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WRITTEN BY <i>F. O. Streck</i> F. O. Streck		ATOMICS INTERNATIONAL A Division of North American Aviation, Inc. TECHNICAL DATA RECORD	TDR NO. 4442
SECTION Sodium Reactors			GO 7508
GROUP Sodium Components			LEDGER ACCT. 3621
UNIT Coolant System Equipment			SUB-ACCT. 4908
APPROVED BY: (SUPERVISOR) <i>J. Leppard</i>		PROGRAM HNPF	TWR 5209
OTHER		PROJECT	DATE February 10, 1960
		Develop & Test Mechanical Pumps	PAGE 1 OF 44

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SUBJECT:

Final Performance Tests of Two-Coolant-Region Sodium Pump Shaft Freeze-Seals

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I STATEMENT OF PROBLEM

A prototype of the two-coolant-region shaft freeze-seals intended for application to the HNPF sodium pumps was fabricated. Tests, under simulated reactor service conditions, were required to determine the operating characteristics of the seal. Required information included:

a) the ability of the seal to retain sodium under all conditions of pump operation; b) the heating load on the seal coolant at various shaft speeds and bulk sodium temperatures; and c) the temperature distribution along the length of the seal under several different combinations of conditions.

II SUMMARY OF RESULTS AND RECOMMENDATIONS

A. Results

It was found that the two region freeze-seal operated satisfactorily only when the lower of the two regions received heat from the fluid (tetralin)* circulated through it. With the inlet temperature of tetralin to the upper region of the seal maintained at 95°F and that to the lower region held in the range of 240-285°F the seal functioned satisfactorily for 1100 hours.

*Subsequent to completion of these tests, tetralin was eliminated as a coolant; NAK was substituted.

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In the case where 95°F* coolant was circulated through both sections of the seal excessive cooling occurred; this resulted in either improper formation of the seal or in seizure of the shaft when rotative speed was low. It was also found in this case that the cooling load on the seal varied directly with both shaft speed and bulk sodium temperature. The maximum cooling load of 2.56 Kw occurred at a shaft speed of 840 rpm and with a bulk sodium temperature of 1000°F.

B. Recommendations

A two-region seal, utilizing heating fluid in the lower region is recommended for use in the HNPF freeze seal pumps. The normal mode of operation is to maintain a constant temperature of 270°F at the bottom of the seal. For conditions of the HNPF plant the coolant to the upper region should have a flow rate of 5.8 gpm of 95°F tetralin, and the lower region should be supplied a tetralin flow of 0.8 gpm at temperatures varying between 240 and 285°F.

III DESCRIPTION OF EQUIPMENT, METHOD USED

A. Introduction

The configuration of shaft-freeze-seals as applied to sodium pumps has been investigated** for each particular set of conditions under which operation was required. The initial testing undertaken for the HNPF program, reported in TDR 4119, was conducted with some modified old equipment in which it was not possible to obtain the normally required operating conditions imposed on the HNPF pumps. In addition, the exact dimensions of the space available for the freeze seal in the prototype pump had not been fixed in time for the initial tests. It was therefore necessary to build another freeze-seal test stand (hereafter called stand No. 2) in which all the required conditions could be obtained, and also a new prototype freeze seal of the proper dimensions.

*The coolant supply temperature specified for the HNPF.

**See NAA-SR Memo 1565.

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The seal was required to prevent leakage of sodium into the pump case under all normal operating conditions of the pump; i.e. bulk sodium temperatures from 350° to 945°F, and shaft speeds from 0 - 835 rpm. A value for differential pressure across the seal was arbitrarily taken as 10 psig. (After design of the prototype pump was finished this Δp was the proper value). A method of seal operation was hopefully to be determined which would prevent shaft seizure at low rotative speeds.*

The experimental work performed with the new equipment was done in two successive series of tests, each of which is reported here.

B. Description of Equipment

1. Test Rig

Freeze-seal test stand No. 2 was used in both series of tests. This stand, shown schematically in Fig. 1, consisted of a simulated pump case with case freeze seal, a thermal barrier and throat bushing, and a bearing housing which supported the shaft. The shaft used was hollow, 4 in. ID and 5 in. OD, in the length of the seal region. An electromagnetic pump was used to circulate the sodium through the system and flows were measured with a magnetic flowmeter. Heat was added to the sodium by a 36 Kw immersion heater. A surge tank was incorporated which could be pressurized with helium gas to force the sodium into the pump case and impress a differential pressure (ΔP) across the seal. A gas pressure reducing station was supplied for controlling the sodium level in the system. A pressure applied on the surge tank caused the sodium level to rise into the seal. A pressure applied to the pump case above the seal could be used to reduce the sodium level in the seal or to force sodium which had leaked past the seal back into the system. (Sodium leakage past the seal occurred only while manipulating sodium during drain and fill operations or while melting a frozen shaft seal). The normal setting of pressures in these two chambers resulted in the 10 psig Δp required across the seal.

*Shaft seizure has recurred with SRE pump

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The tetralin heater shown in Fig. 1 was added for use during the second series of tests. The input power to this 12 Kw capacity immersion heater was controlled by a stepless transformer. The heated tetralin was piped only to the lower region of the shaft freeze-seal.

2. Freeze-seals

Three two-region shaft seals, basically of the same design, but different in detail, were used in the development tests. Common to all three was the design of the upper region of seal, namely a 2-in. long annular chamber concentric with the simulated pump shaft. This chamber contained an axial divider to assure complete circulation of the coolant. The lower region of the three seals differed and must be separately described.

The lower region of the seal (Mark I) used in the initial tests (see TDR 4119) was only $4\frac{1}{2}$ inches long, in which there were six turns of $\frac{1}{2}$ -in. o.d. by 0.035 wall stainless steel coolant tubing. The six turns were evenly spaced over the lower $3\frac{1}{2}$ inches of the seal length.

