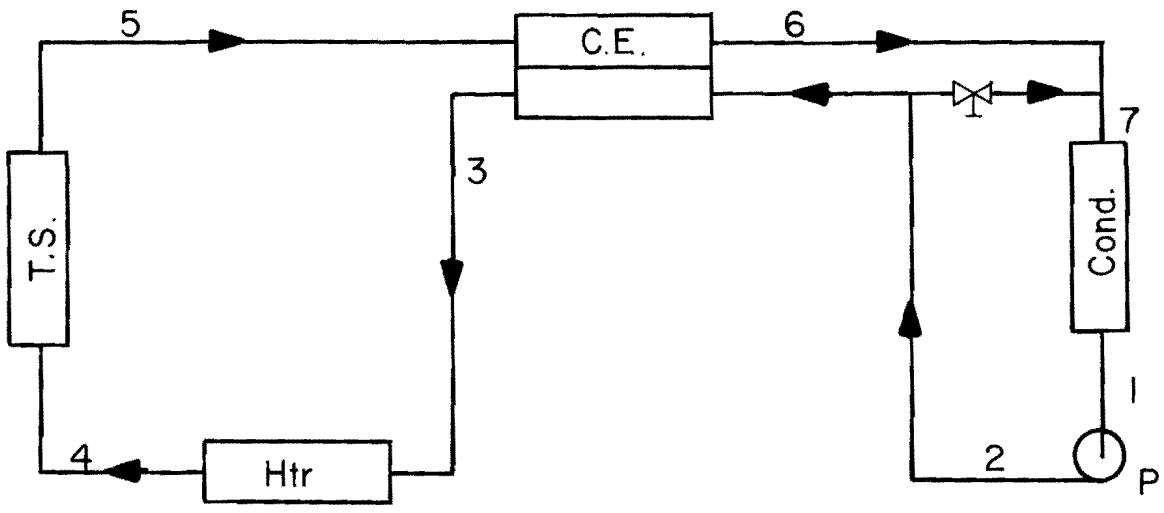

P - Pump
C.E.- Closed Type Exchanger
Htr - Heater
TS - Test Section
Cond - Condenser

Fig. 7. Condensing System.

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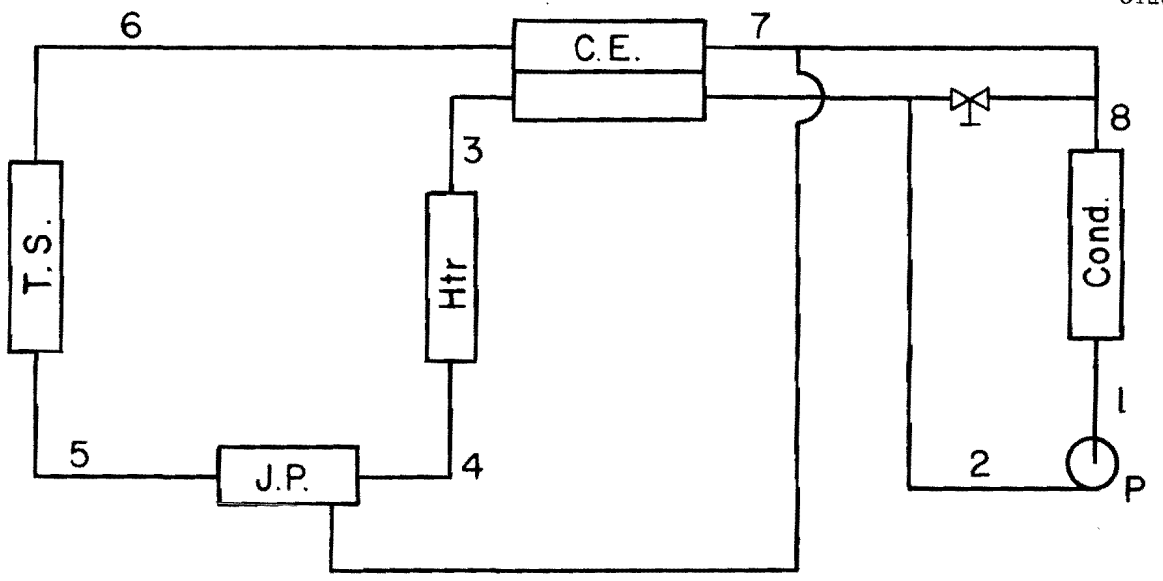

P - Pump
C.E.- Closed Type Exchanger
Htr-Heater
J.P.-Jet Pump
TS.-Test Section
Cond-Condenser

Fig. 8. Jet-Pump System.

this system requires a closed heat exchanger, condenser, pump, heater, and the test section.

Design Criteria

The EGCR experimental loops are designed to provide the following test-section operating conditions:

Pressure in test section, psia	500–1000
Temperature entering test section, °F	600–950
Temperature leaving test section, °F	1050
Power level, Mw	0.335–1.5

From steam tables the following enthalpies are found:

Temperature (°F)	Pressure (psia)	Enthalpy (Btu/lb)
600	500	1298.6
600	1000	1248.8
1050	500	1546.4
1050	1000	1533.2

Thus the flow rates for the 1.5-Mw power level are

$$M_{max} = \frac{(1.5)(1000)(3413)}{1546.4 - 1298.6} = 20{,}700 \text{ lb/hr}$$

$$M_{min} = \frac{5{,}120{,}000}{1533.2 - 1248.8} = 18{,}000 \text{ lb/hr}$$

It is evident that although design from a strength standpoint should be based on the higher temperature and pressure, in those phases of design concerned with pressure losses and compressor power, operation at the lower pressure and higher power level must be considered.

In order to compare the merits of the various types of systems, a single set of operating conditions was selected. These conditions, which are given below, are essentially those given for Case I in ref. 3:

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[3]R. B. Korsmeyer to F. H. Neill, "EGCR Loop Experiments," USAEC Report ORNL CF-60-1-1, Oak Ridge National Laboratory, Jan. 25, 1960.

Pressures, psia	
Entering compressor or pump	605
Entering test section	670
Leaving test section	638
Temperatures, °F	
Entering test section	740
Leaving test section	1050
Flow rate, lb/hr	9660

The following assumptions were made:

Compressor efficiency, %	80
Pump efficiency, %	80
Turbine efficiency, %	80
Nozzle efficiency, %	80
Entrainment efficiency, %	65
Diffuser efficiency, %	80
Cooling water temperature (average inlet and outlet), °F	80
Heat transfer coefficient for gas-to-liquid cooler and open and closed exchangers, $Btu/hr \cdot ft^2 \cdot °F$	10
Heat transfer coefficient for surface condenser, $Btu/hr \cdot ft^2 \cdot °F$	600

Analyses of Systems

Thermodynamic analyses were made for each of the six systems. The processes that made up the cycle of each system are shown on temperature-entropy diagrams in Figs. 9 through 14.

In order to simplify the analyses, the system pressure losses were considered to occur within two or three items of equipment rather than throughout the entire system. In each case one-half the pressure loss was assigned to the test section and one-half to the mainstream cooling equipment. For example, the cycle for system I in Fig. 9 shows the pressure losses occurring in the test section (2-3) and in the cooler (3-1); the cycle for system III in Fig. 11 shows the pressure losses occurring in the test section (2-3), the open exchanger (3-4), and the cooler (4-1).

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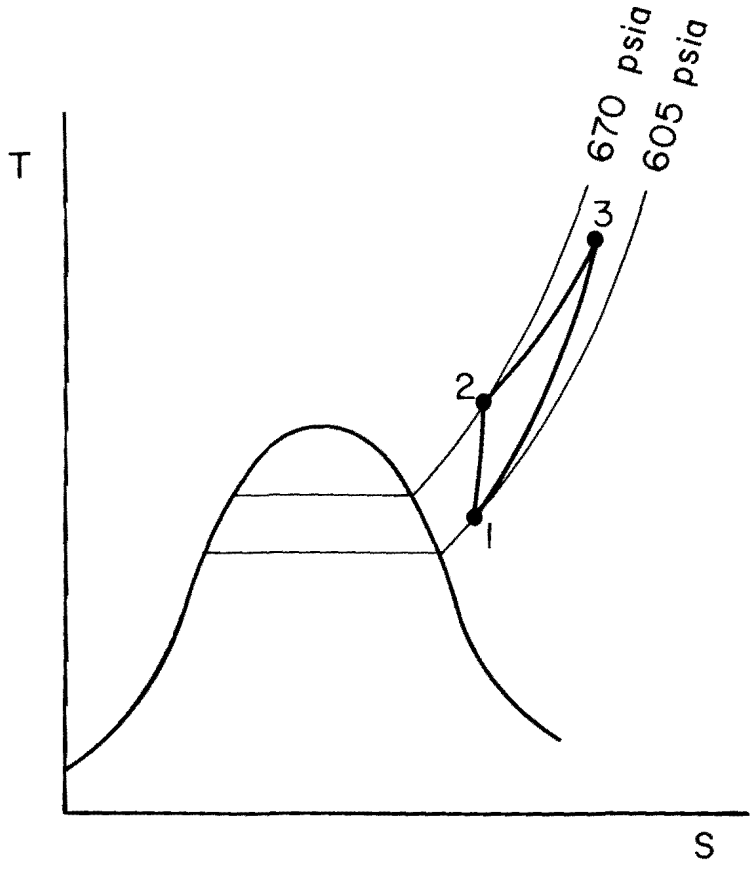

Fig. 9. Temperature-Entropy Diagram for Motor-Compressor System.

