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KNOLLS ATOMIC POWER LABORATORY
SCHENECTADY, NEW YORK

FROZEN SODIUM SHAFT SEAL

W. A. Heywood

August 4, 1954

OPERATED FOR THE
U.S. ATOMIC ENERGY COMMISSION
BY THE
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General Electric Company
KNOLLS ATOMIC POWER LABORATORY
Schenectady, New York

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ABSTRACT

The feasibility of utilizing a frozen sodium annulus as a shaft seal was investigated. ~~Three~~ phases of the investigation were: (1) the torque required to turn a shaft in a frozen annulus, (2) the leakage of sodium past a frozen annulus, and (3) the leakage of argon past a frozen annulus. *It was found that -*

Torques up to 60 ft-lb were required to turn a 1-5/8-inch-diameter shaft in a frozen sodium annulus 3 inches long and 1/16 inch thick;

Sodium leak rates up to 4 grams per day were observed with a 15-psi pressure drop across the annulus; *and -*

Argon leak rates of the order of hundreds of cubic centimeters per minute with pressure drops up to 10 psi were observed.

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FROZEN SODIUM SHAFT SEAL

W. A. Heywood

INTRODUCTION

Considerable interest has been focused on the feasibility of utilizing a frozen sodium annulus around a rotating shaft as a shaft seal. Two possible applications are of prime importance. First, would such a seal be feasible to confine liquid metal in a mechanical pump? (At present there is no known efficient liquid metal seal.) Second, what would be the effect if such a frozen annulus were formed either intentionally or unintentionally around reactor control shafts?

In considering the suitability of a frozen sodium seal for either of these applications, many questions were raised. The answers to several of these questions could eliminate the use of such a seal in one application but not necessarily in the other.

The principal considerations were:

1. If such a seal developed a high resistance to rotation of the shaft, it would be undesirable around the reactor control shafts. However, high torques could be overcome in a mechanical pump application.
2. If such a frozen annulus permitted an appreciable amount of liquid metal leakage, it would not be suitable as a pump shaft-seal. Yet, in itself, leakage of liquid metal in the reactor control rod annulus would not be objectionable.
3. If a frozen annulus proved to have effective gas sealing properties, the requirements for a reactor control rod seal would be reduced and the concern for gas seals on mechanical pumps could be lessened.

Although the experimental apparatus was designed to explore the effects of many parameters, this report covers preliminary results giving information on the three major phases of the investigation: (1) torque required to turn a shaft through a frozen annulus, (2) leakage of sodium past a frozen annulus, and (3) effectiveness of a frozen annulus as a gas seal.

With this information, the feasibility of using such seals can then be better evaluated and a decision made as to the desirability of continuing the investigation.

APPARATUS

A longitudinal section of the apparatus is shown in Figure KS-2289. A cold-rolled steel shaft with a 1-5/8-inch OD is rotated in a 1-3/4-inch-ID cold-rolled sleeve by a standard bench drill press. Depth of penetration of the shaft in the sleeve is adjusted by moving the drill press spindle.

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Each of the four sections of the sleeve contained a nichrome wire heater and a coolant coil to provide longitudinal temperature regulation along the sleeve. Thermocouples imbedded in the sleeve at the ends of each section monitored the sleeve temperature at these points.

Molten sodium from the container was forced up the shaft sleeve annulus by argon pressure. Probes inserted in the sleeve indicated height of sodium in the sleeve. The shaft entered the sleeve through an O-ring seal to control the argon pressure in the sleeve.

The entire assembly was mounted on a turntable bolted to the base of the drill press, making the assembly free to rotate with the shaft. Rotation was restrained by the insertion of a strain beam (on which resistance wire strain gauges had been mounted) between the fixed and free portions of the turntable. The strain beam was calibrated directly into pounds of force vs line deflection of the associated Brush Strain Analyzer. The drag on the rod turning in the sodium annulus was thus transmitted to the strain beam and continuously recorded.

Figure KS-2290 is a photograph of the apparatus as it is mounted on the drill press. Sodium is forced into the sodium container by argon pressure from the transfer flask shown to the right of the apparatus. When torque measurements are being made, this flask is removed.

Figure KS-2291 is a photograph of the control panel. The "scram" is a safety trip device that quickly reduces the pressure if liquid sodium is suddenly forced out the top of the sleeve.