The lower region of the seal (Mark II) used in the first series of tests reported here was $6\frac{1}{2}$ inches long and there were eight turns of $\frac{1}{2}$ -in. o.d. by 0.035-in. wall stainless steel tubing coiled around a slotted sleeve (see Figure 2, Photo 7508-5415F). The coils were evenly spaced over the lower five inches of the seal length.

In the case of the seal (Mark III) used in the second series of tests reported here, the number of coils in the lower region of the seal was reduced to six. The tubing size was reduced to $3/8$ -in. o.d. x 0.035 wall in order to increase the coolant velocity through the coils. Five of the tubing coils were concentrated at the bottom of the $6\frac{1}{2}$ -in. long skirt and only one turn was widely spaced from them in the upper part of the skirt (see Figure 3, Photo 7508-5448F).

3. Instrumentation

All temperature measurements were obtained with chromel-alumel stainless steel sheathed thermocouples recorded on conventional instruments. The location of thermocouples in the seals can be seen in both Figures 2 and 3, and are schematically shown in Figure 4. Tetralin differential temperature measurements (Δt) were made with differential thermocouples connected to a slide wire potentiometer.

Shaft speed measurements were all obtained with a Strobatac.

C. Method Used

1. General

Because of the number of mutually dependent variables entering into the operation of the shaft freeze seal, a statistically designed test program was established for each of the two test series reported here. It was the aim of the statistical design to optimize the number data points to be recorded. With a given freeze seal in place, a seal was established in the usual manner, and tests were conducted over a range of shaft speeds, coolant flows, and bulk sodium temperatures as dictated by the individual runs specified in the test programs.

2. First Test Series

a. Method

In this test series the effort was directed towards the determination of the cooling load on the shaft seal. A general expression was formulated for the heat removed from the seal as a function of the three variables mentioned in the previous paragraph. Details of the statistical analysis are given in Appendix A. Data from test runs were used in a multiple correlation (utilizing an IBM 709) which resulted in the determination of coefficients to be used in the expression to obtain seal cooling loads. Results of the correlation are shown in Appendix B.

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Had the seal performed as expected, the location of the liquid/solid interface within the seal length would also have been determined as a function of the other operating variables. The location of the interface was taken to be between thermocouples which indicated temperatures spanning the 208°F value; in this series the interface was always below the bottom of the seal skirt.

The freeze seal was established as follows: 1) flow of tetralin (95°F) was started in the upper region of the seal; 2) the shaft was rotated between 1/2 and 3/4 of full speed; and 3) the surge tank was pressurized to raise the sodium (at about 350°F) level into the seal. Formation of the seal was assumed complete when a sudden decrease in shaft speed occurred.

Having established the seal, the shaft speed, tetralin flows, and bulk sodium temperatures were adjusted to the values required in individual test runs.

b. Results

The test data indicated that the liquid/solid interface was always located in the throat bushing below the seal when coolant was circulated through both regions of the seal. The total heat available from shearing friction and conduction along the shaft, throat bushing, and thermal barrier was insufficient to keep the seal molten in the lower region. (Or conversely, the cooling capacity of the seal was too great). No combination of conditions were obtained that allowed the solid/liquid interface to rise into the seal region. This condition was intolerable because it brought about two situations adversely affecting pump operation; a) at low shaft speeds the extra length of frozen sodium resulted in shaft seizure, and b) the freeze-seal section acted as an oxide cold trap resulting in scoring of the shaft.

The principal results of these tests are shown in the typical curves of Figs. 4 and 5. Curves A, C, and D of Fig. 4 show that the temperature was essentially constant through both

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regions of the seal. The separation between curves A & B is due to the difference in tetralin flow, that between A & D is due to friction heat generated by shaft rotation, and that between A & C is the sum of effects occasioned by shaft rotation and bulk sodium temperature differences occurring at the extremes of operating conditions. A greater tetralin flow rate yielded a temperature gradient, curve B, though the slope was not as great as desired, and the temperature was low enough to result in shaft seizure when the shaft speed was reduced.

Cooling loads were calculated using the equation shown in Appendix A and the constants for this equation are shown in Appendix B. The results of these calculations show the cooling load on the shaft to be linear with shaft speed and to increase with the increase of bulk sodium temperatures. (see Fig. 5). The sample calculation below was made for approximate HNPF design operating conditions.

$$HR = AT_{NA} + DS + C_{Wc} + D$$

where:

T_{NA} = sodium bulk temperature; 1008°F

S = shaft speed; 835 rpm

Wc = tetralin flow rate; 0.48 gpm (lower region)

A, B, C, and D constants

$$HR = (1008 \times 0.0953) + (840 \times 0.1197) + (0.48 \times 57.2186) + (-78.461) = 145.85 \text{ btu/min.}$$

$$KW = \frac{\text{btu/hr}}{3413} = \frac{60 \times 145.85}{3413} = 2.56 \text{ KW}$$

c. Discussion

In all previous use of two region freeze-seals, as well as in all runs of this test series, coolant at a temperature well below the melting point of sodium was supplied to both regions of the seal. The combination of the thermal barrier, throat bushing, hollow shaft, and seal configuration used here resulted in excessive cooling, too great a length of frozen sodium, and

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ultimately in shaft seizure. In consideration of the several remedial actions that could be taken it was suggested that the temperature of the coolant to the lower region of the seal be increased above the melting point of sodium. This idea was adopted and led to the next series of tests.

