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C-70-716

Records

WANL-TME-2733
SEPTEMBER 1970

MASTER

DATA ITEM T-119

CENTRAL ELEMENT PYROFOIL
SEAL TEST (U)

FINAL REPORT

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DATA ITEM T-119

CENTRAL ELEMENT PYROFOIL SEAL TEST (U)

SPECIAL REREVIEW FINAL DETERMINATION			
Class: <u>4</u>	Reviewers <u>RCD</u>	Class. <u>4</u>	Date <u>4-28-82</u>

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GROUP - 1 EXCLUDED FROM AUTOMATIC DOWNGRADING AND DECLASSIFICATION

INFORMATION CATEGORY <u>C-RD</u>	
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ABSTRACT

The central element pyrofoil seal was designed to prevent the core inlet plenum gas from flowing into the core exit plenum by way of the gap between the central element bore and the liner tube. The central element bore is approximately .100 inch larger than the liner tube O. D. Pyrolytic graphite insulating sleeves are inserted into the annulus along the length of the central element. The seal was designed to be force fitted into the annulus. This produces a blockage to flow and a hoop stress in the central element. Seals of various lengths and wall thickness were designed for the test.

The intent of the test series was to determine the best seal length and wall thickness to provide effective sealing without causing excessive hoop stress in the central element.

The performance of the seal was evaluated against the amount of hydrogen leakage which could be tolerated based on the resultant amount of insulating sleeve corrosion calculated for 10 hours of reactor operation.

As a result, the .25 inch long seals with a loose or medium fit were found to be the best.

An additional series of tests were conducted to determine the central element strength at the threads in the forward end. Strength data were obtained for both plain and instrumented central elements and are documented in this report.

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1.0 INTRODUCTION

1.1 TEST IDENTIFICATION

1.1.1 Type of Report

This is a final report.

1.1.2 Applicable Scope of Test Document

The applicable Scope of Test Document is Number TS:58DE-170-1.

1.1.3 Functional Category of Test

This is a development test.

1.1.4 Contractor

The Westinghouse Astronuclear Laboratory (WANL/14683) under Subcontract NP-1, CY-70.

1.1.5 Test Facility and Dates of Test

WANL Engineering Mechanics Laboratory; August 8, 1969 to July 31, 1970.

1.2 PURPOSE OF TEST

The purpose of the test was to demonstrate the feasibility of the overall approach; to establish optimum length, I.D., and O.D. of seal tube; to determine leakage rates expected through each seal; to determine structural margin between fit required for sealing, and fit causing fracture of the central element; to establish a practical assembly procedure; and to explore the strength characteristics of a threaded attachment.

2.0 REFERENCES AND ASSUMPTIONS

2.1 SPECIFICATION

CEI EC 677558, Paragraphs 3.1.1.1, 2.1.3a and 3.1.1.1.2.3.

2.2 SCOPE OF TEST DOCUMENT

TS: 58DE-170-1.

2.3 DATA RELEASE MEMORANDUMS

<u>DRM Number</u>	<u>Description</u>
51628	Test Plan for Central Element Seal Test
52166	Central Element Tensile Test
52989	Leakage and Structural Test

2.4 TEST SPECIMEN DRAWINGS

<u>Drawing Number</u>	<u>Description</u>
100E641	Central Element
800C599	Grafoil Seal

2.5 FIXTURE DRAWINGS

None

2.6 TEST EQUIPMENT

<u>Instrumentation</u>	<u>Description</u>	<u>Used in Test No.</u>
Tensile Test Machine	WANL	1, 2, 3
X - Y Recorder	Electro Instrumentations	1, 2, 3
SR4 Strain Indicator	BLH Model 120	1, 2, 3
Flow Indicator	Hastings	2

<u>Description</u>		<u>Used in Test No.</u>
Flow Indicator		2
Pressure Gage	Heise Model C	2
<u>Transducers</u>		
Strain Gages	Micro-Measurements	3
Displacement Indicator	Federal	1
Load Cell 100 lbs.	Transducers Inc.	2
Load Cell 500 lbs.	BLH	1

2.7 ASSUMPTIONS

That the test results obtained will be useful in:

Predicting Leakage Rate (U)

Establishing practical Assembly Procedure (U)

3.0 DESCRIPTION OF TEST ARTICLE

3.1 PYROFOIL SEALS

The seals used in the tests were made of pyrofoil material conforming to PDS 30085-1. They were manufactured per Drawing 800C599 in lengths of .250 inch and .625 inch. Seals of the following sizes and designations were tested:

.250 inch long "loose"	-	$.529 \pm .002$ O. D. x $.413 \pm .002$ I. D.
.250 inch long "medium"	-	$.532 \pm .002$ O. D. x $.410 \pm .002$ I. D.
.250 inch long "tight"	-	$.535 \pm .002$ O. D. x $.407 \pm .002$ I. D.
.625 inch long "loose"	-	$.529 \pm .002$ O. D. x $.413 \pm .002$ I. D.

3.2 CENTRAL ELEMENTS

The central elements used in the tests were made of graphite material conforming to PDS 30128. They were manufactured per Drawing 100E641.

4.0 SUMMARY OF TESTS (U)

4.1 NARRATIVE

4.1.1 Static Test

(U) Static tensile tests were performed to determine the tensile strength characteristics of a central element, Part Number 100E641H08. The tensile test setup is shown in Figure 4-1.

4.1.2 Leakage Test

(U) Leakage tests were performed to determine the sealing characteristics of pyrofoil seals.

(U) The leakage tests were conducted using the test fixture shown in Figure 4-2. The leakage tests were performed by flowing helium through the element. A Hastings 300 cc/minute indicator and a pipette indicator with .1 cc graduations were used to determine the flow.

