MAR 22 1964

MASTER

COO
-1402-1

I-B2254-1

CRITICAL REVIEW OF THE DESIGN OF THE HALLAM
MODERATOR ELEMENT
PHASE I

by

K. R. Stearns
Z. Zudans

August 28, 1964

Prepared for

UNITED STATES ATOMIC ENERGY COMMISSION
Chicago Operations

Contract No. AT(11-1)-1402

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission, makes any warranty, representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe upon privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor is engaged in the development, preparation, or dissemination of information, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

THE FRANKLIN INSTITUTE
LABORATORIES FOR RESEARCH AND DEVELOPMENT
PHILADELPHIA
PENNSYLVANIA

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Ced

~~000~~-1402-1

I-B2254 -1

CRITICAL REVIEW OF THE DESIGN OF THE HALLAM
MODERATOR ELEMENT, PHASE I

by

K.R. Stearns
Zenons Zudans

August 28, 1964

Prepared for

UNITED STATES ATOMIC ENERGY COMMISSION
Chicago Operations

Contract No. AT(11-1)-1402

ABSTRACT

A number of documents dealing with the Hallam moderator element development and design were critically reviewed. Comments clarifying some specific points of the reviewed documents were listed. Critical areas needing further investigation were depicted and a brief outline of the required analysis given.

TABLE OF CONTENTS

	<u>Page</u>
Abstract.	i
1. Introduction.	1
2. Review.	2
2.1 NAA-SR-4384.	2
2.1.1 Introduction.	2
2.1.2 Description of Moderator Element.	3
2.1.3 Room Temperature Axial Compression Test	4
2.1.4 External Pressure and Thermal Loading Tests	5
2.1.5 Analysis and Evaluation of Thermal Loading Tests.	6
2.1.6 Fabrication Development	9
2.2 NAA-SR-6508.	11
2.2.1 Introduction.	11
2.2.2 Objectives.	11
2.2.3 Environmental Tests	11
2.2.4 Material Investigation.	19
2.2.5 Friction Test	20
2.2.6 Fabrication	24
2.2.7 Conclusion.	24
2.3 Operating Limits	24
2.4 Transients from Power Scrams at HNPF	27
3. Comments.	28
4. Recommendations	31
4.1 Effects of Lateral Fluid Pressure Difference on Buckling	31
4.2 Possibility of Strain Concentrations at Graphite Joints Caused by Bowing Induced by Temperature Gradients Radial to the Core.	32

TABLE OF CONTENTS CONT'D

	<u>Page</u>
4.3 Ratchet Mechanisms That Might Increase Local Deformations in Sheaths	33
4.4 Friction Forces Developed at Interface of Graphite Log and Stainless Steel Sheath in HNPF Core.	34
5. Mathematical Models and Analysis Methods for Areas Considered Critical.	35
5.1 Effects of Lateral Fluid Pressure Difference on Buckling of Sheaths.	35
5.2 Possibility of Strain Concentrations at Graphite Joints Caused by Bowing Induced by Temperature Gradients Radial to the Core.	35
5.3 Ratchet Mechanisms That Might Increase Local Deformations of Sheaths	35
Appendix A Calculations	A
Appendix B Documents Reviewed	B

LIST OF FIGURES

	<u>Page</u>
Fig. 1 Peripheral Temperature Distribution	A6
Fig. 2 Maximum Strain Comparison - Graphite Log Fastened to Bottom . .	21
Fig. 3 Maximum Strain Comparison - Graphite Log Free from Bottom . . .	21
Fig. 4 Strain Comparison at One Atmosphere-Graphite Log Fastened at Bottom of Element	21
Fig. 5 Distributed Strain Comparison at Two Atmospheres - Graphite Log Fastened at Bottom of Element	21
Fig. 6 Distributed Strain Comparison at one Atmosphere - Graphite Log Free from Bottom of Element	22
Fig. 7 Distributed Strain Comparison at Two Atmospheres - Graphite Log Fastened at Bottom of Element	22
Fig. 8 Total Downward Force On a Cross Section of Moderator Can Caused by Friction.	25

LIST OF TABLES

	<u>Page</u>
Table I Rapid Thermal Shocks.	13
Table II Comparison of Predicted and Measured Strain Caused by Frictional Resistance Can No. 3, Phase II Test.	18

1. INTRODUCTION

An independent critical review of the Hallam moderator element and can design was performed by The Franklin Institute in accordance with the contract No. AT (11-1)-1402, for the U.S. AEC Chicago Operations Office.

In order to depict the areas suspect of high static or cyclic stresses, a systematic review of the documents listed in Appendix B was undertaken. The information found in these documents considered essential for the understanding of the problem is summarized in Section 2 of the present report. In cases where it appeared to the reviewer that an objection or modification to the interpretation of the results contained in these reports was in order, a reference to a comment was inserted.

All comments are summarized in Section 3. They represent the reviewer's criticism and suggested additional explanation of the phenomena discussed in the corresponding section of the document reviewed.

Section 4 outlines four areas considered critical and not fully resolved during the development of the HNPF moderator element:

1. Effects of lateral fluid pressure difference on buckling of sheaths.
2. Possibility of strain concentrations at graphite joints due to bowing induced by temperature gradients radial to the core.
3. Ratchet mechanisms that might increase local deformation in sheath.
4. Friction forces developed at interface of graphite log and stainless steel sheath in the HNPF core.

It is believed that the first three of the above areas can be explored analytically. The results of such an analysis would contribute to better understanding of the failure mechanism of the Hallam moderator cans.

Area number four, however, is not amenable to analytical treatment. Since the basic understanding of the friction phenomena in helium under adverse temperature conditions is lacking, experimental research in this field should be encouraged.

In Section 5 simple mathematical models for the analysis of the first three areas listed in Section 4 are given with the description of the corresponding analysis methods.

Appendix A contains the hand-calculation sheets referred to in the text of this report.

2. REVIEW

- 2.1 This Section is a Review of NAA-SR-4384, Interim Report on HNPFF Moderator Element Development, by L. Newcomb and H.L. Sujata, August 15, 1962, with Reference to Comments

2.1.1 Introduction

The moderator graphite was canned in Type 304 stainless steel to prevent destruction of graphite and solution of carbon into sodium coolant. Nominal thickness of steel was limited to .016 inches to reduce parasitic capture of neutrons.

The two primary objectives of moderator can development project were (1) determination of structural stability and integrity of the cans, and (2) development of an adequate process for their fabrication.

2.1.2 Description of Moderator Element

The 141 closely-packed moderator elements are hexagonal in cross section with corners scalloped. (See Appendix A-1). Nominal gap at the flats is .110 inch (cold) at the top; this is the difference across flats of the spacer and the moderator can.

The moderator can is filled with helium to 5 inches of mercury; the normal operating pressure at operating temperature is thus approximately 5 psia. Cover gas in plenum is at nearly atmospheric pressure and with variation in head of sodium causes a pressure difference on the can of 12 psi at the top to 19 psi at the bottom. This differential and the higher thermal expansion rate of stainless steel compared to graphite cause friction forces at the interface.

The rapid flow of sodium in the process tubes is the heat sink, so that normally scallops are at a lower uniform temperature, but the flats peak at their centers, with a roughly parabolic distribution. Axial temperature gradient is steepest near the middle, approaching zero slope at bottom and top.

It will be obvious from the foregoing that the flats are subjected to axial and circumferential compression from three main sources: pressure difference, friction restraint against expansion, and the restraint of the colder scallops against expansion. The flats are 3.272 inches, or 204 nominal thicknesses, wide so that stability, and particularly creep buckling, enter the design problem. The influence of the lateral pressure, holding the can against the graphite, toward increasing stability has so far been investigated only by a limited amount of experimental work by AI (See Comment 3.1).

The report points out that preheating to prepare for operation of the reactor and certain accident conditions could cause the scallops to become hotter than the flats, so that thermal buckling in these curved panels must be considered.

Cans fit graphite tightly on flats and $3/4$ inch transition radii, but gap .039 inch at center of scallop when cold (refer Appendix A-2,3). This clearance would disappear at about 600°F (See Comment 3.2). A 3 inch space to accommodate swelling of graphite if sodium penetrates the can is provided at top. Across this expansion area the head is provided with fingers that support the can with a .650 inch gap between fingers. Stability of can at finger grooves is analyzed in Appendix A-17, 18.

2.1.3 Room Temperature Axial Compression Test:

The purpose of this test was to gain insight into the buckling behavior of the flats as stiffened by the transition radii and scallops, and forced against the graphite by a lateral pressure of one atmosphere.

The element tested was a 24 inch length of the earlier reference design that was 14 inches across flats rather than 16 in. Axial strain gages were placed on the centers of scallops, transition radii, and flats. On the flat, the gages covered a 12 in. length at the middle of the element and showed an elastic buckling pattern of about 12 inch wave length up to about 12,000 lb. total axial load or about 16,000 psi average compressive stress. Large strains and permanent wrinkles developed near ends at 19,740 lb load.

AI evaluated the data using von Karman's concept of effective width (Trans ASME JAM v54, 1932, p 53-56). Under the condition of lateral support of the flats of the evacuated can by the atmosphere,

the total axial resistance of the can was approximated fairly closely by increasing the multiplier in an expression for the von Karman effective width by a factor of 2.33. The measured and calculated loads coincided at max. strain (1150 microin/in. at the transition arc) but calculated load was about 10% low at 250 microin/in. strain at transitions.

The scallops behaved in a stable manner during this axial compression test.