3. Second Series

a. Method

An immersion heater was added to the tetralin system so that the temperature of the fluid circulated through the lower seal region could be automatically maintained at about 250°F. Because heat was added to the lower seal region, while being removed from the upper region, the parameter of cooling load on the seal was no longer of any concern. Therefore, the statistical design of tests for the second series was directed toward establishing the location of the liquid-solid sodium interface under the range of operating conditions previously stipulated. An expression relating interface position and operating variables was established, data were correlated to obtain proper coefficients, and test sequences for obtaining optimum tetralin flows and temperatures were established. The statistical program is shown in detail in Appendix C.

The initial effort in this second series of test was to establish the optimum flows necessary to maintain the seal under widely varying conditions of operation. The limits of operation were taken to be 0-835 rpm and 450-1000°F. The flow to the lower region of the seal was fixed at 0.2 gpm and the tetralin temperature at 280°F, while operating at maximum shaft speed and bulk sodium temperature (835 rpm-1000°F). By varying the tetralin flow to the upper region it was determined that 5.8 gpm of 95°F tetralin was required to keep the sodium frozen in the upper region of the seal under these conditions. Next, the flow to the upper region of the seal was fixed at 5.8 gpm while operating at minimum shaft speed and sodium temperature (0 rpm - 450°F). By varying the tetralin flow to the lower region it was determined

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that 0.8 gpm of 240-285°F tetralin were required to keep the lower region of the seal at 270°F under these conditions. Since 5.8 gpm tetralin flow was required to keep the upper region frozen at maximum heat conditions, and 0.8 gpm of tetralin was sufficient to keep the lower region molten at minimum heat conditions it can be seen that this combination of flows and temperatures are adequate for all conditions. Having determined the necessary flow rate/temperature conditions, additional tests were then performed to determine the location of the liquid/solid sodium interface over the full range of tetralin flow rates to the lower region, shaft speeds, and bulk sodium temperatures.

The optimum operating conditions for this two region seal were concluded to be as follows:

1. A flow rate of 5.8 gpm of 95°F tetralin coolant should be supplied to the upper region of the seal.
2. A flow rate of 0.8 gpm of 240-285°F tetralin should be supplied to the lower (coil) region of the seal.
3. The temperature at the bottom of the seal should be maintained at 270°F. (Comments about this under the section on discussion).

The heater in the tetralin circuit was controlled by a signal from a thermocouple in the lower region of the seal. As the bulk sodium temperature or shaft speed was increased, the temperature at the bottom of the seal increased. This increase in temperature signaled the stepless transformer to decrease the tetralin inlet temperature. The relatively low temperature of the incoming tetralin then reduced the temperature at the bottom of the seal until the system reached a new equilibrium.

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b. Results

The results of these tests are presented in a series of curves Figures 6, 7, 8, and 9 which indicate the location of the liquid/solid interface at various operating conditions. Observing Figure 6 it may be seen that at maximum design operating conditions it is possible to operate the seal with no tetralin flow to the lower region of the seal. However, if the seal were operated in this manner, and the pump speed or sodium bulk temperature were reduced, it would be necessary to reestablish tetralin flow through the lower region of the seal. This relatively cool tetralin might cause freezing of the seal sodium and possible result in shaft seizure.

The curves in Figures 6, 7, 8, and 9 were based upon an equation obtained from the statistical analysis of the data. The derivation of the equation is given in Appendix C. The sample calculation below was made at approximate HNPF design operating conditions:

$$x = A + B + C + D$$

where:

x = location of the liquid/solid interface below the flange in inches

S = shaft speed 835 rpm

T_{NA} = sodium temperature 945°F

Q_{cs} = tetralin flow to lower region 0.8 gpm

and A, B, C, and D are constants.

Thus:

$$\begin{aligned} x &= 3.7128 - (0.001661 \times 835) - (0.001436 \times 945) - \\ &\quad (1.1261 \times 0.8) \\ &= .068 \text{ in. from the bottom of the flange.} \end{aligned}$$

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This is the nominal location of the interface. Applying the standard positive deviation of the coefficients;

$$\begin{aligned}x &= 3.7128 - (0.0019170 \times 835) - (0.001746 \times 945) - (1.4104 \times 0.8) \\&= -0.666 \text{ in. or } 0.666 \text{ in. above the bottom of the flange.}\end{aligned}$$

Applying the standard negative deviation of the coefficients;

$$\begin{aligned}x &= 3.7128 - (0.0014050 \times 835) - (0.001126 \times 945) - (0.8418 \times 0.8) \\&= 0.802 \text{ in. below the bottom of the flange.}\end{aligned}$$

D. Discussion

It was found that the seal would operate satisfactorily over a wide range of pump speeds and sodium temperatures with a fixed coolant flow rate to both regions of the seal. It was necessary however, to provide a source of heat to the lower region of the seal in order to obtain satisfactory performance at conditions of low shaft speed and low bulk sodium temperatures. At these conditions, the heat generated by shaft rotation and that heat conducted to the seal from the bulk sodium was insufficient to keep the sodium molten in the lower seal region.

As previously stated, a thermocouple at the lower end of the seal skirt signaled the control unit of the tetralin heater; the set point for this constant temperature at the bottom of the seal was 270°F. This 270°F value was chosen in order to insure molten sodium within the length of the lower region of the seal and to be above the cold trapping temperature of the loop. It was observed that for any given set of operating conditions the solid-liquid interface was forced to remain at a given location. An increase or decrease in either shaft speed or bulk sodium temperature caused this interface location to rise and fall within the seal annulus. Because the friction heat of the shearing sodium varied with the interface position, the heat input to the tetralin for the coil

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region varied also, resulting in the range of tetralin inlet temperatures indicated in the second condition specified under optimum operation.

The scheme of heating the fluid circulated through the lower seal region was demonstrated to provide a very adequate, controlled, and stable operating seal. The problems of shaft seizure and oxide cold trapping in the seal were effectively eliminated by this operation.

