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OPERATING EXPERIENCE WITH GAS-BEARING CIRCULATORS IN A HIGH-PRESSURE HELIUM LOOP*

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Abstract

A high-pressure engineering test loop has been designed and constructed at the Oak Ridge National Laboratory for circulating helium through a test chamber at temperatures to 1000°C. The purpose of this loop is to determine the thermal and structural performance of proposed components for the primary loops of gas-cooled nuclear reactors. Five MW of power is available to provide the required gas temperature at the test chamber, and an air-cooled heat exchanger, rated at 4.4 MW, serves as a heat sink.

Three gas-bearing circulators, mounted in series, provide a maximum volumetric flow of 0.47 m^3/s and a maximum head of 78 kJ/kg at operating pressures from 0.1 to 10.7 MPa. Control of gaseous impurities in the circulating gas was the significant operating requirement that dictated the choice of a circulator that is lubricated by the circulating gas. The motor for each circulator is contained within the pressure boundary, and it is cooled by circulating the gas in the motor cavity over water-cooled coils. Each motor is rated at 200 kW at a speed of 23,500 rpm. The three units were designed, fabricated and performance tested by Mechanical Technology, Inc. (MTI).

The circulators have been operated in the loop for more than 5000 h. The flow of the gas in the loop is controlled by varying the speed of the circulators through the use of individual 250-kVA, solid state power supplies that can be continuously varied in frequency from 50 to 400 Hz; these units were manufactured by Servo Optics. To prevent excessive wear on the gas bearings during startup, the circulator motor accelerates the rotor to 3000 rpm in less than one second. Circuits within the power supply monitor both startup and direction of rotation and terminate operation when necessary to prevent bearing damage.

During operation, no problems associated with the gas bearings, per se, were encountered; however, related problems pointed to design considerations that should be included in future applications of

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circulators of this type. The primary test that has been conducted in this loop required sustained operation for several weeks without interruption. After a number of unscheduled interruptions, the operating goals were attained. During part of this period, the loop was operated with only two circulators installed in the pressure vessels with a guard installed in the third vessel to protect the closure flange from the gas temperatures. Unattended operation was achieved, and the design safety controls operated dependably to prevent damage to either the test item or the loop components. Continuous, on-line data collection provided a complete record of the operating history.

BACKGROUND

A high-pressure, high-temperature loop was designed and constructed at the Oak Ridge National Laboratory. The original operating requirements were dictated by the goal of determining the flow and thermal performance characteristics of the fuel assemblies for the proposed Gas-Cooled Fast Reactor (GCFR). For this application, the loop was designated as the Core Flow Test Loop (CFTL). The operating pressure was 10.7 MPa, and the maximum gas temperature was 600°C. For the planned operation, the test structure was the source of heat, rapid transients were specified for both power and pressure, and circulating helium with very low levels of impurities was required. A relatively large pressure increase (78 kJ/kg) was needed to provide flow through the test section and loop piping. This loop has been described in a number of publications. (Refs. 1, 2, 3)

Based on these requirements, a program was initiated to develop, construct, and test a gas-bearing circulator larger than any existing machine of that type. The task was undertaken by Mechanical Technologies, Inc., (MTI) of Latham, NY, and a description of the procurement and construction has been given in detail in a paper presented to the ASME (Ref. 4). The resulting system design consisted of three identical units in series to provide the needed head. This ASME paper also describes the three 250-kVA solid-state, variable-frequency power supplies that were acquired to provide an adjustable speed for the units. Over most of the operating range, the flow was essentially proportional to this speed. The maximum gas temperature at the circulators was originally specified as 340°C, but it was later upgraded to 450°C.

Prior to the operation of the loop in the test of core elements for the GCFR, its mission was redirected to the test of primary loop components for High Temperature Gas-Cooled Reactors (HTGR). As the Component Flow Test Loop (CFTL), the required operating envelope was significantly modified. The maximum operating pressure was 7.2 MPa, and a maximum gas temperature in the loop of 1000°C was needed. Since the test section was no longer a source of heat, a helium heater had to be designed and installed. Probably the most significant change in the operation was the need for long-term, steady-state operation. This imposed a significant new requirement on the circulators. Also, the need to maintain very low levels of impurities was eliminated; however, it was still necessary to control these levels precisely over long time intervals.