The sleeve container differential manometer is the fine control for indicating sodium level in the sleeve. The manometer fluid is octoil, which has a density ratio of 1.05 to 1 with liquid sodium at approximately 100°C. Thus, approximate sodium height above the liquid in the container can be read directly on the manometer.

Figure KS-2292 is a photograph of the accessory control panel.

EXPERIMENTAL PROCEDURE AND RESULTS

Torque Required to Turn the Shaft in a Sodium Annulus

The frozen sodium annulus apparently exists under two conditions.

(1) The annulus is frozen completely, requiring high torques to rotate the shaft. (2) A thin longitudinal film of liquid sodium is present in the frozen annulus, permitting negligible torque to turn the shaft. This condition is unstable; some mechanism causes the thin film to solidify suddenly and the annulus then reverts to the first condition.

When the sodium annulus was frozen completely, the motor on the drill press (3/4 hp) was not powerful enough to turn the shaft in the annulus, and torque measurements were made by rotating the shaft slowly with a wrench.

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FROZEN SODIUM SHAFT SEAL APPARATUS

ASSEMBLY DRAWING

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CONTROL PANEL

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Sleeve Heater Controls

Sodium Container
Heater Controls

Sodium Transfer Heater Controls

Probe Lights

Sleeve Gas Controls

Gas Pressure Regulator

Scram Power Switches

Gas Pressure Regulator

High-Pressure Bypass

Sodium Container Controls

Sleeve-Container
Differential Manometer

Coolant Flow Flowrators

Coolant Flow
Control Valves

Coolant Pump

Coolant Sump

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KS-2271

ACCESSORY CONTROL PANEL

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When the sodium annulus was in the second condition (rotating on a liquid film), the shaft rotated freely, and the torque required to turn it at 400 rpm was less than the 3 in.-lb absorbed by the O-ring seal.

The resistance of the solid sodium annulus to rotation of the shaft acts as an extremely high viscous drag. Assuming the drag to be from an extremely high viscosity fluid, the viscosity of solid sodium was roughly determined as a function of temperature. Since the apparatus is similar to the Searles concentric cylinder,* an approximate value of the coefficient of viscosity for slow rates of rotation can be obtained from the equation:

$$\eta = \frac{F T (R_2^2 - R_1^2)}{8\pi^2 R_1^2 R_2^2 L}$$

where

η = coefficient of viscosity, poise

T = time required for one revolution, sec

F = torque required to turn shaft, dyne-cm

L = length of sodium annulus, cm

R_1 = radius of shaft, cm

R_2 = radius of sleeve, cm

To obtain these data the apparatus was heated to 250°C for one hour to ensure wetting of the sleeve and shaft. The sodium in the sleeve was allowed to cool and was held at the desired temperature for one hour. The shaft was rotated with a wrench through 90° at a peripheral speed ranging from 0.1 to 1.3 cm/sec. The force required to rotate the shaft and the time required for one 90° rotation were determined from the recorder chart. The height of the sodium annulus in the sleeve was determined by probing from the top of the sleeve with the seal cap removed. The length of sodium annulus in contact with the shaft could then be determined from a measurement of the length of shaft projecting from the top of the sleeve. To reduce end effects from the bottom of the shaft, it was raised slightly just after solidification of the annulus.

The data shown in Figure KS-2293 indicate that the viscosity of solid sodium ranges from approximately 2×10^6 poise at 20°C to 70×10^6 poise at 90°C, with a sharp break as the melting point is approached. Knowing the

*Hatschek, E., The Viscosity of Liquids. London: G. Bell & Sons, Ltd, 1928, p. 54.

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coefficient of viscosity, the approximate force required to rotate a shaft at slow speed in a frozen annulus can be predicted from the geometry of the application.

As the investigation proceeded, it became apparent that the force required to turn the shaft was reduced on repeated turning of the shaft in the same sodium annulus. To determine if the torque would return to its original value after allowing the shaft to remain static, groups of five 90° rotations of the shaft were made using the same sodium annulus with 1, 5, 10, and 20 minutes between turns in each group. It was found that the torque decreased independently of periods at rest (up to 16 hr) until an apparent asymptotic value was reached. Consecutive torque measurements taken first at room temperature, then at 40°, 50°, and finally again at room temperature, continued to fall on the same curve (see Figure KS-2294).