E. Recommendations

Because of the successful operation demonstrated with the heated lower region type seal it is recommended that this design be adopted for use with the HNPF pumps. It is also recommended that the operating conditions determined by these tests be used, and that the temperature of the bottom of the seal be controlled in the same manner.

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Figure 1

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Freeze-Seal Test Stand No. 2

MODEL NO.

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FIGURE 2
Freeze-Seal Mark II Design

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FIGURE 3
Freeze-Seal Mark III Design

Seal Temperature Distribution Mark I Shaft Freeze Seal

FIGURE 4

LIQUID/SOLID SODIUM INTERFACE LOCATION MARK II SHAFT FREEZE SEAL

TETRALIN FLOW UPPER REGION - 5.8 GPM @ 95°F

LOWER REGION 0.0 GPM

BULK SODIUM TEMPERATURE OF

FIG 6

LIQUID/SOLID SODIUM INTERFACE LOCATION
 MARK II SHAFT FREEZE SEAL

TETRALIN FLOW UPPER REGION 5.8 GPM @ 93°F

LOWER REGION 0.26 GPM

BULK SODIUM TEMPERATURE OF

FIG 7

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LIQUID/SOLID SODIUM INTERFACE LOCATION MARK II SHAFT FREEZE SEAL

TETRALIN FLOW UPPER REGION 5.8 GPM @ 95°F

LOWER REGION 0.5 GPM

FIG. 8

LIQUID/SOLID SODIUM INTERFACE LOCATION MARK II SHAFT FREEZE SEAL

FIG 9

APPENDIX A

Design of HNPF Shaft-Freeze-Seal Experimental Program

The basic purpose of the HNPF shaft-freeze-seal experimental program is the investigation of the physical capability of the HNPF shaft-freeze-seal under a wide range of appropriate operating conditions. In particular, it is desired to determine a quantitative relationship between the amount of heat which is removed from the seal assembly and the operating variables: coolant flow rate, sodium temperature, coolant inlet temperature, and shaft rpm. In addition, it is necessary to determine the location of the interface between the frozen and liquid sodium in the seal as a function of these same operating variables. Thus

Dependent Variables

1. Heat removed, HR,
2. Location of sodium interface, X,

Independent Variables

1. Coolant flow rate, w_c , (0.5, 1.0, 2.0, 4.0 gal/min.)
2. Shaft speed, S, (0, 500, 835, 1000 rpm)
3. Coolant inlet temperature, T_{CI} , (80, 100, 120, 150 °F)
4. Sodium temperature, T_{Na} , (350, 600, 1000, 1200 °F)

The figures in parentheses represent the levels at which the particular independent variable is to be tested. These ranges should cover at least the regions of major interest. The conditions $w_c = 1.0$ gal/min, $S = 835$ rpm, $T_{CI} = 100^\circ\text{F}$, and $T_{Na} = 1000^\circ\text{F}$ are to be considered the nominal or "central" operating conditions.

A test at each combination of the levels of the four variables would require 256 tests, and, since only about 80 tests are available, a more economic procedure must be used. A careful study of the seal capabilities indicates that not all of the above combinations of levels can be tested.

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In particular, the following test combinations must be avoided for reasons of either complete seal freeze or assembly burnout.

w_c (gal/min)	S (rpm)	T_{CI} (°F)	T_{Na} (°F)
.5	835	all	1200
.5	1000	all	1000, 1200
2.0	500, 835, 1000	all	350
4.0	500, 835, 1000	all	350
4.0	500	all	600

An investigation of the physical mechanisms involved in the operation of the HNPf shaft-freeze-seal was conducted in order to obtain, if possible, a reasonable analytic form upon which to base an experimental program. After combining the effects of conduction and heat generation through shaft rotation, the following general form was derived

$$H.R = A(T_{Na} - T_{CI})^2 + B(T_{Na} - T_{CI}) + D(\dot{w}_c)E + F(T_{Na} + T_{CI})^{1/3}(S)^2 + (GT_{Na}^2 + HT_{Na} + I)(S)^2 + J,$$

where A, B, C, D, E, F, G, H, I, and J are unknown constants. Since only about 80 tests are available and such a form for the heat removed is available, a multiple correlation experimental design is indicated. The results of such an experiment will statistically determine A, B, ..., J and their associated measures of reliability. The multiple correlation for X, the sodium interface location, will be accomplished more or less empirically as a function (probably exponential or quadratic) of H.R rather than directly in terms of the four independent variables.

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The existing Rocketdyne multiple correlation computer program will be used to perform all the calculations.

The suggested experimental program is given in Table I. This schedule represents a fractional portion of a complete factorial experiment avoiding those points given above and emphasizing nominal conditions. An attempt has been made to minimize operational difficulties in the arrangement of tests. Slight deviations from the listed independent variable levels will not disturb the statistical analysis (e.g. $w_c \pm .1$ gal/min, $T_{Na} \pm 10$ °F). Large deviations will necessitate the repetition of the test in question. Several series of reference tests (e.g. numbers 13-15) have been included to check for system change with time.