The pressure boundary of the loop was designed for a maximum temperature of 600°C. To provide gas temperature of 1000°C in the test chamber, attemperation flow was provided between the test chamber and the pressure boundary. The main and attemperation flows were mixed and cooled before returning to the circulators to limit the maximum inlet gas temperature to 450°C. Testing of the circulators proved this to be an acceptable operating condition.

INTRODUCTION

The initial test installed in the CFTL was one to determine the thermal and structural performance of the graphite post used to support the core of the HTGR. In this Core Support Performance Test (CSPT) [Ref. 2], significant experience was obtained in the operation of the three gas-bearing circulators over a period that totaled more than 5000 h. This paper will summarize that experience.

A significant number of interruptions during this test period can be attributed to problems associated with the helium heaters that were installed to bring the helium to the temperature required at the inlet of the test chamber. In addition, the test was limited due to a steady increase, under extreme test conditions, in the pressure drop across a full-flow filter that was installed immediately upstream from the circulators. The details of the performance of these constituents of the loop will not be addressed, even though the pressure drop across the filter did limit the operation of the circulators. Only those problems associated with the operation of the circulators and their associated power supplies will be addressed.

There was one significant problem associated with the materials used in the circulators. That problem and its subsequent resolution are discussed in another paper (Ref. 5), since it was not a problem associated with the circulator operation.

BRIEF DESCRIPTION OF THE CFTL

The CFTL is a closed, out-of-reactor loop circulating helium at temperatures and pressures anticipated in high-temperature gas-cooled reactors (HTGR). Figure 1 shows the major loop components. Three helium circulators are connected in series to provide flow around the loop. This flow is divided upstream of the test vessel into a primary helium stream and an attemperation stream. The total flow and the flow in both legs is measured by vortex shedding flowmeters (Ref. 6) that were specially developed and calibrated for use in this loop. The temperature of the primary helium stream is raised to the desired test

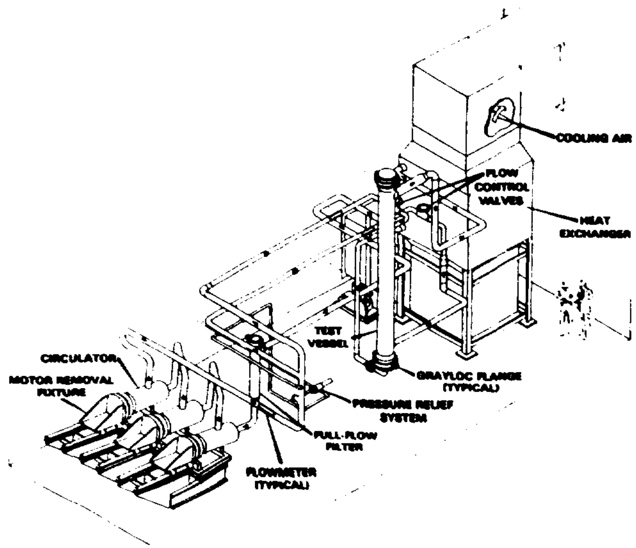


Fig. 1 Component Flow Test Loop (CFTL)

temperature by an electrical resistance heater. This high-temperature helium is mixed with the attemperation flow before it enters an air-cooled heat exchanger in which the helium temperature is reduced to an acceptable inlet temperature for the circulators. The gas flows through a full-flow filter before going to the inlet of the first circulator.

Figure 2 shows the circulator pressure vessels and piping before the thermal insulation was installed. The full-flow filter is shown in the foreground. The interconnecting 6-in., sched. 80, piping must accommodate the differential thermal expansion during heatup.

