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ADVANCED TEST REACTOR

Internals Vibration

Summary

May 1968

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DIVISION
GENERAL OFFICE
LYNCHBURG, VA.

ATOMIC ENERGY DIVISION

5061 FORT AVENUE
P. O. BOX 1260
LYNCHBURG, VA. 24505

TELEPHONE
AREA CODE 703
846-7371

June 28, 1968

Contract AT-(10-1)-1075
ATR Internals
Vibration Analysis
Our 59-3063-06

Mr. K. A. Krauss
Ebasco Services, Incorporated
Two Reactor Street
New York, New York 10006

Dear Mr. Krauss:

The final summary report on the vibration testing at NRTS and the analytical program at Lynchburg is hereby submitted for your information. This report includes the calculations, modification drawings, and actual test data to provide you with a comprehensive idea of the vibration program. Oscilloscope traces made during the testing at NRTS are included in the report along with interpretations by Babcock & Wilcox and a consultant vibration specialist. Also included are the B&W-recommended measures deemed necessary to eliminate the deficiencies, which have already been incorporated as permanent modifications.

Very truly yours,

THE BABCOCK & WILCOX COMPANY
Atomic Energy Division

Roy E. Manoll

Roy E. Manoll
ATR Project Manager

BAW-1322
June 1968

ADVANCED TEST REACTOR
INTERNALS VIBRATION SUMMARY

— May 1968 —

Compiled by
R. E. Manoll
ATR Project Manager

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AEC Contract No. AT(10-1)-1075
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Prepared for
EBASCO SERVICES, INC.
and Submitted to
THE UNITED STATES ATOMIC ENERGY COMMISSION
Idaho Operations Office
by
THE BABCOCK & WILCOX COMPANY
Atomic Energy Division
P. O. Box 1260
Lynchburg, Virginia 24505

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peg

PREFACE

The serpentine geometry of the core of the ATR creates a condition where no true end fixity exists for individual core components. In general, most components are merely resting on the lower end with the upper end restrained by its proximity with adjacent parts and are thus free-standing assemblies. These free-standing bodies differ from most reactor core components, which are usually located and restrained by upper and lower grid plates. This was not possible in the ATR because of the serpentine core.

Any component not securely anchored and in the flow stream of the cooling water is subjected to flow-induced vibration due to the complex flow characteristics of the ATR internals. The approach selected to isolate the real cause of the vibration was a systematic series of tests from which analysis could be performed. In a test program of this type many ideas must be employed, and results using various types of flow control must be evaluated. Much can be learned from this kind of program, and the results of each test dictate the next steps to be taken.

The Babcock & Wilcox Company acknowledges the assistance rendered by the following:

Mr. D. R. Miller of Knolls Atomic Power Laboratory rendered valuable assistance in the program and in the utilization of his theory of positive damping, and features he suggested for incorporation into the design aided in the success of the program.

Idaho Nuclear Corporation personnel (V. Walker, D. Halls, and others too numerous to mention) provided many good ideas for modifications that aided in isolating the problem and also provided sound instrumentation approaches to assist in evaluating the various problems.

Dr. T. P. Rona assisted in the development of hardware and test objectives and analyzed the results to determine the degree of stability achieved.

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1. INTRODUCTION

The systems operational testing of the ATR reactor, which began in December 1965 with the primary system full of water, and the performance of a step-flow rate (to approach full reactor operational flow) revealed the vibration of several components within the reactor vessel as well as excessive vibration of the primary piping. The Babcock & Wilcox Company sent representatives to the ATR site to assess the situation and take corrective measures to reduce the vibration to an acceptable level. The representatives discovered excessive motion in the pressure tube locator ties, center loop, dummy fillers, and safety rods; they had started a program to correct the situation when the primary system piping was found to be defective and all flow testing was curtailed. The vibration testing was resumed after nearly a year of reactor shutdown, and fixes were employed that seemed to solve the vibration problem.

During subsequent systems operations testing, loop positions that had been deemed acceptable suddenly began to vibrate violently, which indicated that the fixes had just approached the threshold of stability and that additional corrective measures were required.

A B&W task force was assigned to study the situation, take corrective measures to get the vibration to an acceptable level, and to determine the margin of stability the new fixes achieved as assurance that the vibration would not occur again at some time in the future.

Modifications were made, tested, and analyzed for all eight NR loop positions, and flow calculations of the positions were made to determine thermal heat removal, loop bowing, and the like. The test results were analyzed to determine how much positive damping had been achieved and how stable a system had been gained by the modifications.

The modifications made and tested were all of a permanent nature except for the center loop, which did not have the actual loop for that

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position modified, but rather NR loop No. 10, which is a "prime tube" but had been rejected by the Naval Reactors Branch due to pitting of the insulation jacket. The modification to the center loop position is similar to that recommended as a permanent modification, but it requires modifications of the splines in the prime tube insulation jacket.

The B&W analytical task force mentioned on page 1-1 consisted of the following personnel:

R. L. Boyer
R. A. Crane
M. W. Croft
R. E. Manoll
A. Mayer
F. A. Mays
R. V. Straub
D. E. Thoren
R. P. Williamson

2. RECOMMENDED PERMANENT MODIFICATIONS

2.1. Safety Rod Positions

The modifications for all safety rod positions consist of these two items (see Figure 2-1):

1. An aluminum liner 82 inches long, located inside the aluminum guide tube of the safety rod, extending down from the extreme upper end of the safety rod (see I.N.C. drawing 035761).

2. A labyrinth flow restrictor, fabricated from 17-4 PH 1100 material and located within the 17-4 PH 1100 extension sleeve between the guide tube and the rack tube of the safety rod (see I.N.C. drawing 035770, Rev. 1).

2.2. Dummy Flux Trap Fillers

The modifications for the two dummy flux trap fillers are similar to those for the safety rods (see Figure 2-2).

1. A 12-inch-long aluminum liner extending down into the guide tube from the extreme upper portion of the safety rod (see I.N.C. drawing 035800, Rev. 2).

2. A labyrinth restrictor slightly longer than that employed in the safety rod, fabricated of type-304 stainless steel, located in the same relative position as the safety rod labyrinth (see I.N.C. drawing 035777, Rev. 1).

2.3. Center Loop Position

The modification to the center loop position is merely a collar, mechanically attached to the splined area of the loop insulation jacket, which reduces the flow through the channel and also provides a hydraulic-type locator by virtue of the limited clearance between the outside of the collar and the inside of the center flux trap baffle. The loop must be modified by machining a groove around the splines to mechanically attach the

collar, which is fabricated of the same basic metal as the loop insulation jacket—type-348 stainless steel (see I.N.C. drawing 035819, Rev. 3, B&W drawing ATR 670 M-1111, Rev. 4, and Figure 2-3).

2.4. Permanent Modifications

Permanent modifications that were made during the early stages of vibration testing are as follows:

1. The latch pins on the inner pressure tube locator ties were made solid to eliminate motion due to the low spring rate discovered. (Each latch pin extends down into one of the neck shim rod sleeves in each wing, thereby preventing rotation of the entire locator tie.)

2. Fins were welded to the upper outer diameter of the dummy flux trap fillers to reduce excessive clearance between the flux trap baffle and the flux trap filler, thereby preventing excessive motion (0.125-inch clearance previously).

2.5. Safety Rod Motion

The following modifications would further reduce the motion of the safety rods and/or loops:

1. The spring-loaded pads on all pressure tube locator ties should be removed and replaced by an adjustable (screw-in) type. These pads, if properly installed, will provide a more positive loop support by positive spring force exerted in clamping the loop to the locator tie. (One set of spacers was modified per drawings SK-PWR-8-24-67-5072-1 and -2, but it was not tested during the vibration program.)

2. The aluminum filler plates and aluminum-hafnium stop plates should be replaced, using a one-piece construction method rather than riveting the handling extensions. This would prevent the motion of the handling extension due to loose rivets. (One set of these plates was fabricated per I.N.C. drawing 035763, Rev. 1, with an oversized outer radius to restrict flow in the outer channel, but it was not tested during the vibration program.)

2.6. Loose Packing Glands

Positive torquing of the packing glands around the NR loops below the reactor head should be employed to reduce the possibility of loss of loop end restraint due to extremely loose packing glands.

Figure 2-1. Final Revisions to Safety Rod

INC-R-11251

Figure 2-2. Revisions to Dummy Loop Positions

INC-R-11252

Figure 2-3. Flow Collar Upon Center In-Pile Tube

3. VIBRATION TEST RESULTS

3.1. Results Without Labyrinth

The first flow-induced vibrations were fairly severe, and remedial actions taken initially dealt with reducing the clearances between components and stiffening the restraining members. This corrective action reduced relative motions somewhat, but not to an acceptable level.

General categories that were then researched were cross-flow-induced and parallel-flow-induced vibrations.

The cross flow of water across the upper portion of the core impinging on the NR loops and/or safety rod assemblies was considered by some to be the major cause of the vibration. Tests were conducted utilizing calibrated flow strings to determine the direction and magnitude of the cross flow. The results of the tests bore out the B&W position that cross flow was not the cause. No agreement could be reached on this opinion, so a series of flow baffles—including one that surrounded the core—and joining strips on the edges of the neck shim housing was tried. No improvement was noted.

The parallel-flow situation was assessed by first applying a flow restrictor between the outside diameter of the safety rod and the inside diameter of the flux trap baffle. This configuration worsened the vibration, and that flow channel was discarded.

The next flow channel assessed was the annulus between the inside diameter of the safety rod and the outside diameter of the NR loop insulation jacket. The first restrictor placed in this annulus provided essentially a 0.030-inch flow channel and severely restricted the flow to about 60 gpm. This restrictor did the job of stopping the vibration and pinpointed the flow channel that required modification. The extreme restrictor could not be used, however, for several reasons, some of which are listed here:

1. Insufficient cooling flow.
2. The safety rod could not be removed independently from the loop.
3. The attachment problems associated with coupling the restrictor to the loop insulation jacket.

This started a series of flow restrictors of varying thickness, length, and configuration, located on the insulation jacket and in the safety rod and combinations of both. All modifications were made so as not to create a situation wherein the pretested safety rods would have to be retested for safeguards reasons and so as to be incorporated as economically as possible.

We had adopted a configuration that seemed to satisfy all the aspects of reactor operation, plus sufficient reduction in vibration, and the matter seemed to be a closed issue, when a safety rod that had been stable suddenly started vibrating very badly.

3.2. Results With Labyrinth

Testing was resumed and a margin of stability for our present modifications was established to assure all parties that the vibration would not re-occur some time later, after the reactor has resumed operation.

The current modifications and those recommended as permanent modifications satisfy the margin-of-stability question.

The current safety rod modifications are a dual restrictor system; one restrictor, a labyrinth located in and attached to the safety rod, stabilizes the rod during withdrawal but provides little stabilization when the rod is fully inserted and in its seat. The second restrictor—a tubular configuration within the upper portion of the safety rod—provides stability when the safety rod is in its seat but provides little or no stability when the rod is being withdrawn or is at the upper limit (fully withdrawn).

The detailed test program is outlined in Appendix A; it reflects the recommendations of the representatives of all the participants, companies, and consultants conducting the tests. Also included in the detailed program are the actual modifications made for each recorded test, instrumentation used, and visual and audible observations, as well as instrumented evaluation of the motions, etc.

3.3. Interpretation Derived From the Detailed Test Program

1. For the purposes of stability and vibration amplitude predictions, the PT-IJ assembly can be represented by a fundamental around 6.7 to 7.4 cps and a first "sinusoidal mode" at 19.0 to 22 cps.

2. The maximum displacement of both the PT and IJ occur approximately at station 77.5 feet;⁵ the two bodies move as if they were in contact.

3. The parallel-flow excitation, according to conservative procedures, would lead to 20 to 25 mils amplitude for 256 gpm in the annulus surrounding the insulation jacket.

4. No significant decrease in apparent damping could be measured when the flow varied from 0 to the value corresponding to 100 psi Δp . The value of damping was larger than 9.5% in all cases.

5. From 4 we conclude that the fixes, as they existed at the time of measurement, are substantially satisfactory to prevent self-induced vibrations and to keep the parallel-flow excitation within tolerable limits.

4. CONSULTANT'S REPORT ON THE ATR VIBRATION PHENOMENA

Dr. Thomas P. Rona, Consultant
(September 1967, Revised March 1968)

This report contains the findings related to vibration phenomena in the ATR loops. It is based on input data received in meetings, reports, and test results as mentioned in Table 4-1. The objective of the analyses and tests performed on the reactor loops was to gain a reasonable certainty that the vibration levels will not be prohibitive in actual operation.

In the ensuing discussion, we propose to show that:

1. A plausible model can be constructed for the insulation jacket-pressure tube assembly and that the experimental resonance frequencies support such a model.
2. The coupling between the oscillations of the insulation jacket and the pressure tube varies between large limits, but it can be bracketed for amplitude prediction.
3. The observed vibratory phenomena are due to parallel-flow excitation rather than self-excited vibration within the limits of our experiments.
4. The loops that have been tested in detail (and the results communicated to and interpreted by the writer) exhibit stable vibratory characteristics within the flow regimes considered.

It is to be understood that all the statements in this report are predicated on the validity of the experimental data submitted.

Table 4-1. List of B&W Reference Material Used by
Consultant

Figure 14.2 in "NR Loop In-Pile Arrangement" report
Memorandum No. 59-3063-06

Drawings

ATR 1075	MTR 670M152
MTR 670M122	MTR 670M153
MTR 670M1112	670 R&D 1351

Exhibits I - III: Test Data (see section 4.3)

Oscillograph records (traces)
Comments on records
Interpretation

4.1. Selected Models

Figure 4-1 shows the model we accepted for this report. It is based on Figure 14.2 in the "NR Loop In-Pile Arrangement," and supplemental information pertinent to safety rod positions and vibration pickups on the pressure tube and the insulation jacket. The following points deserve comment in regard to the model:

1. Three supports with respect to "reference;" the flow turnaround at approximately 97 feet, the locator tie between 86 and 87 feet, and the bottom head closure plate in the vicinity of 68 feet.
2. The quality of the top and bottom support are unspecified; it may be unwise to depend on them as fully clamped supports.
3. Although the locator tie is referred to as "pressure tube locator tie," it actually contacts the 3.211-inch-OD splines of the insulation jacket.
4. The locator tie is spring-loaded and anisotropic; i.e., it does not have the same stiffness in all directions.
5. The pressure tube is supported at the top by part No. 820 (pressure tube and insulating jacket assembly) and at the bottom by part No. 897 (packing for sliding seal).
6. The pressure tube is centered, with respect to the insulation jacket, by locator buttons with unspecified but small clearances.

7. Whereas the pressure tube pickup is approximately in the geometrical center between the locator tie and the bottom head closure plate, the insulation jacket pickup is in the vicinity of the locator tie. If the support offered by the locator tie is stiffer than that of the insulating jacket, the vibratory amplitude "measured" at the insulation jacket pickup will be smaller than the "true" insulation jacket amplitude.

8. No reference is made to, nor are data available on, the so-called "flow tube" internal to and presumably in contact with the pressure tube. Nothing in the text that follows should be construed as containing conclusions valid for the flow tube.

Figure 4-2 shows the simplified two-beam model used for assessing vibration modes and frequencies. In the figure, ABC represents the insulation jacket with the locator tie in (B); DE represents the pressure tube supported in (E) and tied to the subpile portion of the insulation jacket in (D). The approximate locations of the major hydrodynamic forces are shown, as well as the point of application (D) of the exciter as explained further in section 4.3. The changes in cross section and the locations of splines are also indicated.