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Test Number	Coolant Flow Rate (gal/min)	Shaft Speed (rpm)	Coolant Inlet Temperature (°F)	Sodium Temperature (°F)	Comments
1	.5	500	80	350	First block-1
2	1.0	835	80	350	
3	1.0	1000	80	350	
4	1.0	500	120	350	First block-2
5	.5	1000	120	350	
6	.5	835	120	350	
7	1.0	835	100	350	First block-3
8	1.0	500	100	350	
9	.5	1000	100	350	
10	.5	835	150	350	First block-4
11	1.0	1000	150	350	
12	.5	500	150	350	End of first block
13	1.0	1000	80	350	Reference Tests
14	.5	500	80	350	
15	1.0	835	80	350	
16	1.0	835	120	600	Second block-1
17	1.0	0	120	600	
18	.5	1000	120	600	
19	2.0	500	120	600	
20	4.0	835	120	600	
21	2.0	835	100	600	Second block-2
22	2.0	1000	100	600	
23	.5	0	100	600	
24	.5	500	100	600	
25	1.0	835	100	600	

Table I

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Suggested Test Schedule for HNPf Shaft-Freeze-Seal Program

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Test Number	Coolant Flow Rate (gal/min)	Shaft Speed (rpm)	Coolant Inlet Temperature (°F)	Sodium Temperature (°F)	Comments
26	.5	835	80	600	Second block-3
27	1.0	500	80	600	
28	4.0	1000	80	600	
29	2.0	0	80	600	
30	1.0	835	80	600	
31	1.0	1000	150	600	Second block-4
32	.5	0	150	600	
33	4.0	1000	150	600	
34	2.0	835	150	600	
35	1.0	835	150	600	
36	1.0	835	120	600	Reference Tests
37	2.0	500	120	600	
38	4.0	835	120	600	
39	.5	500	120	600	End of second block
40	.5	500	100	1000	Third block-1
41	1.0	835	100	1000	
42	1.0	1000	100	1000	
43	2.0	0	100	1000	
44	4.0	835	100	1000	
45	1.0	1000	80	1000	Third block-2
46	4.0	500	80	1000	
47	.5	0	80	1000	
48	1.0	835	80	1000	
49	2.0	835	80	1000	
50	1.0	0	150	1000	Third block-3

Table I (cont.)

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Suggested Test Schedule for HNPf Shaft-Freeze-Seal Program

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Test Number	Coolant Flow Rate (gal/min)	Shaft Speed (rpm)	Coolant Inlet Temperature (°F)	Sodium Temperature (°F)	Comments
51	.5	835	150	1000	
52	4.0	1000	150	1000	
53	2.0	500	150	1000	
54	1.0	835	150	1000	
55	4.0	0	120	1000	Third Block-4
56	1.0	500	120	1000	
57	.5	835	120	1000	
58	2.0	1000	120	1000	
59	2.0	835	120	1000	
60	.5	500	100	1000	Reference Tests
61	1.0	835	100	1000	
62	1.0	1000	100	1000	
63	2.0	0	100	1000	End of third block
64	1.0	500	150	1200	Fourth block-1
65	1.0	835	150	1200	
66	2.0	835	150	1200	
67	.5	0	150	1200	
68	4.0	1000	150	1200	
69	2.0	500	80	1200	Fourth block-2
70	1.0	1000	80	1200	
71	.5	500	80	1200	
72	1.0	0	80	1200	
73	4.0	835	80	1200	
74	1.0	1000	120	1200	Fourth block-3
75	4.0	0	120	1200	

Table I (cont.)

Suggested Test Schedule for HNPf Shaft-Freeze-Seal Program

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Test Number	Coolant Flow Rate (gal/min)	Shaft Speed (rpm)	Coolant Inlet Temperature (°F)	Sodium Temperature (°F)	Comments
76	2.0	835	120	1200	
77	.5	0	120	1200	
78	1.0	500	120	1200	
79	2.0	0	100	1200	Fourth block-4
80	4.0	500	100	1200	
81	2.0	1000	100	1200	
82	1.0	835	100	1200	
83	2.0	1000	100	1200	
84	1.0	500	150	1200	Reference Tests
85	1.0	835	150	1200	
86	2.0	835	150	1200	
87	4.0	1000	150	1200	End of fourth block

Table I (cont.)

Suggested Test Schedule for HNPf Shaft-Freeze-Seal Program

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APPENDIX B

Statistical analysis and evaluation of tests using
shaft-freeze-seal design Mark II

The basic purpose of the subject program was the determination of a quantitative relationship between the amount of heat which is removed from the seal assembly, (HR), and the operating variables, coolant flow rate, (W_c), sodium temperature, (T_{Na}), and shaft speed, (S). In addition it was necessary to determine the location of the liquid/solid sodium interface, (X), in the seal as a function of these same operating variables.

An investigation of the physical mechanisms involved in the operation of the seal was conducted in order to obtain at least a tentative reasonable analytic form upon which to base the experimental design of the evaluation program. By considering the effect of heat conduction and generation in the seal, the following general form was hypothesized

$$H_a R = A (T_{Na} - T_{CI})^2 + B (T_{Na} - T_{CI}) + D (W_c) + E (T_{Na} + T_{CI})^{1/3} \\ (S)^2 + (F T_{Na}^2 + G T_{Na} + H) (S)^2 + I, \quad (1)$$

where the unknown constants A, B, ..., I were to be determined on the basis of the experimental results. It was planned to then relate the location of the interface, X, directly to the heat removal rate and thus indirectly to the independent variables by means of the above expression.

The nature of the objectives of the program and the ability to generate at least a tentative analytical form with which to interpret the results prompted the formulation of a partial factorial design and a subsequent multiple correlation of the results. The details of this design and the originally suggested test schedule are given in Appendix A. A further revision of

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this design was necessitated after the discovery of additional operational and time restrictions. Although the basic nature of the program and the techniques of analysis were left intact, the number of programmed tests was reduced from 87 to 36.