2.1.4 External Pressure and Thermal Loading Tests

This series of tests was made on a 40 inch long Title I element (16 inches across flats). It was evacuated and held under a regulated external nitrogen pressure to maintain a constant 19.7 psi differential. An attempt was made to heat the flats more rapidly than the scallops. Sixteen runs were made, but only those producing permanent buckling or significant temperature differences were reported and interpreted.

Electrical heaters were installed opposite the six flats of the can with radiation shields over the scallops. Cooling coils were added at the scallops after the ninth run. One-sixth of the can was provided with 33 thermocouples and the temperatures recorded. First, seventh, and ninth run produced buckles, all in the scallops.

During the first run little difference in temperature was noted. In the seventh run to 955°F at the root of the scallop a maximum temperature difference of 50°F was recorded when the scallop at the buckled area was 760°F and the adjacent flat 710°F. During the ninth run four more buckles formed when the maximum difference occurred at 430°F in the center of scallop, 320°F at center of flat (See Comment 3.3).

2.1.5 Analysis and Evaluation of Thermal Load Tests

Axial loading of can is believed responsible for buckling.
Such loading arises from

1. Pressure difference
2. Friction forces
3. Unequal temperatures around perimeter of can.

Pressure difference of 19.7 psi (constant during test) acting on 184 in² area of head of can applied a force of 3620 lb to the nominal cross-sectional area of 0.86 in², so that axial compression was about 4200 psi caused by pressure load.

Stainless steel expands many times as much as graphite when heated. The scalloped can has little ability to support lateral pressure, so that virtually the entire lateral pressure load is carried by the graphite. Thus a friction force develops at the interface as the moderator element is heated. Integrating this traction from the ends of the graphite toward the middle, obviously it tends to peak near the latter point. Newcomb and Sujata assumed a constant ratio of friction force to normal force, so that compressive load in the can caused by friction at the middle of the graphite log became:

$$F_F = fp \frac{L}{2} A_c$$

where F_F = friction force (lb)

f = coefficient of friction (assumed 0.25)

p = pressure difference (19.7 psi)

L = length of graphite (36")

A_c = peripheral length of can (53.8 in)

$$F_F = \frac{(.25) (19.7) (36) (53.8)}{2}$$

$$= 4760 \text{ lb,}$$

indicating

$$\sigma_z = \frac{4760}{.86} = 5500 \text{ psi approximate max. compressive stress caused by friction.}$$

The deformations in run 1 were interpreted as increases in fabrication wrinkles and redistribution of residual stresses.

The significance of run 7 is doubtful; possibly there was local overheating.

In run 9 four permanently buckled areas appeared. The thermal loading at the greatest temperature difference of 135°F during heating, with the help of the mechanical loading, borders upon a magnitude that may explain the plastic buckling.

The report presents in Figure 19 the recorded distribution of temperature at the maximum temperature difference of 135°F. Figure 1 which can be found on Appendix A-6 is a copy of the small-scale figure. Although the mean temperature is at about .36ΔT in Figure 19, AI assumed that the minimum temperature existed over all parts except in the scallop where temperature distribution was assumed to be parabolic. This results in their mean temperature of .141ΔT as subsequently used.

The critical buckling stress was estimated from

$$\sigma_{cr} = \eta CE \frac{t}{r},$$

as given by Equation (67) in Gerard and Becker: Handbook of Structural Stability, Part III, "Buckling of Curved Plates and Shells", NACA TN 3783 (August, 1957), where the plasticity reduction factor

$$\eta = \frac{E_s}{E} \left[\frac{(1 - \nu_e^2)}{(1 - \nu^2)} \cdot \frac{E_t}{E_s} \right]^{\frac{1}{2}}$$

$$v = \text{Poisson's ratio} = v_p - (v_p - v_e) \frac{E_s}{E}$$

v_e = elastic Poisson's ratio = 0.3

v_p = plastic Poisson's ratio = 0.5

E = elastic modulus

E_t = tangent modulus

E_s = secant modulus

C = coefficient of buckling is a function of $\frac{r}{t}$ (foregoing reference)

t = skin thickness = .016

r = scallop radius = 2.42

$$\sigma_{cr} = (0.32) (26.6 \times 10^6) \frac{0.016}{2.42} \eta = 56,300 \eta$$

A value of $C = 0.32$ is predicated on fairly large initial imperfections (Gerard and Becker Fig. 7).

The plasticity reduction factor was calculated from a typical stress-strain curve for type 304 stainless steel as a function of stress and plotted. By trial and error the critical stress was found to be 32,500 psi corresponding to $\eta = .58$. These results are substantiated in Appendix A-7 to 9.

AI shows that the average thermal stress in the scallop was not quite enough to account for buckling at $\Delta T = 135^\circ\text{F}$; 155°F would have been required. (See Comment 3.4)

In run 16 two scallops were cooled so that the flats were subject to thermal compression. AI showed that the flats could carry the total load elastically without permanent buckling, using the same equivalent width analysis used for the room temperature axial compression test (See Comment 3.5).

In Appendix A-10 to 16 rough numerical checks were made of the magnitude of friction forces for various conditions.

2.1.6 Fabrication Development

The longitudinal welds between the panels of the cans were a major problem in the development of the fabrication of the moderator elements. After working out a welding procedure, the welding machine, fixtures, and handling equipment had to be designed and built.

After insertion of the dowels the 17 ft. lengths of assembled graphite were finished as assemblies on a planer-bed milling machine. It was shown that they could be subsequently reassembled without evidence of mismatch and the camber held within .010 in. in 17 feet.

Although the head and finger assemblies did not require extensive special tooling a number of designs were fabricated before adequate sheath support was attained and fabrication defects leading to plastic deformation in loading tests avoided. Completion of all welding except the sheath seal weld before finish-machining the outer contour and slotting between fingers proved most successful. During this development it was found desirable to increase the radii of the transition arcs from 1/4 in. in the reference design to 3/4 in. as used in the reactor to reduce strains during initial evacuation of the can.

Difficulty was experienced in acquiring sheath material meeting purity and flaw limits. Thickness tolerances were acceptable only in narrow widths. Thus the seven Title I cans had a seam in each of the six flats but wider material became available in time for two-piece sheaths in the reactor.

Roll forming of the panels for the sheaths was chosen to obtain close dimensional control at minimum tooling cost. It was established that properly designed rolls of suitable material would turn out satisfactory panels in the quantity needed with welding lips preformed.

It was required that each weld seam be

- a) easily and quickly set up,
- b) free of cracks and porosity,
- c) leak tight,
- d) smooth on inside,

- e) strong as parent sheet,
- f) $.016 < t < .032$

A standing-lip weld by the inert-gas method gave excellent results in joining the sheath panels. The optimum lip height proved to be .040 in. Great care in excluding contamination, including a pressurized enclosure over the welding stake, reduced the incidence of blow holes. The lip outer bend radius was held to one thickness to limit the atmospheric oxygen introduced to the welding region. Welding was done on a flat copper chill bar, with two bevelled upper chill bars accurately spaced .040 in. from the mating flanges of the panels on either side of the joint.

In the absence of commercial equipment for performing an 18 ft standing-lip weld, it was decided to bring the work past the welding stake. The ways and longitudinal feed system of an available 46 ft. gun-boring lathe were incorporated into the panel seam welder to provide the motion.

Each seam was radiographed and accepted before adding the next panel. Dye penetrant aided in pinpointing location of defects requiring repair. Small defects were re-fused manually. At blow holes, filler rod was added. Leaking areas in the completely assembled cans were re-fused with local external copper chills clamped in place. The graphite served as backing for the seam.

A container supported the can sheath during loading of graphite, trimming to length, and welding to heads, and acted as a pallet for inspection and raising to a vertical position for storage or shipping. The container is a stiff trough lined with wood and rubber to fit three lower flats of the moderator can. It is supported on roller trunnions for easy indexing in a wheeled dolly.

Another dolly that supports and guides the graphite was positioned against the can container and locked. It provides a handwheel and jackscrew for sliding the graphite into the sheath one length at a time, placing the dowels while the end of the previous log is yet accessible. The ends of the can were then trimmed square, cleaned, and the heads welded in.

The can periphery was clamped tightly against the head by a copper shill block while the head seam was run manually. Dye-penetrant and then radiographic inspection was made of the head welds. If accepted, the assembly was then evacuated, connected to a mass spectrometer and leak tested with helium gas.

2.2 This section is a review of NAA-SR-6508, Final Report on HNPF moderator element development.

2.2.1 Introduction

This report includes the testing of full-size elements in sodium environment, tests to verify the friction load calculations, and a material investigation. The fabrication procedures for the HNPF moderator and reflector elements are described.

2.2.2 Objectives

The purpose of the test program was to choose and develop a design that would protect the sodium and the graphite from each other. Fabrication procedures had to be devised. The sodium heating test appeared suitable for searching the integrity and dimensional stability of the final-design assemblies.

2.2.3 Environmental Tests

Two sodium environmental tests were run in the core tank of the LCTL (described by H. Strahl "The Large Component Test Loop", NAA-SR-4386), to determine permanent deformation, leakage, and stress levels. The second test, in two phases, examined the effectiveness of design changes that grew out of results of the first test.

First Environmental Test

A seven-element cluster in the inner core tank of LCTL was subjected to the first test. Each graphite log was canned in a six-panel roll-formed sheath. The graphite in the test elements was wider across the flats than the heads or sheaths, so that the fingers did not support the can as intended. The grooves in the graphite were 2 in. longer than necessary. The log assembly was of three equal lengths, totaling 202 inches.