Figure 4-1. Model for Consultant's Report

Figure 4-2. Simplified Two-Beam Model Used for the Assessment of Vibration Modes and Frequencies

4.2. Nature of the Vibration

4.2.1. Vibration Modes of the Insulation Jacket

The numerical calculations are given in Appendix B. Two possible vibration modes are of interest:

1. Fundamental, of the mode shape shown, at approximately 8.13 cps, and
2. Sinusoidal, at approximately 25.6 cps.

Note that, if P₁ and P₂ designate vibration pickups located at 77.5 and about 90 feet, respectively, then the output ratio P₂/P₁ will be small for the low-frequency modes and high for the sinusoidal (high-frequency) mode.

4.2.2. Vibration Modes of the Pressure Tube

The numerical calculations are given in Appendix B. For the simply supported case, the mode shape would be sinusoidal with a frequency of 2.03 cps. With clamped supports in both D and E, a frequency of 4.65 cps would be observed. For future discussions, let us summarize the pressure tube mode shapes and frequencies that might be present (with only D and E supports present):

Note that the fundamentals in all cases are very "soft," i.e., they have lower natural frequencies than the lowest possible fundamental frequencies of the insulation jacket, AS LONG AS THE LOCATOR TIE IN (B) IS IN PLACE.

4.2.3. Vibration Modes of the Insulation Jacket-Pressure Tube Assembly

If the two vibrators are assumed independent, then, when excited in (D), we should have

- the flexural fundamental of the pressure tube at 2.03 to 4.65 cps (higher values for high degree of clamping at D and E)
- the fundamental of the insulation jacket ABC at 8.13 cps
- the first sinusoidal insulation jacket mode at 25.6 cps.

Note that, because of the presence of non-linearities in the supports (seals and locator tie buttons), subharmonic excitation is possible, i.e., any one of the lower frequencies can be excited by the application of twice the modal frequency.

If the pressure tube is considered to be tied to the insulation jacket (with shear restraint), then only two types of modes will be observed, namely

- the low-frequency fundamental of the "loaded" insulation jacket; 7.45 cps
- the first sinusoidal harmonic of the "loaded" insulation jacket at approximately 23.6 cps.

These frequency estimates do not account for the water loading of the insulating jacket; it is estimated that the actual values will be 10 to 15% lower, i.e., 6.3 to 6.7 cps and 20.0 to 21.4 cps for the fundamental and for the first sinusoidal. For subsequent discussing, it is of some interest to note that IF the pressure tube and the insulation jacket move together (i.e., the relatively stiff jacket imposes the vibration of the relatively soft pressure tube) the ratios

$$\frac{\text{PT pickup @ station 77.5 feet}}{\text{IJ pickup @ station 90 feet}}$$

should be -6.35 at the fundamental frequency. At the first sinusoidal mode, this same ratio should be about +0.101. Detailed computations are given in Appendix B.

4.2.4. Excitation Mechanisms

In addition to the motion of supports and the excitation forces introduced for diagnosis, this report concerns itself with two major fluid-induced vibratory mechanisms:

1. Parallel-flow excitation due to pressure fluctuations in the vicinity of the insulation jacket.
2. Self-induced oscillations, mostly generated by the introduction of negative damping through hydrodynamic forces in the motion of the insulating jacket.

Extensive literature is on hand for the first mechanism, and some measure of analytical prediction is warranted. For the second, references are on hand for relatively simple laboratory models,^{3,4} but no predictive method is applicable quantitatively. In Appendix B the amplitudes attributed to parallel-flow excitation of the insulation jacket are computed, using methods published by Burgreen¹ and Reavis.² For 256 gpm in the annulus surrounding the insulation jacket (Channel IV in reference 6), the fundamental vibration amplitudes are found to be 26

mils¹ and 7 mils.² In these calculations 7.45 cps natural frequency has been used.

The relative agreement between the two values (and, as seen from section 4.3, with the order of magnitudes of the observed results) should not be construed as an indication of the reliability of predictions based on these methods. All the authors point out the strong dependency of results on relatively uncontrolled factors, such as non-axial flow velocity components both within and upstream of the channel. A glance at the flow sketches in reference 3 should convince the reader that we are far away from the carefully controlled laboratory tests of the various authors whose results correlate with analytical or empirical formulas within factors of about 3 to 10.

In regard to self-induced vibrations, only qualitative statements can be made for the reactor loops as investigated. When, for example, a flow restrictor is placed at the upstream end of the annulus surrounding the insulation jacket, it is apparent that displacement of the insulation jacket in one direction gives rise to a pressure difference, forcing the rod in the same direction as the displacement. With specific assumptions and in relatively simple cases, it can be shown that this force has components proportional to the displacement and to the displacement velocity. The first results in a negative spring constant, the second in a negative damping term. In general, then, self-induced vibrations evidence a decrease in the apparent vibration frequency and an increase in the magnification factor of the oscillator. For practical purposes, the verification against self-excited vibrations will then consist of (1) establishing the fraction of flow energy necessary to drive the insulation jacket at the limits of acceptable motion of the fundamental, and (2) verifying experimentally that the damping characteristics of the insulation jacket are positive and significant in the presence of the full flow. If (1) results in a very small fraction (say, less than 0.05%), and if (2) shows reasonable values (10% and above) in the presence of full flow, it can be stated that, even in the presence of substantial hydrodynamic energy source, the positive damping introduced by the flow compensates for any energy coupled from the flow to the oscillator (see Appendix B).

4.3. Test Results and Interpretation

4.3.1. Input Data

The following experimental data have been made available:

Exhibit I

49 pages of oscillograms obtained with rotary exciter August 24, 1967. (Only those pages referred to in the comments on Exhibit I are included in this report.)

Exhibit II

19 pages of oscillograms obtained with hydraulic shaker August 27 - 28, 1967, south position, no flow. (Only those pages referred to in the comments on Exhibit II are included in this report.)

Exhibit III

1. Selected records (from the actual oscillograms) of the displacement of the pressure tube and the insulation jacket. The oscillograms were obtained during vibration test No. 31 covering the period from August 31, 1967, through September 4, 1967. The selected records coincide approximately with the response peaks of the summary admittance/frequency plots..
2. Summary plots of the response peaks of the pressure tube-insulation jacket assembly for flow velocities corresponding to various pressure differentials across the core.

Observation minutes by R. Manoll, July 11 through August 19, 1967.

The positions and configurations of the locator ties for the pressure tube-insulation jacket assemblies in the ATR are given in Figure 4-3.

Figure 4-3. Positions and Configuration of the Locator Ties for the Pressure Tube-Insulation Jacket Assemblies in the ATR

4.3.2. Comments on Exhibit I

1. Coupling is evident between the insulation jacket and the pressure tube, since even in the absence of rotary excitation (page I-14), both NS and EW PT pickups are indicating response to the flow.

2. With no exciter but with full flow, the pressure tube exhibits typical quasi-random vibrations with some spectral emphasis around 7.6 cps (page 14).

3. Excitation in the presence of full flow at 7.35 cps (page 4) shows substantial correlation between NS PT and NS exciter and typical quasi-random output in the EW PT channel. Amplitudes are significantly larger in NS PT when artificially excited. There is little change in EW PT between excitation and no excitation.

4. (page 16) No flow 9.0 cps excitation shows significant second-harmonic-level response in both PT pickups. Same observation for pages 26 and 36.

Interpretation — The IJ + PT assembly exhibits at least one resonant frequency around 7.35 to 7.6 cps. Response can be detected around 18 cps through excitation at 9.0 cps. No magnification factor estimates are possible on the basis of these data. The loop is not identified. The NS-EW directions are quite different in their response to presumably isotropic rotary and flow excitation.

RUN # (2)

$\Delta P = 0$
(NO FLOW)

AUG 24 1967

Exhibit I

Oscillogram page 16
8/24/67

W PT 1 mil/line

N PT 1 mil/line

N Exc. $\frac{2}{\pi}$

4.3.3. Comments on Exhibit II (No Flow)

1. At 6.7 cps shaker excitation, both PT channels respond moderately; IJ responds at the third harmonic, i.e., 20 cps. Little third harmonic exists in the PT channels (page 3).

2. At 9.0 cps, the IJ channel responds around 18 cps, 9.0 cps response mostly in both PT channels (page 7). At 9.6 cps this same phenomenon is more clearly visible (page 8); then on page 9 for 10.0 cps.

3. At 11.9 cps excitation, both PT channels respond at 6.0 cps (subharmonic). The insulation jacket picks up the 6.0 cps fundamental but also shows a significant third harmonic at 17.9 cps. Very little third harmonic is apparent in PT-EW, some in PT-NS (page 12). Same phenomenon, reinforced, appears at 12.6 cps; subharmonic at 6.3 and STRONG third harmonic at IJ, 18.9 cps with relatively little 18.9 cps in PT channels (page 13).

4. At 17.6 cps excitation (page 19) the IJ responds strongly in a pure sinusoidal mode; PT-NS follows but not PT-EW; PT amplitudes are much lower than IJ amplitudes.

Interpretation — This mode of excitation, with two PT channels and one IJ channel, is far better than the one used in Exhibit I for determining natural frequencies and mode shapes. (1) In the vicinity of 6.7 cps, there is a resonance detectable by the PT pickups. (2) This mode is coupled to the IJ and can be excited through both the fundamental (6.7 to 7.0 cps) and the subharmonic mode (11.9 to 13.7 cps). (3) The ratio of amplitudes PT/IJ is large for the 6.7 cps-type fundamental. (4) There is a second resonant frequency in the 17.6 to 20 cps region, where the IJ responds relatively strongly and both PT channels respond far more moderately than at 6.7 cps. (5) There is no resonant frequency in the vicinity of 12 to 13.0 cps; the relatively large response of the PT is due to the subharmonic excitation (2) above.

Exhibit II
Oscillogram page 8
8/28/67

Exhibit II

Oscillogram page 9
8/28/67

Exhibit II

Oscillogram page 19
8/28/67

4.3.4. Comments on Exhibit III

4.3.4.1. Tabulated Data

The following tabulated information for vibration test No. 31 is given in Table 4-2:

1. The serial number of the pressure tube-insulation jacket assembly.
2. Its position when forced excited by the hydraulic exciter during test No. 31.
3. The core pressure drop when the oscillograms were recorded.
4. The referenced data pages in the INC logbooks for each set of oscillograms.
5. The oscillogram record numbers for each set of oscillograms.
6. The date the oscillograms were recorded.

Table 4-2. Information for Vibration Test No. 31

<u>Serial number of assembly</u>	<u>Position</u>	<u>Pressure drop across the core, psi</u>	<u>INC^(a) logbook pages</u>	<u>Date oscillograms were recorded</u>	<u>Oscillogram record numbers in each set of records</u>
820-5	SE	0 (ULS) ^(b)	12	9-2-67	SE-1 - SE-27
820-5	SE	100 (LLS) ^(c)	18	9-3-67	SE-1 - SE-27
820-4	S	0 (ULS)	20	9-3-67	S-1 - S-25
820-4	S	100 (LLS)	27	9-3-67	S-1 - S-27
820-10	SW	0 (ULS)	164	8-31-67	SW-1 - SW-31
820-10	SW	100 (LLS)	169	8-31-67	SW-1 - SW-32
820-9	NE	0	35	9-4-67	NE-1 - NE-28
820-9	NE	100	39	9-4-67	NE-1 - NE-24
820-1	E	0	29	9-3-67	E-1 - E-28
820-1	E	100	33	9-4-67	E-1 - E-22

(a) INC: Idaho Nuclear Corporation.

(b) ULS: Safety Rod at Upper Limit Switch.

(c) LLS: Safety Rod at Lower Limit Switch.

4.3.4.2. Selected Oscillogram Records for Exhibit III

SE Position - No Flow (Exhibit III, page 12)

SE-9 — 6.0 cps excitation shows a strong fundamental PT response with the IJ showing small fundamental with superposition of a relatively strong 18 to 20 cps. There is reason to believe that the latter is the manifestation of the so-called sinusoidal mode ("sinusoidal" refers to deflection shape, rather than displacement/time diagram). Even with the relatively large motions, no mutual impact can be detected.

SE-21 — 14.1 cps excitation affects both PT and IJ roughly at the same level (accounting for the differences in measuring stations) and the responses are relatively "pure."

SE-26 — 19.0 cps excitation causes the IJ to respond with relatively large amplitude (except for a very low-frequency superimposition probably due to instrumentation). The PT transducer, being at the node of the sinusoidal shape, records selectively the 6.3 cps "subharmonic."

Interpretation — The information above is quite consistent with the findings of the draft report. There is no evidence of mutual impact; the 6.3 cps, 14.1 cps, and 19.0 cps frequencies, which give apparent peaks of the displacement/force ratio, are very close to the values found previously.

SE Position - 100 psi Flow (Exhibit III, page 18)

SE-8 — At 6.0 cps excitation, PT responds with large amplitude (40 mils) in an almost purely sinusoidal waveform. It is important to notice that a random component caused by the flow is still present, but that its peak-to-peak amplitude is barely 8 mils. The displacement/force ratio, which was 175 for the 0 psi flow is now 188 with 100 psi flow. The difference is well within the limits of experimental error. At the fundamental frequency (and presumably with the fundamental mode shape), the full flow does not add measurably to the "input admittance" of the insulating jacket-pressure tube system. The IJ, incidentally, responds very little at 6 cps, as this is to be expected if the

mode shape assumed in the draft report (page 27) is correct. Of course, it would be more sensitive to the "sinusoidal" mode at roughly three times the fundamental; this is indeed corroborated by record SE-8.

SE-18 — 14.0 cps - Both PT and IJ respond, with the PT also showing approximately 10 mils superimposed. Comparison with SE-21 of the no-flow set shows that there is definitely no magnification following the presence of flow; there is simple superposition of the flow-induced vibration and the shaker excitation.

SE-25 — 20 cps excitation - The record is useful but far from desirable quality. The superimposed low-frequency oscillation does not correspond to any mechanical (known) phenomenon; the 0.5 cps observed would be typical of previous instrumentation defects due to overloading. However, it is clear that the major response of the pressure tube is at approximately 6.3 cps, whereas the IJ responds at the excitation frequency, if at all. Examination of the record and the input admittances indicates that the effect of the flow is essentially to emphasize the 6.3 cps subharmonic, even though the excitation is at a significantly different frequency. This is a new observation, but in no case does it represent amplitude beyond the one observed for the excitation at the fundamental. We may conclude that the measurement of damping at the higher frequencies becomes illusory if subharmonics can be excited through hydrodynamic coupling. The fault is one of method (as pointed out by Mr. Miller) rather than one of the critical behavior of the assembly.

S, SW, NE, and E Positions

The selected oscillograms for these positions are presented in pages 20 and 27 (S), 164 and 169 (SW), 35 and 39 (NE), and 29 and 33 (E) of Exhibit III. Examination of the oscillograms reveals that the 6- to 7-cps excitation also results in a strong fundamental response, and that the full flow does not add measurably to the input admittance of the insulating jacket-pressure tube assembly. In general, the detailed comments presented for the southeast position are also valid for the other positions.

4.3.4.3. Admittance Frequency Plots for Exhibit III

In general, the aspect of these plots does not show significant decrease in damping due to the presence of flow at the 6.3 cps "fundamental." In the presence of full flow, the measured damping (Appendix B) is 11.8% for SE and 12.2% for S. It is noted once again that, although high-frequency excitation in the presence of flow does excite the fundamental at the same level as if the fundamental was directly excited, this should not be construed as evidence of negative damping in the sense used here.