Additional operational difficulties made it impossible to conduct 8 of the 36 programmed tests, but because of the flexible nature of the factorial - multiple correlation experimental design the efficiency of the remaining 28 tests was not seriously affected. Of the nine programmed reference tests, five were actually run (numbers 10, 23, 24, 34, 35, which repeated runs 3, 15, 13, 25, and 27, respectively). With the exception of runs 3 and 10 all other reference pairs exhibited satisfactory repeatability. In fact, the average difference in heat removal rate exhibited by the latter four pairs was about 12 Btu/min which amounts to only about 40 percent of the final multiple correlation standard deviation. Since this latter quantity can be interpreted as random physical and measurement variation the relatively small shifts in the reference runs can be traced to this source and it is reasonable to conclude that no systematic or non-random aging or time effects were exhibited by the seal assembly. No explanation for the statistically significant discrepancy exhibited by runs 3 and 10 is presently available.

Since only 28 tests were actually conducted the determination of the nine unknown constants in equation (1) by means of a multiple correlation could not be attempted and a simpler form was chosen, viz:

$$HR = AT_{Na} + BT_{CI} + CS + D_c + E, \quad (2)$$

where only five constants A, B, C, D, and E are to be statistically determined. The results of this correlation are as follows:

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TABLE I

VARIABLE	COEFFICIENT	STANDARD DEV. OF COEF.	PROBABILITY THAT COEF. IS NON ZERO
Heat Removal Rate Btu/min	- - - - -	32.3425*	- - - - -
Sodium Temp. °F	0.0948	0.0250	.999
Inlet Tetralin Temp. (Lower) °F	0.0732	0.4163	.50
Shaft Speed rpm	0.1193	0.0164	1.000
Tetralin Flow lb/min	57.4143	16.6385	.998
Constant	-85.6872	48.9057	.910

*This is the error of estimate for the multiple correlation.

The multiple correlation coefficient was 0.8599 which is statistically very significant. None of the independent variable partial correlation coefficients were significant.

From these results one can conclude that the set of variables, T_{Na} , T_{CI} , S , and W_c constitute a truly independent set, but that the inlet tetralin temperature has no significant effect on the heat removal rate. The standard deviations of the coefficients average about 32 percent which may be considered satisfactory in view of the small number of data points available for the correlation. Only the coefficient of the shaft speed variable (standard deviation of 14 percent) is to be considered completely meaningful.

In all $(85.99)^2$ 74 percent of the total variation in the heat removal rate is explained by this correlation. Thus there still remain experimental variations, measurement variations, and possibly hidden variables amounting to about 26 percent.

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Since the tetralin inlet temperature proved to be an insignificant variable it was decided to repeat the correlation omitting T_{CI} , using the form

$$HR = AT_{Na} + CS + CW_c + D$$

The results of this correlation are given in the following table:

TABLE 2

VARIABLE	COEFFICIENT	STANDARD DEV. OF COEF.	PROBABILITY THAT COEF. IS NON ZERO
Heat Removal Rate	- - - - -	32.3603	- - - - -
Sodium Temp.	0.0953	0.0248	.999
Shaft Speed	0.1197	0.0163	1.000
Tetralin Flow	57.2186	16.6104	.998
Constant	-78.4861	23.6568	.997

The multiple correlation coefficient was 0.8597 which is statistically very significant. None of the independent variable partial coefficients were significant.

From these results we conclude that we have a true set of independent variables each of which is important in the determination of the heat removal rate. Note that the error of estimate for the multiple correlation did not significantly decrease in dropping T_{CI} since the F ratio

$$\frac{(32.603)^2 - (32.3425)^2}{(32.3603)^2},$$

which has 1 over 24 degrees of freedom, is not significant on the 95 percent confidence level. The average standard deviation

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of the coefficients for this final correlation is about 25 percent. All multiple correlation computations were performed with the assistance of the Rocketdyne multiple correlation computer program.

Since experimental temperature data taken during this program indicated that the sodium interface was always at the bottom of the seal, an unsatisfactory location, no attempt to correlate this variable with the heat removal rate was made. Extensive correlations of this type were conducted on data obtained from tests made with the Mark III shaft-freeze seal design and will be described in a subsequent report.

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APPENDIX C

Statistical design and analysis of the program for the
evaluation of the new shaft-freeze-seal

The experience gained in the testing of the Mark II shaft-freeze-seal led to a reevaluation of the basic operational objectives for testing of the Mark III design. Rather than emphasizing heat removal rate as the basis for the characterization of the seal performance, it was decided to utilize the location of the liquid/solid sodium interface as the main descriptive dependent variable. In addition, it was decided to consider the tetralin flow rate to the flange or upper region as an independent variable for the evaluation of the Mark III seal in order to assist in establishing the location of the sodium interface within a narrow range under widely varying operating conditions.

The specific objective of this particular evaluation program can be summarized as follows:

Determine the optimum combination (or combinations if necessary) of tetralin flow to the upper and lower regions which are required to maintain the sodium interface somewhat below the flange (say between thermocouples 5 and 7, see Fig. 1) over a wide range of shaft speeds and sodium temperatures.

The independent variables for this program were therefore

1. Tetralin flow rate to the upper region, Q_{cf}
2. Tetralin flow rate to the lower region, Q_{cs}
3. Pump shaft speed, S .
4. Sodium temperature, T_{Na} .

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The important dependent variable is the location of the sodium interface, x . Since x cannot be measured directly it was necessary to associate the interface with a local temperature measurements spanning the 208°F value. For the Mark III seal design the tetralin temperature to both regions is controlled. Although it was decided to fix the control temperature for the upper region at 95°F , it was not possible to choose the best control temperature for the lower region without some experimental results. Since the main objective of the seal is to maintain the interface within a very narrow region it is clear that the higher the tetralin temperature to the lower region the larger the thermal gradient through the seal, assuming that the sodium is frozen at the flange. Strictly speaking, therefore, the controlled tetralin temperature at the lower region, TC_2 , was a fifth independent variable, which was to be maximized.