An explanation for this constant decrease in torque may be derived from the observed increase in annulus height as determined by probing (Figure KS-2294). Before shaft rotation the length of the sodium annulus was 1.5 inches, increasing rapidly at first, then approaching an asymptotic value with torque requirements. The highly viscous sodium was extruded up the sleeve with each turn of the shaft. (It could not extrude downward because of solid sodium below it.) This had the effect of thinning the sodium in the annulus, thus reducing the torque required for the next rotation. A reduced torque would then lessen the amount of extrusion. This continued until one process did not affect the other.

Runs to determine the shear stress of the solid sodium in the annulus as a function of temperature were made in the same manner as those of the viscosity determination. A new sodium annulus was formed for each determination and held for one hour. Figure KS-2295 shows the results of these runs. The shear stress divided by the peripheral speed of the shaft, when plotted as a function of the temperature, approximates a straight line for very slow speeds (Figure KS-2296).

Effectiveness of a Frozen Sodium Annulus as a Sodium Shaft Seal

This phase of the investigation was hampered by the instability of the liquid sodium film in the sodium annulus. Substantial motion of the shaft was unpredictable because the sodium annulus would seize the shaft completely at random. A series of runs was made to determine if this seizure was a function of time-temperature dependence of wetting. At the same time, the leakage of sodium past the frozen sodium annulus was determined. Table I is a summary of the data from this series. Sodium leakage was determined by probing the sodium annulus height at frequent intervals. The average growth (or increase in height) of the solid sodium in the sleeve shaft annulus was a measure of the amount of sodium being forced past the solid sodium annulus by the pressure drop maintained across the annulus.

Time to seizure was random with respect to time-temperature dependence of wetting. The data also indicate that sodium does leak past a frozen sodium annulus. One factor that may influence seizure of the shaft is an acceleration

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TABLE I

LEAKAGE OF SODIUM PAST A FROZEN SODIUM ANNULUS

Run No.	Hold Temp, °C	Hold Time, hr	Wetting Time-Temp, degree-hr	Pressure Drop, psi	Running Time, hr	Leak Rate (to probe reading just before seizure), grams/day	Leak Rate (incl reading after seizure), grams/day	Remarks
13	125	1/4	31.3	5	146	0.13	0.23	
24	125	1/4	31.3	5	72	0.15	0.71	
19	125	1/2	62.5	10	17.5	-	4.1	
19A	125	1/2	62.5	10	43.5	0.36	0.93	
19B	125	1/2	62.5	10	38	0.52	1.04	
15	125	1	125	0	259	0	-	Did not seize.
15'	-	-	-	5	33	0.36	0.73	Same annulus as in Run 15. Pressure drop increased.
16	160	1/4	40	10	258	0.19	-	Did not seize.
29	160	1/4	40	15	56.5	3.8	4.2	
30	160	1/4	40	15	89.5	3.9	4.3	
25	160	1/2	80	5	78	0.54	0.77	
28	160	1	160	0.4	20	0	3.7	
27	200	1/4	50	0.4	21.6	0	8.5	
26	200	1/4	50	0.4	1.6	-	15.3	
14	200	1/2	100	0.6	32	-	0.13	
17	200	1	200	0.3	65.4	0	-	Did not seize.
17'	-	-	-	5	0.9	-	1.7	Same annulus as in Run 17. Increased pressure drop.
18	200	1	200	5	258	0.20	-	Did not seize.
18'	-	-	-	10	37	0.63	2.8	Same annulus as in 18. Increased pressure drop.

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of the sodium leak rate. Out of 30 runs, all but three experienced sudden shaft seizure in a comparatively short time after an increase in sodium leakage. Also, three runs terminated by shaft seizure after sodium leakage was intentionally increased by increasing the pressure drop across the solid sodium annulus.

The fact that sodium does leak past the frozen annulus, coupled with the ability of the shaft to rotate freely, is the major premise for assuming the existence of a liquid film. This film probably is maintained by frictional heat, and its thickness may vary with several factors. A film provides a path for liquid sodium to pass the frozen annulus. Just why an increase in flow of sodium in this passage causes the shaft to be seized instantaneously in the annulus some hours later is not clear.

It had been observed that sodium does not leak past the frozen annulus when the annulus is in condition (1) (completely frozen) under a pressure drop of 5 psi. Also no leakage or evidence of seizure were observed when the shaft was in rotation at 400 rpm, and the pressure drop across the solid sodium annulus was just sufficient to force liquid sodium to the top of the frozen annulus.