SOUTHEAST POSITION

Core Pressure Drop = 0.0 psi

Core Pressure Drop = 100.0 psi

SOUTH POSITION

Core Pressure Drop = 0.0 psi

Core Pressure Drop = 100.0 psi

SOUTHWEST POSITION

Core Pressure Drop = 0.0 psi

Exciter Frequency = 7.0 cps

Exciter Frequency = 14.6 cps

Exciter Frequency = 18.5 cps

Core Pressure Drop = 100.0 psi

Exciter Frequency = 7.0 cps

Exciter Frequency = 14.75 cps

Exciter Frequency = 18.5 cps

NORTHEAST POSITION

Core Pressure Drop = 0.0 psi

Exciter Frequency = 5.45 cps

Exciter Frequency = 14.0 cps

Exciter Frequency = 19.1 cps

Core Pressure Drop = 100.0 psi

Exciter Frequency = 7.5 cps

Exciter Frequency = 14.2 cps

Exciter Frequency = 18.9 cps

EAST POSITION

Core Pressure Drop = 0.0 psi

Exciter Frequency = 7.0 cps

Exciter Frequency = 17.0 cps

Exciter Frequency = 19.8 cps

Core Pressure Drop = 100.0 psi

Exciter Frequency = 7.5 cps

Exciter Frequency = 15 cps

Exciter Frequency = 18.1 cps

SOUTH POSITION

Vibration Test No. 31
Date of Test: 9/3/67

Pressure Tube at
77'-6" Elevation

Insulation Jacket at
90' Elevation

$$\frac{\delta}{F} = \frac{\text{Amplitude, mils}}{\text{Hydraulic Exciter Force, lb}} \times 10^3$$

Spring-Loaded
Bumper

Solid Bumper
at Locator Tie

IJ

N-S

$\Delta P = 100$ psi

$\Delta P = 0$ psi

$\Delta P = 100$ psi

$\Delta P = 0$ psi

Exciter Frequency, cps

SOUTHWEST POSITION

EAST POSITION

4.4. Conclusions

1. For the purposes of stability and vibration amplitude predictions, the PT-IJ assembly can be represented by a fundamental around 6.7 to 7.4 cps and a first "sinusoidal mode" at 19.0 to 22 cps.

2. The maximum displacements of both the PT and IJ occur approximately at station 77.5 feet; the two bodies move as if they were in contact.

3. The parallel-flow excitation, according to conservative procedures, would lead to 20 to 25 mils amplitude for 265 gpm in the annulus surrounding the insulation jacket.

4. No significant decrease in apparent damping could be measured when the flow varied from 0 to the value corresponding to 100 psi Δp . The value of damping was larger than 9.5% in all cases.

5. From 4 we conclude that the fixes, as they exist at the time of measurement, are substantially satisfactory to prevent self-induced vibrations and to keep the parallel-flow excitation within tolerable limits.

These conclusions are stated subject to the condition that the information transmitted to the writer represents, within the best practical approximation, the design values, operating parameters, and test results related to the foregoing analysis.

Thomas P. Rona, PhD, Consultant
(submitted September 19, 1967,
revised March 1968)

REFERENCES

Section 4

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- ⁴ Den Hartog, J. P. , "Vibration, a Survey of Industrial Applications," ASNE Journ. 70, No. 4, 1958.
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- ⁶ Mayer, A. , B&W Ref. 59-3063-06, May 1, 1967.

5. CALCULATION RESULTS

5.1. Labyrinth Flow Restrictor Design

Flow losses that occur near the exit of the flow channel provide negative damping to the system. For this reason it is desirable to make flow losses as large as possible in this region without undercooling the safety rod components. The labyrinth was designed to provide a relatively large pressure drop within the allowable dimensional limitations (see Figure 5-1). The critical parameter for such a flow restrictor is the ratio of the pitch between restrictions and the height of each restrictor. If the pitch is too small, flow will not redevelop between restrictors and pressure drops will be greatly reduced; if the pitch is too large, fewer restrictors can be located in the channel and pressure drops are again reduced. Pressure drops across the labyrinth may be calculated from the equation

$$P = 6.5 \rho \frac{V^2}{2g_c}$$

where

P = pressure drop, lb/ft²

ρ = coolant density, lb/ft³

V = coolant velocity at restriction, ft/sec

g_c = gravitational constant $\frac{\text{lb}_m}{\text{lb}_f} \frac{\text{ft}}{\text{sec}^2}$

Detailed calculations for the design of the flow restrictor are included in Appendix D. The predicted pressure drop for the labyrinth is shown graphically in Figure 5-2.

5.2. Hydraulic Analysis

The various types of experimental flux traps of the ATR have been analyzed from a hydraulic standpoint to determine their hydraulic performance with the recommended permanent modifications described in part 2 of this report. The results and calculational methods are described below.

5.2.1. Safety Rod

Based on a concentric condition, the safety rod inner channel flow rates calculated are in the order of 187 and 220 gpm in the withdrawn and inserted positions, respectively, which are adequate to meet cooling requirements. The analysis has shown that, due to the position of the labyrinth, approximately half of the inner channel pressure drop occurs below the articulated joint and the average velocities do not exceed 40 fps.

The flow rates and pressure drops for the various safety rod channels were determined using an iterative method made possible by curves describing flow rate as a function of pressure drop obtained by using the CHATA (Core Hydraulic and Thermal Analyses, BAW-230) computer code. The code is designed to calculate the flow rate through a channel satisfying a given pressure drop, or vice versa, depending on the user's choice. The required input data are fluid conditions and channel geometry. Known form losses may be input; others are calculated using the code's fitted Kays and London form loss curves. The friction factors are obtained from Moody curves fitted for computer use.

The safety rod modifications are designed to prevent stagnant water and possible hydrogen formation from radiolytic water decomposition by means of small grooves machined in their mounting surfaces.

Hydraulic calculations were made to determine the flow rate within the grooves with the restrictors in their appropriate locations. Both maximum and minimum flow rates were determined, since the effective groove flow areas are significantly affected by their dimensional allowances. The following are the resulting flow rates through the grooves between the 82-inch "stovepipe" and the strongback (channel 44) and between the labyrinth and extension tube (channel 66).

<u>Safety rod position</u>	<u>Channel geometry</u>	<u>Flow rates, gpm</u>	
		<u>Channel 44</u>	<u>Channel 66</u>
Up	Min	2.15	3.47
Up	Max	4.28	5.72
Down	Min	2.85	3.38

According to the data presented by V. P. Calkins in reference 8, Appendix D, hydrogen formation is not a problem at the water temperature and neutron flux levels within the flow channels of concern.

The safety rod hydraulic performance resulting from the eccentric inner annuli evolving from the loop thermal bow phenomenon has been investigated using the model shown in Appendix D.2.2 and basing frictional effects on an assumed 160-gpm flow rate. Computations were performed considering eccentricities peaking to a maximum of 122 and 146 mils and varying along the channel length as shown in figure D.2-13. The results, when compared with the concentric flow rate of 187 gpm, exhibit a flow rate increase of 10% for the 122-mil eccentricity and 15% for 146 mils.

5.2.2. Center Loop Position

The hydraulic performance of the center loop position with the recommended permanent modification described in section 2 was determined by the calculational methods of Appendix D.3. The basic method utilized to determine the flow rate through the center loop concentric annuli flow channel was by a summation of the constituent pressure losses occurring under the 100-psi total available pressure differential.

The calculated flow rate with the 100-psi pressure differential is 117 gpm and the average bulk coolant velocity through one of the six restrictor flow passages is 85.2 fps.

5.2.3. Dummy Flux Trap Filler

The dummy flux trap filler modifications, as described in section 2, consist of a 12-inch aluminum liner and a labyrinth restrictor slightly longer than the type used for the safety rod. The increased labyrinth length essentially induces another velocity head and friction loss.

The complete calculational methods used to determine the flow distribution of the NE loop position with the dummy flux trap filler and the pertinent modifications are described in Appendix D.4. The analytical method described consists of a system breakdown into constituent channels. Each channel is analyzed individually, considering all pressure changes resulting from geometric changes and friction with the end result being an equation describing the pressure drop of the channel as a function of its flow rate. A plot of these values was used in an iterative method to obtain the following flow distribution, which satisfies the 100-psi total available system pressure differential.

<u>Channel No. *</u>	<u>Flow rate, gpm</u>	<u>Pressure drop, psi</u>
I	177	64.0
II	166	68.0
III	36	4.0
IV	141	6.1
V	202	2.0
EXIT	343 (Total)	30.0

The average velocities occurring in Channel I at the labyrinth and the 12-inch aluminum sleeve are approximately 34 and 32 fps, respectively. In Channel II, the velocity at the smallest cross section is 53 fps.

5.3. Thermal Analysis

Temperature gradients in the insulator jacket and the pressure tube require an iterative solution with rod thermal bow. Because of gradients in the heat generation rates within the safety rod, a thermal bow is produced on the hot side of the insulator jacket and the pressure tube. As a result of this bow, coolant flow is restricted around the hot side of the insulator jacket and is enhanced on the cool side. The thermal gradient is thereby aggravated and results in increased bowing.

The thermal gradient is a function of the bow of both the insulator jacket and the pressure tube. The amount of bowing in the insulator jacket has been assumed (or calculated in a previous iteration). The thermal gradient will now be calculated as a function of the pressure tube bow; results are given graphically in Figures 5-3 and 5-4 for the center loop and

*Refer to Figure D.4-1 of Appendix D for channel locations.

in Figures 5-5 and 5-6 for the outer loops. The calculations are based on conditions that occur at the hot and cold spots.

It is assumed (and was later verified) that, because of thermal boundary conditions, the maximum temperature will occur somewhere in the pressure tube. The exact position of this maximum is a function of the pressure tube bow. In each case a point of maximum temperature is selected, and the corresponding pressure tube bow is later determined. The accompanying curves can be generated after calculating several of these cases.

The point of maximum temperature is a point of no heat flux. Therefore, all the heat generated inside this radius will be conducted to the coolant flowing inside the pressure tube. Knowing the velocity, temperature, and heat transfer coefficient for this coolant, we can determine the temperature distribution of the pressure tube.

Similarly, the amount of heat flowing outward radially from the point of maximum temperature may be determined, and the temperature gradient across the insulator jacket can be found. Having found the temperature gradient across both the pressure tube and the insulator jacket, and knowing the quantity of heat being transferred, we can determine the associated gap between the two surfaces. This gap fixes the corresponding pressure tube bow for any case. The method for finding the final iterated bow is explained in the following section. Assumptions used in these calculations are as follows:

1. Heat was assumed to flow in the radial direction only.
2. Radiation heat transfer was negligible.
3. Water temperature inside pressure tube was assumed to be 650 F.
4. Inlet temperature of the water flowing outside the insulation tube was assumed to be 130 F.
5. No azimuthal variation in the temperature of the water flowing around the insulation tube.
6. Pressure tube inside surface heat transfer coefficient was assumed to be 8960 Btu/hr-ft²-°F.

A derivation of the basic formulas used in the thermal analysis and sample calculations are presented in parts 4 and 5 of Appendix C.

5.3.1. Gamma Heating Rates

5.3.1.1. Outer Loop

Because of inadequacies in the analytical methods for determining heat generation rates, a +25% uncertainty factor has been applied to all calculated values.¹ This uncertainty applies to the absolute magnitude of the heat generation rates within the safety rod assemblies. In order to verify the accuracy of these calculations, a gamma heat measurement was made in a dummy pressure tube in the E flux trap. The results of this experiment have been evaluated statistically to predict the radial profile for gamma heat to within a confidence level of 99%, but absolute values could not be determined.² For thermal calculations, these analytical and experimental results have been combined, and the recommended uncertainty factors have been applied so as to present the most severe thermal bow.

5.3.1.2. Center Loop

Gamma heat rates for the center loop are based on the radial distribution reported in reference 3 with a +25% uncertainty factor applied to the absolute magnitude. Since the reported generation rate does not include the effects of a 60/40 power split, it has been assumed that the rates at the hot and cold spots are respectively 10% above and below the reported nominal rate.

5.4. Mechanical Analysis

Due to the cloverleaf cross section of the ATR core, there will be inherent circumferential temperature differentials around each of the specimen loops and an axial temperature distribution through the active core region. An outer lobe position has only 180 degrees of fuel around its circumference, compared with an inner lobe, which has 270 degrees of fuel and was thus considered the most critical position of the two. The center loop has essentially symmetrical circumferential fuel distribution, but with a power split a circumferential temperature differential would exist. A 60/40 power split was taken as the worst case.

Temperatures were calculated for the hot and cold sides of the pressure tube and the insulation jacket as a function of the size of the helium gap between the two tubes for a given coolant flow rate between the

insulation jacket and the safety rod and for an assumed thermal bow of the insulation jacket sufficient to alter the circumferential flow distribution. The nominal flow rate was calculated as outlined in the hydraulic section for a fix or combination of fixes for both the inner/outer and center configurations.

For the outer loop position, the deflections of the pressure tube and insulation jacket are calculated by two models. The first model (see Appendix E.5) considers three simple supports: the top head, the pressure tube locator tie, and the bottom head. With this model, the deflection of the insulation jacket at the snubber tube assembly is also calculated and limited to the radial gap of 0.015 inch between the splines and the inner snubber tube. The deflections in excess of those calculated with the first model were calculated with the second model (see Appendix E.6), which considers a fourth simple support at the snubber tube assembly.

The center loop has only three supports, and therefore the deflections were calculated using the first model. The three supports on the center loop were considered at the top head, the center flux trap baffle (with the 3.5-inch collar attached), and the bottom head.

For both configurations, the total midcore deflections for the pressure tube and the insulation jacket were calculated for the temperature differentials at several helium gaps. A helium gap was then calculated for each temperature differential from the relative deflections of the two tubes and compared with the helium gap at which the temperature differentials were taken. The solution was iterated until the assumed gap equaled the calculated gap. The deflection of the insulation jacket was also iterated until it equaled the deflection assumed in the thermal calculations.

The following assumptions were used in the calculations:

1. For the outer position, the insulation jacket is simply supported at the top head closure plate, the pressure tube locator tie, the snubber tube assembly (after a deflection of 0.015 inch at that point), and at the bottom head closure plate. The three simple supports for the center loop are at the top head closure plate, the center flux trap baffle (with

the 3.5-inch collar attached to the loop), and the bottom head closure plate. The pressure tube is simply supported at the top and bottom head closure plates for both cases.

2. Stiffness due to the splines on the insulation jacket is neglected. The moment of inertia for each tube is calculated as an "equivalent" moment of inertia rather than a variable moment of inertia along the length.

3. The effects of the weight of the loop, the lead shielding to be used during operation, and other dead loads are neglected.

4. The axial temperature gradient is sinusoidal for the incore region. The temperature gradient across the tube wall is linear.

5. The mechanical properties of the 348 SS material are at 300 F for the insulation jacket and 800 F for the pressure tube.

The recommended permanent modifications for the inner and outer loops are (1) an 82-inch-long "stovepipe" attached on the inside diameter of the safety rod strongback, and (2) a labyrinth flow restrictor attached on the inside diameter of the safety rod sleeve. The calculated coolant flow rate in the channel between the safety rod and the insulation jacket with the two modifications in place is 187 gpm. It has been estimated that the total inner channel flow will increase to 201 gpm for a bow of 0.120 inch. The total calculated midcore deflections of the pressure tube and insulation jacket are 0.151 and 0.132 inch, respectively, for temperature differentials of 47.0 and 52.6 F, respectively. The helium gap in the hot side of the loop is reduced from the nominal 0.0475 inch to 0.0291 inch.

Deflections of insulation jacket at the pressure tube spacer rings and the final total loads on the spacers were calculated and are indicated below at the elevation of the spacer rings.

Elevation, ft/in.	88/6	85/6	82/6	77/6	74/6	71/6
Deflection, in.	-0.019	0.014	0.078	0.093	0.043	0.016
Load, lb	1.06	5.76	1.46	0.41	3.25	0.19

The nominal radial clearance between the insulation jacket and the safety rod is 0.185 inch. A midcore deflection of 0.132 inch will leave a coolant flow channel 0.053 inch wide. Since the solution was iterated,

the deflection is steady state, and there will be no problem in cooling the loop. The coolant gap is adequate in that no contact between the insulation jacket and the safety rod will occur and the safety rod does not have to tilt at the articulated joint to accommodate the deflected loop. The maximum bending stresses in the pressure tube and insulation jacket were calculated from the three-support model and are 856 and 200 psi, respectively. The yield stresses for the SS 348 pressure tube and insulation jacket are 20,000 psi at 800 F, and 30,000 psi at 300 F, respectively.