PREPROGRAMS

Since a complete experiment with five independent variables would have taken a prohibitively long period of time, it was decided to optimize two of the independent variables: tetralin flow rate to the upper region and the controlled tetralin temperature at the lower region, in a short preprogram. This decision was based on the tacit assumption that levels for the other three independent variables could be chosen for this preprogram that were appropriate for the optimization. The two types of preprogram tests which were required, representing extreme "hot" and "cold" seal operation, are given respectively, by the following test levels:

	$T_{Na} = 1000^{\circ}\text{F}$
	$S = 835 \text{ rpm}$
"hot"	$Q_{cf} = 4.0 \text{ gpm (this was the minimum possible flow)}$
	$Q_{cs} = 0.2 \text{ gpm}$
	$TC_2 = 280^{\circ}\text{F}.$

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"cold"

$T_{Na} = 450^{\circ}F$
 $S = 0 \text{ rpm}$
 $Q_{cf} = 5.5 \text{ gpm}$ (this was thought initially to be the maximum flow necessary)
 $Q_{cs} = 0.8 \text{ gpm}$
 $TC_2 = 260^{\circ} F \text{ or lower}$

Note that the operational variable Q_{cs} is used in these tests to compensate for the effects of the other variables. The eight tests constituting this initial preprogram are given in Table 1. (Tests 1-8) None of these tests were successful; that is, the sodium interface was above the flange during the first four tests and below thermocouple no. 5 (see Fig. 1) during the last four.

In order to gain some positive results, it was then necessary to conduct three special tests (9, 10, and 11 in Table 1). The location of the sodium interface was still too low during test 9, but was satisfactory for tests 10 and 11.

On the basis of a heat transfer study of the results of this preprogram it was decided that the controlled temperature at the bottom of the seal (TC_2) would have to be greater than $265^{\circ}F$ but less than $270^{\circ} F$ in order for the seal to operate at expected extreme conditions. In addition, because of the results of the first four tests, it was clear that an increase in the maximum tetralin flow rate to the upper region (5.5 gpm) was necessary.

A second short preprogram was therefore designed to optimize Q_{cf} under hot conditions and with TC_2 fixed at $270^{\circ}F$. (See Table 2, tests 12-19). After checking the validity of the level $TC_2 = 270^{\circ}$ (test No. 12), a sequential type of design was utilized (tests 13 through 18). That is, all tests through 18 were to be omitted after the first test in which the sodium

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TABLE I

Initial Preprogram for New Shaft-Freeze-Seal Evaluation

Test No.	T _{Na} (°F)	S (rpm)	Q _{cf} (gpm)	Q _{cs} (gpm)	TC ₂ (°F)
1	1000	835	4.0	.2	280
2	1000	835	5.5	.2	280
3	1000	835	4.0	.2	260
4	1000	835	5.5	.2	260
5	450	0	5.5	.2	280
6	450	0	4.0	.8	280
7	450	0	5.5	.8	260
8	450	0	4.0	.8	260
9	450	0	4.0	.6	260
10	450	600	4.0	.6	260
11	450	835	4.0	.6	260

TABLE 2

Second Preprogram for New Shaft-Freeze-Seal Evaluation

Test No.	T _{Na} (°F)	S (rpm)	Q _{cf} (gpm)	Q _{cs} (gpm)	TC ₂ (°F)
12	450	0	5.5	.8	270
13	1000	835	5.5	.2	270
14	1000	835	7.0	.2	270
15	1000	835	8.5	.2	270
16	1000	835	10.0	.2	270
17	1000	835	11.5	.2	270
18	1000	835	13.0	.2	270
19	450	0	OPT*	.8	270

*The value of Q_{cf} used in the last test in the series 13-18

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interface was located in a satisfactory position. The final test (19) of this second preprogram was to evaluate the optimum Q_{cf} condition under "cold" conditions.

The results of test 12 were satisfactory. The results of tests 13, 14, and 15 indicated that for $TC_2 = 270^\circ$ the location of the sodium interface was just at thermocouple no. 7 (see Fig. 1) and moreover was quite insensitive to changes in Q_{cf} . Tests 16, 17, and 18 were therefore omitted, the level of Q_{cf} was set at 5.8 gpm and the controlled tetralin temperature, TC_2 , was dropped slightly to 265° . Then test 19 was conducted with $Q_{cf} = 5.8$ gpm and $TC_2 = 265^\circ F$, and a final test was performed to evaluate these optimum levels under "hot" conditions. ($T_{Na} = 1000^\circ F$, $S = 835$ rpm and $Q_{cs} = 0.2$ gpm). Tests 19 and 20 gave satisfactory results, indicating that a very fine optimum for Q_{cf} and TC_2 had been located.

MAIN PROGRAM

It was now possible to design the main seal evaluation program under the conditions $TC_2 = 265^\circ F$ and $Q_{cf} = 5.8$ gpm. For this purpose a "thinned out" factorial experimental plan was formulated, very similar in principle to that employed in the evaluation of the original shaft-freeze-seal (see Ref. (1)). This 39 test program design is given in Table 3. Seven special reference tests were included to evaluate the repeatability of the seal operation (numbers 38, 47, 48, 57, 58, 67, and 68). Although some of the tests had to be repeated due to operational difficulties, the program was run very much in the manner in which it was planned.