4.1.3 Structural Test

(U) The structural tests were performed to determine structural margin between fit required for sealing and fit causing fracture of the central element. The element was instrumented with two strain gages in the area of the seals placement. The location of the strain gages are shown in Figure 4-3. The test setup is shown in Figure 4-2.

4.2 TEST CONDITIONS

(U) The tensile, leakage and the structural tests were performed at room temperature.

4.3 TEST RESULTS

4.3.1 Tensile Test

(C-RD) The series of six elements without an instrumentation hole were tested. The failures ranged from 675 pounds to 1020 pounds, with an average of 831 pounds. A summary of each test is tabulated in Figure 4-4. A typical failure through the threaded section of the element is shown in Figure 4-5.

Figure 4-1. Tensile Test Setup

Figure 4-2. Leakage and Structural Test Setup

Figure 4-3. Strain Gage Location

	Specimen	Type of Failure	Elongation (Inches)	Load at Failure (Lbs.)
6	Without Instrumentation Hole	A	.034	840
5	Without Instrumentation Hole	A	.046	1020
2	Without Instrumentation Hole	A	.035	850
4	Without Instrumentation Hole	A	.049	780
3	Without Instrumentation Hole	A	.048	820
1	Without Instrumentation Hole	A	.033	675
7	With Instrumentation Hole	A	.033	650
12	With Instrumentation Hole	B	.028	600
8	With Instrumentation Hole	A	.036	680
10	With Instrumentation Hole	A	.026	300
11	With Instrumentation Hole	A	.028	450

Figure 4-4.

TEST RESULTS SUMMARY

Figure 4-5. Tensile Test Failure

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The second series of tests were conducted with elements having an instrumentation hole. The failure load ranged from 300 to 720 pounds, with an average of 536 pounds. Of the five elements tested, four failed in the threaded section and one failed in the central part of the element. The two types of failures are shown in Figures 4-6 and 4-7. The failure loads are summarized in Figure 4-4. A typical load versus deflection plot is shown in Figure 4-8.

4.3.2 Leakage Test (U)

The leakage test identified in Figure 4-9 was conducted using seals individually and in various combinations. The leakage rate ranged from less than .01 cc/min. to 27.4 cc/min.

The test setup is shown in Figure 4-2. A seating tool was used to locate the seal in the test assembly. The force required to insert the seal into the element is the maximum load in pounds during the insertion and was recorded with a X-Y Recorder. The results of all the tests conducted are shown in Figure 4-9. Test designations L-1 through L-12 cover .250 inch loose fitting seals. Test designations M-1 through M-8 cover .250 inch medium fitting seals. Test designations L-13 through L-21 cover .625 inch loose fitting seals. Plots of leakage versus insertion force for the .250 inch of the loose, medium and tight fitting seals are shown in Figures 4-10, 4-11, and 4-12.

4.3.3 Structural Test

The structural tests identified in Figure 4-13 were performed using seals of various configurations. The location of the strain gages are shown in Figure 4-3. Test designation L-22 covers .250 inch loose fitting seals. Test designations L-23 and L-24 cover .625 inch loose fitting seals. Test designation M-9 covers .250 medium fitting seals. Test designation T-11 covers .250 inch tight fitting seals. Test designation M-10 covers .625 inch medium fitting seals and the element failed during the insertion of the second seal. The element failed along its length and is shown in Figure 4-14.

4.4 DISCUSSION OF DATA

The data that are covered in this report will be utilized in obtaining all information required to satisfy full compliance with the applicable Scope of Test.

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Figure 4-6. Tensile Test Failure