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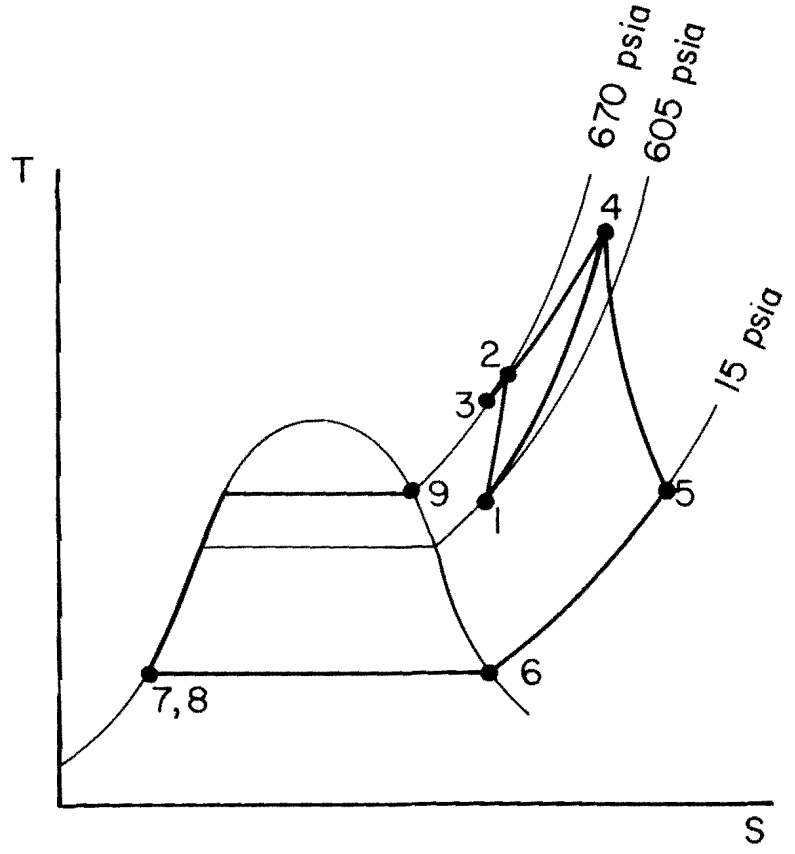

Fig. 10. Temperature-Entropy Diagram for Turbine-Compressor-Cooler System.

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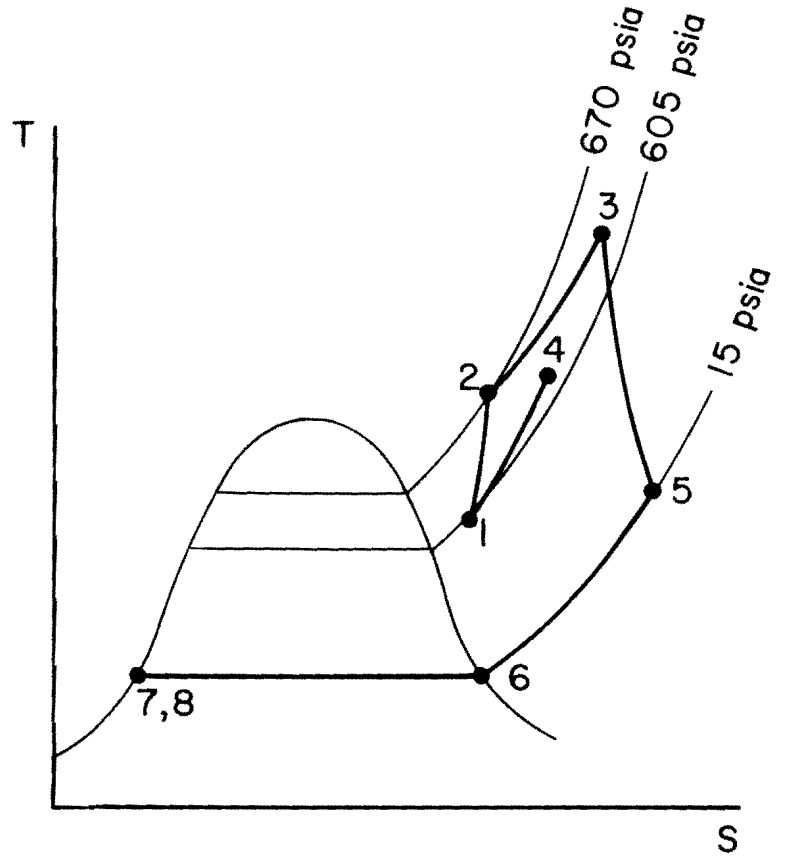

Fig. 11. Temperature-Entropy Diagram for Turbine-Compressor-Exchanger-Cooler System.

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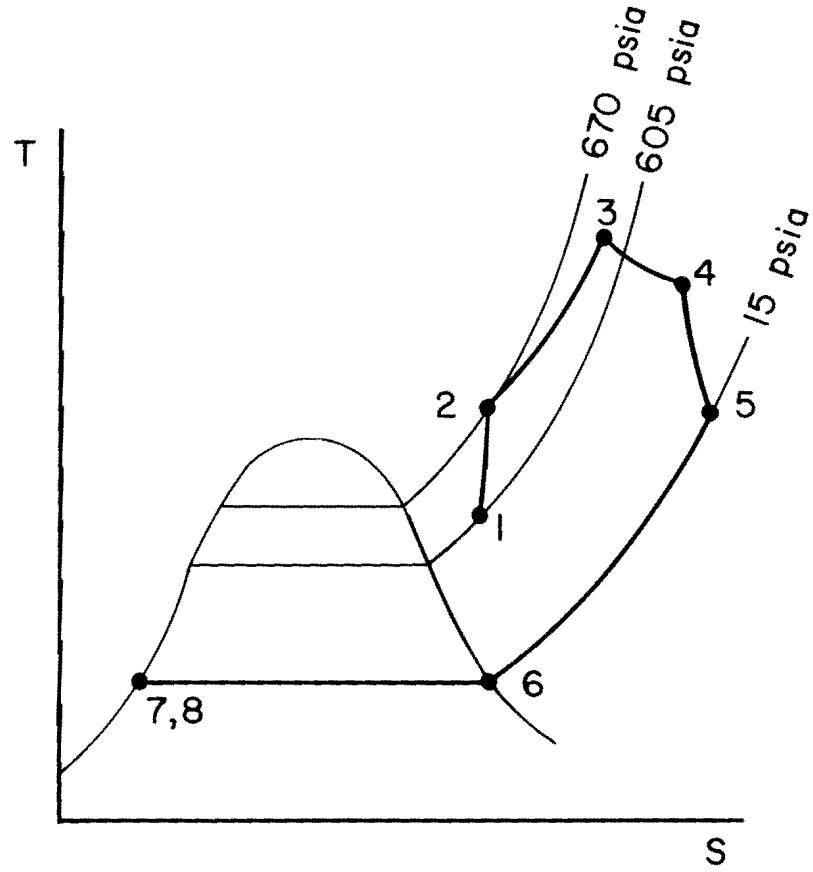

Fig. 12. Temperature-Entropy Diagram for Turbine-Compressor-Exchanger System.

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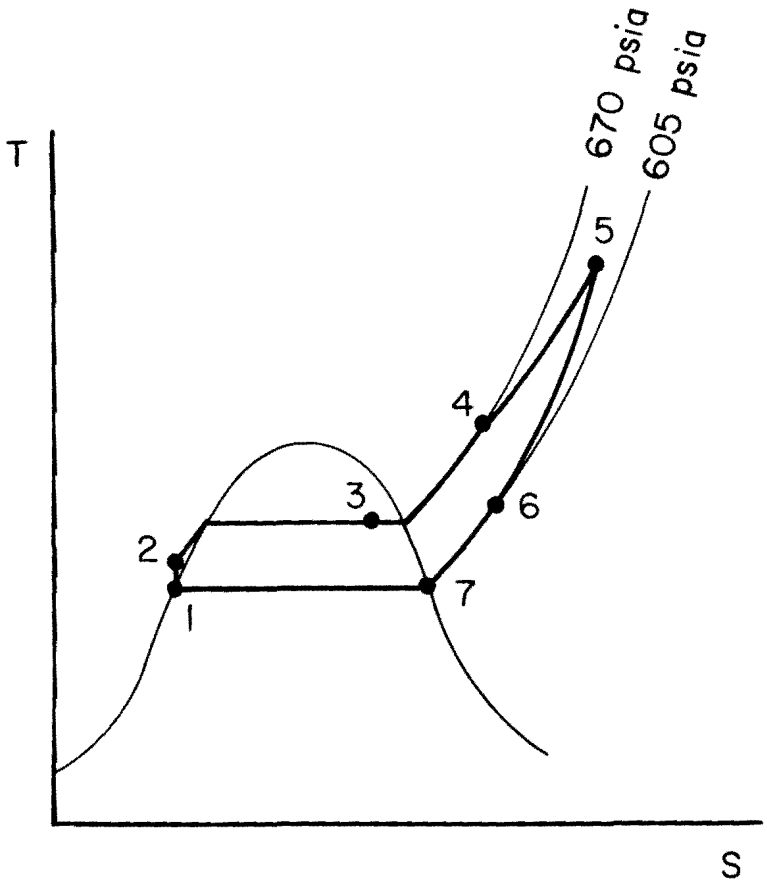

Fig. 13. Temperature-Entropy Diagram for Condensing System.