The recommended permanent modification for the center loop is a 3.5-inch-long collar attached to the insulation jacket splines near the top of the neck shim housing. The calculated flow rate in the channel between the insulation jacket and the center flux trap baffle with this modification is 120 gpm.

The total midcore deflections of the pressure tube and insulation jacket are 0.119 and 0.118 inch for temperature differentials of 27.8 and 47.7 F, respectively. The helium gap on the hot side of the loop is reduced from the nominal 0.0475 to 0.0458 inch.

Deflections of the insulation jacket at the pressure tube spacer rings and the final loads exerted on the spacers were calculated and are indicated below at the elevation of the spacer rings.

Elevation, ft/in.	88/6	85/6	82/6	77/6	74/6	71/6
Deflection, in.	-0.015	0.011	0.067	0.088	0.052	0.028
Load, lb	3.36	8.27	4.32	11.88	12.10	1.59

The nominal radial clearance between the insulation jacket and the center flux trap baffle is 0.250 inch. A midcore deflection of 0.118 inch will leave a coolant flow channel 0.132 inch wide. Since the solution was iterated, the deflection is steady state, and there will be no problem in cooling the loop. The coolant gap is adequate in that no contact between the insulation jacket and the flux trap baffle is made. The maximum bending stresses in the pressure tube and insulation jacket were calculated from the three-support model; they are 656 and 345 psi, respectively. The yield stresses for the SS 348 tube and jacket are 20,000 and 30,000 psi at 800 and 300 F, respectively.

The two recommended permanent modifications for the inner/outer loop configurations were checked for stresses and found to be acceptable.

The 82-inch stovepipe, as shown in I.N.C. drawing 035761, is ample to withstand a differential pressure of 800 psi, which is more than twice the total system pressure. The critical buckling pressure, considering the stovepipe as a column, is 208 psi, which is more than twice the total pressure drop across the core region.

The labyrinth flow restrictor, as shown in I.N.C. drawing 035770, can withstand 4600 psi differential pressure, which is 15 times the total system pressure. The maximum shear stress on the attaching bushings is 8000 psi, which is much less than the 49,000 psi allowable shear stress for Inconel X-750.

The center NR loop flow restrictor, as shown in B&W drawing SKM-832, has been checked for stresses and has been found to be acceptable. The following paragraph is a summary of the conditions checked and the results obtained.

The maximum shear on the 0.093-inch diameter pins at assembly equals 10,400 psi, due to the preload of 283 pounds. The preload will decrease to 176 pounds when the loop and collar are subjected to system pressure. During operation, the differential expansion between the loop and the collar will increase the load on the pins to 482 pounds for a shear stress of 17,700 psi in the pins. Under operating conditions, the maximum stresses will be 19,600 psi tension in the collar, 7,600 psi compression in the loop insulation jacket, and 9,000 psi shear on the plug welds in the collar assembly. The bearing stress on the lower flat of the collar has been calculated at 2,700 psi for the 100-psi downward pressure across the collar. All of these stresses are less than the respective allowables, and therefore, they are acceptable.

Figure 5-1. Labyrinth Flow Restrictor for the ATR Safety Rod

Note: Dimensions are given in inches.

Figure 5-2. Pressure Drop in Labyrinth Vs Labyrinth Flow Rate

Figure 5-3. Temperature of Center Loop Pressure Tube at Mid-Core With 120-gal/min Flow and 0.150-Inch Bow

Figure 5-4. Temperature of Center Loop Insulating Jacket at Mid-Core With 120-gal/min Flow and 0.150-Inch Bow

Figure 5-5. Temperature of Outer Loop Pressure Tube at Mid-Core With 201-gal/min Flow and 0.150-Inch Bow

Figure 5-6. Temperature of Outer Loop Insulating Jacket at Mid-Core With 201-gal/min Flow and 0.150-Inch Bow

REFERENCES

Section 5

- ¹ Howard, J. O. to Croft, M. W., memo, "NR Loop Pressure Tube Heating Rates," The Babcock & Wilcox Company, Lynchburg, Virginia, January 17, 1964.
- ² Tappendorf, J. C. to Walker, V. A., memo, "Gamma Heat Measurement in Dummy Pressure Tube," September 18, 1967.
- ³ Advanced Test Reactor Final Shielding Report, The Babcock & Wilcox Company, ATR-S-R-129 (Ca-7), Lynchburg, Virginia, December 1963.

APPENDIX A
Details of Tests Conducted at NRTS

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Test No. 1

The purpose of this test procedure is to plan the testing in sufficient detail, so that upon the resumption of flow testing, the evaluation of the component modifications can be carried out as expeditiously as possible.

A. Pre-Test Phase

1. Installation of modified assemblies and temporary restraints.

a. Locator Ties

(1) Install the four modified corner locator ties and record the radial motion allowed by the fastener fit up.

(2) Install temporary restraints to the instrument thimbles on the southwest locator tie as shown in Figure 6. Record radial motion allowed by fasteners and temporary restraints.

b. Upper Vibration Tie Assembly

(1) Install the tube to tube grid assembly and special components at elevation 92' - 9" as shown on PP Co. Drawing ATR-E-1520.

(2) Install the 8 braces between the grid assembly and the "T" bars as shown in Figure 7.

(3) Check all fasteners for secureness and record all radial motion of the loops allowed by the tie system.

c. Install the modified center pressure tube and record any radial displacement due to component clearances.

d. Install the modified dummy flux trap fillers and record any radial displacement due to clearance.

e. Install the four-piece flow restrictor in the southeast safety rod in place of the regular flux trap filler and secure in place.

f. Record the radial displacement of the upper end of all five safety rods on two axes at two different elevations of withdrawal:

(1) Two inches above the top of the flux trap baffle.

(2) Two inches before the guide buttons engage the pressure tube splines.

(3) With safety rod engaged on spline (ULS) (1) top of rod (2) top of baffle.

g. Install the sub-pile room end fixity assembly, using care to avoid damage to the insulating jackets.

2. Instrumentation

a. Install the appropriate recording accelerometer systems in the pressure tubes in the southeast and southwest facilities. (flow tubes removed).

b. Install an optical target system in the pressure tube of the southeast facility.

c. Externally excite the instrumented tubes and attempt to correlate the instrumentation readings with measured displacements and frequencies. It may be necessary to perform this function on more than one radial axis.

d. Mount one pressure transducer in the pressure vessel upper plenum.

3. Flow Indicator Strings

a. Install nylon flow strings as shown in Figure 4 at elevations 83' - 6", 85' - 0", and 87' - 0".

b. Install nylon flow strings over the thermal shield area as shown in Figure 5.

c. Install 2 small convex mirrors to aid in viewing the flow strings during flow testing.

4. Safety Rod Flow Instrumentation

Instrument the NW safety rod to allow the measurement of coolant velocities in the various flow annuli at a partially withdrawn position. Shim the safety rod at the top to minimize hydraulic induced vibration. (Elevation 32".)

5. Withdraw the southwest safety rod to the full out position.

B. Evaluation of Component Vibration With All Restraints in Place

1. Pressure and regulate total reactor flow to 25,000 gpm.

a. Record any visual or instrumented evidence of loop or component motion or vibration.

b. Visually check for vibration of the primary piping.

2. Repeat steps a, b, and c for:

a. 30,000 gpm

b. 35,000 gpm

c. 40,000 gpm

d. 45,000 gpm

e. Full flow

Note: All objectional loop and component vibration should be eliminated before proceeding to Part B.

C. Evaluation of Safety Rod Vibration

1. Maintain full primary flow.

Note: Suspend testing if there is evidence of damaging component vibration.

2. Raise the south control rod to the full-out position and record performance data.
3. Raise the north control rod to the full-out position and record performance data.
4. Insert all safety rods except the NW rod.
5. Shut-down the primary pumps and depressurize the primary system.

D. Reactor Top Observations - 3/20/67

Flow 25,000 gpm — No tube movement detected. Southwest rod raised to ULS with no apparent vibration.

30,000 gpm, 54 psi reactor ΔP — No tube movement detected in the southeast visually. No vibration detected by the optical system. Southwest rod lowered to LLS and no apparent vibration. Southeast rod raised and vibration detected at 12-1/4" (accelerometer readings somewhat smoother at 12-1/2" than with rod at LLS). Rod vibration continued from 12-1/4" until the rod reached 14" at which time vibration stopped. No vibration detected from 14" to ULS, at which time rod was scrambled.

Southeast rod withdrawal started again to determine as accurately as possible the ranges of vibration and movement first detected 10.150" as read from reactor control room selsyn indicators and vibration stopped at 13.5", rods scrambled from 13.5" and brush recording taken in sub-pile room.

35,000 gpm, 73 psi reactor ΔP — No vibration detected in southeast rod by use of the optics. SW Rod - small but definite movement observed at 28.7", withdrawn movement continued until rod reached ULS. Rod scrambled and deflection recorded on brush in sub-pile room. SE Rod - movement first detected at 8.0" and this movement continued until the

rod was withdrawn between 13-1/4 and 13-1/2. Movement definitely stopped at 13.5", no movement detected between 13.5" and ULS. Rod scrambled and deflection measured on brush in sub-pile room.

40,000 gpm, 90 psi reactor ΔP — No tube movement detected. No movement detected in SE by use of optics. SW Rod - very small but detectable movement seen at 9.1" movement continued until rod reached 11.3" at which time it stopped, lowered rod to 11.0" no movement detected, lowered rod to 10.7" at which time movement was observed. Movement next detected at 27.4". Lowered rod to 27.0" and movement increased considerably, held rod at 27" while sub-pile room made brush recording of tube deflections. Vibration remained constant until rod reached 35-1/4" where it started up on the splines at ULS. Rod started vibrating more than it did at 35-1/4", also IPT seems to be vibrating a small amount. SE Rod - very very slight movement detected at 4.750", this movement continued until rod reached 6.6" at which point it stopped. Movement detected again at 8.3" (approximately 2 cycles per second). At 9.5" the rod really started banging. However, vibration slowed drastically at 13.3". At 17.7" rod vibration is described as high frequency low amplitude, this type vibration continued until the rod reached ULS. At ULS the rod and IPT started vibrating together slightly. However, no optic indication of vibration was visible. Rod, IPT, and vibration tie is moving, however, vibration tie moves less (laterally) than rod.

45,000 gpm, 100 psi across all quadrants — NE IPT moving with a high frequency and low amplitude. No filler movement observed, INP movement not visible above locator tie, no optic indication in SE tube. Center IPT definitely moving in sub-pile room, however, no movement can be detected inside the vessel. SW Rod - movement first detected at 9.3" (observed with binoculars) motion described as random. No movement detectable with binoculars at 11.8". A small flutter detected at 14.5" (not constant) and flutter continued until rod reached 23.7" where vibration increased very slightly. At 27.2" a high frequency low amplitude vibration started and continued until rod reached ULS.

At ULS IPT is also moving. There is some question as to whether or not movement can be detected visually looking down the IPT from the top. SE Rod - definitely vibrating in baffle at LLS, vibration increased

at 5" and again at 8-3/4". At 10" safety rod and IPT vibrating at different frequencies (quite bad). IPT has higher frequency than safety rod. Safety rod amplitude decreased some at 13.4", however, IPT frequency remain about the same. Safety rod continued a high frequency low amplitude vibration until the rod reached 19.2" at which point the frequency decreased drastically. However, IPT vibration remained unchanged. IPT and upper locator tie definitely vibrating worse, at 22.6" vibration is random but of high frequency. Detected a flow stream stuck in safety rod at 27.2". Vibration can be detected through the optic at 27.2". Lowered SE safety rod to reduce the tension on the flow stream wire and strapped the rod.

Detected random movement of flow restrictors in B6 and B7 on west side of core. B7 movement is greater than B6. Some movement detected in B1, 2, 3, and 8 also.

S Rod withdrawal, small movement detected at 15.4", very slight movement detected by binoculars at 22", at which point it stopped.

Flow string stuck in SW safety rod at 22.5", rod strapped at this position.

Accelerometer traverse made at "top of locator tie clamp" and at "Core center line" in SW IPT with rod at 22.5" and in the SE IPT with the rod at 20.250".

N Rod - no movement detected in baffle with rod at approximately 3". Rod movement detected at 7.9" and continued until rod reached 11.5" where it stopped. However, IPT movement can be seen, but is random, erratic and mild. This motion continued until rod reached 14.1" where vibration decreased, no change in IPT detected. Rod vibration the same between 14.1" and 19-3/4" with vibration decreasing again at 27". Rod vibration increased slightly and held at this value until rod reached 35-1/4" at which point vibration nearly stopped. At ULS rod continued to move slowly.

General Comment — Once vibration had started it could be increased by inserting the rod.

E. Information Needed to Complete Test No. 1 Data Package

1. Measurements - Ref: (1) B&W Test Procedure
 - a. Four corner locator ties.

- b. SW locator tie brace.
 - c. Upper vibration tie measurements.
 - d. Center pressure tube.
 - e. Dummy fillers in NE, E, and W.
 - f. Safety rods as/item 6 of B&W Test Procedure pg. 2.
 - g. Tube measurements - External exited as/item 3 of ref.
2. Test No. 1
- a. Upper plenum pressure transducer recordings.
 - b. NW instrumentated safety rod readings.
 - c. Data recorded by Ebasco.
 - d. Drawings of NW instrument rod.
 - e. Pressure transducer reactor inlet line.

Test No. 2

3/23/67

A. Following Modifications Made in Addition to Those Outlined in Test No. 1.

1. Modified 4 regular flux trap fillers as per sketch of Roy Manoll of B&W and installed in SW Position. (Modified regular fillers installed in SW rod during Test No. 1.)
2. Removed flow tube from NE in-pile tube.
3. Transferred regular flux trap fillers and hafnium plates from S safety rod to SE safety rod. (Removed special flow restrictor flux trap fillers of Jack Liebenthals and left out of vessel for Test No. 2.)
4. Installed regular flux trap fillers and hafnium plates in S position.
5. Installed hafnium stops in N position. (Removed regular flux trap fillers.)
6. Flow strings installed around outside of core.
7. Static pressure probe installed neck shim housing in SE position between IPT and neck shim housing.
8. Two instrumented FE installed in position 16 and 20.
9. Accelerometers in SW and SE position located at top of flux trap baffle. Elevation 83'0".
10. Bullet nose adapter installed on C-IPT in sub-pile room.
11. NW rod at 36" and strapped.

B. Test Performed

1. Run rod drop on SW safety rod at full flow - 141 milliseconds.
2. Run rod drop time on SE safety rod at full flow - 150 milliseconds.
3. Run rod drop time on S safety rod at full flow - 168 milliseconds.
4. Observe flow strings and write general description of observation.
5. W/D N rod at full flow and record observations.
6. W/D SE rod at full flow and record observations.
7. W/D SW rod at full flow and record observations.
8. Record data from static pressure probe (full flow).

9. Record data from instrumented fuel elements (at full flow) - 25,000.
10. Take accelerometer reading in SE and SW positions during rod W/D plus any others required.
11. Record observations in sub-pile room.

Note: NE position and C position movement - sounds - etc. at full flow.

12. Take accelerometer readings in NE position (traverse) at full flow.
13. Torque SW regulating rod at full flow.

C. Reactor Top Observations - 3/23/67.

The following observations are those made by personnel stationed at the top head observing the reactor internals through the viewing ports through the use of six-power binoculars.

Full Flow 100 psi ΔP in each quadrant — The following is the status of all in-pile tubes, dummy and prime:

N - Steady	NW - Steady
NE - Very slight movement	W - Steady
E - Steady	C - Steady
SE - Steady	SW - Steady
S - Steady	

Dummy fillers in the W, E, and NE positions were all steady and no movement was observable.

All rods, except the NW rod at LLS - NW rod at ULS - no movement observable in any of the rods.

The center inpile tube is observed to have oscillation when viewed in the sub-pile room - movement is in the NW - SE plain.