Figure 4-7. Tensile Test Failure

Figure 4-8. Load Versus Deflection Plot Element Without An Instrumentation Hole

TEST DESIGNATION	ELEMENT NUMBER	LENGTH OF SEAL (in.)	TYPE OF SEAL	SEAL INSERTION FORCE IN POUNDS				*Δ FIT IN INCHES				INPUT PRESSURE IN POUNDS AND LEAKAGE IN CC/MINUTE					
				1	2	3	4	1	2	3	4	50	75	100	125	150	175
L-1	4	.250	LOOSE	47.5				.0107					5.0		13.3	18.0	23.3
L-2	10	.250	LOOSE	68.0				.0107				1.0	2.1		5.4	8.0	
L-3	4	.250	LOOSE	40.0				.0079									27.4
L-4	2	.250	LOOSE	45.0				.0074				.316	1.06	1.61	2.61		
L-5	3	.250	LOOSE	8.0								<.01		.021	.035		.123
L-6	3	.250	LOOSE	24.0				.0023				<.01	<.01		<.01		<.01
L-7	3	.250	LOOSE	26.0				.0018				.42		1.56	2.5		5.4
L-8	3	.250	LOOSE	13.5				.0013				.493		1.44	2.0		3.13
L-9	3	.250	LOOSE	9.0	29.0			.0006	.0034			.25		.406	.56		.83
L-10	1	.250	LOOSE	21.0	22.0	31.0		.0017	.0012	.0027		.373		.33	.9		1.5
L-11	3	.250	LOOSE	15.0	25.0	5.0	19.0	.0013	.0024	.0023	.0028	<.01			<.01	<.01	.023
L-12	4	.250	LOOSE	12.5	10.5	27.0	15.0	.0018	.0008	.0026	.0028	.063			.2	.27	.323
M-1	2	.250	MEDIUM	36.0				.0056					<.01	<.01	<.01		<.01
M-2	2	.250	MEDIUM	55.0				.0081						<.01	<.01	<.01	<.01
M-3	3	.250	MEDIUM	55.0				.0082				.576	1.62			2.14	2.15
M-4	3	.250	MEDIUM	62.0				.0077				.075	.082		.088		
M-5	2	.250	MEDIUM	53.0				.0119				<.01	<.01	<.01	<.01		
M-6	9	.250	MEDIUM	53.0				.0079				<.01		<.01	<.01	<.01	<.01
M-7	2	.250	MEDIUM	64.0	47.0			.0095	.0081			<.01		<.01	<.01	<.01	<.01
M-8	2	.250	MEDIUM	74.5	76.5	51.5		.0125	.0082	.0064		.025		.013	.056		.066
M-9	1	.250	MEDIUM	45.0	37.0	46.0	23.0	.0097	.0077	.0097	.0042	<.01			<.01	<.01	<.01
T-1	3	.250	TIGHT	34.0				.0176				1.8	4.0	5.8			24.6
T-2	9	.250	TIGHT	78.0				.0162				<.01	<.01	<.01			<.01
T-3	3	.250	TIGHT	72.0				.0156				<.01	<.01	<.01	.049		
T-4	1	.250	TIGHT	77.0				.0159				<.01		<.01	<.01		<.01
T-5	9	.250	TIGHT	61.0				.0159				<.01			<.01	<.01	<.01
T-6	2	.250	TIGHT	62.0				.0151									
T-7	2	.250	TIGHT	51.0				.0141					2.83	4.3	6.0		9.06
T-8	2	.250	TIGHT	80.0	87.0			.0156	.0156			.123			.146	.16	.17
T-9	2	.250	TIGHT	66.0	74.0	39.0		.0131	.0166	.0096			>.01	>.01		.02	.03
T-10	1	.250	TIGHT	45.0	37.0	46.0	23.0	.0097	.0077	.0115	.005	<.01			<.01	<.01	<.01
T-11	8	.250	TIGHT	42.0	69.0	65.5	74.0	.0127	.0162	.0167	.0179	<.01			<.01	<.01	<.01
L-13	1	.625	LOOSE	56.0				.0049					.76	1.38	2.01		4.9
L-14	1	.625	LOOSE	96.0				.0059				<.01			<.01	<.01	.013
L-15	2	.625	LOOSE	93.0				.0064					.045	.325		1.26	1.46
L-16	3	.625	LOOSE	47.0				.0018				.191		.63	.858		2.5
L-17	3	.625	LOOSE	105.0				.0028				.04		.143	.3		.66
L-18	1	.625	LOOSE	68.0				.0027				<.01		.063	.15		.353
L-19	3	.625	LOOSE	68.0	54.0			.0013	.0018			<.01			.01	.011	.166
L-20	3	.625	LOOSE	31.0	100.0	88.0		.001	.0013	.0028		<.01		<.01	<.01	<.01	<.01
L-21	1	.625	LOOSE	37.0	108.0	73.0	126.	.0037	.0017	.0032	.0022	.01			.011	.013	.015

* ΔFit is the amount of radial seal compression between the I. D. of the element and the O. D. of the liner tube.

Figure 4-9. Leakage Test Results Summary

.250 Inch Seals - Medium Fitting
Figure 4-10. Seating Force is the Maximum Load in Pounds
Recorded During the Seal Insertion

W59940

Figure 4-11. Seating Force is the Maximum Load in Pounds
Recorded During the Seal Insertion

W58840

Figure 4-12. Seating Force is the Maximum Load in Pounds
Recorded During the Seal Insertion

(The Seals were Inserted One at a Time and a Total
of four Seals were Inserted for Each Test)

Test Designation	Length Of Seal	Type of Seal	Force in Pounds To Insert Seal	Max Strain in μ in. on Top Gage During Seal Seating	Max. Strain in μ in. on Bottom Gage During Seal Seating	Strain in μ in. on Top Gage When Seal was Seated	Strain in μ in. on Bottom Gage when Seal was Seated
T11	.250	TIGHT	42.0	217 μ in.	244 μ in.	10 μ in.	28.8 μ in.
T11	.250	TIGHT	69.0	333 μ in.	324 μ in.	10 μ in.	13.0 μ in.
T11	.250	TIGHT	65.5	335 μ in.	335 μ in.	8.8 μ in.	22.2 μ in.
T11	.250	TIGHT	74.0	410 μ in.	444 μ in.	15.5 μ in.	45.0 μ in.
M9	.250	MEDIUM	45.0	283 μ in.	227 μ in.	22.2 μ in.	11.0 μ in.
M9	.250	MEDIUM	37.0	190 μ in.	154 μ in.	22.0 μ in.	11.0 μ in.
M9	.250	MEDIUM	46.0	210 μ in.	157 μ in.	18.0 μ in.	0
M9	.250	MEDIUM	23.0	219 μ in.	170 μ in.	26.0 μ in.	22.0 μ in.
L22	.250	LOOSE	12.5	73 μ in.	43 μ in.	0	0
L22	.250	LOOSE	17.5	36 μ in.	16.5 μ in.	2.0 μ in.	2.5 μ in.
L22	.250	LOOSE	20.0	85 μ in.	59 μ in.	4.0 μ in.	2.5 μ in.
L22	.250	LOOSE	15.0	84 μ in.	49 μ in.	4.0 μ in.	2.5 μ in.
L23	.625	LOOSE	35.0	70 μ in.	10 μ in.	18.0 μ in.	10.0 μ in.
L23	.625	LOOSE	108.0	230 μ in.	230 μ in.	20.0 μ in.	40.0 μ in.
L23	.625	LOOSE	73.0	215 μ in.	220 μ in.	20.0 μ in.	42.0 μ in.
L23	.625	LOOSE	126.0	40 μ in.	260 μ in.	35.0 μ in.	200.0 μ in.
L24	.625	LOOSE	108.0	500 μ in.	480 μ in.	80.0 μ in.	80.0 μ in.
L24	.625	LOOSE	40.0	190 μ in.	140 μ in.	80.0 μ in.	50.0 μ in.
L24	.625	LOOSE	134.0	520 μ in.	400 μ in.	100.0 μ in.	105.0 μ in.
L24	.625	LOOSE	120.0	165 μ in.	335 μ in.	80.0 μ in.	300.0 μ in.
M10	.625	MEDIUM	140.0	880 μ in.	1300 μ in.	260.0 μ in.	230.0 μ in.
M10	.625	MEDIUM	220.0	250 μ in.	1200 μ in.	Element cracked along its length.	