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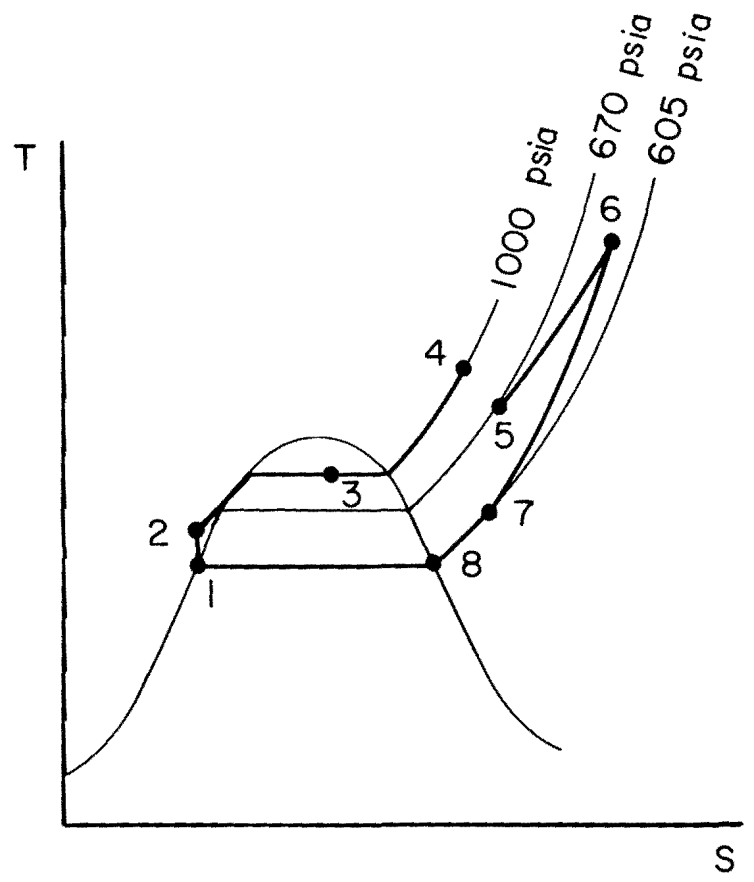

Fig. 14. Temperature-Entropy Diagram for Jet-Pump System.

Mixing processes occur in some of the systems, and for these cases the temperature-entropy diagrams may appear to be incomplete. In the turbine-compressor-cooler system (Figs. 4 and 10), fluid at state 2 mixes with fluid at state 9 to produce fluid at state 3. In the turbine-compressor-exchanger-cooler system (Figs. 5 and 11), the mixing occurs inside the open exchanger where fluid at state 3 mixes with fluid at state 8 to give fluid at state 4. A similar process is found in the turbine-compressor-exchanger system shown in Figs. 6 and 12. In the jet-pump system shown in Figs. 8 and 14, the mixing occurs within the jet pump.

The results of the thermodynamic analyses are given in Table 1, and the details of the calculations associated with these analyses are given in Appendix A. Those quantities pertinent to the selection of the most suitable system are listed in Table 1 for the various components of the systems studied. The four quantities, heat transfer rate, work transfer rate, temperature difference, and surface area, were selected as the basis for comparing the systems. The heat and work transfer rates are indirectly indicative of the size of the components and, of course, indicate directly the amounts of cooling water needed or quantities of energy required. The value of the temperature difference for the heat transfer equipment is an indication of the magnitude of the thermal stress and thermal expansion problems associated with the design of the equipment. The heat transfer surface area is indicative of the physical size of the equipment.

In addition to the quantities listed in Table 1, consideration was given to the number of components (major components) required in each system and the availability of the components. Availability of a component involves whether or not the item can be obtained "off the shelf" or must be developed.

A crude comparison of the various systems was made by ranking the systems according to their desirability on six different bases. The items used for this comparison were the number of major components in the system, the amount of cooling water required, the amount of power required for heating purposes, the amount of work required, and the heat transfer area required. The results of this comparison are shown in Table 2.

Table 1. Results of Thermodynamic Analysis

Component	System I	System II	System III	System IV	System V	System VI
Heat transfer, Btu/hr						
Boiler		432,000				
Cooler	1,819,200	1,668,200	1,216,000			
Condenser		437,000	457,600	1,675,700	7,150,000	6,565,000
Exchanger, closed					3,200,000	1,792,000
Exchanger, open			520,100	1,566,700		
Heater					5,470,000	5,030,000
Test section	1,673,100	1,673,100	1,673,100	1,673,100	1,673,100	1,673,100
Work, Btu/hr						
Compressor	145,900	139,500	145,900	145,900		
Pump		1,100	1,200	4,000	2,900	11,190
Temperature difference, °F						
Cooler	788	792	732			
Condenser		133	133	133	407	407
Exchanger, closed					144	342
Surface Area, ft^2						
Boiler		1.5				
Cooler	231	211	166			
Condenser		5.5	5.7	21	29.3	26.9
Exchanger, closed					2,220	525
Exchanger, open			65	196		
Heater					943	952

Table 2. Comparison of Systems

Item of Comparison	Relative Weight					
	System I	System II	System III	System IV	System V	System VI
Number of major components	1	5	5	3	2	3
Amount of cooling required	3	4	1	1	6	5
Amount of heating required	1	4	1	1	6	5
Amount of work required	4	3	5	6	1	2
Temperature difference	6	5	4	1	2	3
Heat transfer area	3	1	4	1	6	5
Summation	18	22	20	13	23	23

Comparison of Systems

The results presented in Tables 1 and 2 indicate that system IV should be selected and that system I is the second choice. In Table 2 it may be noted that system IV ranks first in four of the six areas of comparison. It ranks last in the amount of work required. This is not a serious disadvantage, since systems I, II, III, and IV require approximately the same amount of work, and this amount is not excessive. Systems V and VI, which have considerably lower work requirements, were eliminated from consideration for reasons discussed below. The main disadvantage of system IV is that it is more complex, based on the number of major components, than either I or V.

Systems V and VI were eliminated because of the extremely large amounts of heating and cooling needed and because of the large heat transfer areas required. Systems V and VI do possess an advantage over the other systems in that a steam compressor is not needed. It was for this reason that these systems were considered originally.

Systems II, III, and IV are similar. The only essential difference in these systems is in the method of cooling the main gas stream as it flows from the test section to the compressor. Table 2 shows that the only area in which either system II or system III is superior to system IV is in the amount of work required. A glance at Table 1 indicates, however, no real significant difference. Thus systems II and III need not be considered further.

While these results suggest that system IV should be selected, it seems unwise to eliminate system I immediately from further consideration. A comparison of systems I and IV based on the results in Table 1 shows the following: system I requires only slightly more cooling (1,819,200 Btu/hr versus 1,675,700 Btu/hr) than IV, both require essentially the same amount of work, and I demands only a slightly greater amount of heat transfer area (231 ft^2 versus 217 ft^2). Based on these three items there is little preference for one system over the other. The big difference shown by Table 1 is in the temperature difference anticipated in the cooler of system I (788°F) as compared with the temperature difference expected in the condenser of system IV (133°F). This number (the

temperature difference), which reflects the difficulties of design and fabrication, predicts a more complex and more expensive heat transfer unit for system I than for system IV.

Probably the most serious disadvantage of system I does not appear in the results given in Tables 1 and 2. A suitable method of connecting the motor and compressor is not readily apparent. It appears to be impractical to enclose the motor and compressor in a single housing, since the maximum permissible operating temperature of the motor will be considerably less than the saturation temperature of the steam. Separating the motor from the compressor gives rise to the difficult problem of sealing against leakage where the shaft enters the compressor.

The important advantages of system I are that it is less complex (fewer major components); it would be easier to start (brought from ambient temperature to operating temperature); and it would be easier to operate (fewer components to control).

Conclusions

The choice of system IV or system I is somewhat dependent upon time. At this time, it is recommended that system IV be selected. The components of system IV are sufficiently similar to existing equipment or equipment now in the final stages of development to make it more probable that this system could be designed, fabricated, and installed on schedule than could system I. On the other hand, should a reliable sealing system for the compressor shaft become available before the final decision on the type of system must be made, system I would conceivably be preferred. The simplicity of system I and the fact that it would be easier to start and operate are so attractive that serious thought should be given to a program to develop a suitable shaft sealing system for the compressor.