NE Rod — The mechanical "bang", as reported on the 3/20/67 test, is no longer present in the NE position.

The flow strings in the SE, SW, and NE quadrants are caught between the gear box support beams (one string per quadrant being caught).

SE Rod — Pulling SE rod - random movement of rod observable at 3.5". Stopped rod for observation - dropped rod. Pulling the rod again - at 5" rod movement observed. Movement continued unchanged in frequency and amplitude until approximately 8" where amplitude and

frequency increased very slightly. At 13.2" rod motion decreased considerably. No loop movement observed.

Stopped rod at 15.2" where movement decreased to the point where detection of movement very difficult. However, ascertained as very, very slight oscillation. Movement continued at very slight to 20". At 20" increased slightly and remained constant until 24" where rod was stopped to establish a base line for visicorder readings in the sub-pile room.

Accelerometer readings from sub-pile room reported as .056" in NS plain, .040" in EW plain. Accelerometer carriage located at elevation 83' 0".

With light placed in sub-pile, movement in NE loop is observable; i. e. , rings of light can be seen from the top head.

All B-hole flow restrictors are vibrating rather severely. Pulling SE rod to 25" - where vibration increased slightly in amplitude. Movement in loop was detected. At 26" and still pulling movement remains the same. At 30" movement increases in frequency and amplitude. At 35" frequency increases, amplitude decreasing. At ULS rod and tube vibrating together. SE pressure tube tie moving slightly. All movement deemed to be synchronous. SE rod scrambled. Drop time for first 12", 150 milleseconds.

SW Rod — Withdrawing rod in SW position at 1.3" movement is observed and adjudged to be more severe than the movement observed in SE position - no loop motion observed. At 4.0" movement continues at same amplitude and frequency. No loop movement.

At 6" amplitude decreased slowly.

At 8.0" amplitude and frequency decreased.

At 9.0" amplitude and frequency started increasing.

At 11.0" loop started moving.

At 12.0" loop and rod amplitude and frequency increased.

At 12.6" to 12.7" loop and rod stopped moving.

At 13.7" rod pulsed (erratic-random - slow movement).

At 26.5" frequency increased.

At 30.0" started high frequency vibration.

At 33" (approximately) loop and rod started vibrating together.

SW rod scrambled 12" drop time 141 milliseconds.

S Rod — Very slight motion observable as rod is removed from flux trap baffle - at 9" rod motion continues very mild and random. At 12.2" rod movement stopped - at 14.7" random motion started again.

18.8" motion remains constant - rod stopped for observation. Motion observed - adjudged by observing parties to be very acceptable.

22.2" motion decreasing.

Holding at 24" to establish base line for visicorder.

View through transit for SW loop reveals movement in a NE/SW direction. Dot is 1/8" - as viewed, observers conclude dot is moving 1/2 of its diameter.

At 25" frequency and amplitude of S rod increased; however, movement still considered mild.

At ULS no movement is observable in the S loop or the locator tie. Very slight random motion of rod continues.

S rod scrambled. Scram time 168 milliseconds.

Sub-pile room reports mechanical sounds issuing from center position.

N Rod — Withdrawing N rod - very slight motion (mild and random) observed - at 3.5".

At 10.5" all motion stopped.

At 13.5" slight random motion started. Rod dropped accidentally at approximately 18". NE locator tie observed to be moving.

At 17" motion decreased in amplitude.

At 32" sub-pile room detects tube movement.

At 34" amplitude decreased.

At ULS rod motion (vibration) slight or mild and random.

At this point the observers left the reactor area to discuss forthcoming tests. Data accumulation from the dynamic probe, accelerometer readings in NE position, etc., continued and will be reported separately.

D. Sub-pile Room Observations

Flow 25,000 gpm — Accelerometers at elevation 83' in both SE and SW in-pile tubes. Small water leaks from snubber tube gland seal packing on E, NE, SW, and S positions. Original type packing installed in

all positions. No detectable movement (visual) on any tubes. No detectable noise (metal-to-metal contact) from any position.

30,000 gpm — No detectable movement (visual) on any tubes. No detectable noise (metal-to-metal contact) from any position.

35,000 gpm — No detectable movement (visual) on any tubes. No detectable noise (metal-to-metal contact) from any position.

40,000 gpm — Center tube has barely detectable movement (visual and measurement) - all other tubes no detectable movement. No detectable noise (metal-to-metal contact) from any position.

42,000 gpm — No detectable noise (metal-to-metal contact) from any position. Can feel vibration in prime tubes N, NE, SW, and SE - although not severe. Center tube shows vibration which is erratic - about every 30 seconds the tube will vibrate for 2 or 3 seconds, then stop. Vibration of center tube can't be measured.

45,000 gpm — No detectable noise (metal-to-metal contact) from any position. Can feel vibration in all prime tubes (N, NE, SW, and SE) - no detectable difference from vibration felt at 42,000 gpm. Center tube vibrating slowly but continuously with low amplitude - $\approx 1/16$ " movement on end of facility seal plug.

Raised SE rod to 24" - indications of acceleration of in-pile tube on brush recorder - display scope showing radial motion of in-pile tube (clockwise). Steady hard knocking noise detected by placing ear against end of SE in-pile tube in sub-pile room. Deflections as read on brush recorder show the following deflections: N-S 52 mils total, E-W 36 mils total.

Frequency of vibration is 7-8 cycles per second (cps). Took picture of SE tube motion as shown on display scope. SE tube displacement readings indicate a shuddering effect in that the displacement builds up to a peak amplitude then drops to a smaller amplitude - this cycle continuously repeats itself. From 25" to rod upper limit (36") - can detect no change in knocking noise level in sub-pile room - tube displacement readings did not change from 25" to 36". Scrammed SE rod - displacement readings (in-pile tube) decreased to: N-S 12 mils total, E-W 7 mils total.

Started withdrawing SW rod. At 5" - no change in tube displacement readings. At 9.7" - first detectable increase in tube displacements - this increase can be detected on brush recorder and by touching the tube; no detectable noise. At 11" - pounding noise detected as evidenced both by brush recorder and by listening at tube. To 12.7" then inserted rod to come back past the 11" position - during rod withdrawal the display scope indicates the in-pile tube has a clockwise radial motion. At 19" - displacements are N-S 24 mils total and E-W 20 mils total. At 23.6" - displacement readings erratic with spikes of 40 mils N-S and 25 mils E-W - knocking noise intermittent at 23.6". At 30" - scope indicates clockwise radial motion of in-pile tube - displacements are 90 mils both N-S and E-W - motion is now fairly consistent and regular with occasional stopping of vibration for approximately 1 second - knocking noise is steady and hard. At 36" - knocking severe - can see movement on in-pile tube snubber housing seal plug and can feel vibration by placing hand on bottom of in-pile tube - displacement is primarily NW to SE.

NE in-pile tube - no audible knocking in this position, noise heard during Test No. 1 must have been due to flow tube - in-pile tube shows shuddering type of vibration as noted above.

Note: SE tube appears more stable than NE tube
(visual observation - with SE safety rod in the seat).

Checked center dummy tube - easily detectable knocking noise with a frequency of 2 or 3 cps - knocking is not hard but very regular.

No detectable vibration differences in sub-pile room during withdrawal of south safety rod.

Withdrew north safety rod - approximately 14" noticed intermittent vibration of in-pile tube of low amplitude and frequency. No detectable knocking noise.

Moved accelerometer from SW in-pile tube to NE in-pile tube.

Note: With sub-pile vibration tie clamps removed from NE and SW tubes there was no detectable increase in movement of the bottom ends of the in-pile tubes over that observed with the tie clamps installed.

Completed vertical tranverse in NE tube as follows:

1. Accelerometer at bottom of locator tie-displacement N-S 20 mils, E-W 25 mils, frequency 7 cps.
2. Accelerometer at top of flux trap baffle - elevation 83'-0" displacement N-S 70 mils, E-W 60 mils, frequency 8 cps.
3. Accelerometer at core L - elevation 82'-0" displacement N-S 70 mils, E-W 85 mils, frequency 8 cps.

Note: Occasional oscillations to 110 mils N-S and 75 mils E-W.

E. Information Needed to Complete Test No. 2 Data Package

1. Upper plenum pressure transducer readings.
2. Static pressure probe readings from SE position.
3. F.E. readings from positions #16 and 20 (25,000 and full flow).
4. Drawings of instrumented fuel element.
5. Accelerometer readings from SW and SE positions at elevation 83".
6. Accelerometer traverse in NE position.
7. Flow string diagrams and observations.
8. NW safety rod readings.
9. Torque readings on SW regulating rod taken in rod access room.
10. Sketches per Roy Manoll B&W flux trap fillers.
11. Pressure transducer reactor inlet line.

F. S SW-4R Torque Readings

<u>Console reading</u>	<u>Torque in inch #</u>
48"	28
32.2	27
25.6	30
~22	SW SR dropped
17.8	28
12.6	32
8.0	31
3.7	>80

Test No. 3

3/25/67

A. The following modifications were made prior to Test No. 3:

1. Move instrumented element from position 20 to position 40. (The second instrumented element left in position 16.)
2. Install N₂ injection system in 4 positions in the tank at top of thermal shield. S-SE-SW and N.
3. Modify fillers presently located in SW rod (fillers modified previously by Manoll) as per Jack Liebenthal's sketch and instructions. Fillers to be reinstalled in SW position.
4. Remove Merle Griebenow static probe from NE position.
5. Install one pressure transducer in NW position and one in the SE position as directed by Merle Griebenow. (Transducer mounted on SE safety rod 2-1/2" above top of outer shim cylinder gear box) (transducer mounted on NW safety rod 3-1/2" above flux trap baffle.)
6. Leave instrumented rod in NW position at 36 inches and strap.
7. Move SE rod to 36 inches and strap.
8. Install shims designed by McPherson on rod in SE position.

B. Tests Performed

1. Determine flow pattern by judicious use (adjustment) of N₂ gas injection.

Caution: Be careful of injecting too much. After each injection degas for 30 minutes before injecting again. Monitor the PCS pumps closely for unusual noises.

2. W/D SW rod at full flow and record observation.
3. Record FE 16 and 40 data at 25,000 and full flow conditions.
4. Record pressure transducer readings on NW and SE rods at 25,000 and full flow conditions.
5. Record SE rod and tube observations at full flow.

Note: Have all rods at ULS for item 3 and 4 when readings are recorded.

6. Take accelerometer readings in SE and SW positions at full flow with accelerometers located at 83 feet 0 inches.

7. N and S rod W/D and record observations.

8. Run drop time on SW safety rod at full flow 140 milliseconds.

C. Reactor Top Observations

The following observations are those made by personnel stationed at the top head observing the reactor internals through the viewing ports through the use of six-power binoculars.

Quadrant, P = 90 psig — SE Rod and tube vibrating loop tie vibrating NE - inpile tube vibrating.

Quadrant, P = 100 psi, flow 44,500 gpm — SE Rod, Tube and pressure tube locator tie vibrating rather severely - motion is in SW-NE plane.

NE loop (tube) vibrating with high frequency low amplitude.

N, E, S, SW, W, C, and NW - All steady.

SW Rod W/D @ LLS rod is moving in baffle random motion.

@ 8 inches amplitude decreased.

@ 9.5" to 10" tube started moving.

@ 12.5" motion stopped.

@ 14" motion started again mild, random - tube high frequency low amplitude - tube seems to pulse.

@ 23" tube motion decreased.

@ 25.5" rod higher frequency low amplitude.

@ 29" rod frequency increased.

@ 33" rod and tube motion same (together).

@ ULS rod and tube motion severe.

This is the first time tube motion has been observed above the pressure tube locator tie - cannot observe any motion of SW tie.

Optic movement approximately 1 dot (dot = 1/8")

S Rod W/D very very light, mild, random type motion observed to ULS.

Viewers concur rod and tube motion in south half is more than observed in previous tests, however, degree of increase cannot be determined.

N Rod W/D

@ LLS no movement.

A 2" slight, mild, random motion rod dropped from ~7" all rods dropped.

W/D N Rod

@ 10" movement decreased.

@ ~12" motion stopped.

@ 14" very mild erratic movement.

@ ~15.5 frequency increased very slightly.

@ 18.2" motion stopped momentarily (pause) and then continued very mild random.

@ ~26.5" frequency increased very slightly.

@ ~32.5" motion decreased in frequency and amplitude.

@ ~35 amplitude decreased considerably.

@ ULS - Rod motion very mild.

- Tube motion is observable but very slight and sporadic.

Note: Motion throughout the core is considered acceptable with exception of SW and SE rod tube and locator ties.

D. Sub-pile Room Observations - 3/25/67

Accelerometers at elevation 83'-0" in both SW and SE in-pile tubes. SE rod fully withdrawn to 36" and shims inserted between buttons on the hafnium sections and the in-pile tube splines.

Full flow - Center dummy tube vibration same as that observed during Test No. 2, i.e. with a frequency of 2-3 cps, amplitude at bottom of facility seal plug on end of tube if less than 1/16" knocking detected is not hard. SE Tube - Displacement N-S 120 mils total; E-W 60 mils total, frequency 7 cps.

Knocking noise on SE tube is intermittent and not as loud as that observed during Test No. 2. SW tube - safety rod at upper limit (36") loud knocking noise detected. Loud knocking started and deflections got worse when started engagement with in-pile tube splines. Now, with both SE and SW rods at 36" readings are as follows: SE N-S 90 mils total; E-W 90 mils total, frequency 7-1/2 cps. SW N-S 70 mils total; E-W 180 mils total, frequency 8 cps.

With SE rod at 36" and SW rod in seat readings are as follows:
SE N-S 90 mils total; E-W 80 mils total, frequency 7-1/2 cps. SW N-S
28 mils total; E-W 14 mils total, frequency 7 cps.

Note: Radial tube motion observed on both SE
and SW tubes in all combinations of rod
positions.

No detectable noise from any of the other tube positions, i. e. E,
S, W, NW, NE and N.

Pressure transducers installed on SE safety rod (#104) and between
inpile tube and upper part of neck shim housing on NW tube (#103). Vent
line plugged on NW transducer (#103) so can't obtain reading. Pressure
transducer on SE safety rod (#104) gives the following readings: Pressure
fluctuation of 2 psi, frequency 7-8 cps.

E. Gas Injection Observations - 3/25/67

Full flow — With injection at either of the 3 injection tubes on south,
flow appears to be upward along reactor vessel wall with a dead layer
near the upper locator tie plate.

With injection on north of reactor, flow appears to be generally
south across the neck shim housing and tubes at an elevation generally
below neck shim to IPT locator tie.

25,000 gpm — Gas injection at north side does not show strong
cross-flow N-S across tank. Flow is more orderly near SE SR and
with little if any horizontal component. With south gas injection bubbles
rise uniformly toward top of Reactor Vessel before dispersing traveling
generally northward near the upper locator tie.

F. Information needed to complete Test No. 3 Data Package

1. Upper plenum transducer readings.
2. F.E. 16 and 40 data at 25,000 and full flow.
3. Pressure transducer on NW and SE lobes at 25,000 and full flow.
4. N.W. safety rod readings.
5. Accelerometer readings in SW and SE at elevation 83'-0".
6. Sketches flux trap filler as per Jack Liebenthal.
7. Sketch of solid shims by McPherson.
8. Pressure transducer reactor inlet line.

G. Observations and Conclusions Drawn From Results of Tests
No. 1 Through No. 3 by Reactor Top Observers
(D. P. Halls and J. A. James)

NE In-pile Tube — During Test No. 1 the flowtube was in the in-pile tube and as reported there was an audible banging reported in the sub-pile room. Test No. 2 the flow tube was removed and sub-pile room reported the audible banging was no longer present. A view from the top head revealed movement in the NE tube. Test No. 3 movement was still observable in the NE in-pile tube. It is concluded that the banging heard during Test No. 1 was definitely attributable to the flow tube based upon the lack of such banging during test No. 2 or 3. Our conclusion at this point; motion is observable in the NE tube—however, such motion is acceptable.