Figure 4-13. Structural Test Results Summary

Figure 4-14. Element Failure

5.0 ANALYSES

The test data were analyzed to determine pyrofoil sealing performance and central element strength margin (hoop strength and tensile strength).

5.1 ANALYTICAL MODELS

Paragraph 5.1.1 presents the analytical model employed to determine the pyrofoil seal performance related to the amount of corrosion damage to the pyrolytic graphite insulating sleeves caused by hydrogen leakage permitted by the seal.

Paragraph 5.1.2 presents the analytical models employed to determine central element tensile strength margin and hoop strength margin.

5.1.1 Seal Leakage and Corrosion

5.1.1.1 Seal Leakage Flow Relations

The leakage flow through the seal is caused by the pressure gradient across the seal. Assuming that the leakage is by porous flow through the volume of the seal, the pressure gradient across the seal might be represented by the form, as reported in Reference (1),

$$\frac{-dp}{dx} = a\mu V + b\rho V^2 \quad (1)$$

in which a and b are constants for a given seal, μ is the viscosity, ρ is the density of the fluid. The first term ($a\mu V$) is due to the viscous effects and the second term is due to the inertial effects. For very low velocity flows, i.e. Darcy's flow, the pressure gradient is due to the first term only, i.e. it is a linear function of the velocity V . At higher velocities, departure from Darcy's law are due to inertial effects. In order for equation (1) to reduce to the Darcy limit at small velocities, the constant " a " equals $1/k$ where k is defined as the permeability of the porous medium. Substitution for " a " and rearrangement of equation (1) gives:

$$\frac{-k}{\mu} \frac{dp}{dx} = V + \frac{bk}{\mu} \rho V^2 \quad (2)$$

Applying the continuity equation and equation of state

$$\left. \begin{aligned} W &= \rho VA \\ p &= \rho RT \end{aligned} \right\} \quad (3)$$

where T is the temperature, R is the gas constant, W is the flow rate, and A is the area, equation (2) can be written as

$$\frac{-k}{\mu} \frac{p}{RT} dp = \left[\frac{W}{A} + \frac{bk}{\mu} \left(\frac{W}{A} \right)^2 \right] dx \quad (4)$$

Integration of equation (4) gives

$$\left(\frac{\bar{p} \Delta p}{\mu RT} \right) = \frac{1}{k} \left(\frac{WL}{A} \right) + \left(\frac{b}{\mu L} \right) \left(\frac{WL}{A} \right)^2 \quad (5)$$

where $\bar{p}$ is the average pressure, and L is the length of the seal. The area of the porous medium, normal to the flow direction, A , is hard to determine. For reference and for comparison of experimental data, it is taken as the physical cross sectional area of the seal. For Darcy's relations, where the inertia term can be neglected, equation (5) is of the familiar form which shows the flow rate $\left(\frac{WL}{A} \right)$ being directly proportional to the parameter

$$\left(\frac{\bar{p} \Delta p}{\mu RT} \right) \quad \left(\frac{WL}{A} \right) = k \left(\frac{\bar{p} \Delta p}{\mu RT} \right) \quad (6)$$

Another approach to show the deviation of the flow rate from Darcy's relation is to have an exponent on $\left(\frac{\bar{p} \Delta p}{\mu RT} \right)$ i.e.

$$\left(\frac{WL}{A} \right) = k \left(\frac{\bar{p} \Delta p}{\mu RT} \right)^a \quad (7)$$

Comparison of equation (5) and (7) shows that for fixed $\left(\frac{\bar{p} \Delta p}{\mu RT} \right)$ parameter, the exponent "a" is equal to 1 for Darcy's flow, and less than 1, for cases where the inertial effects are important. Leakage flow data plotted in the form of equation (7) on log-log paper show

a straight line with a slope of "a" and an intercept equal to the permeability k . From the value of the intercept, the permeability constant k can be determined and the slope "a" can also be determined from the data.

Correlation of the experimental data in the form of equation (7) has been performed and the results are discussed in Section 5.2.1. The seal leakage in the NERVA reactor has been determined by application of the reactor value of the $(\bar{p} \Delta p / \mu RT)$ parameter to the seal data correlated in this manner. This is given in Section 5.2.1.

5.1.1.2 Corrosion Due to Seal Leakage Flow

In the reactor hydrogen flow due to the seal leakage passes through the central unfueled element causing corrosion of the pyrolytic graphite insulating sleeves located between the central element and stainless steel liner. The leakage flow should be small so as not to cause heavy corrosion damage of these pyrolytic graphite insulating sleeves. The analysis of the corrosion for the leakage flow corresponding to reactor conditions was performed using the Isolated Channel Analysis Program (ICAP).