Primary Loop Components

A schematic flow diagram of the proposed experimental loop based on the turbine-compressor-exchanger system is shown in Fig. 15. The steam flows from the in-pile test section at 1050°F to an open-type heat

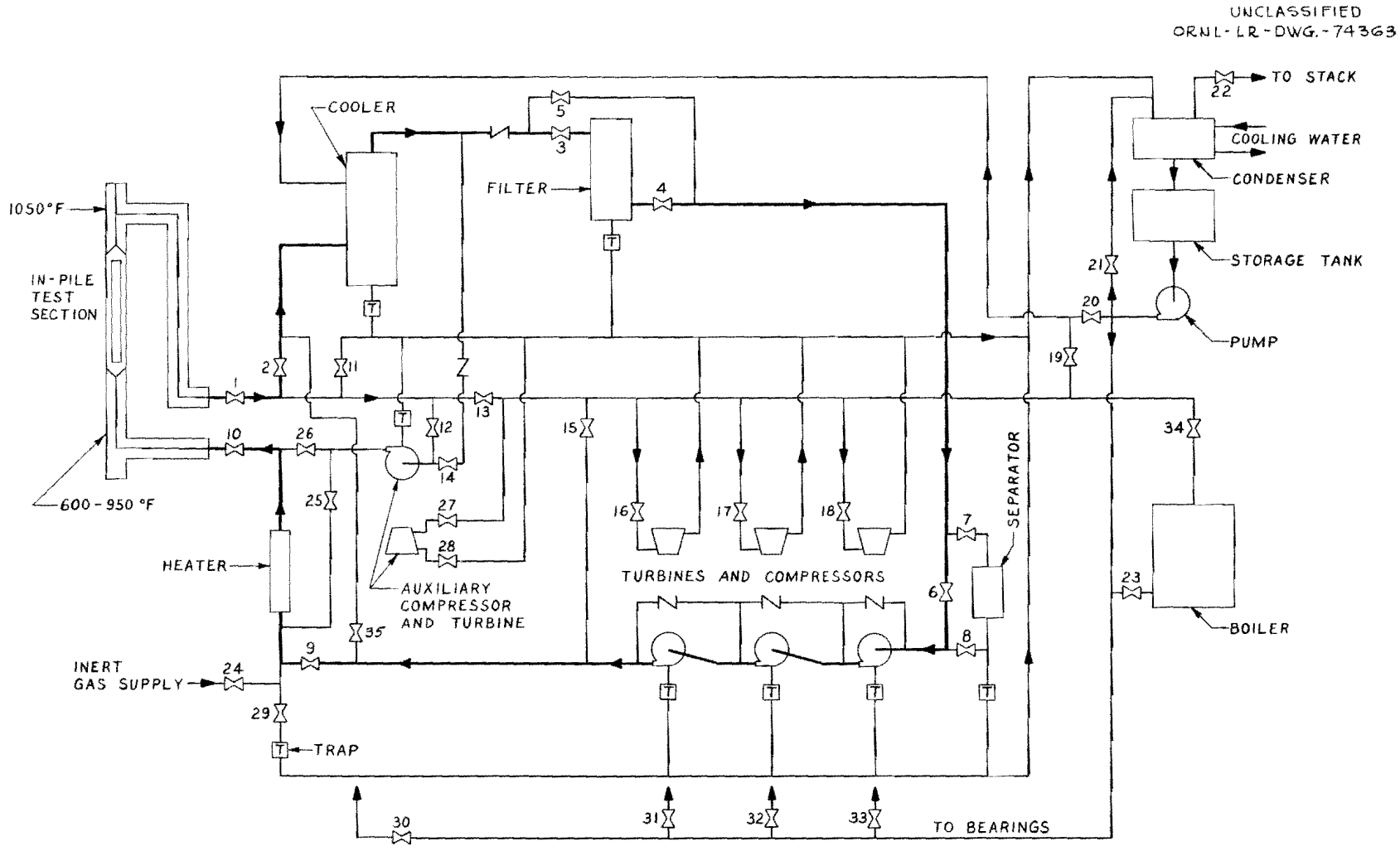

Fig. 15. EGCR Steam-Cooled Experimental Loop Flow Diagram.

exchanger (cooler), where the steam is mixed with liquid being pumped from the storage tank. The steam that leaves the exchanger, cooled but still superheated, passes through a filter and to the compressors. There are three compressors in the main loop, each driven by a steam turbine. From the compressors, through which the steam passes in series, the fluid flows through a heater and on to the test section.

A portion of the steam coming from the test section is supplied to the turbines, which exhaust to a condenser. The liquid from the condenser is pumped to the open exchanger and to the hydrostatic bearings in the compressors and turbines.

The boiler and separator and the auxiliary compressor and turbine are needed during startup. The auxiliary compressor and turbine are also for emergency use.

Through-Tube Assembly

The through-tube assembly consists of the through-tube, the top nozzle tees, and the bottom nozzle tees. The through-tube is type 347H stainless steel seamless tubing 9 1/2 in. OD and approximately 64 ft long. A preliminary design analysis[4] indicated that a 0.500-in.-thick wall would be adequate for an internal pressure of 1100 psia and an external pressure of 300 psia.

The through-tube is designed so that it may be replaced if necessary. Final attachment of the tube to the reactor pressure vessel is performed by remotely welding the tube to the top and bottom inner tees. To replace the tube, the tube-to-tee welds are removed by remotely machining the weld. The through-tube has an orifice and a guide ring that fit inside a guide sleeve located in the bottom-grid support structure of the reactor core. This orifice, which is installed and replaced with the through-tube, limits the reactor gas flow rate up the outside of the through-tube. The reactor gas removes the gamma and neutron heat generated in the tube and in the graphite surrounding the tube, and its flow rate

[4]C. Michelson and F. H. Neill, "EGCR Experimental Loops Preliminary Design Report," USAEC Report ORNL-TM-134, Oak Ridge National Laboratory, March 27, 1962.

must be adequate to keep the through-tube wall temperature below 1075°F. The through-tube is insulated in the inside from the hot loop gas by a metallic-foil reflective type of insulation.

The top and bottom nozzle tee sections are shown in Figs. 16 and 17, respectively. The top and bottom nozzle outer tees are welded to the reactor pressure vessel nozzle extensions and become a permanent part of the reactor vessel. The branches of the inner and outer tees of each top nozzle are welded to the primary piping and secondary containment piping, respectively, so that the primary loop piping is connected to the through-tube, and the secondary, or containment, piping is connected to the reactor pressure vessel.

The primary piping is fabricated of type 347H stainless steel, as are those portions of the secondary containment piping that are subject to high temperatures. Those parts of the secondary piping that are not subject to high temperatures are fabricated of carbon steel. All parts of the top and bottom nozzle inner tees that are subject to axial thermal gradients and may be exposed to the liquid phase are overlaid with Inconel to a finished thickness of 1/16 in.

Mainstream Cooler

The proposed mainstream cooler is an open type of heat exchanger in which the steam from the test section is cooled by mixing, in direct contact, with the liquid from the condenser. The cooler, shown schematically in Fig. 18, must cool the steam from 1050°F to temperatures that may range from 550 to 900°F. The cooler must be sized to exchange an amount of energy that is approximately equal to the amount generated in the test-section fuel assembly, or approximately 500 kw. Also, it must be capable of operating properly at various other, but smaller, energy exchange rates.

A detailed design of the cooler has not been made. The cooler shown in Fig. 18 is simply a concept of the type of cooler to be employed. The use of a direct contact exchanger as the mainstream cooler has certain significantly desirable characteristics. No secondary coolant is required, and the direct contact feature simplifies the energy transfer process

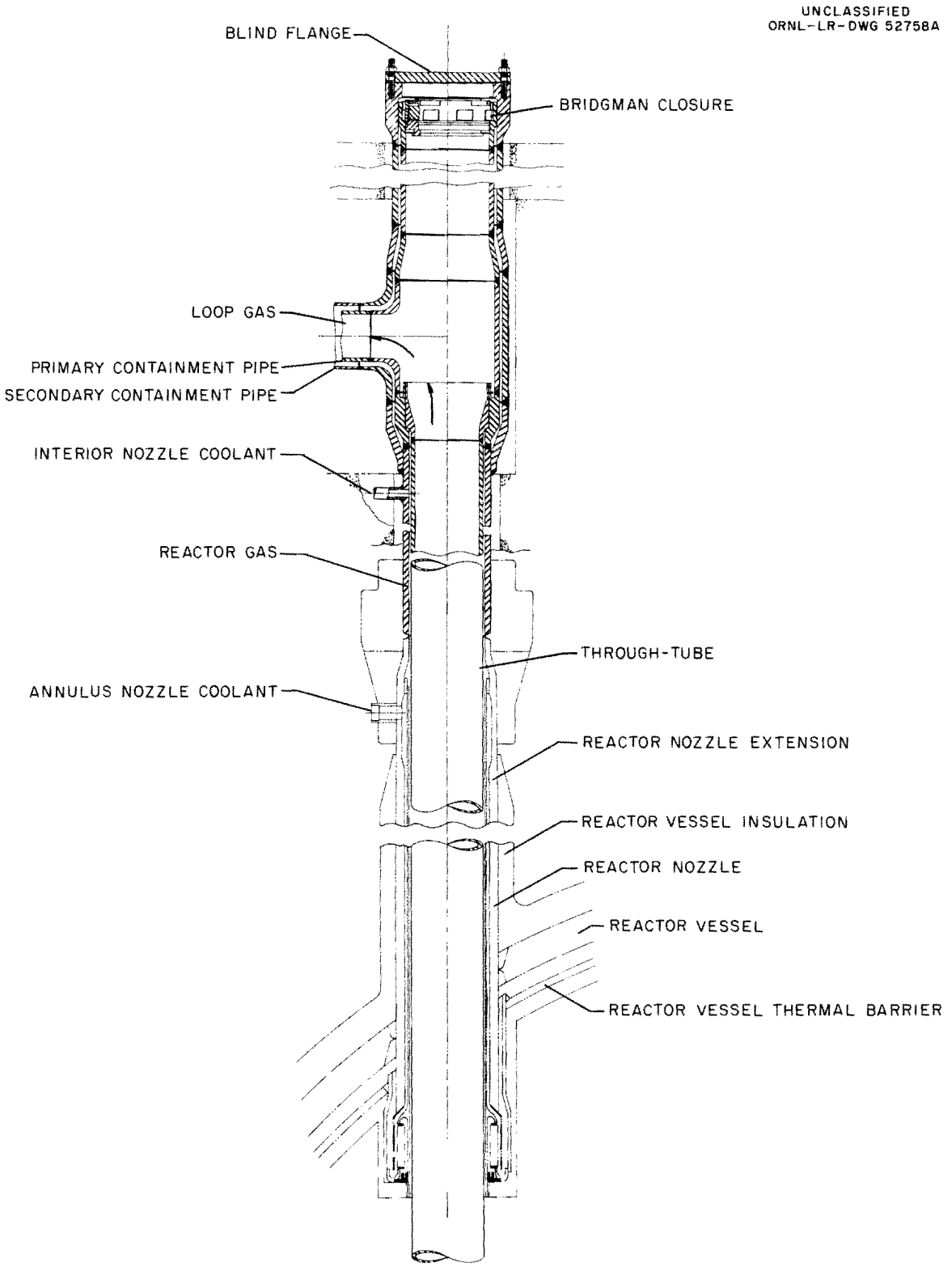

Fig. 16. Top Nozzle Tee Section for 9 1/2-in.-OD Single Through-Tube.