N Position — The difference in the N position between Tests No. 1 and Tests 2 and 3 is that during Test No. 1 standard aluminum filler plates were in the safety rod whereas in tests 2 and 3 hafnium stops were inserted in the safety rod. Although there are slight differences reported in the rod motion at different elevations between Tests 1 and 2 and 3 these motions are described as being very slight, sporadic, random, etc. and it is impossible to establish any degree of difference—therefore, it is concluded that there may be a difference between the rods action with the filler and with hafnium stop, but in both instances the motion is considered completely acceptable.

NW Position — Throughout Tests No. 1, 2, and 3 the hafnium was removed from the NW rod and in its place the prototype hafnium simulators were installed. These prototype hafnium simulators have been modified to allow the incorporation of pressure taps.

During Test No. 1 the rod was strapped at 32" with mechanical stops incorporated into the simulated hafnium fillers to fill the gap between the in-pile tube and the ID of the hafnium stop top pieces. During Tests 2 and 3 the rod was strapped at the upper limit switch i.e. 36" withdrawn. During all three tests data was accumulated and will be recorded separately.

W Position — Throughout all testing the W position had the gas loop dummy filler consisting of the in-pile dummy section and in-pile dummy

loop section throughout all testing no movement was observed in the W position.

Center Position — During Test No. 1 the center position was occupied by a dummy loop with the modifications to the upper spline area no movement was observable from the top head in the center position-however movement was observable in the sub-pile room on the end of the center in-pile dummy. For Test No. 2 the bullet nose adapter extension was installed to the center in-pile dummy and it is concluded that the motion was comparable in both tests. Based on observations to date it is concluded that when the center in-pile tube is connected to the out of pile sections that the movement will be completely acceptable.

E Position — Throughout all tests the E position was occupied by a dummy in-pile tube in conjunction with a dummy flux trap filler and without exception no movement was detected in any test.

SE Position — In Test No. 1 specially designed flow restrictors were installed in place of the flux trap fillers in the SE rod. During Test No. 2 the regular aluminum flux trap fillers were installed-these fillers remained during Test No. 3. Based on the observations made during Tests 1, 2, and 3 it is concluded that the specially designed and installed flow restrictors present during Test 1 had a very detrimental effect as far as vibration is concerned as compared to the regular flux trap fillers installed during Test 2 and 3.

It must be noted that during Test 2 the SE rod was operated in its normal mode-however in Test No. 3 the rod was withdrawn to the upper limit switch and strapped there. At the 36" position the hydraulic snubbers in the hafnium mounts were shimmed solid against the splines of the NR loop-therefore no relative movement was permitted between the loop splines and the safety rod. Observations during Test No. 3 revealed relatively the same vibration, however, the vibration is now seen to be transmitted moreso into the tube evidenced by the increase in vibration of the neck shim locator ties and the observation of loop movement above the neck shim locator ties. Based upon this observation it is definitely concluded that the solid shimming of the hydraulic snubbers has a pronounced detrimental effect on the vibration of the pressure tube locator ties and pressure tube per se.

S Position — The only differences between Test No. 1 and Tests 2 and 3 in the S position is that of changing standard flux trap fillers—that is in both sets of tests standard fillers were used, however, a different set was in Test 1 than that employed in Test 2 and 3. In all tests the very slight motion reported in the rod is adjudged by observing parties to be highly acceptable and the only conclusion which can be drawn from this particular position is that the changing of standard components has no effect on rod motion.

SW Position — During Test No. 1 the SW position was fitted with regular flux trap fillers in the safety rod; in Test No. 2 the flux trap fillers were modified as per the attached sketch by R. E. Manoll; in Test No. 3 the fillers were further modified as per the attached sketch by Jack Liebenthal. Based upon the observations made during the three tests it is concluded that all changes made to date have been detrimental to the vibration in this position and this will be further substantiated by Test No. 4 wherein standard flux trap fillers will be reinstalled.

Test No. 4

3/28/67

A. The following modifications were made prior to Test No. 4:

1. SW locator tie temporary restraint removed.
2. Four foot core reflector tank extension installed.
3. Modified flux trap fillers (as per Jack Liebenthal's sketch) removed and regular flux trap fillers installed in SW position.
4. NW pressure transducer repaired and reinstalled. Instrumented safety rod strapped at 36".
5. McPherson shims removed from SE rod and special shims designed by R. A. Clemons installed. Rod strapped at 36".
6. Installed regular fillers and hafnium plates in N safety rod.
7. Relocated nitrogen injection tubes. Two tubes located on top of the outer shim cylinder support beams in the N and S axis. One tube located approximately 11" above the elevation of the thermal shields on the N vessel wall. One tube each located at the top of the tank extension on the E, W, and S.
8. A 1/4" pressure tube installed between safety rod and in-pile tube in NW position. Bottom end located at elevation of holes in snubber tube.
9. Removed flow strings

B. Tests Performed

1. Make accelerometer traverse in NE tube at full flow.
2. Make accelerometer readings in SE and SW positions at full flow with accelerometers located at 83'-0".
3. Record fuel element 16 and 40 data at full flow.
4. Record pressure readings from NW pressure tap at full flow.
5. Determine flow pattern by judicious use (adjustment) of nitrogen gas injection.

Note: After each gas injection degas approximately 30 minutes before injecting gas again. Also monitor the primary coolant system pumps closely during this period for any unusual noises.

6. Withdraw SW rod at full flow and record observations.
7. Record pressure transducer readings on NW and SE safety rods at full flow.
8. Record SE rod and tube observations at full flow.
9. Withdraw S rod at full flow and record observations.
10. Withdraw N rod at full flow and record observations.

Note: Have all rods at ULS for items 3 and 7 when readings are recorded.

11. Run drop time on S safety rod at full flow.
12. Run drop time on SW safety rod at full flow.
13. Observe B-hole flow restrictors and record observations of vibration.
14. Observe H-hole flow restrictors and record observations.
15. Run drop time on N safety rod at full flow.

C. Reactor Top Observations - 3/28/67

The following observations are those made by personnel stationed at the top head observing the reactor internals through the viewing ports using 6X binoculars.

Flow increased in 1,000 gpm increments to a total of 25,000 gpm flow and the following observations noted:

All B-hole restrictors were observed to be vibrating.

No H-hole flow restrictor movement detected.

South gas inlet line at top of tank extension - bubbles go almost directly downward - a very small amount reaches the fuel element channel but most seem to disappear into the SW area between instrument thimbles 6 and 9.

All loops calm no motion detected at 25,000 gpm.

N gas inlet line at vessel wall - bubbles generally drift upward in a lazy manner and generally cover the entire tank with approximately 90% going north and west of tank.

E gas inlet line at top of tank extension - bubbles generally downward between outer shim cylinder gear box and tank extension wall with occasional bursts covering gear box and generally spilling over into east outer flux trap baffle and northeast baffle.

West gas inlet at top of tank extension - same comment as for east gas line above.

North gas inlet line located at the top of the outer shim cylinder gear box - bubbles switch, going from north directly under gear box to south direction directly into fuel elements. No rise in bubbles. Very fast switch.

South gas inlet line located at top of outer shim cylinder gear box - 99% of bubbles go directly south into I-holes and gear box beam between tank extension and gear box.

Flow increased from 25,000 gpm to 37,900 gpm in 1,000 gpm increments while closely observing the reactor internals and the tank extension. At 37,900 gpm both the north and south sides of the tank extension were observed to be vibrating or fluttering a very small amount. Quadrant ΔP at this time was 75 psi. Vibration adjudged serious enough that further flow increases were abandoned and the following observations were recorded:

37,900 gpm, 75 psi quadrant ΔP , Reactor ΔP 85.5 psi —

NE - slight movement (mild)	N - steady
E - steady	SW - steady
SE - steady (some movement observed by John James, however, very, very, mild)	W - steady
	NW - steady
N - steady	S - steady
	C - steady

No movement detected in H-hole restrictors at 37,900 gpm.

Gas Injection — North gas inlet line located at vessel wall - gas bubbles go straight up then south under vibration tie assembly. Some go directly down through the core and the rest diffuse throughout the tank.

East gas line located at top of tank extension - as a general rule the gas bubbles flow directly down toward the I-holes.

South gas inlet at top of tank extension - as a general rule the gas bubbles flow directly down toward the I-holes.

West gas inlet at top of tank extension - as a general rule the gas bubbles go directly down toward the I-holes.

North gas inlet line located on the top of the outer shim cylinder beams - approximately 50% of the bubbles are observed going down the I-holes. Direction switches occasionally to the south with the major portion of the other 50% going down the fuel element channels.

South gas inlet line located at the top of the outer shim cylinder beam - approximately 75% of the bubbles are observed going into the gear box beam itself with the rest switching and going down into the I-holes.

Withdraw southwest rod - no movement observed in baffle at LLS. At 3" very slight motion observed. At 4" motion detected easily - random - oscillating. At 6-1/2 to 7" motion decreased. At 9" motion increased in frequency and amplitude. At 11" motion stopped. At 13.5" motion started again. At 15" motion decreased slightly. At 18" motion increased (amplitude), pulsing. At 21" motion considered random, low frequency, medium amplitude. At 33" increased in frequency. At 35" motion decreased considerably. At ULS rod motion mild - inpile tube steady.

D. Sub-Pile Room Observations

Instrument conditions for this test are as follows:

1. Pressure transducers installed on SE safety rod (#104); (#103) in NW position between safety rod and neck shim housing; and (#CA-29) on end of impulse line that is inserted in NW position to measure pressure fluctuations in area of exit flow holes in outer snubber tube.

2. Brush recorder inputs are:

N-S and E-W displacements for SE inpile tube.

N-S and E-W displacements for SW inpile tube.

N-S acceleration for SW inpile tube.

Pressure transducers #103, 104, and CA-29.

24,000 gpm — No detectable vibration (visual) in any tube position.

No detectable noise in any tube position.

Displacements:

SE Tube

N-S 8 mils total

E-W 4 mils total

frequency 8 cps

SW Tube

N-S 5 mils total
E-W 8 mils total
frequency 8 cps

38,000 gpm —

Displacements:

SE Tube

N-S 36 mils total
E-W 24 mils total
frequency 8 cps

SW Tube

N-S 16 mils total
E-W 16 mils total
frequency 8 cps

Transducers:

Developed leak in NW transducer and lost reading at 1615.

Recorded readings from transducer (104), SE position, and gave section of chart with these readings to Merle Griebenow.

Barely discernible movement in center tube - movement is erratic with no detectable knocking noise.

No detectable movement in any other positions.

Barely discernible, erratic noise in NE position - can't really tell if this is a knocking noise.

No detectable noise in the remaining positions; NW, N, W, E, SW, S, and SE.

Raising SW Safety Rod:

Detectable increase in displacement when rod reached 14". Slight knocking noise detected when rod reached 32" with corresponding detectable increase in tube displacements, both N-S and E-W. At 36" displacements are: N-S 40 mils total, E-W 36 mils total, frequency 7-1/2 cps.

Picture taken of SE and SW rod motions as observed on scope. Very slight and erratic knocking noise in SW with rod at 36".

Note: SE transducer showing 7-1/2 cps frequency and peak to peak pressure fluctuation of 0.87 psi. SE tube displacements are: N-S 30 mils total, E-W 22 mils total, frequency 7-1/2 cps.

Reactor vessel upper plenum pressure transducer shows fairly strong frequency of 2 cps with detectable intermingling pressure fluctuation frequency of approximately 5 cps of less amplitude - total peak-to-peak pressure fluctuation of approximately 0.2 psi.

Stopped brush recorder at 1715.

E. Information Needed to Complete Test No. 4 Data Package

1. Upper plenum transducer readings.
2. FE-16 and 40 data at 37,900 gpm flow.
3. Pressure transducer readings on NW and SE lobes at 37,900 gpm flow.
4. NW instrumented safety rod readings.
5. Accelerometer readings in SW and SE at elevation 83'-0".
6. Pressure transducer readings of reactor inlet line.

Test No. 4A

3/30/67

The following are the observations made by observers (Halls and James) stationed at the top head viewing the internals with 6X binoculars:

21,000 gpm — "B" hole baskets 7, 8, 4, and 5 moving with random oscillating vibration.

25,000 gpm — All "B" baskets moving 1 through 8.

40,000 gpm, ΔP 80 psi — Southeast rod motion can be detected through the use of the 6X binoculars. Motion is very slight and high frequency random and erratic.

44,000 gpm, Quadrant ΔP 93.5 psi — SE rod motion can be detected with the naked eye. Although considered very slight in amplitude, motion is high frequency.

Positions

NE Loop	Very slight motion
N Loop	Steady
NW Loop	"
W Loop	"
S Loop	"
SW Loop	"
C Loop	"
H Holes	"

45,800 gpm, Quadrant ΔP 100 psi — SE rod tube and locator tie shaking together. Motion of the loop is observable above the locator tie.

Nitrogen Gas Injection

North Wall — Bubbles come up with good dispersion traveling south to neck shim housing and drop directly into fuel element and flux trap baffles.

Southeast Safety Rod Inject — Bubbles sweep from view in port No. 4 over to fuel element No. 20. From port No. 3 view, bubbles sweep to element No. 15. Bubbles travel downward with dispersion only as noted above.

South Inside Tank Injection — Views from both ports 3 and 4 showed bubbles generally going down to I holes. Approximately 75% follow the path to the I holes sweeping as far as thimble 6 to the east and thimble 8 to the west. Approximately 25% disperse in random fluttering motion to flux trap baffles and fuel elements in south side of port.

South Rod Inject at Top of Locator Tie — Very definite downward motion, however, sweeping around to tube (similar to oscillating sprinkler) covering entire flux trap baffle and surrounding fuel elements.

North Rod Inject at Top of Locator Tie — Basically the same bubble pattern characteristic for north position as that described for south position.

Southwest Inject at Top of Four Foot Temporary Tank — Bubble dispersion sweeping from instrument thimble 9 to thimble 7. Bubbles generally going down into I holes and sweeping into southwest flux trap baffle occasionally.

Sub-pile room reports loud banging in southeast position. Banging is mechanical in sound. Also northeast position, however much milder and more random. Center position also has mechanical banging.

Southwest Safety Rod —

At 5-1/2" movement detected - random.

At 10" tube motion observed.

At 10.5 to 10.75" rod frequency increased.

At 12" rod motion stopped.

At 11" banging reported in sub-pile room.

At 13.5" rod motion detected - random pulsing motion - tube motion high frequency low amplitude.

At 17.5" rod gave shuddering type motion, i. e., pulsing - random motion.

At 25" frequency increased - tube frequency also increased.

At 28.5" locator tie motion observed.

At 33" frequency increased.

At 35" frequency decreased somewhat.

At ULS rod and tube vibrate together - locator tie also vibrates.

Southwest rod

scrammed - 142 msec
release - 10 msec

'H' holes - no motion observed.

North Rod —

At LLS no motion detected.

At 2.5" rod motion detected.

At 8.5" increase in frequency and amplitude.

At 10.5" rod motion stopped.

At 14" rod motion detected - very mild.

At 16.5 to 17" motion decreased somewhat - mild motion - relatively calm - occasional movement only.

At 23" frequency and amplitude increased.

At 24" motion decreased.

At 27.5" rod motion increased a small amount - motion mild - random.

At 32" motion decreased in frequency and amplitude.

At ULS rod and tube moving - rod at high frequency low amplitude.

Sub-pile room reports tube movement considerably greater this time over previous tests - vibration decreased with rod at LLS.

North Safety Rod

scrammed - 162 msec
release - 15 msec

Northeast locator tie observed to be moving.

Note: Northeast tube is moving more severely than seen on previous tests. Degree of increase indeterminate.