Figure 5-1 shows a schematic of the flow path through the seal. The corrosion analysis model is taken as a parallel plate geometry with 3.25 mil gap and with one corrodible (pyrolytic graphite insulating sleeve) side. The axial temperature distribution is taken from the worst possible temperature conditions, i.e. for minimum support stem flow. It is conservatively assumed that the entire leakage flow passes between the central element and insulating sleeves (hot side of the sleeve), where the corrosion rate will be a maximum. The results of the corrosion calculations are discussed in Section 5.2.1.

5.1.2 Central Element

5.1.2.1 Tensile Strength (Threads)

The stress in the central element at the cold end threaded attachment is assumed to follow the relationship $S = KF/A$. The axial load is F ; A is the loaded cross-sectional area, and K is a stress concentration factor. The expected failure stress for this

Figure 5-1: Schematic of Leakage Flow and Corrosion Model

cross-section at room temperature is (3520,500) psi. The ordered pair of numbers represent the estimated mean and standard deviation of ultimate tensile strength for the test specimen material, graphite, PDS 30022. This strength is a 20% degradation from that given in Reference (2) for unirradiated Graphitite G, PDS 30020. This estimate, as suggested by the Materials Department, is used due to the unavailability of PDS 30022 graphite material properties data.

5.1.2.2 Hoop Strength

The hoop stress in the central element due to internal pressure when compared to a plane stress thickwall cylinder from Reference (3) is:

$$S_{\theta} = \frac{b^2 P}{a^2 - b^2} (1 + a^2/r^2)$$

where b and a are the respective inner and equivalent outer radii, and P is the internal pressure. For a seal of length L and radius b the internal pressure exerted on the element during seal insertion is the insertion force per friction loaded area.

$$P = \frac{F}{4\pi b L \mu}$$

The expected failure stress in the hoop direction at room temperature is (2240,300) psi. This estimate, as suggested by the Materials Department, represents a 20% degradation of the mean ultimate tensile strength for unirradiated Graphitite G in the hoop direction from Reference (2) due to the unavailability of PDS 30022, graphite material property data.

5.2 COMPARISON OF PREDICTION AND RESULTS

Seal leakage and corrosion prediction and results comparisons are presented in Paragraph 5.2.1. Central element tensile and hoop strength prediction and results comparisons are presented in Paragraphs 5.2.2 and 5.2.3.

5.2.1 Seal Leakage and Corrosion

5.2.1.1 Seal Leakage

The data for the central element pyrofoil seal test (Test Plan 58-DE-170) has been reported in Figure 4-4. There were three different types of seal: loose, medium, and tight. There were two different lengths: 1/4 inch and 5/8 inch. Since the design calls for one 1/4 inch seal, analysis has been performed primarily on 1/4 inch seal test data. The leakage flow in standard cc/minute was recorded for six different pressure differentials: 50, 75, 100, 125, 150, and 175 psid. For each test, the maximum force used to insert the seal and total compression (Δ Fit) is recorded. For some tests, the seal was very effective and the data were reported as less than .01 standard cc/minute when no appreciable leakage was found even after a long holding period of the test.

Figures 5-2 to 5-11 give the leakage flow (WL/A) in ($lbm\text{-}in/sec\text{-}in^2$) versus the parameter ($\bar{p} \Delta p / \mu RT$) in ($lbm/in^3\text{-}sec$), for various tests. The test designation is given on the figures. Leakage flow plots are made for all tests except for 5/8 inch long seals and for some 1/4 inch long seals with less than .01 cc/minute leak rates.

Also shown on the figures is the range $1.24 \times 10^{+4} - 2.28 \times 10^{+4} \left(\frac{lb_f\text{-}sec}{in^4} \right)$ of the ($\bar{p} \Delta p / \mu RT$) parameter calculated for the reactor conditions. The first number is for start of life reactor conditions (minimum support stem flow) with average seal temperature of $1025^\circ R$. The second is for 60% throttled conditions at end of life with average seal temperature of $720^\circ R$. The average pressure ($\bar{p}$) and seal pressure drop (Δp) for both cases is taken to be 535 psi and 170 psid.

From the figures, the reactor leakage flow (WL/A) for ($\bar{p} \Delta p / \mu RT$) value of $1.25 \times 10^{+4}$ (highest temperature condition) is given in Table 5-1. Using the correlations, equation (7), in Section 5.1.1, the slope "a" and permeability "k" for the tests have been obtained and are also shown in Table 5-1. The slope "a" is very close to 1, showing the validity of the Darcy's relation for most of the cases. The values of the permeability "k" for these tests are also tabulated. The difference in values of the permeability k may be due to the change in porosity caused by the mechanical effects of seal insertion force and

Figure 5-2, Leakage Flow Versus ($\bar{p}\Delta p/\mu RT$)

Figure 5-3. Leakage Flow Versus $(\bar{p}\Delta p/\mu RT)$

Figure 5-4. Leakage Flow Versus $(\bar{p}\Delta p/\mu RT)$

Figure 5-5. Leakage Flow Versus ($\bar{p}\Delta p/\mu RT$)

Figure 5-6. Leakage Flow Versus $(\bar{p}\Delta p/\mu RT)$

Figure 5-7. Leakage Flow Versus ($\bar{p}\Delta p/\mu RT$)

Figure 5-8. Leakage Flow Versus $(\bar{p}\Delta p/\mu RT)$

Figure 5-9. Leakage Flow Versus $(\bar{p}\Delta p/\mu RT)$

Figure 5-10. Leakage Flow Versus $(\bar{p}\Delta p/\mu RT)$

Figure 5-11. Leakage Flow Versus ($\bar{p}\Delta p/\mu RT$)