The double-walled inner core tank acted as a thermal baffle against the colder stagnant sodium in the outer tank. A grid plate supported the elements under test. The elements were heated by the 275 kw heater in the 3 inch loop of the LCTL. The hot sodium was brought through the lower plenum in a double-walled manifold and discharged through the pedestals into the gap between the moderator elements, rising through the moderator coolant channels to the upper plenum.

In the scallops of the elements 24 process tubes were in place, sealed by piston rings to ensure that only cold sodium from the lower plenum, driven by the 6 inch loop of LCTL, passed through them during cold-shock periods.

In the first test the center element had 82 thermocouples and 86 strain gages. Three other elements had 16 and 18 respectively. No strain data were obtained because of breakdown of the insulation on connecting wiring during initial heating, but nearly complete records of temperature were obtained.

In the first phase of the test of the seven-element cluster seven slow thermal cycles simulated reactor start-up and shut-down. From a base temperature of 600°F the elements were raised to 650°F, held for one hour, cooled to the base temperature and reheated. The upper temperature was increased by 50°F for each successive cycle so that 950°F was reached in the seventh cycle. The maximum heating and cooling rates were 25°F per hour.

The second phase shocked the heated elements with a cold sodium flow through the process tubes (Table I). The chilling of the scallops set up circumferential gradients more or less symmetrical with the centers of the flats. The maximum differences measured varied from 24 to 154°F (instantaneous values). Rapid fluctuations and reversals indicated strong cross convection currents. The temperature at one point varied 150°F in two seconds.

Table I
RAPID THERMAL SHOCKS*

Run No.	Temperature (°F)		Temperature Difference Across Flats [†]	
	Element Before Shock	Shock Coolant	Maximum (°F)	Planned (°F)
1	650	600	24	50
2	700	600	51	50
3	750	650	64	50
4	800	700	68	50
5	850	650	60	75
6	850	650	87	100
7	900	600	117	125
8	950	550	149	150
9	1000	500	154	175
10-14	1010	500	154	175
15	900	600	---	125

*Duration of shocks 3 to 5 minutes.

[†]Maximum shock temperatures at center of flat.

It was found after the first test that the flats, scallops, and transition radii all had buckled. There was a concentration at the heads and the joints between segments of graphite, with others scattered. At the joints the graphite had separated and the unsupported can buckled inward. It appeared that the greater axial expansion of the cans had lifted the graphite by friction forces larger than the weights of the sections. The scallops developed more buckles than the flats. There was general buckling into the finger grooves.

During fabrication all seven elements were tested for leaks by helium mass spectrometry. After installation in LCTL core tank, the four instrumented elements (1, 2, 4 & 7) were rechecked; the other three elements had retained too much helium from fabrication for successful use of the spectrometer. Two elements showed leaks in the welds between heads and sheaths that were located and repaired. The center (No. 1) element was suspected, but no leak could be pinpointed.

After four weeks of outdoor storage, following the cyclic-heating and cold-shock tests, all cans were again helium-checked for leaks. No. 1 was so badly cracked in three scallop-to-head welds that it could not be evacuated. Cans 2, 4 & 7 were helium tight; 3, 5 & 6 had high helium background but were readily evacuated to high vacua and thus appeared leak-tight. Two months later cans 4 and 7 leaked helium when tested.

When the sheath of element No. 1 was removed, no sodium had leaked through the head weld cracks indicating that they had formed after the tests. A small sodium leak was found near the middle of one one panel weld that accounted for the weak indications of leakage before cycling. The removal of sheath No. 2 disclosed no leaks, but after two months, dye-penetrant tests found minute leaks along four seams, and in the transitions and bottoms of scallops. The graphite of element No. 3 was found to be soaked with sodium and broken from leaks near the upper-head-to-sheath weld.

Elements No. 5 and 6 leaked no sodium, but showed leaks and cracks two months after removal of cans.

The cracks were shown to be intergranular. From the results of corrosion tests reported later the steel appears to have been sensitized by the heating-test environment and then corroded between grains during atmospheric exposure so that it could not endure the cold work involved in removal of the sheaths.

Second Environmental Test.

Three moderator elements were tested. No. 1 and 2 sheaths were annealed Type 304 stainless steel; No. 3 sheath was 1/8 hard Type 304 stainless steel, HNPF production material. Connections to monitor internal pressure were added. The graphite log of element 1 was in three sections pinned to prevent separating between sections. Elements 2 and 3 had six sections of log dowelled to allow free relative axial separation while maintaining central coincidence.

All three elements had full bearing on the fingers lapping the end of graphite by 1/2 inch, then gently tapering inward. The twelve transition knuckles were fitted with finger extensions to prevent collapse of the can into the grooves.

Wide material was available to enable press-brake forming the cans in halves, eliminating 2/3 of the panel welds and giving smooth cans with close control of dimensions.

Elements 2 and 3 were provided with zirconium-sponge getters to test this means of trapping of out-gassed contaminants from the graphite.

Elements 1 and 2 were subjected to Phase I and elements 2 and 3 to Phase II of the second environment test.

The pair of elements under test was supported in a fixture that included a borescope for viewing the facing flats of the sheaths. They were manifolded to permit evacuation, leak detection, and backfilling without removal from the LCTL vessel. Without sodium, tank heaters heated the elements. With sodium, the loop heater was used. No thermal shock was involved in the second test.

Transducers for recording temperature, strain in sheath and internal pressure were provided.

Phase I 800°F Test

The two elements in place in LCTL were backfilled with argon to 2 cm Hg absolute and heated to 380°F in an argon atmosphere while strain and temperature were monitored. Difficulty with calibration invalidated internal-pressure records. Borescope examination of visible flats showed but one diagonal wrinkle in No. 1. Instrument leads were removed, cover gas changed to helium, both elements leak-checked by spectrometer, and then backfilled to 4 cm Hg abs. with He.

At 400°F, Na was admitted and heating continued to 600°F base temperature, from which four cycles to peaks of 650, 700, 750 and 800°F successively were imposed. Time rates of temperature did not exceed $\pm 25^\circ\text{F/hr}$. After cooling, the elements were removed from core tank and washed with water. No. 1 was opened, but No. 2 was stored intact outdoors for 2 weeks.

Phase II 1000°F Test

Elements 2 and 3 were placed in core tank, backfilled with argon to 2 cm Hg abs., heated to 400°F and cooled to 80°F. At the peak temperature no distortion of the two fully-visible flats could be observed by boroscope. Both elements were again evacuated and No. 3 helium leak-tested (No. 2 had too much helium remaining from Phase I). After backfilling with He to 2 cm Hg abs. they were heated to 500°F in argon atmosphere. Strain and temperature were observed at intervals in both heating and cooling runs. After removing leads and changing to He cover, sodium was admitted to tank at 500°F. From a base temperature of 800°F the elements were cycled to 850°F, 900°F, and 950°F; in the fourth and final cycle the base temperature was 850°F and the peak was 1000°F maintained for 50 hours, cooled, washed in distilled water and stored in dry argon until disassembly.

Tab specimens of annealed and 1/8 hard can sheet were exposed in LCTL, one set in first phase, a second in the second phase, and a third set during both tests. Various cleaning and storage methods were used on lots from these sets after the test.

In the Phase I tests the measured strains in can No. 1 caused by friction on the graphite agreed fairly well with the values predicted by analysis that will be described later. Strain readings from can No. 2 were not considered reliable. Both cans showed deformation at heads and log joints. Wrinkling outlined the log broken at the pinning in can No. 1. Upon disassembly of this can no sodium had leaked in, but the bottom segment of graphite was broken through the transverse pin hole, evidently after the friction test, but during the slow cycling.

During the friction test of Phase II strains much larger than those predicted were measured at the log junctions. (See Comment 3.6). However, readings under suspicion were discarded in averaging the strain indications, so that distributions of strain caused by friction predicted by the analysis were said to be fairly closely borne out by the experimental results. (Refer Table II, see Comment 3.7).

The zirconium getters were effective in holding the internal pressures of cans No. 2 and 3 below 1.5 psia during the period of 50 hrs at 1000°F, in fact can No. 3 pressure fell from 1.3 at the beginning to 1.0 psia at the end of the period.

After exposure to sodium both sheaths showed minor discontinuities at all graphite joints and head junctions. No new wrinkles were formed in can 2 in Phase II. Can 3 had 2 to 4 wrinkles that showed a maximum height of .006 in. in each of five scallops near the lower head.

Upon disassembly, neither sheath had leaked sodium, but the fingers of No. 3 were smeared with graphite. The graphite alignment pins appeared polished by axial rubbing.

Table II

SIX SEPARABLE ELEMENT LOG, CAN NO. 3, PHASE II TEST

1	14
2	15
3	16
4	17
5	18
6	19
7	20
8	21
9	22
10	23
11	24
12	25
13	26
14	27
15	28
16	29
17	30
18	31
19	32
20	33
21	34
22	35
23	36
24	37
25	38
26	39
27	40
28	41
29	42
30	43
31	44

Gages No	Predicted Strain at 400°F μ in/in Compression - Tension +	Measured Strain Caused By Frictional Resistance To Thermal Expansion μ in/in		
		348°F	404°F	445°F
1 & 14	0	- 207	- 153	+ 79
2 & 17	- 188	- 93	- 22	- 52
3 & 19	- 17.3	- 30	- 53	- 108
4 & 21	- 201	- 195	- 146	- 142
5 & 23	- 34.6	- 145		- 67
6 & 25	- 222	- 109	- 85	- 58
7 & 28	- 51.9	- 60	- 10	+ 63
8 & 32	- 240	- 268	- 246	- 208
9 & 35	- 69.2	+ 111	+ 153	+ 248
10 & 37	- 258			
11 & 39	- 86.5	- 196	- 185	- 253
12 & 41	- 276	- 170	- 188	- 85
13 & 44	- 104	- 659	- 585	- 405

Tab samples showed no sensitization during the 800°F heating phase. All samples (both annealed and 1/8 hard) were sensitized in the 800 - 1000°F phase in sodium but were free of intergranular corrosion. Samples of both materials suffered intergranular corrosion upon one month's exposure to ambient atmosphere after having been subjected to the 800 - 1000°F heating in sodium. Sensitizing in sodium to 1000°F increased the UTS and YS of both materials with a corresponding loss of ductility.