In general, sodium leakage past a solid annulus approximately 2 to 2 1/2 inches long and 1/16 inch thick, and with a temperature gradient from 100°C at one end to 75°C at the other, ranged from 0.2 to 0.5 gram per day with a pressure drop of 5 to 10 psi and shaft rotation of 400 rpm. However, increasing the pressure drop to 15 psi caused a ten-fold increase in leak rate (~4 grams per day). This large increase may not have been caused entirely by the increase in pressure drop. An increased flow of sodium in the annulus caused an increase in annulus temperature. This in turn may have had the effect of enlarging the leak passage (that is, liquid film).

Figure KS-2297 indicates the leak rate of sodium past the frozen annulus as a function of pressure drop.

Figure KS-2298 is a plot of typical runs showing increase in height of the solid sodium annulus as a function of time of shaft rotation. As can be seen, shaft seizure occurred some time after an increase in sodium leak rate. There was nothing in the data to give an indication of the cause of this increase.

Effectiveness of a Frozen Sodium Annulus as a Gas Shaft Seal

As expected, no gas leakage was observed when either solid or liquid sodium was maintained in the sodium container and sleeve below the frozen sodium annulus. However, leakage of argon past only the frozen sodium annulus was much greater than expected.

A sodium annulus was frozen in the desired portion of the sleeve, and the remaining sodium was transferred back into the transfer flask. Leakage of argon was determined from a pressure-time curve. The pressure in the sodium

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container was held at 10 psi and the sleeve pressure over the sodium annulus at 1 psi. A solenoid valve in the container pressure line was closed at zero time, and the decay in pressure in the container was followed by a Statham pressure transducer, the signal of which was recorded on a photoelectric recorder. Knowing the volume of the system, the average leak rate over a small increment of time could be determined from the pressure-time curve. With the sleeve pressure constant the pressure drop across the frozen annulus is known at any given time and the gas leak rate as a function of pressure drop across the sodium annulus can be determined.

It was found that motion of the shaft (400 rpm) caused an increase in leak rate over that when the shaft was static. Also, the leakage increased with time in motion. Figure KS-1071 shows the leakage of argon as a function of the pressure drop across the annulus with the shaft stationary.

Figure KS-1072 shows the leak rate of argon past a similar frozen annulus with the shaft turning at 400 rpm, indicating not only the increase in leak rate associated with shaft motion but also the increase in leak rate as motion was continued.

DISCUSSION OF RESULTS AND SUGGESTED FUTURE WORK

The results obtained in this preliminary survey, in which only a very few of the desired parameters have been examined, indicate that a frozen sodium seal by itself may not show much promise. Because of the possibility of high torques required to turn a shaft through such an annulus, sodium freezing around the control rod shaft may prove to be objectionable in reactor control mechanisms, especially during a power failure scram. Although the high torque is not a particular hindrance in a pump application, the fact that sodium does leak past such an annulus would be objectionable. The gas leakage tests indicate that a frozen annulus probably cannot be depended upon to act as an effective gas seal.

A great deal of work is still required to answer the questions remaining. A better definition of the mechanism causing the sudden seizure of the shaft in the annulus is required. If this mechanism could be defined and controlled, negligible resistance to shaft rotation attributed to the frozen annulus could perhaps be achieved, and a frozen annulus may be developed that would be suitable.

A better understanding of this mechanism might also lead to a means of reducing sodium leakage, since this leakage is a function of the liquid film that apparently exists in the annulus.

Since the liquid film, when it exists, appears to be a very short distance out from the rotating surface, surface finish within conventional machining ranges probably has little effect on the results reported.

A more thorough examination of the effect of shaft rotational speed, type of motion, and eccentricity on the three major phases of this investigation is required to understand the problem better. Another unknown factor is the effect

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of the purity of the sodium. Could a slow accumulation of sodium oxide migrating to the cold zone (annulus) cause the sudden shaft seizures observed?

These are some of the answers still required before a complete evaluation can be made on the effectiveness and suitability of a frozen metal shaft seal. The results from the work reported here are preliminary in nature and are intended only as a guide for decisions as to practicality of further work on this problem.

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LEAK RATE OF ARGON PAST SOLID
SODIUM ANNULUS vs. PRESSURE
DROP ACROSS ANNULUS

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