HISTORY OF THE CIRCULATORS

There are a few historical comments about the development and testing of the circulators that are significant to the subsequent events in the operating experience. All three units are identical and, therefore, interchangeable. In discussing the operations, it is convenient to refer to three major segments. One is the pressure vessel with its closure flange, the second is all of the internal parts that are mounted on the closure flange, and the third is the variable-frequency power supply (VFPS).

Fig. 2 Circulator pressure vessels and piping in CFTL

In the development, manufacturing, and testing of the circulators, MTI received one pressure vessel and installed it in a test loop in Latham, NY. One VFPS was delivered by Servo Optics in 1978 and provided to MTI for use in conjunction with the test loop. MTI then manufactured the first prototype of internals and proceeded to determine its performance characteristics before manufacturing the other two units. This prototype unit was operated at all ranges of speeds and temperatures within the operating envelope. It was also subjected to three rapid depressurizations.

After successful testing of the prototype, an order was placed for two additional units. The operational characteristics of these units were verified by installing them in the same pressure vessel that was used for the prototype unit. Each circulator was subject to a 100-h endurance run at the design operating temperature and pressure. A total of 13 depressurization tests were performed during the testing of all three circulator segments.

Finally, when the desired operating temperature of the circulators was increased to 450°C, the prototype unit was tested at this temperature. Thermocouples installed in the electrical windings of the stator field, which was the component most sensitive to elevated temperatures, indicated a safe operating range at the elevated gas temperature. Testing at this elevated temperature did, however, produced a distinct discoloration of the 304 SS pressure vessel at the circulator end.

The two remaining pressure vessels and the two remaining VFPS were delivered directly to the Oak Ridge site. These two power supplies were delivered in 1981, and the internal circuits were significantly different from the first unit. The operating specifications for all three units were the same.

DESIGNATION OF MAJOR CIRCULATOR SEGMENTS

For convenience in the following discussions, these major segments of the circulators are designated with specific numbers 1, 2, and 3. The initial pressure vessel delivered to MTI and the prototype circulator internals are designated Vessel #1 and Circulator #1, respectively. The VFPS delivered to MTI was transferred to ORNL after the other two VFPS were delivered and installed. Therefore, it is designated VFPS #3. The two units delivered in 1981 were identical and designated as VFPS #1 and VFPS #2.

The two additional pressure vessels were delivered to ORNL and were installed so that the designations of 1, 2, and 3 corresponded to the upstream to downstream orientation of the three units. There are no significant differences between Vessels #2 and #3, except for their location.

Except for a limited time interval during the initial testing period, VFPS #1 was always connected to the circulator in Vessel #1. The same was true for VFPS #2 and #3. Initially, Circulator #1 (the prototype) was installed in Vessel #1; Circulator #2 was in Vessel #2; and Circulator #3 was in Vessel #3. This relationship was subsequently altered as discussed in the operating experience.

OPERATING EXPERIENCE

Initial Operation

In the initial testing of the circulators installed in the loop, a section of straight pipe was installed in place of the test vessel shown in Fig. 1, and no flow control valves were installed. A fixed orifice was installed to simulate the pressure loss in the test chamber. This "shakedown" operation was started in October 1981, and acceptance testing was completed in December 1981. This operation was delayed by damage to the circulator bearing; however, this incident should be attributed to electrical noise on the bearing capacitance probes. This was the first significant operating occurrence.

Capacitance probes were placed at 90° at the journal bearings. These two probes, connected to the x and y axes of an oscilloscope, provided a continuous indication of the shaft displacement from the bearing surfaces. During this initial operation, the sensors in Circulator #1 indicated an instability that had not been experienced during the earlier single-unit tests at MTI.

Circulator #1 was removed and inspected, and the bearing clearance was readjusted. The bearing pads were sprayed with molybdenum disulfide; during bakeout to remove volatile material in the spray, the pads were overheated and warped. This deformation of the pad resulted in a failure of the bearing during subsequent bench test operation in air. The bearing was repaired, and subsequent operation intermittently produced the same apparent indication of journal bearing instability.