2.2.4 Material Investigation

Series of experiments were run on tabs of annealed Type 304 SS heated to different temperatures for periods up to 163 hours in alternating environments of sodium and either nitrogen or argon. Sensitization (carbide precipitation) was confirmed by boiling in acid copper sulphate. Cover gas interaction was studied by before-and-after weighing. Steam cleaning and atmospheric exposure failed to produce the cracking observed in the first LCTL tab tests.

1. Protracted heating to 1010°F precipitated carbides in grain boundaries and sensitized material.
2. Sodium under such heating removed the Cr_2O_3 protective surface layer, to form Na_2O .
3. Nitriding of material was indicated by weight gain.

All three actions lowered subsequent resistance to corrosion. The sheaths from the LCTL tests were corroded and cracked in certain areas by one to three months of atmospheric exposure. The report states that stress accelerates but appears to play no fundamental role in intergranular corrosion cracking. (See Comment 3.8)

2.2.5 Friction Tests

Buckling of sheaths at junctions of 3-segment logs of first seven-element LCTL test emphasized friction problem. Separation of 1/2 inch while hot was found. Assumption of .25 coefficient of friction and 1 atmosphere pressure difference results in calculated force double that needed to lift log against gravity. Compressive stresses in can would be high with long segments.

A number of experiments were run on a 4-inch square sheath 48 inches high with a single-piece graphite log having provisions for bolting it to lower head of can. The model can was mounted in a pressure vessel in order to heat it by forced-convection immersion heaters in an oil bath with a cover gas pressure that could be maintained up to one atmosphere gage.

Strain gages and thermocouples were mounted along the sheath. The gages were balanced after evacuation and imposition of cover gas pressure. Four tests were run: two at a Δp of 1 atmosphere, with and without fastening log to bottom head; and two at a Δp of 2 atmospheres, also free and fixed. Isothermal heating was achieved and the gages monitored at approximately 5°F intervals, up to 200°F. The plotted results from the report are shown in Figures 2 to 7.

Analytical Prediction of Friction Loading

If there were no slip the axial force set up in the can by restraint of its thermal expansion would be

$$F_t = \frac{\Delta T(\alpha_s - \alpha_g)}{\frac{1}{A E_g} + \frac{1}{A E_s}}$$

and the elastic strain caused by this force

$$\epsilon_{cs} = \frac{\Delta T (\alpha_s - \alpha_g) A E_g}{A E_s + A E_g}$$

Figure 2 - Strain Comparison - Graphite Log Fastened to Bottom

Figure 3 - Strain Comparison - Graphite Log Free From Bottom

Figure 4 - Strain Comparison at One Atmosphere - Graphite Log Fastened at Bottom of Element

Figure 5 - Strain Comparison at Two Atmospheres - Graphite Log Fastened at Bottom of Element

Figure 6 - Strain Comparison at One Atmosphere - Graphite Log Free from Bottom of Element

Figure 7 - Strain Comparison at Two Atmospheres - Graphite Log Free from Bottom of Element

Where F_t = thermal expansion force (compressive on can for the materials involved here)

ϵ_{cs} = strain in sheath

ΔT = change in temperature

α_s, α_g = linear coefficient of expansion of steel, graphite.

A_s, A_g = area of cross section of steel, graphite

E_s, E_g = modulus of elasticity of steel, graphite

The friction force must be integrated from a free end of the log, at distance ℓ from upper end of log in Figure 8

$$F_f = \mu C \int_0^{\ell} \Delta P d\ell$$

where μ = coefficient of friction of stainless steel and graphite

C = circumference of can

ΔP = pressure differential on can sheath

If the average ΔP in distance ℓ is $\overline{\Delta P}$

$$F_f = \mu C \ell \overline{\Delta P}$$

When the temperature rise is high enough to cause slipping in both directions away from the point of maximum sheath compression, inasmuch as the downward friction force on the can from the upper end of a free log also includes the weight of the log, equilibrium at point of maximum compression requires

$$F_{f1} - F_{f2} = W_g \rightarrow x = x_0$$

or

$$\mu C (L - x_0) \overline{\Delta P} - \mu C x_0 \overline{\Delta P} - W_g = 0$$

that may be solved to x_0 , in the simple case of uniform pressure difference on the sheath.

If the log were fastened down, or its weight were in excess of the available friction force, the triangle OAB would represent the distribution of compressive force in the can caused by friction.

At lower temperature the thermal expansion forces are not sufficient to overcome static friction in the regions of nearly constant strain found in the tests. (See Comments 3.9 and 3.10)

2.2.6 Fabrication

A number of modifications resulted from evaluation of the fabrication of the seven elements for the first LCTL test. Dimensional precision was improved by use of sheets wide enough to produce the sheaths in halves, using brake forming in place of rolling. Stretcher-levelling enabled use of stronger 1/8 hard sheets.

The graphite was stacked vertically with the heads in place and the sheath lowered over it. A fixture was devised to permit jacking six tubular mandrels of sheath length radially into the scallops simultaneously to obtain uniform cold clearance between sheath and each scallop of the graphite. Head-to-sheath welds were made with suitable chill blocks in place, radiographed and repaired. Helium-spray leak test was used after evacuation to one-half micron. As a final check a plastic sleeve surrounding the element was filled with helium. The elements were stored in a vertical position.

2.2.7 Conclusion

As a result of the foregoing program it was concluded that the cans as fabricated for Hallam were not likely to leak and would not deform to degree to render removal from the reactor difficult.

2.3 Operating Limits

Excerpts from
APPENDIX A
of Technical Specifications as Amended for Operation
at Power for HNPF
Undated

E.1.a Moderator and Reflector Elements graphite, modified hexagonal prisms, 16 in. across flats, 17 ft long, clad type 304 SS, 0.016 thick, 141 elements.

E.2.a Thermal power: 256 Mw, max.

Figure 8 - Total Downward Force on a Cross Section of a Moderator can Caused by Friction

b. Max Temperatures

- 1) sodium inlet plenum 650°F.
- 2) sodium upper plenum 1000°F.

F.2. Safety System Operating Limits

a. Conditions that cause scram:

1. Fuel channel outlet temperature $\geq 1025^{\circ}\text{F}$
5. Step change in fuel channel outlet temperature $\geq \pm 25^{\circ}\text{F}$.
6. Sustained rate of change in measured fuel channel outlet temperature $\geq \pm 75^{\circ}\text{F/hr}$.
9. Less than 8.5 ft sodium above moderator elements.

2.4 Transients from Power Scrams at HNPF

3. COMMENTS

3.1 (See Review Section 2.1.2) Analytical attack with computer numerical solutions, not simply of the elastic model, but with attention given to creep rates of buckling and relaxation of type 304 SS, appears to be needed.

3.2 (See Review Section 2.1.2) At 950°F the can would have an excess perimeter of approximately .014 inches per scallop (Appendix A-5) that would tend to make the can stand free of the graphite at the 3/4 inch transition radii where the inward pressure difference would be most readily resisted.

3.3 (See Review Section 2.1.4) Although the flats are the hotter parts of the can during operation, it appears that the intent was to study buckling onset in scallops during preheat or accident regimes during this series of tests.

3.4 (See Review Section 2.1.5) Reviewer believes that ninth-cycle buckle pattern appears (Fig. 13 of NAA-SR-6508) rather localized at center of flat, where thermal stress approached 1.5 times average value for the AI assumption of parabolic distribution. The maximum thermal stress for AI distribution was:

$$\sigma_T = E\alpha (0.859) \Delta T$$

$$\sigma_T = 26.6 (9.5) (0.859) (135)$$

$$\sigma_T = 29,300 \text{ psi}$$

Remembering that the stress caused by axial pressure load is approximately 4,200 psi and by friction about 5,500 psi, the calculated critical buckling stress would have been exceeded in a considerable region along the centers of the scallops.

In the foregoing analysis it will be noted that AI ignored the interaction of the lateral pressure difference.

3.5 (See Review Section 2.1.5) The reviewer believes that the difference in behavior of scallops is caused by the lateral compressive forces that are generated by the inward buckling of a curved panel, so that the buckle itself is unstable and virtually no increase in loading is possible once the buckle "oilcans". By contrast, the flats of the can in buckling would induce

helpful lateral tension from the restraint of the graphite bearing against the transition arcs, enabling the flat to survive considerable load past elastic buckling without permanent deformation by an elastic-foundation action of its own lateral-catenary strips. Such models would indicate that the scallops would be much more sensitive than the flats to any local departure from axial straightness introduced during fabrication of the can.

3.6 (See Review Section 2.2.3) It is suggested that the high strains in cans measured at graphite joints in the friction test of Phase II included bending strains induced in the unsupported can by superposition of normal pressure loading on the axial compression. Also sagging and contraction of the can into the open joint would resist the effort of the shrinking can to drag the material over the corner of the graphite, and thus change the distribution of friction loading.