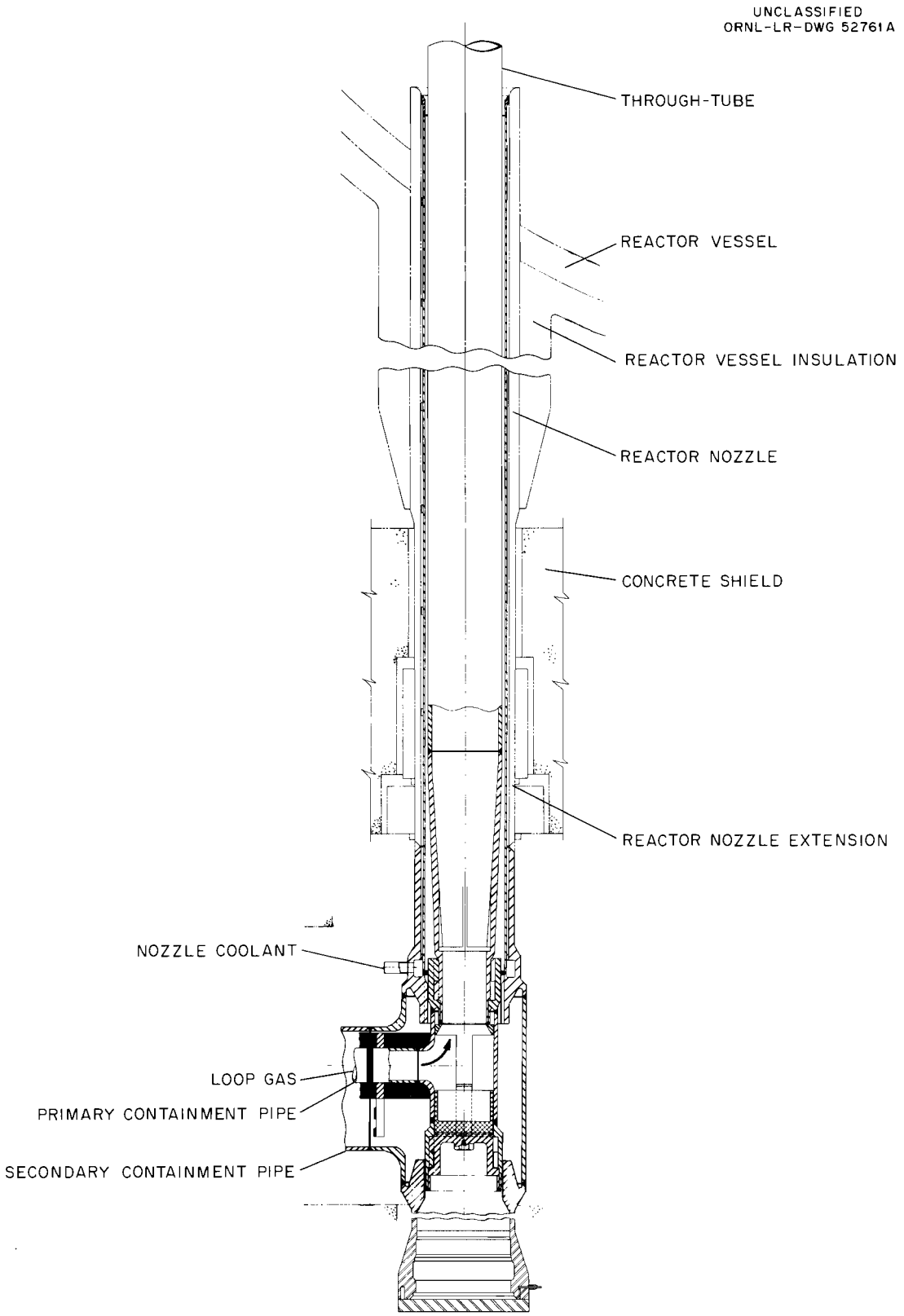

Fig. 17. Bottom Nozzle Tee Section for 9 1/2-in.-OD Single Through-Tube.

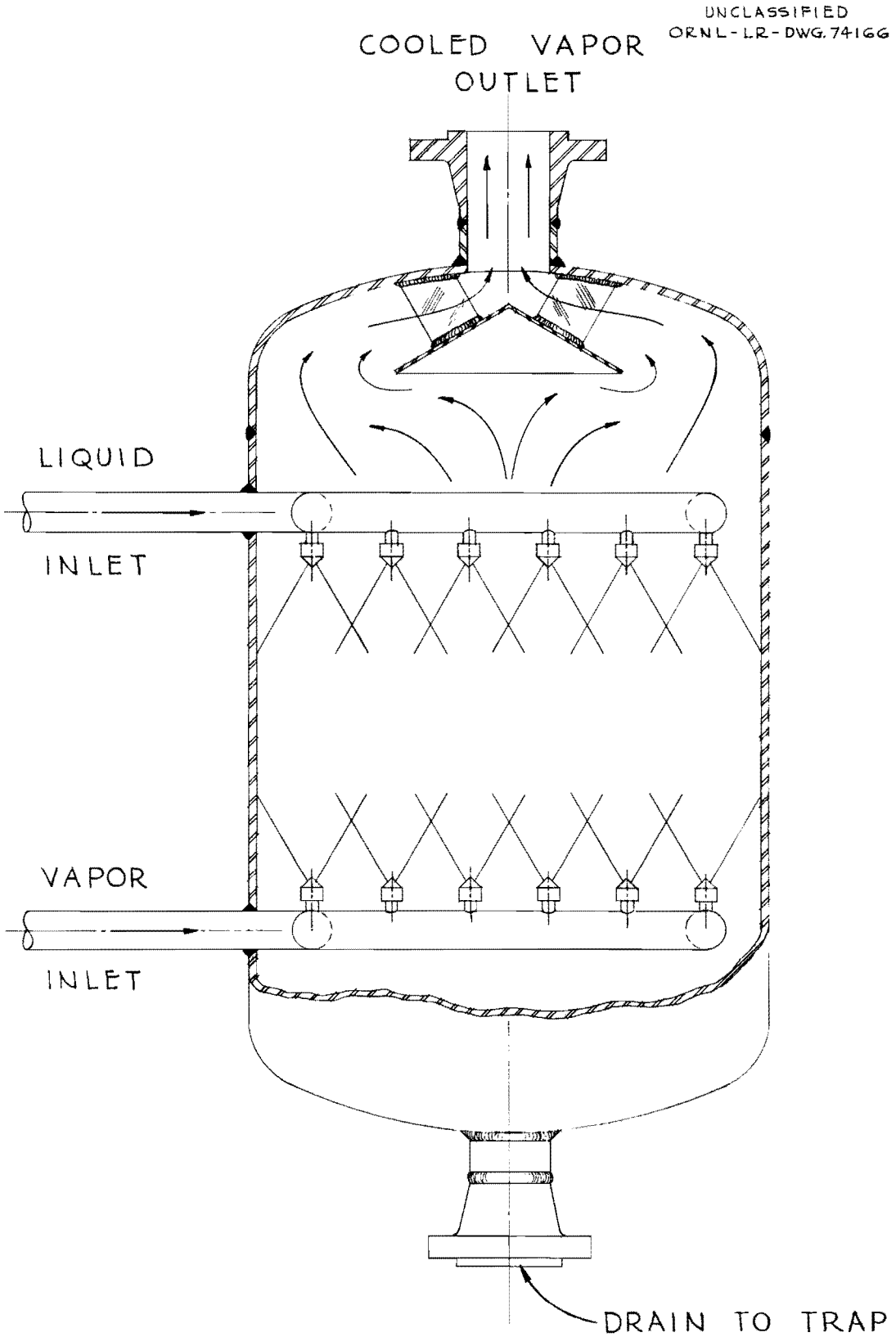

Fig. 18. Mainstream Cooler.

and eliminates the thermal expansion problems associated with a shell-and-tube type of exchanger. In the proposed system the transfer of energy from the loop fluid to a secondary coolant, which must occur somewhere in the system and which might have been accomplished in a mainstream cooler of a different type, takes place in a condenser where the heat transfer coefficient is high and the maximum temperature low.