A capacitance sensor readout system was connected directly to the sensors at the circulator. This connection eliminated about 15 m of coaxial instrument lead, and eliminated the electrical noise. The bearing performance was found to be completely satisfactory.

During the investigation of the apparent bearing instability, it was postulated that the pressure differences caused by connecting the three circulators in series might affect the bearing performance. To check this effect, Circulators #1 and #2 were interchanged between Vessels #1 and #2. This had no effect, since the units were essentially identical. However, Circulator #1 (the prototype) remained in Vessel #2.

Interruption in Operation

The circulators were idle from December 1981 through December 1982 to permit modification of the loop. This included fabricating and installing the test vessel, two helium flow control valves, and the interconnecting piping.

Pretest Operation for the CSPT

An initial test of the loop was required prior to the installation of graphite in the test chamber. This test would prove the ability to provide continuous, unattended operation of the loop and the ability to control the concentration of impurities in the helium gas in the absence of graphite.

In December 1982, the loop was pressurized, and the circulators were operated briefly. During January 1983, protective circuits for the helium heaters and the cooling air system of the heat exchanger were installed. The protective alarm and scram systems for both attended and unattended operation were tested.

In February the circulators were operated for 81 hours; however, problems with the VFPS prevented operation of the CPTL in the unattended mode. Assistance from a factory representative from Servo Optics Systems of Dallas, was required on several occasions.

The control circuits that provide emergency stopping of the VFPS were revised to avoid electrical overstressing of the large silicon-controlled rectifiers. Overstressing appeared to be a problem with the previous method used to stop the circulators rapidly. In the revised method, recommended by Servo Optics Systems, controlled deceleration of the circulators was provided by using internal logic circuits of the VFPS. Members of the ORNL electrical engineering staff made concerted efforts to attain reliable operation of the VFPS, and from mid-March to the end of May, the VFPS operated without failure.

From February to mid-March, the circulators and VFPS sustained a number of unplanned scrams arising from signals provided by the capacitance probes that determined the gap width between the plates of the thrust bearings. (It should be mentioned that the shaft of the circulator was installed with a 8° slant from the horizontal to insure that the thrust bearing would always be loaded.) The automatic action associated with the width of this gap was changed from scram to alarm only.

If operation of one circulator was interrupted due to some fault such as a VFPS failure, the temperature of the impeller end journal bearing and motor stator in this idle circulator quickly reached design limits. This resulted from the loss of forced internal circulation within the motor cavity and the "soakback" of heat from the hot gas. To avoid damage to an idle circulator, it was necessary to stop all three circulators if any one became inoperable. An existing differential pressure sensor, which measured the total head for the three circulators, was connected to the protective circuits. A signal from this sensor scrams the other two circulators when any one is stopped. This signal provided a reliable method of protecting the circulators.

All three circulators operated very satisfactorily during this pretest operation from February 1983 through June 1983. A number of delays were attributable to the VFPS and to the initiation of unattended operation, but none were directly caused by the circulators during 1900 hours of operation.

Interim Testing

Prior to initiation of the testing program with graphite installed in the test chamber, it was necessary to know how much air would be introduced by examination of the graphite piece in situ. To evaluate this operation, the loop was depressurized, inspection ports were opened, the loop was evacuated, and the loop was filled with helium.

During evacuation of the system, a significant leak was discovered in Vessel #3. The vessel head was removed, and the circulator assembly was dismounted from the head. Inspection of the Ceramaseal penetration through the head for the electrical leads for the motor revealed a small hole in the weld that seals the fitting to the flange. A replacement bulkhead fitting was installed and seal welded to the closure flange. The hole appeared to have been made by an electrical arc to ground.

During the handling and replacement of the circulator assembly, a very fine magnetic black powder was found trapped in holes drilled in the inlet of the impeller front shroud. The powder contained iron and iron oxide, and there was considerable speculation about its source.

Initial Operation with Graphite Test Blocks Installed

By mid-August of 1983, the graphite structure was installed, the pressure boundary was closed, and the preliminary steps were completed. On August 22, the circulators were started. After about 5 hours of operation, the circulators scrammed. Inspection revealed that the stator in Circulator #1, which was installed in Vessel #2, had a short circuit to ground.