3.7 (See Review Section 2.2.3) The report lays considerable stress on the possibility that a can may not always have been in contact with the graphite during a friction test. If this implies that the can supported any material fraction of the pressure load by its own circumferential stiffness, then this notion appears without validity, because calculations indicate that even a can of the harder material is capable of supporting less than 1 psi pressure difference without gross distortion under complete plastic redistribution of stresses at room temperature, as shown in Appendix A-21. Although not stated in the report, the pressure in the LCTL was presumably close to atmospheric during the foregoing friction tests.

3.8 (See Review Section 2.2.4) Reviewer would not discount ability of moderate cyclic stresses to increase intergranular corrosion rate through several orders of magnitude where a protective film in molecular thickness would otherwise be rather effective as a principal inhibitor. It is common experience, however, that decreasing solubility of oxygen of sodium with increasing temperature tends to clear oxygen from reactor, the hottest part of the loop.

Another phenomenon that is not considered in report is the sensitization of the weld-affected zone in Type 304. Possibly the chill blocks and thin lip of heads made this factor insignificant.

3.9 (See Review Section 2.2.5) Great elaboration in friction calculations is hardly warranted where the frictional resistance includes many arbitrary variables. However, the calculated strains in the can caused by friction could readily include the effect of variation of head of sodium along the can. Refer to Appendix A-22.

3.10 (See Review Section 2.2.5) There is a possibility that a thermal ratchet mechanism may have contributed to the difficulties with the moderator cans at Hallam. Nightingale et al state in "Nuclear Graphite" Academic, 1962, Chapter 6, in discussing the coefficient of friction of graphite that the static friction is always higher than the dynamic friction, where stick-slip occurs; that it increases upon reversal of motion, and increases with rising temperature.

Granted that the normal pressure on the interface of the can and graphite is dependent only on the pressure difference, nevertheless the direction of the friction on an element of length depends on the space distribution and time history of the thermal strain input. If the friction on the element reverses, the point of no slip may wander along the log and a net motion of the log with respect to the can may result.

In addition to the foregoing, the axial gradient and its differences during the startup and scram may produce net incremental upward motion of the log in the can in each cycle. As a result, the gap between two logs can increase and produce unsafe conditions. It is believed that the proof of such an incremental motion can be produced by a more sophisticated analytical investigation suggested in the second phase scope on this project.

Wrinkles and buckled areas not in contact with graphite would respond to variations in coolant temperature more quickly than areas of good contact. Cyclic variations of temperature may thus aggravate such distortions. Distortions may interact with flow distribution in a manner to amplify the oscillations of temperature and consequently the plastic distortion per cycle.

4. RECOMMENDATIONS

The following critical areas appear to reviewer not to have been wholly resolved during the development of the HNPF moderator elements and are believed to need a concentrated effort toward analytical evaluation of their influence on structural adequacy:

1. Effects of lateral fluid pressure difference on buckling of sheaths.
2. Possibility of strain concentrations at graphite joints caused by bowing induced by temperature gradients radial to the core.
3. Ratchet mechanisms that might increase local deformations in sheath.
4. Friction forces developed at interface of graphite log and stainless steel sheath in the HNPF core.

4.1 Effects of Lateral Fluid Pressure Difference on Buckling

The problem of the interaction of the pressure difference across the sheath with buckling is amenable to solution by computer. Obviously in the way of the graphite log, the pressure difference assists the can in resisting buckling caused by axial compression whether mechanical (hydrostatic end load on head of element, weight of log and other components) or thermal (restraint of expansion of sheath by friction on graphite or by cooler parts of the sheath's own periphery). It is a matter of observation that inelastic inward buckles form readily in a wide curved panel e.g. NACA TN 3783 Handbook of Structural Stability Part III - Buckling of Curved Plates and Shells, G. Gerard and H. Becker August 1957, page 10, where it is noted that incipient buckling of such a body (scallop) coincides with its maximum resistance to axial loading. Circumferential compressive forces are set up by the deformation, so that the buckle itself is unstable as soon as it oilcans inward. The restraint of the graphite may possibly promote diamond pattern buckling of the sheath by increasing the circumferential compression. Also, the buckle may as a result be more sharply curved at incidence, so that the gain in stability under compressive loading that would be expected in a free-standing cylinder as a result of pressurizing it internally would not be fully realized in the scallops of the HNPF moderator sheaths.

Considering the stability of the flats under axial load, the graphite limits them to radially-outward buckling. For this configuration, the lateral restraint of the sheath across the flat from pressure on the scallop and friction on the transition radius of the log sets up a beneficial tension and consequent elastic support that enables them to support considerable increases in loading beyond the onset of buckling without perceptible plastic deformation. Furthermore, the buckling pattern of the flats would tend to be the full width of the flat, with the half wavelength a little more. On such an area the lateral load from fluid pressure difference would be of considerable consequence. It is likely that computer numerical analysis of the foregoing models would show clearly that the scallops are more prone to buckling damage in regions of slight waviness resulting from fabrication than the flats.

On the other hand, over areas not supported by graphite, particularly at separating sections of the log, three factors, the axial and circumferential compression in the sheath, and the lateral pressure load, are cooperating to force the sheath inward. There is definite, though small, degradation of the room temperature yield stress of Type 304 at 600°F that becomes pronounced at 1000°F. Likewise, even at the lower temperature, a small creep rate would be observed at rather moderate stress. A low rate of creep buckling would increase the axial offset of the buckle, consequently the bending stresses, and probably would accelerate the deformation at an increasing rate during service.

4.2 Possibility of Strain Concentrations at Graphite Joints Caused by Bowing Induced by Temperature Gradients Radial to the Core

With orifices adjusted for equal outlet sodium temperatures from all process tubes, one would expect sextant symmetry in the temperature distribution of the skin of each moderator element, with the net tendency toward bowing an element rather minor. At the edge of the core a moderate amount of heat must be taken in from the surrounding rows of reflector elements so that a driving gradient radial to the center of the core exists, but the good thermal conductivity and lively convection of the coolant would tend to keep this radial gradient small. The anomalies in heat generation around the moderators that are believed to have leaked sodium at Hallam cause

lateral gradients, but these are after the fact of failure. No evidence of large, persistent gradients across a can during steady operation has been presented.

The reviewer believes, however, that the indications of strong buoyancy disturbances to the steady convection found in the cold-shocking tests (see 2.2.3) may be a clue to the present difficulties at Hallam. Provided that the flow paths during the seven-element test simulate those of the prototype adequately, these cold shocking tests are the analog of a scram from power generation. On page 18 of NAA-SR-6508 there is the statement that temperature at a given point varied as much as 150°F during a period of two seconds. Rapid reversals of temperature between centers and edges of flat of sheath are also cited as evidence of cross currents.

During scram the coolant flow will be most rapid in the innermost process tubes, so that cold sodium will traverse them sooner and remove the stored heat of the moderator coolant and sheaths more rapidly at the middle of the core. The radial gradient thus engendered could be intensified near the top of core by radially inward displacement of hot moderator sodium by more dense coolant spreading outward at the bottom of core. A difference in temperature across the diameter of a moderator can would tend to bow it. The sections of graphite log are much stiffer, tending to concentrate the bowing into the short free lengths at the gaps between sections. Analytical examination of such a model might reveal surprisingly high local plastic strains in the wrinkle on the compressive side in view of the obstacle to axial spreading of compressive strain presented by the corners of the ends of the adjacent logs after inward buckling has been established.

4.3 Ratchet Mechanisms that Might Increase Local Deformations in Sheaths

Thermal ratchet mechanisms may result from cyclic heating when a load or restraint differs during heating from its value during cooling in a manner to cause a net growth in remanent strain with the increase of number heating cycles. An inward buckle in a curved panel tends to be irreversible on cooling because of the snap-through action of the reverse bending of the circumferential fibers. During subsequent rapid increases

in local coolant temperature, the buckled metal in a scallop will heat more rapidly than the adjacent sheath material so that its depth and area may increase slightly by thermal buckling that is partially plastic and not completely removed during the next cooling period. As it grows, its vulnerability to slugs of hot coolant gradually increases.

A friction ratchet may be conceived. Moving friction is less than static friction, but on reversal of the traction force, the static friction will be larger than before. On a macroscopic scale, movement of the expanding sheath flats past the end corners of a log into a wrinkle extending into the element between segments is clearly not so readily reversed on cooling.

Using simplified model of friction and assuming elastic behavior, an analysis should be developed for the purpose of demonstrating the credibility of graphite logs ratcheting in the cans.

4.4 Friction Forces Developed at Interface of Graphite Log and Stainless Steel Sheath in HNPf Core

A good correlation between analysis and test results was obtained for the 4 inch square vacuum model in oil bath up to 153°F by assuming a uniform coefficient of friction of 0.25. However, relatively higher friction forces have been reported in helium at higher temperatures*. As the zirconium getters in the Hallam elements reduce the absorbed oxygen and water vapor levels in the logs, the friction forces would be expected to rise. On the other hand, a wearing in, with reduction in friction, has been found in air tests of friction of graphite on steel. Irradiation has not shown significant influence on friction of graphite.

The foregoing phenomena cannot be discussed by existing analytical methods and require painstaking experimental investigations.

---

*Nightingale, R.E. Editor Nuclear Graphite Academic Press 1962

5. MATHEMATICAL MODELS AND ANALYSIS FOR AREAS CONSIDERED CRITICAL

5.1 Effects of Lateral Fluid Pressure Difference on Buckling of Sheaths.

Buckling of scallops and flat sections under axial load due to hydrostatic end pressure, friction forces, and temperature variation in circumferential direction can be analyzed using the mathematical model and methods discussed in NACA TN No. 3783 ("Handbook of Structural Stability, Part III - Buckling of Curved Plates and Shells" by George Gerard and Herbert Becker) and NACA TN No. 3784 ("Handbook of Structural Stability, Part IV - Failure of Plates and Composite Elements" by George Gerard) modified to include the restraint offered by the graphite.