H-hole flow restrictor tops were dyed (1/2 of each top) with Prussian blue. Even though no motion is visible, motion is known to occur gradually by the relative location of these dyed tops. Motion has to be occurring very slowly in a circular direction. Lighting and visual access to the H-hole area is very limited but close observation revealed that the H-hole flow restrictor located directly behind the east IPT is vibrating with an extremely high frequency random motion; however, no circular motion can be detected.

South Rod —

At LLS no motion.

At ~2.75" mild random motion.

At 7.5" increase slight frequency and amplitude.

At 9.0" amplitude increase.

At 10.5" motion stopped.

At 13" small random motion low frequency.

At 15" amplitude increase.

At 16" amplitude and frequency dramatic increase but still mild.

At 19" amplitude decreased.

At 21" very hard to detect motion - must study to see motion - hold at 24".

At 25.5" frequency and amplitude increase slight.

At 35" decrease in amplitude and frequency (dramatic).

At ULS very slight motion is observed if studied with 6X binoculars.

(1) Release Time - 34 msec
Scram Time - 162 msec

(2) Release Time - 34 msec
Scram Time - 161 msec

Note: Observed in Sub-Pile Room

Noise heard in southeast position (tube)
with south rod withdrawn decreased
noticeably when south rod scrambled!
Noise remained much quieter for period
of approximately two seconds and then
picked up again.

Test No. 5

3-31-67

The following are the observations made by the observers at the reactor top head. Observations were made through ports 1, 2, and 3 (N, NE, and SW). All observations were made with the aid of 6X binoculars:

At 1610 and 12,000 gpm — N rod pulled to 8" to observe better!

22,000 gpm — N rod is moving slightly.

W/D N rod —

Rod motion slight and random until ~11.5" where very definite movement of rod in N to S direction - motion steady. (Rod moved to south and is staying in new position.)

Inserting N rod —

At 10.7 rod moved off south position and continued slight motion in circular (CCW) direction as viewed from north (port 1). (Rod held at 10.7.) Stopped rod at 8.5".

W/D N rod —

Steady to 19" then rod inserted. Motion observed by two different individuals at same time at ~11" (i.e.). Rod moved sharply to north and thereafter continued circular motion as before.

35,000 gpm and Quad Δp 61 psi —

N - at 8" motion slight (generally NE - SW direction)

NW - Steady

NE - Steady

E - Steady

C - Steady

SE - Steady

S - Steady

SW - Steady

W - Cannot observe below tie.

H Holes - Steady

B Holes - All observable are moving. Movement more on N&S quadrants (1 and 8, 4 and 5) than E&W quadrants 2 and 3, 6 and 7.

40,000 gpm and Δp 78 psi — SE rod motion very slight. High frequency low amplitude. N-SR moving with low frequency.

45,500 gpm and Δp = 100 psi —

NW - Steady

N - SR slight random motion at 8"

NE - Loop motion high frequency - tie also moving

E - Steady

SE - Rod and tube moving - high frequency considered less than test 4A vibration

S - Steady

SW - Steady

W - Steady

H Holes - Steady

N₂ Inject

On instrument thimble 6 - very dramatic vortex as bubbles stream from line and seems to be from Inst. thimble going toward SE loop bubbles shift E&W - go as far as F.E. 20.

SE as reported from sub-pile room - Accelerometer readings less than test 4A. However, mechanical banging more than 4A.

W/D/N rod from 8" —

Stopped pull at 10.75 due to detection of loop movement. Rod movement occasional strong erratic pulse. Rod motion stopped as rod pulling was beginning - tube motion picked up considerably - high frequency in tube with rod very steady at 13.0".

Insert N rod from 13" —

13 → 12.5 No change

At 11.0 → 10.5 rod starts moving tube slows down

W/D Re-run 10.5 to 11 same characteristic

Point established between 10.5 and 11" at which rod stops and tube motion increases

W/D —

At 18.9 rod steady but tube motion has noticeable reduction in frequency and amplitude.

At ~30.5 rod moves in pulsing random - slight manner.

At 34" rod motion started increasing in frequency but amplitude light.

At ULS rod moves at higher frequency but still low amplitude - rod motion rated as mild.

Insert N Rod —

Tube motion steady until typical 10.5 - 11" rod movement steady until ~8" when motion of rod subsides.

At ~4" motion increased slightly - ran out of light.

Note: Microphone in SE position gave peak noise at elev. 83'-0" $\pm$ 1'-0".

Test No. 6

4-1-67

The following are the observations made by the observers at the reactor top head. Observations were made through ports 1, 2, and 3 (N, NE, and SW). All observations were made with the aid of 6X binoculars:

Q = 20,000 gpm and Δp 21 —

NW - Steady

N - Steady

NE - Steady

E - Steady

C - Steady

W - Steady

SW - Steady

S - Steady

SE - Steady

"B" Baskets - 1, 2, 3, 4, 5, 6, 7, 8 - Moving; 1, 8 and 4, 5
move more than those on E-W

"H" Holes - Restrictor directly behind north locator tie vibrating with very high frequency

41,000 gpm —

NE - Tube moving - low amplitude

NW - Rod moving in seat

N - Rod moving in seat

S - Rod moving in seat

44,400 and 100 psi Δp , Reactor Control Room — (No change difference in instruments only)

NW - Tube steady - rod moving in seat
N - Tube steady - rod moving in seat } Same flow

45,800 and 100 psi Δp , Process Water Control Room — (No change difference in instruments only)

NE - Tube moving - more than 41,000
E - Tube steady
C - Tube steady
W - Tube steady
SW - Tube steady - can't see rod
S - Tube steady - rod moving in seat
SE - Tube steady - Steady to very slight
movement occasionally } Same flow

Note: South rod and north rod move less than
NW rod.

Estimated that NW rod moves at ~ twice
frequency of N rod. N moves more than
south.

Pulling SW Rod —

At 3.5" movement observed, low frequency and amplitude.
At 6" frequency increases.
At 11" movement stopped.
At 13" started to vibrate in pulsing manner.
At 16" movement-amplitude increase frequency decrease.
At 19" stopped rod for observation - rod movement considered pulsing medium amplitude high frequency.
Sub-pile room reports 8 cps.
At 20.5" amplitude increases.
At 23.5" high frequency pulse motion, low amplitude. Tube motion detected.
At 27.25" rod stopped for observation, rod tube and locator tie vibrating rather violently.
Viewers conclude vibration is as bad if not worse than any previously seen in SW position.
At ULS rod, tube, and tie vibrating.
N₂ Inject at SE position right above rod on splines acts as sprinkler going all around tube.
SW view thru transit > 1 dot.
Scram; when rod dropped-dot steady.

W/D N Rod —

At LLS motion random - mild.
At 4" motion increased.
At 8" motion reduced considerably.
At 10" tube motion observed.
At 11.5" rod motion stopped and tube motion decreased.
At 35" very slight rod motion.
At ULS rod and tube steady.
N tube motion throughout withdrawal much less than that on Test No. 5.

W/D NW Rod —

At LLS random - mild motion.
At 3.5" rod motion increased in amplitude.
At 11" rod motion stopped.

At 12.5" rod leaned toward tube in SE direction. lowered to 10.250" where motion was detected.

At 11" rod motion stopped.

At 13.5" rod motion started - medium amplitude low frequency.

At 18" frequency increased.

At 23.5" tube motion detected.

At 31" rod frequency increased - random amplitude decreased.

At 35" frequency and amplitude really decreased.

At ULS motion acceptable.

N₂ Injection

North on vessel — Bubbles diffuse and cover entire core region - bubbles then flow directly down through core.

SE rod low on rod — Acts as sprinkler.

SW on Inst. Thimble No. 8 — Very dramatic vortex pattern off of thimble. Bubbles sweep from west position to SW flux trap baffle - single vane of bubbles.

SW rod just below locator tie — Sprinkler effect seems to cover entire lobe.

North rod at locator tie — Bubbles oscillate E-W with occasional burst to N.

South rod at locator tie — Bubbles go directly down acting like sprinkler covering all around south flux trap baffle.

Pulling SW rod to obtain microphone readings.

Small increase in microphone readings at 78, 83, 85.

Test No. 7

4-4-67

A. The following changes were made prior to test No. 7:

1. Remove 4 foot tank extension.
2. Installed a flow restrictor on top of flux trap filler in NE position (See sketch by Jack Liebenthal attached).
3. Installed a 3 foot section of pipe on center inpile tube in sub-pile room. (See attached sketch.)
4. Removed flow splitter from SW position.
5. Changed pressure transducer locations as follows: two each located on SE inpile tube approximately 2 inches above the top of the safety rod when rod is at ULS. Located on outside between inpile tube and instrument thimbles. Both sensing probes pointing directly at instrument thimble No. 6.
6. Installed flow restrictor on SW inpile tube at top of flux trap baffle and strapped rod. See sketch by Jack Liebenthal.
7. Relocated instrumented fuel elements in position 40 and 16 to positions 5 and 26 respectively.
8. Nitrogen gas injection lines located as follows: North injection lines 11" above elevation of inlet flow baffle located on T-bar slot. SW line located on instrument thimble No. 8 one located on S safety rod at locator tie top. One on SW rod at top of locator tie - one at top of north rod and one located at top of locator tie on SE rod.

B. Tests Performed

1. Withdraw NW rod at full flow and record observations.
2. Run drop time on NW safety rod at full flow.
3. Observe NE rod at full flow and record observations.
4. Withdraw SW rod from 18" to ULS at full flow and record observations.
5. Withdraw N rod at full flow and record observations.
6. Run drop time on N safety rod at full flow.
7. Record observations of center inpile tube and 3 foot extension in sub-pile room.
8. Withdraw S rod at full flow and record observations.

9. Run drop time on S rod at full flow.
10. Record N₂ gas injection observations.
11. Record observations of SE rod at full flow.
12. Record instrumented fuel element reachings in position 5, 26, and 30.
13. Record reactor inlet pressure transducer readings at full flow.
14. Record upper plenum pressure transducer readings at full flow.
15. Record accelerometer readings in SE and SW inpile tubes at full flow at elevation 83'-0".
16. Record microphone output of selected inpile tubes.
17. Record pressure transducer reading on SE inpile tube.
18. Lower SE rod off splines at full flow and record observations.
19. Make traverse in NE inpile tube.

C. Reactor Top Observations

The following are the observations made by the observers at the reactor top head. Observations were made through ports 2, 3, and 4 (NE, SE, SW). All observations were made with the aid of 6X binoculars.

Note: East tank light directly over core out, also east light mounted on vessel T-bar out. Therefore, tank lighting on North and East side of vessel very poor for this test.

26,500 gpm — Motion observed in SW Rod at ULS.

Lowering SW Rod

At 35 amplitude increases.

At ~30 frequency and amplitude decrease.

At ~18 random motion with high amplitude.

Tube vibration from sub-pile room

SW at 70 mills N-S & E-W

SE at 8 mills N-S & 4 E-W

Note: Radial clearance on clamp, SW-.080, SE-.030. SW clamp has lead in cut on top and bottom.

General observation at 18" on SW tube, Rod, and ties are vibrating worse than any previous test at this flow.

NE Tube - No movement.

Withdraw SW Rod - motion violent over entire range 18" to ULS.

From sub-pile room at ULS

N-S 90 mills E-W 75 mills

Motion is E-W as confirmed through transit.

Flow increased stepwise to 35,000 gpm, $\Delta P = 62$ psi — SW Rod

At ULS - motion violent, more motion between rod and inpile tube than ever observed before.

From sub-pile room

110 NS 100 E-W

Very loud rattling.

NE - tube - no movement

NW tube - Steady

Rod - Steady LLS

N tube - Steady

Rod - Steady LLS

NE tube - Steady

E tube - Steady

C tube - Steady

W tube - Steady

SW tube - moving rather violently-rod same but at different frequency and amplitude

S tube - Steady

Rod - Steady LLS

SE tube - Steady

Rod - Steady LLS

Dropping flow SW rod off ULS ~33" Rod vibrated at all flows down to pump shutoff.

SW Rod "Jogged" down over clamp to LLS.

Flow being increased 31,000 gpm — Detect movement in SW tube thru transit at top (slight).

SW Rod at LLS-movement

From sub-pile room

.012 EW .008 N-S

35,000 gpm — Sub-pile room reports

SW tube

N-S 8 mills; E-W 14 mills

SE tube

N-S 8 mills; E-W 6 mills

Core scan naked eye - no change.

PCR

45,500 gpm, 100 psi/quad. —

NW tube - Steady

Rod - Steady LLS

N tube - Steady

Rod - Steady LLS

NE tube - movement, but very slight, reduced from previous runs

	E tube - Steady	
	C tube - Steady	
PCR	W tube - Steady	
44,200	SW tube - Steady	Rod - Steady
	S tube - Steady	Rod - Steady LLS
	SE tube - Steady	Rod - Steady ULS

From sub-pile room

SE - 11 E/W & 20 N/S
 SW - 12 E/W & 8 N/S
 NE - nothing detected

Gas Injection

Top SE locator tie — Bubbles travel at an angle greater than -45° from horizontal sweeping around tube in a general NW direction. They burst going downward.

Inst. Thimble No. 8 — Bubbles approximately 50% time toward vessel wall then up and disperse throughout vessel. The other 50% travel very fast toward SW and S flux trap baffles - movement is not 50% going each direction but oscillates.

North Wall — Bubbles disperse over core clear to S side. Can observe cross flow in W to E direction at point above beryllium and below locator tie (from port 4).

South Rod top of locator tie — Bubbles generally downward approximately 1/2 way to top of core then sweep north behind tube and down flux trap baffle. Flow sweeps lazily and occasionally so that bubbles go into and down SE and SW flux traps generally behind in-pile tube.

SW at Top of locator tie — Bubbles sweep around loop covering elements behind S loop and W loop. No bubbles fed elements at outer SW lobe.

N Rod at locator Tie — Bubbles sweep around tube random and covering both sides of N.F.T.B.

Withdraw NW Rod —

@ 1-1/2" very slight random motion observed.

@ 3" motion increased - erratic and random.

@ 11.5" rod moved toward SE (i.e. closer to IPT) and held steady.

@ 13.5" motion started - milder than before.

@ 30.5" frequency increased - decreased amplitude.

@ 35" motion decreased to the point it can barely be detected.

Note: Inpile tube motion is so small, if any, it can't be detected for a certainty. Instrument would be required to detect accurately.

NW drop time 145 milliseconds.

Release time 11 milliseconds.

SE Rod lower —

@ 35" steady - no change detected

@ 34" steady - no change

Withdraw SW Rod from LLS to 9-1/4" — motion medium

@ 9-1/4 motion increases - dramatic increase in amplitude.

Sub-pile reading on SW tube

N/S 30 E/W 28

Inserted SW Rod C - in-pile tube — With extension assembled to center inpile tube motion can be stopped relatively easy while pulling on the extension in the S, SW, and W direction. Motion is practically impossible to stop when pulling in any other direction. Once motion stopped tube remains quiescent for ~30 sec.

Withdraw S Rod —

@ 7.5 very slight random motion.

@ 8.0 frequency increases and amplitude very definite increase

@ 11 - stopped motion.

@ 13.25 motion-very mild amplitude.

@ 15.5 slight increase in frequency.

@ 19.0 frequency decreased.

@ 24.0 holding to set up for scram very very random - motion no set period - just every few seconds rod moves all over.

@ 26.0 frequency increases slightly, amplitude still very small.

@ 35 - motion stopped.

@ ULS - no detectable movement in loop or rod

Dropped Rod —

Release time - 31 milliseconds

Scram time - 160 milliseconds

Withdrawn N Rod —

@ LLS very slight - random motion detected.

@ 4" amplitude increased.

@ 5" amplitude decreased - motion mild.

@ 13.5" no motion detected.

@ ULS steady - no motion rod, tube or locator tie.

Rod drop time 162 milliseconds

Release time 13 milliseconds

D. Sub-pile Room Observations

Flow established @ 20,750 gpm

Brush Recorder Readings

South West tube recording N-S and E-W deflection.