Filter

It is anticipated that the main stream of steam will pass through a filter system before entering the compressors. The filter will be designed to remove most of the particulate matter which may be carried by the steam. Because of the possibility that fission products may accumulate in the filter, the filter vessel will be shielded; and when filter replacement is necessary, the filter and filter vessel will be disposed of by burial. A bypass line around the filter will permit operation of the loop if the filter becomes clogged or must be taken out of service for other reasons.

Compressor

In the proposed system shown in Fig. 15, the steam is circulated in the main circuit by three centrifugal compressors connected and operated in series. In the event that one of the three compressors fails, the remaining two will be operated at increased speed to provide the proper flow rate. Each compressor is driven by a steam turbine. The turbine and compressor are mounted on the same shaft and are enclosed in a single housing. Steam is supplied from the test section directly to each turbine and exhausts from the turbines to the condenser.

The compressor and turbine have hydrostatic bearings that use liquid water as the lubricant. The water is pumped to the bearings from the storage tank located below the condenser. A preliminary analysis* indicated that using liquid water as the lubricant would be more dependable and would provide greater flexibility of operation than employing the

*W. K. Stair, personal communication, February 25, 1960.

vapor as the lubricant. The water that serves as the lubricant is returned from the turbine-compressor through a trap to the condenser.

The design of the steam-cooled loop has not proceeded far enough to establish, except in a general way, the compressor operating conditions; therefore, detailed design of the compressors and turbines has not been attempted.

Mainstream Heater

The mainstream heater performs several functions. It is needed during the startup operation in order to preheat the in-pile test section and the chase piping to near the operating temperature before fission heating is available. It may be needed to maintain the loop temperature during shakedown tests or during experiments in which no fission heat source exists. Also the heater may be needed during normal loop operation to provide control of the temperature of the gas entering the test section.

It is proposed that the heater consist of two straight sections of seamless steel pipe joined at one end by a 180° turn. This U-tube type of heater will be heated by passing a large electric current through the two straight sections of pipe. A detailed design of the heater has not been made.

Joints, Valves, Traps, and Piping

Pipe joints are needed to facilitate the removal and replacement of the loop compressors and the mainstream filter. These are to be mechanical joints containing double, metallic seals, with a pressurized gas-buffered zone between the seals. The buffer gas, probably helium, should be pressurized from 50 to 100 psi above the loop fluid pressure and monitored continuously for leakage. This type of joint provides positive assurance that radioactive loop gas will not leak into the experimenters' cell in the event of seal leakage. Where small-size joints (2 1/2-in. IPS and below) are needed, single-seal mechanical joints are to be provided.

The commercially available joint best suited for this application is the Conoseal joint manufactured by the Marman Division of the Aeroquip

Corporation, which is shown in Figs. 19 and 20. Selection of this type of joint was based on the results of an extensive testing program,[5] which demonstrated the reliability of these joints for conditions similar to those to be encountered in the steam loop.

Several types of valves are required to assure proper and safe operation of the experimental loop. Isolation valves are needed to separate the in-cell portion of the mainstream piping from the piping inside the reactor containment vessel and to isolate the loop compressors, the auxiliary compressor, and the mainstream filter from the remainder of the system. These should be hand-operated valves that are normally in the open position. Other smaller hand-operated isolation valves are needed throughout the loop.

The filter bypass valve should be a motor-operated valve that provides protection against loss of coolant flow because of a clogged filter. Normally, this valve will be in the closed position.

Check valves are to be provided to bypass the flow around each mainstream compressor if the compressor fails. A check valve should also be provided in the intake line to the auxiliary compressor to prevent reverse flow through this compressor to permit it to be on line and ready for use at all times. Also, a check valve is to be placed in the line to the filter to prevent reverse flow in the in-cell piping and thus assure flow through the test section when the auxiliary compressor is in operation.

Pressure-relief valves are to be installed in the loop to provide protection against overpressurizing any part of the system. Steam traps should be installed at all points in the system where liquid may tend to collect during startup or during normal operation.

At the present time, the design of the steam-cooled loop has not been carried far enough to have determined the specifications for the loop piping, except the through-tube and chase piping. It appears that the piping material would be one of the stainless steels. Before a

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[5]J. C. Amos and R. E. MacPherson, "Interim Report - Mechanical Joint Evaluation Program," USAEC Report ORNL CF 60-9-77, Oak Ridge National Laboratory, Sept. 26, 1960.

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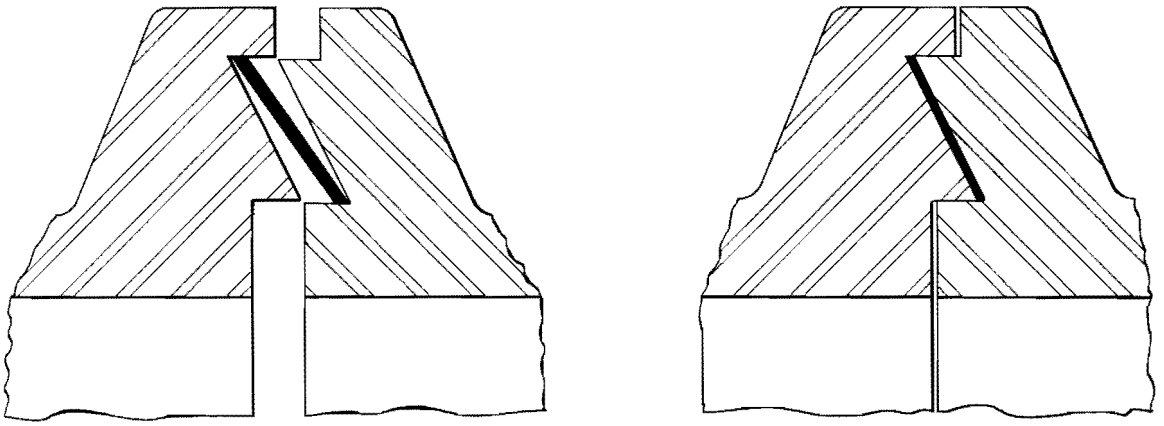

Fig. 19. Cross Section of Conoseal Gasket, as Installed.

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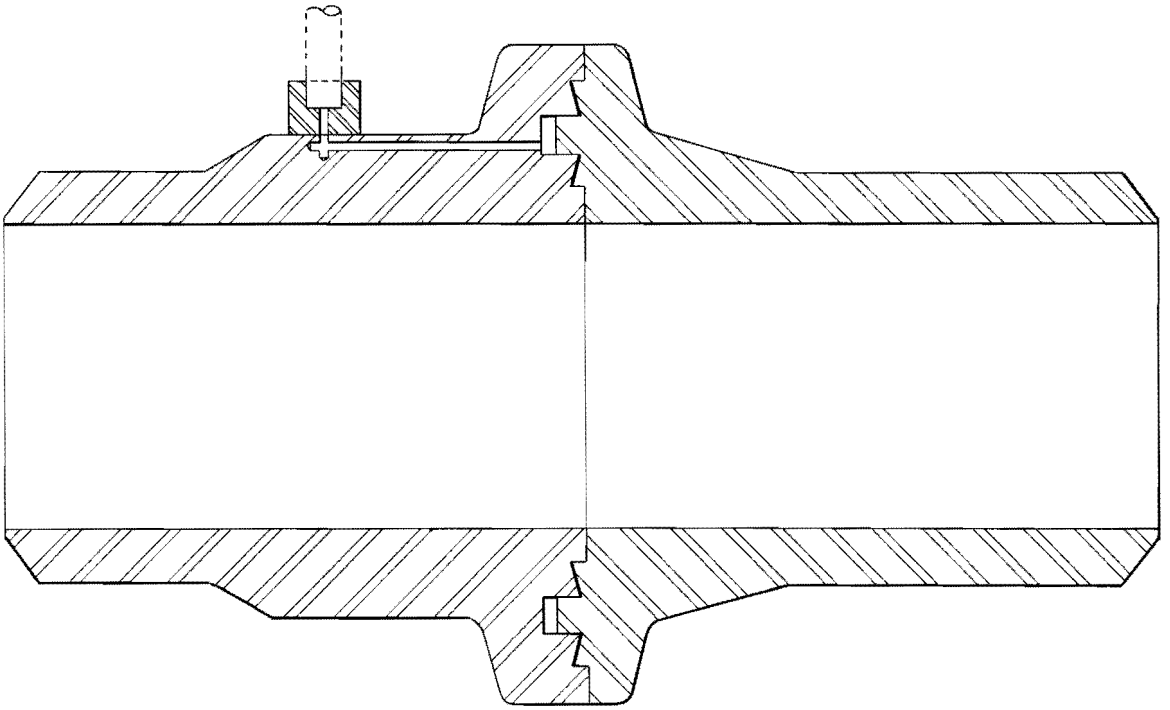

Fig. 20. Cross Section of Conoseal Double-Sealed Gas-Buffered Mechanical Joint, as Installed.

decision is made, however, the danger of stress-corrosion (chloride) should be carefully considered.

Auxiliary Systems and Equipment

In addition to the mainstream system described above, there are supporting or auxiliary systems necessary for the proper operation of the proposed loop. Some of these are (1) a system to supply the demineralized water for the experimental loop, (2) service water (probably river water) needed as cooling water for the condenser, (3) an inert gas supply system required during startup and to permit pressurizing the through-tube when the loop is shut down but the reactor is operating, (4) a means for decontaminating the loop equipment to transfer and store the experimental loop fluid, (5) provisions for detecting leaks and for sampling gas to obtain information on fission-product release and deposition, (6) a system to permit safe discharge to the atmosphere of the noncondensable gases, (7) equipment needed for the startup operation of bringing the entire system to operating conditions, (8) a service machine for installation and removal of experimental assemblies, and (9) an experimental assembly removal cooling system to provide cooling of the experimental equipment while it is in transit from the through-tube into the service machine and while it is contained within the service machine. Other services which must be provided include normal and emergency electrical power, a communication system, and fire and evacuation alarms. Of the various auxiliary systems and equipment, only the startup system has been given any detailed study.