The circulator was removed, and the motor cooling jacket (made of Inconel) was removed. Since the motor assembly was installed by a shrink fit into the jacket, it was necessary to heat the jacket with low-pressure steam to remove the stator. The short circuit occurred where the stator electrical insulation had been worn by vibration and fretting between the stator and an adjacent corner of the stator iron laminations. The local plant Electric Motor Shop rewound the stator, vacuum impregnated it with varnish three times, and baked it after each impregnation for 4 hours at 160°C. It passed high potential and ground resistance tests and was reinstalled in the motor cooling jacket.

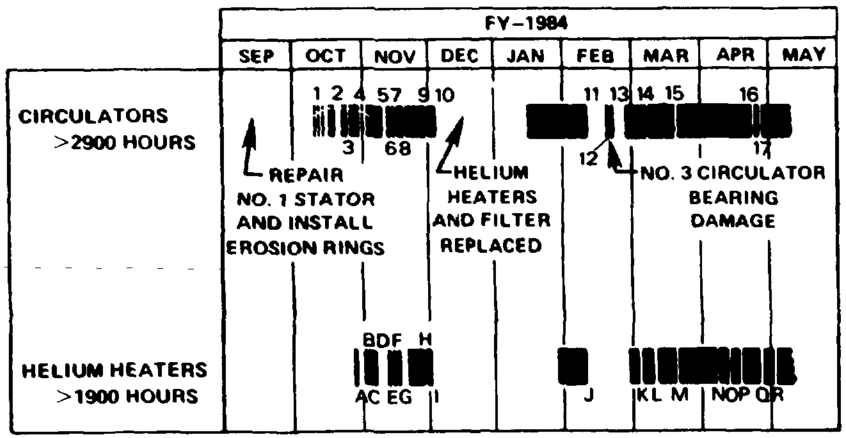
While repairs were being made to the stator, an examination of other rotary assembly components was made by an engineering representative from MTI. This inspection revealed damage to the interior surface of the impeller end ring, which formed half of the impeller housing at the inlet side. This damage consisted of distinct V-shaped grooves cut into the interior surface of the stationary shroud at the impeller inlet. Investigation of the cause of these grooves and the remedy for the situation is the subject of another paper (Ref. 5).

Test Operation is Resumed

The operating history for the remainder of this test for the circulators and the loop is presented graphically in Fig. 3. The figure presents the operating experience with the circulators, the helium heaters, and the full-flow filter; however, only the operation of the circulators and the VFPS are discussed in this paper. There is, of course, a vital link between the operation of the circulators and the other components in the loop.

Test operation was resumed in mid-October, and three runs of 120, 150, and 430 hours were achieved from then until the first week in December. Near the end of October, VFPS #1 failed, was repaired, and resumed operation within 4 days. After operating 150 hours, the circulators were shut down manually to provide for a 2-day inspection