TABLE 5-1
CORRELATION OF LEAKAGE FLOW DATA

Test Designations	Hydrogen Leakage Flow (WL/A) at Reactor Conditions (lbm-in/sec-in ²)	Slope α	Permeability k (in ²)
L1	7.8×10^{-7}	1.03	1.23×10^{-13}
L2	3.8×10^{-7}	1.08	3.52×10^{-14}
L4	2.2×10^{-7}	1.29	2.95×10^{-15}
L5	5.4×10^{-9}	1.65	2.31×10^{-18}
L7	1.8×10^{-9}	1.13	1.06×10^{-14}
L8	9.2×10^{-8}	0.83	0.99×10^{-13}
L9	4.1×10^{-8}	0.59	$3.97 \times 10^{-13*}$
L10	1.0×10^{-7}	0.60	$9.20 \times 10^{-13*}$
L12	3.6×10^{-8}	0.73	$0.96 \times 10^{-13*}$
M3	1.0×10^{-7}	1.08	1.02×10^{-14}
M4	1.7×10^{-9}	0.21	6.29×10^{-13}
M8	4.7×10^{-9}	0.59	$4.53 \times 10^{-14*}$
T1	8.5×10^{-7}	1.19	2.80×10^{-14}
T7	2.5×10^{-7}	0.77	4.69×10^{-13}
T8	6.4×10^{-9}	0.20	$2.51 \times 10^{-12*}$

*These are multiple seals in series which deviate considerably from Darcy's relations.

$$(WL/A) = kg (\bar{p}\Delta p/\mu RT)^{\alpha}$$

where g , acceleration due to gravity = $386.4 \text{ lbm-in/lb}_f\text{sec}^2$.

Δ fit. The effect of seal insertion force and seal fit on the permeability or leakage were not correlated in this section. However, the effect of these variables were discussed in Section 4.3.

From Table 5-1, the maximum seal leakage flow (WL/A) for reactor conditions is 8.5×10^{-7} (lbm-in/in²-sec), which is equivalent to 3.1×10^{-7} lbm/sec for one 1/4 inch seal.

5.2.1.2 Corrosion

The corrosion analysis was performed using ICAP computer code for 3.25 mil gap with the hydrogen leakage rate obtained for the poorest performing seal 3.1×10^{-7} lbm/sec. This corresponds to .012 lbs. of hydrogen in 10 hours. The wall surface temperature distribution for the pyrolytic graphite insulating sleeve is taken from the TAP-B cluster model at start of life reactor conditions, which are the highest temperature conditions. This axial surface temperature distribution is given in Figure 5-12. The reaction rate constants are taken from Reference (4), for the pyrolytic graphite insulating sleeve, and raised by a factor of 10 which is within the scatter and uncertainty of the data. The axial corrosion profile is shown in Figure 5-13, which shows a maximum corrosion depth of 11 mils after 10 hours of operation. The sleeves are .055 inch thick.

5.2.1.3 Seal Leakage and Corrosion Results

The following conclusions are drawn based on the seal leakage analysis and corrosion evaluations described in Sections 5.1.1 and 5.2.1:

- 1) For the majority of the seals tested, the leakage flow relation closely fits the Darcy's law, i.e. leakage flow equals a constant time $\rho \Delta p / \mu$.
- 2) For individual seal tests, this constant and, therefore, the leakage flow varies over a wide range. Equivalent single cluster hydrogen leakage flow rates calculated for reactor conditions, utilizing the test results, vary from a negligible amount to .012 lbs. of hydrogen in 10 hours.

Figure 5-12: Axial Temperature Distribution of the Hot Side Surface of the Pyrolytic Graphite Sleeves

Figure 5-13: Axial Corrosion Depth Profile at End of 10 Hours Operation

3) Corrosion of the insulating pyrolytic graphite sleeves, located between the central support element and the support stem liner, is the major adverse effect of the leakage of this seal in the reactor. Corrosion calculations based on the most conservative assumptions show that the maximum leakage seal would result in corrosion of 1.4 grams of graphite per central element from these insulating sleeves with a maximum corrosion depth of 11 mils in 10 hours.

4) This seal leakage test was run to obtain design guidance but was not intended to be a proof test of the seal under simulated reactor conditions. Conditions which may have an adverse effect on seal leakage should be checked in future seal tests. These include: long duration operation, relative motion of component parts due to thermal expansion and vibration, and temperature level.

5.2.2 Central Elements Stress Calculations From Test Data (Threads)

5.2.2.1 Without Instrumentation Hole

Based on six tests, the mean and standard deviation for failure load was:

$$F = (831,81) \text{ lbs. (mean, standard deviation).}$$

The minimum cross-section at the threads is $A = (.247, .0034)\text{in}^2$. With the assumption of normal probability density functions and a stress concentration of 1.0, the modeled failure stress based on the failure loads is the following:

$$S = \frac{KF}{A} = (3350,330) \text{ psi.}$$

5.2.2.2 With Instrumentation Hole

Five tensile tests were performed on specimens with an instrumentation hole and the statistical failure load was computed to be:

$$F = (536,142) \text{ lbs.}$$

The cross-sectional area for an element with an instrumentation hole is $A = (.240, .0034)\text{in}^2$. Since the data indicated an inherent weakness in the instrumented central, the prediction model is modified by an assumed deterministic stress concentration factor of $K = 1.5$. With this modification, the modeled failure stress based on experimental results is:

$$S = \frac{KF}{A} = (3340,890) \text{ psi.}$$

5.2.2.3 Model Evaluation

A comparison of the probability density functions can be made between the expected failure stress (strength) and the modeled stress at failure. The modeled stress at failure is computed from the experimental results being applied to the assumed model. If the probability of modeled failure stresses exceeding expected failure stresses is greater than .5 the model is conservative, and if that probability is less than .5 the model is non-conservative. When that probability is .5 the modeled mean failure stress is identical to the expected mean failure stress. This type of analogy may in instances be applicable only in the stress range of computations. The above statements should be interpreted as the statistical definition of modeling conservatism with respect to failure criteria.