Startup System and Procedure

The pieces of equipment that will be used during the startup operation and only at this time are the boiler and the separator. Other items needed for startup have other functions. The auxiliary compressor-turbine is required for startup, but it also serves as emergency standby equipment. The mainstream heater will be used during startup and also during normal operation for regulating the temperature of the fluid entering the test section.

When installing or removing loop experimental equipment with the EGCR service machine, it will be necessary that the fluid in the test section and chase piping be helium; also, it will be desirable to prevent condensation from occurring in this portion of the loop. For these reasons the loop is to be arranged so that it may be operated as two separate systems. That part of the loop consisting of the test section, chase piping, auxiliary turbine-compressor and the heater will operate with helium, while the remainder of the loop will operate with steam.

Because the system fluid will appear in both the liquid and vapor phases during startup, this operation represents a more difficult problem in the steam-cooled loop than in the other (helium, carbon dioxide, and hydrogen) loops. For this reason a detailed procedure for startup is presented.

In discussing the startup procedure, reference is made to the main valves in the system. The valves are numbered and are shown in Fig. 15. A tabulation of the valve positions for each step of the procedure is given in Table 3. It is assumed that the system is filled with air at ambient temperature and pressure and that the system fluid (water) is stored as a liquid in the storage tank and boiler. From these initial conditions the system may be brought to operating conditions by the following steps (the lettered valve positions A through K refer to columns in Table 3):

Step 1. The valves are placed in the startup position (position A).

Step 2. Valve 24 is opened to allow inert gas to purge the air from the test section (position B).

Step 3. Valve 11 is closed (position C) and the boiler fired. The system pressure is allowed to build up to approximately 70 psia (303°F) and the gas pressure in the test section is raised to match the steam pressure at all times. The air in the system is purged through the condenser to the stack.

Step 4. During the warming period, valves 16, 17, 18, and 27 are opened sufficiently to permit warming up of the turbines but not enough to start them (position D). The valve opening may have to be reduced as the pressure builds up.

Table 3. Valve Positions for Startup

Valve No.	Valve Position										
	A	B	C	D	E	F	G	H	I	J	K
1	O[a]	O	O	O	O	O	O	O	O	O	O
2	C[b]	C	C	C	C	C	C	C	O	O	O
3	O	O	O	O	O	O	O	O	O	O	O
4	O	O	O	O	O	O	O	O	O	O	O
5	O	O	O	O	O	O	O	O	O	O	C
6	O	O	O	O	O	O	C	C	C	C	O
7	O	O	O	O	O	O	O	O	O	O	C
8	O	O	O	O	O	O	O	O	O	O	C
9	C	C	C	C	C	C	C	O	O	O	O
10	O	O	O	O	O	O	O	O	O	O	O
11	O	O	C	C	C	C	C	O	C	C	C
12	O	O	O	O	O	O	O	O	O	C	C
13	C	C	C	C	C	C	C	C	C	C	C
14	C	C	C	C	C	C	C	C	C	O	O
15	O	O	O	O	O	O	C	C	C	C	C
16	C	C	C	PO[c]	PO	PO	O	O	O	O	O
17	C	C	C	PO	PO	PO	O	O	O	O	O
18	C	C	C	PO	PO	PO	O	O	O	O	O
19	O	O	O	O	O	O	O	O	O	O	C
20	C	C	C	C	C	C	C	C	C	C	O
21	C	C	C	C	C	C	C	C	C	C	O
22	O	O	O	O	O	O	O	O	O	O	O
23	O	O	O	O	O	O	O	O	O	O	C
24	C	O	O	O	O	O	O	C	C	C	C
25	O	O	O	O	O	O	O	O	O	C	C
26	C	C	C	C	C	C	C	C	C	O	O
27	C	C	C	PO	PO	O	O	O	O	PO	PO
28	O	O	O	O	O	O	O	O	O	O	O
29	C	C	C	C	C	C	C	O	O	O	O
30	C	C	C	C	O	O	O	O	O	C	C
31	C	C	C	C	C	C	O	O	O	O	O
32	C	C	C	C	C	C	O	O	O	O	O
33	C	C	C	C	C	C	O	O	O	O	O
34	O	O	O	O	O	O	O	O	O	O	C
35	O	O	O	O	O	O	O	O	C	C	C

[a]Open.

[b]Closed.

[c]Partially open.

Step 5. After the auxiliary turbine is warm, valve 30 is opened to permit lubricant to flow to the auxiliary turbine and compressor bearings (position E).

Step 6. Valve 27 is opened and the auxiliary turbine started (position F).

Step 7. After establishing gas flow in the test section, the heater is turned on and the test section heated to 300°F.

Step 8. After the entire system has been brought to approximately 300°F, the system pressure is reduced to 25 psia. This will cause any small amounts of liquid which might accumulate in untrapped places to evaporate.

Step 9. Valves 31, 32, and 33 are opened, valves 6 and 15 closed, and the turbines started by opening valves 16, 17, and 18, as needed (position G).

Step 10. With the valves in position G, the loop will be operating as two separate systems: (1) the auxiliary compressor will be circulating gas through the heater and test section; (2) steam will be circulating through the rest of the loop. Operation may continue in this manner until the experiment is inserted into the test section.

Step 11. The inert gas in the test section is replaced with steam by opening valves 9, 29, and 11 and closing valve 24 (position H).

Step 12. After operating briefly in position H, valve 11 is closed, valve 2 opened, and valve 35 closed (position I).

Step 13. The auxiliary turbine-compressor is taken off the line by closing valves 12, 25, and 30 and opening valves 14 and 26. Valve 27 is partially closed; it should be left open enough to keep the turbine warm but not enough to permit the turbine to operate (position J).

Step 14. As reactor power comes up, the boiler is taken off the line and the cooler put into operation by closing valves 34, 23, 19, and 5, opening valves 20, 21, and 6, and closing valves 7 and 8 (position K).

With the valves in position K the system will be ready to be brought to the desired testing conditions.

Loop Accidents

Various types of accidents may result from a failure of the loop piping, of the loop components, or of the auxiliary equipment serving the loop. Each of the possible accidents must be studied with care in order to determine the nature and extent of the damage and the danger associated with them. Only one of the various possible accidents that might occur with the steam-cooled loop, a leak in the through-tube, has been analyzed.

Contamination Resulting from a Steam Leak

A failure of the through-tube of the proposed EGCR steam loop would permit the steam to leak into and mix with the reactor coolant. A sleeve, which surrounds the through-tube and which is sealed to the through-tube at the bottom but open at the top, will prevent the escaping steam from impinging directly onto the graphite. Instead, the steam will mix with the reactor coolant at a point above or downstream of the graphite. The mixture (helium and water vapor) will in due time be circulated through the reactor and can lead to a chemical reaction between the steam and the graphite.

The following reactions would occur:

$$(1) \quad C + H_2O \rightarrow H_2 + CO$$

$$(2) \quad C + 2H_2O \rightarrow 2H_2 + CO_2$$

$$(3) \quad C + CO_2 \rightarrow 2CO$$

$$(4) \quad CO + H_2O \rightarrow CO_2 + H_2$$

These reactions occur in the manufacture of water gas and are predominantly endothermic. The literature[6,7] indicates that at temperatures of 1300°R and less the steam has little part in the reactions involved in producing water gas.

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[6] J. A. Goff, "Chemical Reactions in the Gas Producer," Ind. Engr., 18(6): 585 (1926).

[7] Mechanical Engineers Handbook, 5th Ed., L. S. Marks (Ed.), McGraw-Hill, p. 349, 1951.

Since the reactor graphite in contact with the reactor coolant will be at a temperature greater than 1300°R, it is necessary to determine the extent to which it may be expected that the water-gas type of reactions can occur. For purposes of this determination, the following assumptions are made:

Reactor coolant (helium)	
Volume, ft^3	10,440
Pressure, psia	315
Average temperature, °F	780
Graphite surface temperature, °F	1000
Water vapor	
Volume, ft^3	150
Pressure, psia	1000
Average temperature, °F	825

Further, chemical equilibrium will be obtained at 1000°F.

In order to determine the amount of steam that will leak out into the reactor coolant, it is assumed that the steam remaining in the loop expands isothermally to 315 psia. Calculations (see Appendix B) show that the mixture entering the graphite consists of 248 moles of helium and a maximum of 8.33 moles of water vapor. The four reactions that can occur indicate that the products will include H_2, CO, and CO_2.

Tables 4 and 5 give the results of the reaction calculations. If the steam-graphite reaction proceeds to equilibrium at 1000°F, the amount of graphite involved will be 31 lb, and the resultant gas mixture will be 0.25% CO, 0.74% CO_2, 1.23% H_2, 1.47% H_2O, and 95.81% He.