The first step in the analysis of the data from these tests was to study the unexplained large experimental variations in the temperature readings at stations six and seven demonstrated by the reference tests. Since it was not possible to attribute

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TABLE 3

Main Evaluation Program for New-Shaft-Freeze-Seal

(TC₂ = 265°F; Q_{cf} = 5.8 gpm)

Test No.	T _{Na} (°F)	S (rpm)	Q _{cs} (gpm)	Comments	Test No.	T _{Na} (°F)	S (rpm)	Q _{cs} (gpm)	Comments
30	1000	835	0.0	Ref.	59	450	935	0.8	
31	1000	300	0.5	Ref.	60	450	300	0.8	
32	1000	600	0.25		61	450	600	0.0	
33	1000	0	0.8		62	450	0	0.5	
34	1000	300	0.8		63	450	835	0.25	
35	1000	300	0.25		64	450	600	0.8	
36	1000	600	0.0		65	450	835	0.5	
37	1000	0	0.5		66	450	600	0.25	
38	1000	835	0.0	Ref.	67	1000	835	0.0	Ref.
39	800	0	0.8		68	1000	300	0.5	Ref.
40	800	600	0.25						
41	800	300	0.5						
42	800	835	0.0						
43	800	835	0.25						
44	800	600	0.5						
45	800	835	0.5						
46	800	600	0.8						
47	1000	835	0.0	Ref.					
48	1000	300	0.5	Ref.					
49	600	835	0.25						
50	600	300	0.25						
51	600	600	0.0						
52	600	0	0.5						
53	600	0	0.8						
54	600	600	0.5						
55	600	300	0.8						
56	600	835	0.8						
57	1000	835	0.0	Ref.					
58	1000	300	0.5	Ref.					

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these inconsistencies to measurement errors, it was felt that there existed an additional independent variable which had not been controlled during the experiment. The most likely candidates for this role appeared to be the inlet tetralin temperatures to the upper region and coil, which varied over a nine and ten degree range during the reference tests, respectively. Consequently, statistical correlations of these variables and the temperature readings obtained at stations six and seven were conducted. It was found that there was no correlation between the temperature at station seven and the inlet tetralin temperatures to the upper region and coil, but that a statistically very significant correlation existed between the temperature at station six and the inlet tetralin temperature to the coil. Subsequent careful study of the seal assembly indicated that these rather surprising results were due to the fact that thermocouple six was in close proximity to the coil and therefore just as sensitive to the tetralin temperature in the coil as to the sodium temperature in the seal. (This situation has been remedied in the seal presently being used in the HNPF pump evaluation program).

Using the statistical correlation a correction factor was developed for the thermocouple at station six as a function of the measured tetralin inlet temperature to the coil. This correction factor was then applied to all the test results. In many cases this procedure resulted in a much more believable seal temperature profile but in other runs the correction did not improve the results significantly or was even in the "wrong direction." Because of this inconsistency and also because the magnitude of the correction was comparable with the experimental variations exhibited by the data, it was decided not to correct any data but rather to obtain a smoothed estimate of the seal temperature profile by statistical curve-fits of the temperature readings at stations no. 3 through no. 7 versus the locations

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of these stations relative to the seal flange. Since there were five pairs of points available for these curve-fits, the experimental error in the final curve-fit could be expected, statistically speaking, to be $1/5^{\text{th}}$ of that associated with each temperature reading.

Therefore, the temperature data from all 39 runs were curve-fit using the method of least squares and assuming a quadratic relation between seal position (measured from the flange) and sodium temperature. In general the curve fits had rms errors of about two percent, on the 95 confidence level, although there were a few that were as bad as six or seven percent. A typical curve is given in Figure 2.

Under the assumption that the sodium interface was located at that point in the seal at which the sodium temperature was 214°F , it was an easy matter to locate the interface during each run by using the quadratic curve-fits.

In 84 percent of the cases the interface was located between stations six and seven as desired. Only in one case was the interface estimated to be above station seven (run 67) and the results of this test are somewhat doubtful since under identical conditions (runs 30, 38, 47, 57, and a rerun of 67) the interface was located at 1.07, 0.83, 0.53, 0.94, and 0.89 inches respectively. The conditions for these runs were $T_{\text{Na}} = 1000^{\circ}\text{F}$, $S = 835 \text{ rpm}$ and $Q_{\text{CS}} = 0$. In no case was the interface below station no. 5.

In order to quantitatively describe the dependence of the interface location, x , on T_{Na} , S , and Q_{CS} , a multiple correlation was performed using the values of x obtained from the curve-fits. Recalling the results of the correlation studies described in Appendix A, the form employed was

$$x = As + BT_{\text{Na}} + CQ_{\text{CS}} + D,$$

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where the constants A, B, C, and D were to be statistically determined from the data. The results of the correlation are given below:

VARIABLE	COEFFICIENT	STANDARD DEV. OF COEF.	PROBABILITY THAT COEF. IS NONZERO
x	- - - - -	0.4132*	.9995**
S	-0.001661	0.0002560	1.0000
T _{Na}	-0.001436	0.0003100	0.9999
Q _{cs}	-1.1261	0.2843	0.9996
Constant	3.7128	0.3034	1.0000

* This is the multiple correlation standard deviation

**This is the probability of total correlation

These results indicate an exceptionally fine correlation. The average standard deviation for the coefficients is 17.6 percent, a very good result considering the experimental errors inherent in the original temperature data.

The results of the correlation can be summarized by the equation $x = 3.7128 - 0.001661S - 0.001436T_{Na} - 1.1261Q_{cs}$. Based on this equation, plots of x versus Q_{cs} for extreme values of S and T_{Na} were constructed. From these curves an optimum selection of operating values of Q_{cs} can be made, depending on the variation in x which is considered tolerable. For example, from Fig. 6 we see that the interface location will be maintained between 0.33 and 2.50 inches from the flange under all operating conditions if Q_{cs} is set at 0.5 gpm. On the other hand, if it is desired to maintain the interface within a narrower range, then two or more levels of Q_{cs} can be employed over fixed ranges of T_{Na} and S.

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APPENDIX C FIG 2
TYPICAL SEAL TEMPERATURE PROFILE