5.2.2.3.1 Without Instrumentation Hole

Expected Failure Stress = (3520,500) psi

Modeled Failure Stress = (3350,330) psi

P = Probability (Based on Normal Probability Density Functions)

$P [(\text{Modeled Failure Stress}) > (\text{Expected Failure Stress})] = .4$

This result indicates that at these stress levels, the assumed model is slightly non-conservative.

5.2.2.3.2 With Instrumentation Hole

Expected Failure Stress = (3520,500) psi

Modeled Failure Stress = (3340,890) psi

$P [(\text{Modeled Failure Stress}) > (\text{Expected Failure Stress})] = .45$

Although both of these models tend to be non-conservative, it should be mentioned that in this range of stress, the probabilities of expected failure-stress exceeding the modeled failure-stress are .6 and .55 respectively.

5.2.2.4 Design Reliability

The design reliability is computed from both the experimental failure load data and from the modeled failure stress based on experimental load data for the purpose of comparison.

5.2.2.4.1 Without Instrumentation Hole

5.2.2.4.1.1 Load Analysis. The "expected" operating load in the central element (with a stem failure) is (84,5) lbs., and the observed central element failure load was (831,81) lbs. Based on normal distributions, the design reliability is $.9_{20}$.

5.2.2.4.1.2 Stress Analysis. The "expected" operating stress in the central element based on a stem failure condition is (340,21) psi, and the expected strength is (3520,500) psi. With assumed normal distributions, the reliability is $.9_{10}$. The reliability, based on stress analysis, is significantly less than that based on the load analysis because of the relatively large standard deviation of strength.

5.2.2.4.2 With Instrumentation Hole

5.2.2.4.2.1 Load Analysis. The "expected" operating load is (84,5) lbs. and the observed failure load was (536,142) lbs. The reliability is .9993 with assumed normal distributions. This relatively small reliability can be attributed to the large failure load standard deviation which could be due to the presence of the instrumentation hole in the central element.

5.2.2.4.2.2 Stress Analysis. The "expected" operating stress based on the previously discussed model is (525,32) psi and the expected strength is (3520,500) psi. The reliability is .99. Since this reliability is significantly greater than that computed by load analysis, the assumed stress model appears to be very non-conservative in the operating load range of (84,5) lbs. The obvious indication that there is not a good predictable relationship between load and stress is the large coefficient of variation indicated in the failure loads on specimens with an instrumentation hole. This type of comparison indicates the need for experimental results because of the unknown variabilities that can be introduced by the geometry of close tolerances.

5.2.3 Central Element Hoop Stress

Figure 5-14 is a plot of experimental results showing a correlation between seal insertion force and the maximum value of strain measured on the outer surface of the central element. The data points include the tight, medium and loose fitting 0.25 inch seal; and the loose fit 0.625 inch seal. The mean and 2.3 σ insertion forces are indicated for each of the four different seal sets. A comparison of size reveals that the shorter tight fitting seal requires only about one-half the insertion force as the larger loose fitting seal. This is due to an increase of friction loaded area on the larger seal.

Figure 5-15 is a plot of insertion force versus tensile hoop stress at the outer surface of the central element. The experimental curves were computed with Hooke's law from the strain data, and the theoretical curves were computed from the equations in Section 5.1.2.2 with the following constants:

$$\begin{aligned}a &= .395 \text{ in.} \\b &= .2635 \text{ in.} \\L &= .25 \text{ of } .625 \text{ in.} \\\mu &= .15 \text{ (Reference 5).}\end{aligned}$$

The modulus used in Hooke's law was:

$$E = 1.0 \times 10^6 \text{ psi (Reference 2).}$$

W58932-1

FIGURE 5-14 : Seal Insertion Force Versus the Maximum Recorded Hoop Strain on the Element Outer Surface

FIGURE 5-15 : Seal Insertion Force Versus the Element Outer Surface Hoop Stress Based on the Maximum Strain Indications

5.2.3.1 Model Evaluation

The central element hoop stress model given in Section 5.1.2.2 must be evaluated in a deterministic fashion due to the nature of the experimental data. If a statistical comparison were possible between experimental and theoretical results, the probability of modeled stresses exceeding experimental results would be computed at a given insertion force. For a set of seals of given length and tightness of fit, a wide range of insertion forces are observable, and consequently a probabilistic comparison with the theoretical results is not directly applicable. What can be shown from the deterministic curves on Figure 5-15 is that in the expected range of insertion loads, the theoretical curves indicate larger stresses than the experimental results. This comparison shows that the theoretical predictions are conservative in this load range. An additional comparison is that the theoretical prediction is linear with load and the experimental results are non-linear. The trends on Figure 5-15 would indicate that the theory becomes non-conservative at loads much greater than the expected range.