CIRCULATOR AND HELIUM HEATER OPERATION
CFTL/CSPT TEST ZERO



SCRAM NO	CIRCULATOR	CIRCULATOR DOWN TIME (h)	SCRAM NO.	HELIUM HEATER
1	CIRC. OPER & VIB. CHECKS	1.0	A	FUNCTION CHECK
2	VFPS* NO. 1 FAULT	168.0	B	FUNCTION CHECK
3	MAINT. OF AUX. CIRCUIT	0.1	C	Sch. – TO CHECK HELIUM BYPASSING HEATER
4	VFPS NO. 1 FAULT	100.0	D	Sch. – TO RAISE HIGH–TEMP. SCRAM SETTING
5	Sch. – MIN. INSP. VFPS	48.0	E	FLUCTUATION IN HEATER CONTROL TE
6	VFPS NO. 3 FAULT	3.0	F	DEFECTIVE GROUND FAULT INDICATOR
7	VFPS NO. 1 FAULT	0.1	G	CIRC. SCRAM NO. 6
8	CALIBRATING PRESS. SWITCH	0.1	H	CIRC. SCRAM NO. 9
9	VFPS NO. 3 FAULT	45.0	I	HELIUM FILTER PLUGGING – LOW HTR. FLOW
10	HELIUM FILTER PLUGGING	~(5 wks)	J	CIRC. SCRAM NO. 11
11	VFPS NO. 3 FAULT	168.0	K	Sch. – GRADUAL FILTER PLUGGING
12	CIRC. NO. 3 BEARING PROBLEM	168.0	L	Sch. – TO ADJ. H_2 H_2O RATIO
13	Sch. – TO CHECK HEAT SHIELD	24.0	M	CIRC. SCRAM NO. 15
14	MAINT. OF IDLE VFPS NO. 3	0.1	N	Y–12 AIR FAILURE TO HELIUM FLOW VALVE
15	MAINT. OF IDLE VFPS NO. 3	0.1	O	FAILURE AIR BLOWER IN INDUCTION VOLT. REG.
16	ADJ. CIRC. ΔP TRIP SET POINT	< 0.1	P	Sch. – TO RUN 100°C GRAPHITE TEST
17	Sch. – TO EVACUATE LOOP	6.0	Q	Sch. – TEST ZERO COMPLETED
			R	Sch. – POST TEST ZERO INVESTIGATION

*VARIABLE FREQUENCY POWER SUPPLY

Fig. 3 Operating experience during the CSPT

of the VFPS by an engineer from Servo Optics System. Six hours after operation was resumed, a fault occurred in VFPS #3; it was repaired, and operation was resumed 3 hours later. The circulators were then operated continuously for 430 hours.

The operation was interrupted for 45 hours by a failure of several capacitors in VFPS #3. Operation was resumed on November 30, only to be halted on December 1 by a problem with the helium heater. Problems with the heater and increasing pressure drop across the full-flow helium filter prevented further operation until the middle of January 1984.

Operation was resumed on January 20, and then interrupted in mid-February by a fault in VFPS #3. When the fault was repaired, circulator #3 would not restart. Examination of the unit revealed damage to the surface of the gas lubricated journal bearings. Circulator #3 was returned to MTI so that the bearing surfaces could be refurbished. It was concluded that this damage was caused by the particulate previously observed in the circulator; this particulate was associated with the V-shaped grooves observed in the stationary shroud at the impeller inlet. Operation was continued using only circulators #1 and #2.

To protect the Teflon seal of the closure flange of Vessel #3 from the operating gas temperature during this operating period, a heat shield was constructed and installed. This shield consisted of a baffle and layers of insulation between the impeller end of the vessel and the closure flange. The temperature of the Teflon seal was limited to a maximum of 175°C by reducing the temperature of the inlet helium at the circulator cavity to 335°C rather than the normal value of 425°C. This change in operating parameters required the use of more power to the helium heater and more heat removal in the air-cooled heat exchanger.

The system operated satisfactorily in this mode through the remainder of the test, which was completed on May 17, 1984. Circulators #1 and #2 operated approximately 2900 hours in this test and 1900 hours in the preliminary test, plus approximately 200 hours during shakedown operation. The total operating time was 5000 h each. Circulator #1 (the prototype) has been started about 260 times.

CONCLUSIONS

The circulators met the CFTL operating requirements. The performance over the operating period can be considered very good.

The one operating failure of the gas bearing was due to the presence of solid particulate in the gas. This emphasizes the necessity of keeping particulate out of the gas when operating bearings with very small clearances.

The one major problem encountered in the use of the circulators was due to a failure to properly heat treat the stationary shroud at the circulator inlet. This problem is discussed in detail in an associated paper. (Ref. 5)

The three variable frequency power supplies (VFPS) did not perform in a comparable manner even though all three were acquired using the same purchase specifications. The dependability of the three VFPS was not the same. This difference was due to advances in the state-of-the-art for solid-state devices of this type over a 3-year period. The first unit acquired did not provide service equal to that of the two units delivered later.

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