5.2 Possibility of Strain Concentrations at Graphite Joints Caused by Bowing Induced by Temperature Gradients Radial to the Core.

The mathematical model for the analysis of such effects will consist of the moderator section contained between middle sections of two adjacent graphite logs. The analysis methods will be based on the interaction of can and graphite under the assumption of no relative displacement between the can and the log at the middle point of the log.

5.3 Ratchet Mechanisms That Might Increase Local Deformations in Sheaths.

Analysis is suggested only to demonstrate the credibility of graphite logs ratcheting in the cans. For that purpose, a simplified mathematical model will be assumed in the form of a unit thickness strip of graphite between two unit widths of metal sheaths subjected to constant lateral pressure. This configuration will be subjected to cycling temperature corresponding to the startup and scram conditions.

K.R. Stearns

K.R. Stearns, Manager
Applied Mechanics Laboratory

Lenons Zudans
Lenons Zudans
Project Engineer

Approved by:

N. R. Droulard

N. R. Droulard
Technical Director

APPENDIX A
CALCULATIONS

APPENDIX A

A.I DWG 7518-D 71109 GRAPHITE LOG ASSY

7518-D 71114 SKIN-MOD. CAN HALF

CAN SKIN ASTM A167 GR.3

AI SPEC. NBO160-001 TYPE 304

(DWG 7518-D71112 → SPACER 16.030 $\pm .003$ ACROSS FLATS)
SPACER IS 405 SS (MODIFIED)

RAD. TO CORNER OF HEX SPACE:

$$\frac{8.007}{\cos 30^\circ} = \frac{8.007}{.86603} = 9.246$$

RAD. TO CORNER OF CIRCUMSCRIBED HEX OF GRAPHITE LOG:

$$\frac{7.944}{.86603} = 9.173$$

$$\begin{aligned} \text{NOM. RADIUS TO SCALLOP (GRAPHITE)} &= 9.173 - (.052 + 2.260) \\ &= 6.861 \end{aligned}$$

$$\begin{aligned} \text{NOM. RADIUS TO SCALLOP (INSIDE CAN)} &= 9.246 - (2.330 + .016) \\ &= 6.900 \end{aligned}$$

NOM. COORDINATES OF CENTER OF .750 R.

CAN:

$$\phi = \sin^{-1} \frac{.813}{3.096} = \sin^{-1} .26260$$

$$\phi = 15.224 \quad \cos \phi = .96491$$

$$\overline{AC} = 3.096 (.96491) = 2.987$$

$$\overline{OC} = 4.623 - 2.987 = 1.636$$

$$\begin{aligned} \text{GRAPHITE: } \overline{CB} - \overline{AD} \cos 30 &= .813 - .125(.866) \\ &= .705 \end{aligned}$$

$$\phi' = \sin^{-1} \frac{.705}{3.010} = \sin^{-1} .23422$$

$$\phi' = 13.546^\circ \quad \cos \phi' = .97218$$

$$3.010 (.97218) = 2.926$$

$$\begin{aligned} \overline{AD} \sin 30 &= .062 \\ \hline 2.988 &\sim \overline{AC} \end{aligned}$$

IT APPEARS THAT NOMINALLY SURFACE OF GRAPHITE AND INNER SURFACE OF CAN WOULD EXACTLY COINCIDE ALONG SIX FLATS & TWELVE 0.750^{IN} RADII, BUT WOULD LEAVE A 0.039^{IN} GAP AT MIDDLE OF EACH SCALLOP.

PERIMETER OF GRAPHITE BETWEEN POINTS OF INFLECTION OF SCALLOP WILL BE CALCULATED:

$$2\theta' = 2(60^\circ - \phi') = 2(60 - 13.546) = 92.908^\circ$$

$$\text{ARC LENGTH} = 2r\theta = \frac{2.260 (92.908)}{57.2958} = 3.6647 \text{ GRAPHITE}$$

$$\text{HALF CHORD} = (2.260) \sin 46.454^\circ = 2.26(.72482) = 1.63809$$

THE 2.346 RAD. TO INSIDE OF CAN PASSES CLOSE TO ENDS OF CHORD. APPROX. HALF ANGLE IS

$$\sin^{-1} \frac{1.63809}{2.346} = \sin^{-1} .69825 = 44.286^\circ = .77294 \text{ RAD.}$$

$$\text{ARC LENGTH} = 2(2.346)(.77294) = 3.6266 \text{ CAN}$$

$$\text{DIFFERENCE IN ARC LENGTH} = 3.6647 - 3.6266 = .0381^{\text{IN}}$$

CORRESPONDING STRAIN TO PUT CAN & GRAPHITE IN CONTACT. (NO SLIP AT POINTS OF INFLECTION) :

$$\epsilon = \frac{.0381}{3.6266} = .00105$$

STRESS

$$\sigma = E\epsilon = 28(10)^6 (.00105) = 29,400 \text{ PSI}$$

PRESSURE DIFFERENCE TO CAUSE CONTACT (AT 68°F)

$$p = \frac{\sigma t}{r} = \frac{29,400 (.016)}{2.338} = 200 \text{ PSI}$$

WITH NO FRICTION, THE ACTIVE ELASTIC PERIMETER OF CAN WOULD BE ABOUT $2\frac{1}{2}$ TIMES AS GREAT, SO THAT STRAIN, STRESS & PRESSURE TEND TOWARD 40% OF FOREGOING. HENCE BELOW 600°F CAN SCALLOP MAY NOT TOUCH GRAPHITE, SINCE CAN + GRAPHITE NOMINAL PERIMETERS EQUALIZE AT ~600°F (NEXT PAGE).

UNDER THE WORST COMBINATION OF TOLERANCES, CANS COULD STAND FREE IN SCALLOPS INTO OPERATING RANGE OF TEMPERATURES, INCREASING THERMAL LAG OF FLATS DURING TRANSIENTS, POOR CONDUCTION TO GRAPH. WORKING IN SAME DIRECTION AS NEARNESS TO FUEL ELEMENTS HAVING HIGHER VELOCITY OF Na FLOW.

NOMINAL PERIMETER OF MODERATOR CAN ON MIDDLE LAYER FOR ONE-TWELFTH OF PERIPHERY (68°F):

TRANSITION .758 R., $74.776^{\circ} = 1.3051 \text{ RAD.}$	LENGTH 9.89 IN
$\frac{1}{2}$ SCALLOP 2.338 R., $44.776^{\circ} = .78149 \text{ RAD}$	1.827
$\frac{1}{2}$ FLAT	1.636
	4.452 IN

SAME FOR GRAPHITE, REFLECTED ON MIDDLE LAYER:

.758 R., $76.454^{\circ} = 1.3344 \text{ RAD}$	$\rightarrow$	1.011
2.252 R., $46.454^{\circ} = .81077 \text{ RAD}$	$\rightarrow$	1.826
FLAT		1.636
		4.473 IN

$$\text{DIFF.} = .021 \text{ IN}$$

AT 950°F THE THERMAL EXPANSION WOULD BE, FOR CAN:

$$4.452 (950 - 68) (10.2) (10)^{-6} = .040 \text{ IN } \frac{1}{12} \text{ OF PERIPHERY}$$

& FOR GRAPHITE SURFACE:

$$4.473 (950 - 68) (1.2) (10)^{-6} = .005 \text{ IN } \frac{1}{12} \text{ OF PERIPHERY}$$

NOMINAL PERIMETERS AT 950°F , $\frac{1}{12}$ OF PERIPHERY

$$\begin{array}{lcl} \text{CAN:} & 4.452 + .040 = & 4.492 \text{ IN} \\ \text{GRAPHITE} & 4.473 + .005 = & 4.478 \text{ IN} \end{array} \quad .014 \text{ IN DIFF}$$

Figure 1 - After Fig. 19, NAA-SR-4384 Peripheral Temperature Distribution

GERARD & BECKER: HANDBOOK OF STRUCTURAL STABILITY
PART III - BUCKLING OF CURVED PLATES & SHELLS
NACA TN 3763 AUG. 1957 P. 57, INELASTIC-BUCKLING
BEHAVIOR: PLASTICITY - REDUCTION FACTOR IS

$$\eta = \frac{\sigma_{cr}}{CEt/r} = \frac{E_s}{E} \left[\frac{(1-\nu_e^2)}{(1-\nu^2)} \cdot \frac{E_t}{E_s} \right]^{\frac{1}{2}}$$

WHERE

$$\nu = \nu_p - (\nu_p - \nu_e) \frac{E_s}{E}$$

ν_e = ELASTIC POISSON'S RATIO = 0.3

ν_p = PLASTIC POISSON'S RATIO = 0.5

E_t = TANGENT MODULUS

E_s = SECANT MODULUS

TYPE 304 SS
AFTER NAA-SR-4384, FIG. 20

STRESS	25, 00	30,000	40,000
ϵ	$940 (10)^6$	1190	2700
E_s	$26.6 (10)^6$	25.2	14.8
E_t	$24.4 (10)^6$	15.0	3.0
E_s/E	1.0	.95	.555
$(\nu_p - \nu_e) E_s/E$	.2	.19	.111
ν	.3	.31	.389
$1 - \nu^2$	.91	.904	.849
E_t/E_s	.92	.60	.20
$(1 - \nu_e^2)/(1 - \nu^2)$	1.0	1.01	1.07
$(E_t/E_s) \left(\frac{1 - \nu_e^2}{1 - \nu^2} \right)$	.92	.606	.214
$\sqrt{\quad}$	.96	.78	.46
η	.96	.74	.256

IN VIEW OF SMALL SCALE OF AUTHORS' FIG.20, THESE VALUES OF η SHOW SUBSTANTIAL AGREEMENT WITH THEIR FIG 21.