Table 4. Equilibrium Mixtures at Various Equilibrium Temperatures

Gas	Equilibrium Mixtures (moles)			
	At 1200°R	At 1400°R	At 1600°R	At 1800°R
CO	0.03	0.31	1.83	5.03
CO_2	1.04	1.80	1.95	1.16
H_2	2.11	3.91	5.73	7.35
H_2O	6.19	4.39	2.60	0.95
He	248.00	248.00	248.00	248.00

Table 5. Amount of Graphite Reacted at Various Equilibrium Temperatures

Equilibrium Temperature (°R)	Graphite Reacted	
	Moles	Pounds
1200	1.07	12.8
1400	2.11	25.3
1600	3.78	45.4
1800	6.19	74.3

That a steam-graphite reaction would occur in the event of a leak is fairly certain, but the actual extent of this reaction is somewhat a matter of conjecture. The results given above and in Tables 4 and 5 represent the maximum reaction to be expected in the event of a leak. For an equilibrium at 1460°R the resulting mixture would be 259 moles of gas. The increase from 245 moles of helium to 259 moles of mixture would produce an increase in the reactor coolant pressure from 315 to 329 psia.

The analysis indicates that a dangerous hazard would not be produced; however, it can be expected that a loss of graphite in the reactor and a contamination of the coolant gas would occur. It is likely that the main loss of graphite will be suffered by the removable sleeves and the coolant gas cleanup system will eliminate much of the steam before it has an opportunity to react with the graphite; therefore it is suggested that the through-tube not be doubly contained but that it have a protective sleeve around it.

Appendix A

THERMODYNAMIC CALCULATIONS

Calculations were made for each system under consideration. The details of the calculations for system IV are given below. The results of the calculations for all systems were given in Table 1.

The temperature-entropy diagram for system IV is shown as Fig. 12. The given conditions are:

p_1 = 605 psia

p_2 = 670 psia, T_2 = 740°F

p_3 = 638 psia, T_3 = 1050°F

p_6 = 15 psia, T_6 = 213°F

M = 9660 lb/hr

Compressor efficiency, %	80
Turbine efficiency, %	80
Pump efficiency, %	80
Heat transfer coefficients, Btu/hr·ft^2·°F	
For condenser	600
For exchanger	10
Cooling water temperature, average, °F	80

From steam tables[1] the following enthalpies were obtained:

h_2 = 1370.3 Btu/lb

h_3 = 1543.5 Btu/lb

h_6 = 1150.8 Btu/lb

h_7 = 181.11 Btu/lb

For a compression efficiency of 80%, h_1 was found to be 1355.2 Btu/lb, and h_8 was 183.4 Btu/lb.

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[1] J. H. Keenan and F. K. Keyes, Thermodynamic Properties of Steam, John Wiley and Sons, Inc., New York, 1936.

Energy balances for the turbine-compressor and the exchanger yielded, respectively:

$$9660\ (1370.3 - 1355.2) = m\ (1543.5 - h_5)\ ,$$

$$9660\ (1543.5 - 1355.2) = m\ (1543.5 - 183.4)\ ,$$

where m is the mass flow rate through the turbine. From these equations,

$$m = 1337\ \text{lb/hr}\ ,$$

$$h_5 = 1434.4\ \text{Btu/lb}\ .$$

The compressor work is

$$w_c = 9660\ (1370.3 - 1355.2)$$
$$= 145{,}900\ \text{Btu/hr}\ .$$

Heat transfer in the test section is

$$q_T = 9660\ (1543.5 - 1370.3)$$
$$= 1{,}673{,}000\ \text{Btu/hr}\ .$$

Heat transfer in the exchanger is

$$q_E = 1337\ (1355.2 - 183.4)$$
$$= 1{,}566{,}700\ \text{Btu/hr}\ .$$

Heat transfer in the condenser is

$$q_c = 1377\ (1434.4 - 181.1)$$
$$= 1{,}675{,}700\ \text{Btu/hr}\ .$$

In order to reduce the size of the condenser, it is considered that part of the pump discharge is mixed with the steam from the turbine so that saturated steam enters the condenser. The quantity of water to be recirculated is found from

$$1337\ (1434.4 - 1150.8) = m'\ (1150.8 - 183.4)\ ,$$

$$m' = 392\ \text{lb/hr}\ .$$

The pump work is

$$w_p = (1337 + 392)(183.4 - 181.1)$$
$$= 3976\ \text{Btu/hr}\ .$$

The temperature difference within the condenser is

$$\Delta T = 213 - 80 = 133\,^{\circ}F \ .$$

The heat transfer area required is, for the condenser,

$$A_c = q_c/U\,\Delta T$$

$$= \frac{1{,}675{,}700}{(600)(133)} = 21 \text{ ft}^2$$

and for the exchanger,

$$A_E = q_E/U\,\Delta T$$

$$= \frac{1{,}566{,}700}{(10)(800)} = 196 \text{ ft}^2 \ .$$

For the exchanger, no heat transfer surface in the usual sense exists. The area A_E is simply indicative of the size of mixing chamber required.

Appendix B

CALCULATIONS FOR STEAM-GRAPHITE REACTION

The reactions expected to occur when steam comes in contact with graphite are

$$(1)\quad C + H_2O \rightarrow H_2 + CO$$

$$(2)\quad C + 2H_2O \rightarrow 2H_2 + CO_2$$

$$(3)\quad C + CO_2 \rightarrow 2CO$$

$$(4)\quad CO + H_2O \rightarrow CO_2 + H_2$$

The following assumptions are made:

Reactor coolant (helium)	
Volume, ft^3	10,440
Pressure, psia	315
Average temperature, °F	780
Graphite surface temperature, °F	1000
Water vapor	
Volume, ft^3	150
Pressure, psia	1000
Average temperature, °F	825

Chemical equilibrium will be obtained at 1000°F.

It is assumed that the steam at 1000 psia and 825°F will expand isothermally to 315 psia if a leak occurs.

From the steam tables,

$$v_{825°F,\ 1000\ psia} = 0.7065\ ft^3/lb\ ,$$

$$v_{825°F,\ 315\ psia} = 2.373\ ft^3/lb\ ,$$

$$\Delta m = \frac{150}{0.7065} - \frac{150}{2.373} = 149\ lb\ ,$$

$$n_{H_2O} = \frac{149}{18} = 8.3 \text{ moles of water vapor}\ ,$$

$$n_{He} = \frac{(315)(144)(10{,}440)}{(1545)(1240)} = 248 \text{ moles}\ .$$

If the final equilibrium mixture is considered to consist of a moles of CO, b moles of CO_2, c moles of H_2, d moles of H_2O, and e moles of He, where

$$e = 248$$

$$c + d = 8.3$$

$$\frac{a}{2} + b + \frac{d}{2} = \frac{8.3}{2}$$

it is found that

$$d = 8.3 - a - 2b \ ,$$

$$c = a + 2b \ .$$

The equilibrium is, then,

$$CO = a$$

$$CO_2 = b$$

$$H_2 = a + 2b$$

$$H_2O = 8.3 - a - 2b$$

$$He = \frac{248}{256.3 + a + b}$$

The equilibrium constants for the reactions (1), (2), (3), and (4) are

$$k_1 = \frac{(P_{H_2})(P_{CO})}{(P_{H_2O})} = \frac{(a + 2b)\ a(p)}{(8.3 - a - 2b)(256.33 + a + b)} \ , \qquad (1)$$

$$k_2 = \frac{(P_{H_2})^2(P_{CO_2})}{(P_{H_2O})^2} = \frac{(a + 2b)^2\ b(p)}{(8.3 - a - 2b)^2(256.3 + a + b)} \ , \qquad (2)$$

$$k_3 = \frac{(P_{CO})^2}{(P_{CO_2})} = \frac{a^2(p)}{b(256.3 + a + b)} \ , \qquad (3)$$

$$k_4 = \frac{(P_{CO_2})(P_{H_2})}{(P_{CO})(P_{H_2O})} = \frac{b(a + 2b)}{a(8.3 - a - 2b)} . \qquad (4)$$

Since $k_2/k_1 = k_4$, all equations are satisfied if k_3 and k_4 are satisfied.

From Obert,[1] the values of k_3 and k_4 are

Temperature (°R)	k_3	k_4
1200	6.3×10^{-5}	12.6
1400	4.47×10^{-3}	5.13
1600	0.141	2.37
1800	1.78	1.35

Solving Eqs. (3) and (4) for the values of a and b gives the following:

Temperature (°R)	a	b
1200	0.028	1.04
1400	0.312	1.80
1600	1.83	1.95
1800	5.03	1.16

The equilibrium mixtures were calculated and presented in Table 4.

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[1]E. F. Obert, Thermodynamics, Figure VI, McGraw-Hill, New York, 1948.

Internal Distribution

1. R. G. Affel
2. S. E. Beall
3. M. Bender
4. A. L. Boch
5. W. F. Boudreau
6. R. B. Briggs
7. T. J. Burnett
8. W. H. Carter
9. F. L. Culler
10. C. W. Cunningham
11. I. T. Dudley
12. A. P. Fraas
13. W. R. Gall
14. D. R. Gilfillan
15. B. L. Greenstreet
16. A. G. Grindell
17. L. R. Koffman
18. T. S. Kress
19. M. I. Lundin
20. R. N. Lyon
21. H. G. MacPherson
22. H. McLain
23. W. D. Manly
24. A. J. Miller
25. H. G. O'Brien
26. A. M. Perry
27. T. W. Pickel
28. M. W. Rosenthal
29. H. W. Savage
30. A. W. Savolainen
31. M. J. Skinner
32. I. Spiewak
33. E. Storto
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