5.2.3.2 Design Reliability

The experimental strains were measured on the outer surface of the test elements. The location of maximum hoop stress is at the inner surface of the element. From the hoop stress equation in Section 5.1.2.2, the ratio of stress at the inner radius to that at the equivalent outer radius can be computed as 1.63 for this geometry. Figure 5-16 is a plot of the insertion force versus the maximum hoop stress. These stress curves are based on the experimental strain measurements and the theoretical relationship between the stresses at the outer and inner radii. The reliability of each set of seals can be computed as the probability that the central element maximum hoop stress does not exceed the hoop strength during the insertion process. The mean and standard deviation of the central element hoop stress induced by each set of seals is determined from Figure 5-16 by applying to Figure 5-16 the mean and standard deviation of insertion force shown on Figure 5-14 for each set of seals. With assumed normal probability density functions, the individual seal reliabilities

FIGURE 5-16: Seal Insertion Force Versus Maximum Hoop Stress at Inner Surface of Test Element

are computed by comparison with the strength mean and standard deviation, (2240,300) psi.
The following table summarizes the seal induced stresses and reliability.

TABLE 5-2

THE PROBABILITY THAT CENTRAL ELEMENT HOOP STRESS
IS LESS THAN HOOP STRENGTH DURING SEAL INSERTION

<u>SEAL</u>	<u>CENTRAL ELEMENT MAXIMUM STRESS ~ PSI</u>		<u>RELIABILITY</u>
	<u>MEAN</u>	<u>σ</u>	
L = 0.25 TIGHT	545	113	.9 ₇ ⁴
L = 0.25 MEDIUM	367	42	.9 ₉ ⁷
L = 0.25 LOOSE	122	21	.9 ₁₂ ²
L = 0.625 LOOSE	432	261	.9 ₅ ⁷

REFERENCES

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- (2) DRM 51225A, June 1969, Graphite G Material Properties
- (3) W. Flugge, Handbook of Engineering Mechanics, McGraw Hill, New York, 1962
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6.0 CONCLUSIONS

The test results indicate that the central element pyrofoil seal design is adequate. Figure 5-13 shows that for the seal having the most leakage, the predicted leakage at R-1 reactor conditions determined from the test data would cause a peak corrosion depth of 11 mils to the insulating sleeve at core station 22 after 10 hours of operation. Considering that the corrosion is a local effect and that the ΔT across the insulating sleeve is small at this location, 11 mils is well within the acceptable corrosion range. Furthermore, many of the seals tested had leakages too small to measure (less than .01 std. cc/min.). Table 6-1 indicates that the maximum predicted leakage at R-1 conditions determined from the test data is less than the estimated value which would not degrade the thermal-hydraulic characteristics stated in the Cluster Hardware Specification.

As described in Section 3.0, the designations loose, medium, and tight were applied to parts 800C599 H03A, 800C599 H02A, and 800C599 H01A, respectively. However, some of the seals labeled by the supplier as complying to a certain part number were found to comply dimensionally with a different part number when inspected. The Δ fit or interference listed in Figure 4-9 for each seal was established from the measured wall thickness of the seal and the radial gap between the O. D. of the simulated liner tube and I. D. of the particular central element used for each test run. This accounts for the lack of correlation between seal type and Δ fit results in Figure 4-9. Considering these facts and test results on leakage for the seals, the deciding factor in determining the optimum seal configuration was the hoop strength reliability. Therefore, seals manufactured to the configuration of part number 800C599 H03A are recommended for reactor use.

Figure 6-1 shows the trend of using multiple seals. The leakage rate decreases with more seals. The possibility of having excessive leakage due to one defective seal is lessened because the other three act as backup seals.

TABLE 6-1

TEST RESULTS VERSUS THE CLUSTER HARDWARE SPECIFICATION REQUIREMENTS

EC-677558 Specification Requirement

Test Results

3.1.1.1.2.1.3 a) Core Support, Malfunction

The Cluster Hardware shall be capable of supporting or transferring to adjacent clusters, the full cluster axial loads in the event of a failure of an individual support stem.

The expected operating load on the central element forward end attachment is (84,5)* lbs.

Observed Failure Load
(831,81) Lbs. Without Instrumentation
Hole
(536,142) Lbs. With Instrumentation
Hole

3.1.1.1.2.3 Thermal-Hydraulic Characteristics

The thermal-hydraulic characteristics of the CH supporting the Reactivity Control requirements shall be in accordance with Table 1 and Table 2. In addition, the CH shall accommodate the radial and azimuthal temperature and pressure variations existing in the support stem inlet plenum as specified in the Fluid Distribution and Collection requirements of EC-677561.

It is estimated that .025 inch of corrosion can be tolerated locally on the insulating sleeves without having a significant effect on the above thermal-hydraulic characteristics. The leakage value calculated to yield this amount of corrosion during operation is 7×10^{-7} lbm/sec.

Maximum Predicted Leakage at R-1
Conditions Determined From the
Test Data
 3.1×10^{-7} lbm/sec.

*84 is the mean value, 5 is the standard deviation. These values from Section 5.2.2.4.1.1 of this report.

Figure 6-1. Effect of Using More Than One Seal on Leakage (1/4" Loose)

The tensile strength of the central element without instrumentation hole is adequate based on the load analysis reliability value of $.9_{10}$ calculated from the test data.

The tensile strength of the central element with instrumentation hole is marginal based on the load analysis reliability of .9993 calculated from the test data. Additional testing is recommended to better determine the tensile strength reliability of the central element, factoring in any design changes that would improve this reliability.

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	Central Element Pyrofoil Test	
DOCUMENT NO.	WANL-TME-2733	DATE 28 Sept. 1970
ABSTRACT <p>The central element pyrofoil seal was designed to prevent the core inlet plenum gas from flowing into the core exit plenum by way of the gap between the central element bore and the liner tube. The intent of this test series was to establish the optimum seal size and to study its effect on the central element during assembly.</p> <p>An additional series of tests were conducted to determine the central element tensile strength at the threads in the forward end.</p>		
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