LINEAR THERMAL COEFFICIENT OF EXPANSION, $\text{IN}/\text{IN}^\circ\text{F}$:

MEAN VALUE $32^\circ\text{F} - 932^\circ\text{F}$ TYPE 304 SS $= 10.2(10)^{-6}$

FROM METALS HNBK 8TH ED, 1961 v.1 p.422

GRAPHITE $\alpha = 1.4(10)^{-6}$ (NAA-SR-6508 p.48)

MODULUS OF ELASTICITY

304 SS AT 75°F . $E = 28(10)^6$ PSI

AT 950°F $23.6(10)^6$ PSI

GRAPHITE $E = 1.2(10)^6$ PSI (NAA-SR-6508 p.48)

ALTHOUGH GRAPHITE IS ONLY $\sim 1/20$ RIGIDITY OF
STEEL PER UNIT AREA, LOG HAS ~ 220 TIMES
CROSS-SECTIONAL AREA OF CAN; ELASTIC STRETCHING
(AXIALLY) OF LOG IS NEGLECTED IN FOLLOWING
PRELIM. ESTIMATES.

THE 12 CONVEX .758" RADII ARE STIFFER AGAINST EXTERNAL PRESSURE THAN EITHER SIX 3.272" FLATS OR THE SIX CONCAVE 2.338 RADIUS SCALLOPS. FROM THE SYMMETRY, THE PRESSURE AND CONSEQUENT FRICTION WOULD TEND TO CLAMP THE CAN AT THE AXIAL CENTER-LINES OF THE FLATS & SCALLOPS & FORCE THE EXCESS METAL INTO THE CONVEX PROTRUSIONS, LIFTING THE CAN OFF THE .750" RADII OF THE GRAPHITE AS HEATING PROGRESSES. IN THE AXIAL DIRECTION THE PRESSURE LOAD IS TENDING TO CLAMP THE CAN AT THE MIDDLE OF EACH PIECE OF GRAPHITE & THE FRICTION FORCES BUILD UP A PEAK OF ^{AXIAL} COMPRESSIVE STRESS IN THE CAN AT THE MIDDLES OF THE GRAPHITE PIECES. THE PEAK COMPRESSIVE FORCE IS $\sim \Delta p \frac{\lambda}{2} \cdot \mu$ PER INCH OF CIRCUMFERENCE, SINCE THE ABILITY OF THE CAN ALONE TO SUPPORT Δp IS NEGLIGIBLE. CORRESPONDING STRESS FOR $\lambda = 33.66$ IN & $\mu = .25$ WOULD BE

$$\sigma_x = \frac{14.7 (33.66) (.25)}{2 (.016)} = 3870 \text{ PSI/ATMOS.}$$

EXCEPT AT THE GRAPHITE JOINTS, THE FREESTANDING .750" RADII OF THE CAN WOULD PARTICIPATE

AGAINST THE RESTRAINT OF THE GRAPHITE THROUGH
SHEAR, UP TO BUCKLING STRESS UNDER AXIAL LOAD

$$\sigma_{CR} \sim 0.6 E \frac{h}{a} = 0.6 (23.6)(10)^6 \frac{.016}{.758} \sim 300,000 \text{ PSI}$$

(REF: TIMOSHENKO: ELASTIC STABILITY, P. 470)

SHELL OF THICKNESS MORE THAN 20% OF RADIUS
IS RATHER STABLE (ELASTIC CONDITIONS) FOR
ANY TYPE OF LOADING; LATERAL PRESSURE, SHEAR, OR
AXIAL,

LATERAL PRESSURE CAUSES PERIPHERAL
COMPRESSION IN CONVEX PANELS:

$$\sigma_{\phi} = \frac{r}{t} \Delta p = \frac{.758}{.016} \Delta p = 700 \text{ PSI/ATMOS.}$$

= 1130 PSI AT BOTTOM OF CAN

STATIC HEAD OF Na $\sim 28'$ AT BOTTOM OF CAN, $11'$ AT TOP

$$\text{AV. TEMP. Na} = \frac{17 \left(\frac{600 + 950}{2} \right) + 11(950)}{28} = 850^{\circ}\text{F}$$

$$\gamma = 52.4 \text{ LB/FT}^3$$

$$\rho = \gamma h = \frac{52.4 \overset{(11)}{(28)}}{144} = \begin{cases} 4.0 \text{ PSI } n_a \text{ TOP} \\ 10.2 \text{ PSI } n_a \text{ BOTTOM} \end{cases}$$

TOTAL PRESSURE AT BOTTOM OF CAN WITH 1 ATMOS. ABS.
ON COVER GAS: $\Delta p = 14.7 + 10.2 = 24.9 = 1.62 \text{ ATMOS.}$

$$\sigma_x = 1.62 (3870) = 6260 \text{ PSI CAUSED BY FRICTION}$$

ON P.A-11, GRAVITY OF GRAPHITE WAS NEGLECTED.
 SP. GR. 1.62 - 1.74, AV. 1.68 = 105 LB/FT³ = .061 LB/IN³
 CROSS-SECTIONAL AREA EQUIV ~ 15.4 DIA CIRCLE (186 IN²)

$$WT \text{ OF LOG PER INCH} = .785 (15.4)^2 (.061) = 11.35$$

$$WT \text{ OF } 202'' = 2300 \text{ LB}$$

IN HOT CONDITION, ALL GRAPHITE IS SUPPORTED BY Δp FRICTION
 ON CAN; AXIAL COMPRESSION AT BOTTOM OF CAN =

$$\sigma_x = \frac{2300}{12 (4.452) (.016)} = 2690 \text{ PSI}$$

AT MIDDLE OF LOWER 33.66" SECTION σ_x WOULD BE

$$\sigma_x = \frac{11}{12} 2690 = 2470 \text{ PSI} \quad \left(\begin{array}{l} \text{CAUSED BY WT.} \\ \text{OF GRAPHITE} \end{array} \right)$$

THIS WOULD ADD TO 6260 PSI CAUSED BY FRICTION
 (P.7) TO GIVE $\sigma_x = 8,730 \text{ PSI}$

NOTE: WT. EFFECT DECREASES LINEARLY TO TOP OF CAN.

PRESSURE ON UPPER HEAD OF CAN CAUSES

$$\sigma_x = \frac{.785 (15.4)^2 \Delta p}{12 (4.452) (.016)} = \frac{186 \Delta p}{.855} = 218 \Delta p$$

$$10 \text{ FT HEAD OF Na} + \text{VACUUM} (-14.7 \text{ PSIG}) \longrightarrow \sigma_{x \Delta p} \sim 4100 \text{ PSI}$$

CIRCUMFERENTIAL TEMPERATURE DIFFERENCES IN
MODERATOR CAN:

REF: HNPF REACTOR OPERATIONS APRIL, 1964 MO. RPT
NO. 20 FIG 23 APRIL 25 AT 125 MW T, ELEV 1412.25'
T.C. #18 905°F. FLAT
T.C. #19 820°F. EDGE OF SCALLOP $\Delta T = 85^\circ\text{F}$

EXTREME OF TEMPERATURE FROM MEAN MUST LIE
BETWEEN 42.5 & 85°F FOR THIS PARTICULAR CONDITION.

$$\begin{aligned} \alpha &= 10.8(10)^{-6} \quad \text{AT } 905^\circ\text{F} \\ &= 10.6(10)^{-6} \quad \text{AT } 820^\circ\text{F} \end{aligned} \left. \vphantom{\begin{aligned} \alpha &= 10.8(10)^{-6} \quad \text{AT } 905^\circ\text{F} \\ &= 10.6(10)^{-6} \quad \text{AT } 820^\circ\text{F} \end{aligned}} \right\} \begin{array}{l} 304 \text{ SS.} \\ \text{"INSTANTANEOUS" VALUES} \end{array}$$

$$E = 24.5 \text{ TO } 24(10)^6$$

$$E_\alpha = 260 \text{ PSI}/^\circ\text{F} \text{ IN THIS RANGE}$$

THERMAL σ_x WOULD BE $\left\{ \begin{array}{l} 11,000 \\ 22,000 \end{array} \right\}$ PSI FOR $\left\{ \begin{array}{l} 42.5 \\ 85.0 \end{array} \right\}^\circ\text{F}$
DIFFERENCE BETWEEN LOCAL AND PERIPHERAL
MEAN TEMPERATURE, COMPRESSIVE AT HIGHEST TEMP.

SCRAM TRANSIENT IS IN DIRECTION TO COOL
SCALLOP MORE RAPIDLY THAN FLAT, INCREASING
FOREGOING STEADY-STATE ΔT .

IF THE CONVEX .750 RADII OF THE CAN STAND FREE OF THE GRAPHITE AT ELEVATED TEMPERATURES THEY WILL FOLLOW THE Na TEMPERATURE MORE CLOSELY IN A DOWNWARD TEMPERATURE TRANSIENT. THEY SEE SODIUM FLOW CLOSE TO PROCESS TUBES. THERE IS A SLIGHT POSSIBILITY THAT THE ANOMALOUS BEHAVIOR OF THERMO-COUPLE #20 IN FIG 17 OF MARCH REPORT & FIG 23 OF APRIL MIGHT HAVE BEEN PARTLY CAUSED BY LOCAL CIRCUMFERENTIAL CREEP & BUCKLING AFFECTING HEAT TRANSFER BETWEEN CAN & GRAPHITE.

SUMMARY OF AXIAL STRESSES IN MODERATOR CAN SKIN

CAUSE	TOP	BOTTOM
WEIGHT	NIL	2690
FRICTION AT MIDDLE OF LENGTH OF GRAPHITE	3870	6260
PRESSURE ON UPPER HEAD	4100	4100
$\sigma_x =$	<u>7970</u>	<u>13,050</u>

CIRCUMFERENTIAL VARIATION OF TEMPERATURE
 WOULD BE EXPECTED TO PEAK JUST ABOVE MIDDLE OF
 CORE, CAUSING 260 PSI/°F OF ΔT LOCAL INCREASE
 FROM MEAN CIRCUMFERENTIAL TEMPERATURE. AT ELEV.
 IN QUESTION, ADDING TO AXIAL COMPRESSIVE STRESS ABOVE.

STABILITY OF CAN ACROSS FINGER GROOVES

CAN SPANS FINGER GROOVES IN GRAPHITE FLAT, BUT STANDS FREE OF $.750''$ RADII WHEN HOT. CONSIDER UNIT WIDTH STRIP "REMOTE" FROM END OF CAN & FROM RUNOUT OF GROOVE.

$$\text{LET } k^2 = \frac{P}{EI}$$

REF. TIMOSHENKO: STRENGTH OF MATERIALS V. 2 1ST ED. SECTION 4.

$$k^2 = \frac{14.2 (10)^{-6}}{24 \left[\frac{.016^3}{12(1-\nu^2)} \right]} = 1.73$$

$$u = \frac{kl}{2} = \frac{1.315(.650)}{2} = .428$$

MOMENT AT END OF SPAN

$$\begin{aligned}
 M &= -\frac{q l^2}{12} \cdot \frac{\tan u - u}{\frac{1}{3} u^2 \tan u} \\
 &= -\frac{18.7(.650)^2}{12} \cdot \frac{.4561 - .4280}{\frac{1}{3} (.428)^2 (.4561)}
 \end{aligned}$$

$$M = -.659 (1.01) = -.666$$

END LOAD WELL
BELOW CRITICAL.

BENDING STRESS:

$$\sigma_B = \frac{6M}{t^2} = \frac{6(.666)}{(.016)^2} = 15,600 \text{ PSI}$$

DIRECT COMPRESSIVE STRESS

$$\sigma_D = \frac{14.2}{.016} = 890 \text{ PSI}$$

COMBINED

$$\sigma_{\phi} = 16,500 \text{ PSI}$$

AT 950°F, PLASTIC FLOW TOWARD A MEMBRANE MODEL OF RESISTANCE WOULD BE EXPECTED, FINALLY FLATTENING & OIL-CANNING CONVEX RADII OF CAN OVER GROOVES IN .750 RADII OF GRAPHITE. HOWEVER, THIS APPEARS SELF-LIMITING FAR SHORT OF FAILURE.

INFLUENCE OF JOINTS IN GRAPHITE:

CONSIDER UPPERMOST JOINT ELEV. $\sim 1415.8'$

COOLANT $\sim 950^\circ\text{F}$

FREE EXPANSION OF $33.66''$ SECTION OF GRAPHITE
(ADJACENT HALVES OF TWO UPPER PIECES):

$$33.66 (1.4) 10^{-6} (950 - 68) = .041''$$

CORRESPONDING PART OF CAN

$$33.66 (10.2) 10^{-6} (950 - 68) = .300''$$

AV. COMPRESSION OF CAN BY FRICTION FORCES

$$\int \frac{\sigma dl}{E} = \frac{3870}{2} \cdot \frac{33.66}{23.6} (10)^{-6} = .003''$$

ESTIMATED GAP BETWEEN GRAPHITE PIECES

$$\Delta = .300 - .003 - .041 = .256''$$

ALTHOUGH ELASTICALLY STABLE & NOT HIGHLY STRESSED BY COOLANT PRESSURE, THE SKIN SPANNING THE GAP AT A JOINT IS VULNERABLE BY VIRTUE OF THE STRAIN-CONCENTRATING MECHANISM OF THE THERMALLY UNRESPONSIVE, MASSIVE GRAPHITE PIECES THAT EXTEND FOR 33.66 IN. EITHER WAY, UNDER A

LATERAL TEMPERATURE GRADIENT CAUSED BY MALADJUSTMENT OF CONTROL ORIFICES OR ANOMALIES IN HEAT GENERATION, THE BOWING RESPONSE OF THE MODERATOR CAN WOULD BE CROWDED INTO THE GAPS AT THE GRAPHITE JOINTS BY THE RESTRAINT IMPOSED BY THE EXTERNAL PRESSURE, FRICTION, & UNCOMPROMISING STRAIGHTNESS OF THE GRAPHITE BETWEEN GAPS.

$$I_{\text{STEEL}} \sim \frac{A r^2}{2} = 16\pi(.016) \frac{8^2}{2} = \pi(8)^3(.016)$$

$$I_{\text{GRAPHITE}} \sim \frac{\pi r^4}{4} = \frac{\pi(8)^4}{4} \sim 125 \text{ TIMES } I_{\text{STEEL}}$$

RESISTANCE OF CAN TO EXTERNAL PRESSURE IF UNSUPPORTED BY LOG.

304 ANNEALED Y.S. = 36,400

$\frac{1}{8}$ HARD Y.S. = 68,500

CONSIDER SEGMENT $\bar{AB}$ OF PERIMETER OF CAN A FREE BODY. BY SYMMETRY, NO SHEAR AT $\bar{B}$. THEN FOR EQUILIBRIUM, MOMENT AT $\bar{A}$ WOULD BE

$$M_A = .89(6.908)\Delta P + \frac{.89^2}{2}\Delta P + \frac{2.17^2}{2}\Delta P - M_B$$

$$= 8.90\Delta P - M_B \quad \text{IN-LB/IN}$$

IN LIMIT ANALYSIS, MOMENT WOULD EQUALIZE TO $4.45\Delta P$ AT BOTH $\bar{A}$ & $\bar{B}$. PLASTIC SECTION MODULUS OF CAN WOULD BE $Z_p = \frac{t^2}{4}$ PER INCH = $\frac{.016^2}{4} = 64(10)^{-6}$ IN³/IN

ΔP PRESSURE TO COLLAPSE UNSUPPORTED CAN AT ROOM TEMP:

$$\Delta P = \frac{1}{4.45} \begin{cases} (36,400) \\ (68,500) \end{cases} (64)(10)^{-6} = \begin{cases} 0.52 \text{ PSI} & \text{ANNEALED} \\ 0.98 \text{ PSI} & \frac{1}{8} \text{ HARD} \end{cases}$$

FRICTION BETWEEN LOG & SHEATH

ASSUME :

1. SLIPPAGE PRESENT
2. LINEAR PRESSURE DISTRIBUTION

$$F_1 = \mu C \int_{x_0}^L p(x) dx$$

$$F_2 = \mu \int_0^{x_0} p(x) dx$$

$$p(x) = p_0 + \gamma(L-x)$$

EQUILIBRIUM OF LOG OF WEIGHT W

$$W + F_2 - F_1 = 0$$

AFTER INTEGRATION WE OBTAIN

$$x_0^2 - 4 \left(\frac{p_0}{\gamma} + L \right) x_0 - \frac{2W}{\mu \gamma C} + \left[2 \left(\frac{p_0}{\gamma} + L \right) - L^2 \right] = 0$$

FROM WHICH x_0 AND ACCORDINGLY F_1 & F_2 CAN BE EASILY DETERMINED.

APPENDIX B
LIST OF DOCUMENTS REVIEWED

LIST OF DOCUMENTS REVIEWED

1. Interim Report on HNPf Moderator Element Development, NAA-SR-4384, by L. Newcomb and H. L. Sujata, Aug. 15, 1962.
2. Final Report on HNPf Moderator Element Development, NAA-SR-6508, by L. Newcomb, June 15, 1964
3. Final Summary Safeguards Report for the Hallam Nuclear Power Facility NAA-SR-5700, April, 1961
4. Hallam Nuclear Power Facility Reactor Operations Analysis Program Monthly Report No. 19, March 1964, AI letter No. 64AT2716.
5. HNPf Reactor Operations Analysis Program Monthly Report No. 20, April 1964, AI letter NO. 64AT3473.
6. Appendix "A" of Technical Specifications as Amended for Operation at Power for HNPf.
7. HNPf Scram Behavior.
8. Fabrication Specification NA0103-003
9. Welding Specification NA0107-002
10. Penetrant Inspection Specification NA0115-001
11. Graphite Specification ND0115-003
12. Moderator Leak Test Specification NA0115-005
13. Radiographic Inspection Specification NA0115-007
14. Stainless Steel Specification NB0160-001
15. Method of Measuring and Recording Dimensions of Graphite Log Assembly Spec. 7518-S71141
16. Final Assembly of HNPf Moderator Cans Spec. 7518-S71153
17. Installation of Moderator Elements, Reflector Filler Elements and Drain Adapter Assemblies at HNPf Spec. 7518-S71161
18. AI Inter-office letter from D.N. Glass to F.C. Gronemeyer, July 31, 1964, Statistical Evaluations of Acceptance Inspection Data from Hallam Moderator Elements.