South East tube recording N-S and E-W deflection - transducers 103 and 314 stopped together in the SE position.

Transducer 101 is located in upper plenum.

Transducer CA-29 is located in spent d/p top indicating outlet pressure.

Observations:

SW tube erratic with knocking at this slow. Lowered the rod to 27" with no visible change in noise. The base plate standard for the west position were vibrating quite badly. First time this has vibrated per J.H.C.

Brush readings at 27" on SW Rod and 20,750 gpm

SW deflection - NS 70 mills E-W 70 mills

SE deflection - NS 8 mills E-W 4 mills

Frequency very erratic and unable to determine.

Brush readings at 36" on the SW Rod and 20,750 gpm

SW deflection - N-S 90 mills E-W 75 mills

SE deflection - N-S 4 mills E-W 6 mills

Frequency is 8 cycles/sec.

Increased primary flow to 35,000 gpm

Knocking was quite bad, worst J.H.C. had seen in the SW

SW deflection - N-S 110 mills E-W 100 mills

SE deflection - N-S 8 mills E-W 6 mills

Started decreasing flow - @ 31,500 gpm the traces settled down considerably.

Shut off all pumps to lower SW rod to seat.

Restarted flow with SW rod in its seat.

Pressure transducer in SE rod started responding.

Previously it had not been working.

At 30,000 gpm - no knocking. All rods feel approximately the same.

SW deflections - N-S 8 mills E-W 12 mills

SE deflections - N-S 4 mills E-W 5 mills

At 35,000 gpm, no visual change in the vibration. No noticeable knocking in any position.

SW deflection - N-S 8 mils, E-W 6 mils

SE deflection - N-S 8 mils, E-W 6 mils

Took 314 transducer off and put SE, N-S accelerometer on.

At 42,000 gpm maintenance installed center position extension - total length 45" from bottom head.

At 45,000 gpm center extension vibrating very badly @ 200 cycles per minute.

SW deflection - N-S 8 mils, E-W 12 mils

SE deflection - N-S 20 mils, E-W 12 mils

Note: By pushing center extension West or South and holding, you can stop the vibration. Pushing East or North has no effect.

Per J.H.C. @ 45,000 gpm, "the tubes look better than ever."

Note: If the center position extension was pushed to the side and released at the right moment it would not vibrate for a while. Duplicated this a couple of times.

Started pulling the NW Rod and got a slight metallic checking at 36" (per J.H.C.) Scrammed the rod and had no noise.

Lowered the SE rod to 34" with no change in vibration and no knocking. Raised the rod to 36" again with the same results.

Switched CA-29 to the SW quadrant space d/p top and started withdrawing SW Rod.

SW Rod @ 9.25"

SW deflection - N-S 30 mils, E-W 28 mils

SE deflection - N-S 22 mils, E-W 10 mils

Frequency - 8 cps on the SW and 7-1/2 cps on the SE

Placed a pair of accelerometers in the NE tube and raised the elevation.

Accelerometer location - 82 ft elevation

NE Tube displacement - N-S 44 mils, E-W 42 mils

Frequency - 8-1/2 cps

Accelerometer location - 83 ft elevation

NE Tube displacement - N-S 30 mils, E-W 24 mils

Frequency - 7-1/2 cps

Accelerometer location - Bottom of locator tie

NE Tube displacement - N-S 4 mils, E-W 4 mils

Frequency - unreadable

Lowered a microphone in the SE tube and monitored the trace as it was slowly removed. Reactor top recorded locations of noise level changes.

Shift #3
4-4-67

- 30 - Installed flow blocking collar on SW inpile tube.
 - Installed special shim on NE dummy flux trap filler and lock wired it.
 - Installed RP #1, 3, and 4, top vent open filling vessel — rudder and intank light removed.

0255 - Top vent closed, Rtr full.

0500 - Removed RP #3. Removed plastic dymax strap and buckle which was loose and hanging from inpile tube center support — south vibration arm.

0530 - Installed RP #3, top vent open.

0630 - Top vent closed, Rtr full.

Note: Need a new 1 ft adapter hose for air wrench as the old one is plugging up and blocking the air - also suggest that they pin the socket to the wrench so it won't always keep falling off; since the wrench is only used with that socket it wouldn't create any problem.

Shift #4

- 2215 - Removed port #1 and installed light and ladder in the tank. Measured positions of clamps on the SE and SW inpile tubes.

Test No. 8

A. The following modifications were made in the vessel prior to test No. 8:

1. Moved flow restrictor from SE rod and installed on SW rod at same elevation originally installed on SE rod.
2. Moved flow restrictor from SW rod and installed on SE rod at same elevation originally installed on SW rod.
3. Move fuel elements from positions 30, 26, 5 to positions 10, 36, 35 respectively.
4. Repaired and reinstalled one transducer.
5. Changed location of N₂ lines. (1 located on SE tube @ locator tie) (1 located on North wall at same elevation as test No. 7) (1 located on SW rod at locator tie) (1 located on instrument thimble No. 8) (1 located on top of outer shim cylinder beam between SW and S flux trap baffle) (1 located on top of outer shim cylinder gearbox immediately above FE-26).

B. Tests Performed

1. Record observations of SW rod at full flow.
2. If possible, lower SW rod at least 2 inches at full flow, and record observations.
3. Observe SE rod closely while raising flow and record observations.
4. Record N₂ gas injection observations.
5. Record instrumented fuel element readings in position 10, 36, and 35.
6. Record reactor inlet pressure transducer readings at full flow.
7. Record upper plenum pressure transducer readings at full flow.
8. Record accelerometer readings in SE and SW in-pile tubes at full flow at elevation 83'-0".
9. Record microphone output of selected in-pile tubes.
10. Record pressure transducer readings.
11. If SE rod vibrates so bad that full flow can't be reached, shut-down flow and lower rod to LLS and finish test on SW rod.

C. Reactor Top Observations

Q = 30,000 gpm — SE Rod @ ULS - Rod is vibrating with high frequency-medium amplitude.

32,000 gpm — Rod - vibration increased - tube motion and tie motion can be observed. Lowered Rod @ 34" rod vibration increases dramatically - considered severe.

Lowering Flow —

@ 28,000 vibration decreased sharply.

@ 23,000 gpm @ 33" motion random, medium vibration.

Raise rod to 34" - noticed sharp decrease in vibration as soon as rod started up.

Lowering flow — Rod motion same.

16,000 gpm — Rod lowering vibration continues

@ 26" rod motion decreased.

@ 22.5" rod motion increased.

@ 18" vibration medium, random - unacceptable.

Shut off pump - cannot drop flow below 16,000.

SE rod lowered over collar to elevation 10.9" and holding.

Raise Flow 25,000 — SE Rod starts movement.

~40,000 — SE Rod motion - amplitude decreased - frequency increased.

PCR

46,000, $\Delta P = 100$ psi — SE Rod motion is reduced - gives shudder occasionally, random.

RCR

44,600, $\Delta P = 100$ psi — Motion increased as rod lowered sharp increase at 9".

Tried raising rod - no change.

Lower rod - motion - random.

@ 6.5" rod motion decreased to very mild.

Same motion down to LLS.

SW Rod lower from ULS

35" - no change "Beautiful".

34" - no change "Beautiful".

N₂ Inject

Line laying on top of gearbox support beam - cover plate directly SE from SW loop - bubbles go directly into FE-24.

Line laying on top of gearbox support beam - cover plate SW of SW loop - bubbles go directly into FE-26.

On thimble #8 ~4" off top of support beam - bubbles oscillate NW/SE sweeping FE from S to W loops predominately to west loop. Bubbles go into elements 24 → 28.

Shutdown flow and relocated flow restrictors on the inpile tubes as follows:

1. The 0.080 inch clearance flow restrictor on the SE inpile tube was raised to 19" above the top of the flux trap baffle.

2. The 0.030 inch clearance flow restrictor on the SW inpile tube was lowered to 3-11/16" above the top of the flux trap baffle.

Flow was started with both safety rods at ULS and the following observations were made at the reactor top:

25,000 gpm —

SE Rod motion observed - motion mild low amplitude - random.

Flow increased - as flow increased SE vibration also increased.

@ 30,000 gpm —

SE Rod, Tube, and Locator Tie is vibrating rather severely.

SW - steady

Lowered SE Rod

@ 35" motion increases dramatically when rod dropped to 35.

@ 34" rod motion considered violent.

Reducing Flow

Motion remained same to 20,000 gpm

Raised Rod to ULS and increasing flow to allow measurement of quadrant ΔP in flow distribution tank.

@ 30,000 gpm —

From sub-pile room on SE Rod

90 N-S 35 E-W

also considerable banging.

Rod, tube, and locator tie moving but not as bad as with Rod off ULS.

Reactor engineering (Griebenow) is tracing ΔP between NE and SE Quadrant and outlet pressure of SE quadrant in flow distribution tank.

View through transit gives less motion through tube than seen looking through port! (Relative!!!)

Holding @ 30,000 gpm to allow accelerometer readings @ different elevations in SE position.

SW Rod Lowering

From ULS to 18" rod - steady to very very slight movement - judged completely acceptable - holding @ 18".

From Sub-pile Room with SW @ 18"
no noise and accelerometers read:
.016" NS .008" EW

Shutdown flow and lowered SE Rod to LLS!

Raising Flow

22,000 gpm — Motion can be seen in SW with study through binoculars - completely acceptable.

@ 30,000 gpm — No movement in SW Rod @ 18".

Withdraw SE Rod

@ LLS motion very slight mild stopped motion at ~4".

@ 6" very mild motion then motion stopped at just above 6".

39,000 gpm — SW Rod movement observed by very very mild.

RCR

45,000 Withdraw SW Rod - from 18"

100 psi motion observed @ 29" very slight and completely acceptable.

PCR Motion continued to ULS where motion virtually stops.
46,400

	<u>Tube</u>	<u>Rod</u>
SW	Steady	Steady
S	Steady	Steady
SE	Steady	Steady
E	Steady	
C	Steady	
W	Steady	
NW	Steady	Steady
N	Steady	Steady
NE	Very Slight	

D. Sub-pile Room Observations

Raised flow to 18,600 gpm - SW and SE rods @ 36". Detectable slight, erratic knocking noise in SE position. SW has no detectable noise or vibration.

Increased flow to 31,800 gpm - severe knocking in SE position - no detectable vibration or knock in SW. Lowered SE rod to 34" - displacement of tube increased and knocking worsened. Started lowering flow.

Flow at 16,000 gpm - lowered rod to 18" - knocking still detectable.

Stopped all flow - lowered SE rod to 10.9" - raised flow to 30,000 - no knocking. Lowered SE rod to seat - no knocking.

Raised flow to 46,000 gpm —

Displacements

SW Tube

Safety rod at 36"
N-S 14 mils total
E-W 10 mils total

SE Tube

Safety rod in seat
N-S 14 mils total
E-W 8 mils total

46,000 gpm — Lowered SW rod to 34"

Displacements

N-S 28 mils total
E-W 28 mils total

Shutdown flow to relocate collars on inpile tubes.

Wednesday Afternoon Run:

Raised flow with SW and SE safety rods at 36".

25,200 gpm — SE vibrating - detectable knocking noise.

30,000 gpm — SW tube steady, SE tube - detectable loud knocking.

Displacements

SW Tube

Safety rod @ 36"
N-S 4 mils total
E-W 4 mils total

SE Tube

Safety rod @ 36"
N-S 60 mils total
E-W 30 mils total

Lowered SE rod to 34" - severe erratic knocking - lowering flow.

Flow @ 20,000 gpm - rod back at 36" - no detectable noise.

Raised flow to 30,000 gpm —

Displacements

SE

N-S 90 mils total
E-W 35 mils total
Frequency 7 cps

Note: First detectable noise on SE tube.

@ 24,000 gpm —

Rod @ 36"

Held flow @ 30,000 gpm and lowered SE accelerometer as follows:

Acc. @ 73'-5-1/2"
N-S 80 mils total
E-W 30 mils total

Acc. @ 76'-6-1/2"
N-S 140 mils total
E-W 30 mils total

Lowered SW rod to 18" - flow @ 30,000 gpm

Displacement

N-S 16 mils total
E-W 8 mils total

E. Information Needed to Complete Test Data
Package for Test No. 8

1. Fuel element data in positions 5, 26, and 30.
2. Pressure transducer readings of reactor inlet line.
3. Upper plenum transducer readings.
4. Accelerometer readings in SE and SW inpile tubes at 83'-0".
5. Brush recordings of microphone output, if any taken.
6. Pressure transducer readings on SE inpile tube.
7. Traverse of NE inpile tube if taken.
8. Pressure transducer readings from the flow distribution tank as measured by pressure tap indicator lines.

INTERNAL OBSERVATIONS

A. Boroscopic Examination

The center and SE flux trap sections in the core were boroscoped on 4/6/67 and 4/10/67.

The central flux trap was viewed all the way down from the top of the neck shim housing. One or two vertical marks (discolorations) were noted near the top (in the NW to W quadrant) then continued straight down for approximately 13 feet. At the 13 foot elevation some circular rings were observed which were also discolorations. No abrasive marks were found, or areas that were considered targets for a banging inpile tube.

The SE flux trap was viewed down to the top of the inner snubber tube. The top 4 feet of the baffle was visually inspected with a flashlight. One long vertical mark was obvious on the east side of the baffle and it extended the full length of the core. The boroscopic examination found some deep gouges in the top lip of the inner snubber tube in the SW quadrant which extended all the way around the NE quadrant (viewed clockwise). The deep scratches varied in length from approximately 1/2 to 1-1/2 inches and seemed to be placed there in a random fashion. Immediately below the lip, predominately in the NE quadrant, large vertical marks were observed which went clear down to the four inner snubber tube holes. Even though the boroscope could not be lowered further it was possible to see that some of these marks extended below the snubber tube holes.

B. Visual Observations

1. Safety Rod

Note: "Wear marks" mean shiny spots.

a. Standard filler on rod has vertical scratch ~ 12" long that can be felt with a fingernail. (Possibly a removal mark.)

b. Vertical wear marks on upper and lower couplings some of which can be felt with fingernail.

(1) Lower coupling wear marks are opposite the rack.

c. Horizontal wear marks on upper end of rack tube at two places - top of teeth and ~ 3" down.

d. Horizontal wear marks on extension sleeve ~ 4" from top.

e. Vertical scratch on extension sleeve ~6" long that can be felt with a fingernail (possible removal mark).

2. In-pile Tubes (Prime and Dummy)

a. Both have wear marks from ~24" below the upper spline to almost the top of the spline.

b. The dummy (modified) seems to have considerably fewer marks on the upper end of the spline than the prime tube.

c. Modified - enlarged splines show wear.

d. On lower end of splines each spline edge is becoming rounded.

e. Can't really inspect lower splines closely, but they don't seem to have as many wear marks.

f. Dummy tube has a bow in it that seems to start at a weld ~ half way between upper and lower splines and goes to the bottom. An estimate of 1/2" bow was made.

Test No. 9

A. The following modifications were made in the vessel prior to Test No. 9.

1. The NW and SE safety rods were transferred from one position to the other.
2. A flow tube was installed in the NE position.
3. A prime inpile tube, with modified upper and lower splines, was installed in the center position. The bottom end was anchored in the sub-pile room and an accelerometer was installed.
4. A pressure transducer was installed on the impulse line, in the flow distribution tank, to all four quadrants.
5. Instrumented fuel elements in positions 10, 36, and 35 were moved to positions 10, 31, and 30 respectively.
6. The 0.030" collar was removed from the SW inpile tube.

B. Tests Performed

1. Gradually increase flow while closely observing the center in-pile tube both in the sub-pile room and the vessel. Hold the flow, as a minimum, at 25,000 and 35,000 gpm while an accelerometer traverse is made and recorded. A decision on whether to increase flow will be made after each traverse.
2. With all safety rods at LLS record the output pressures of all 4 quadrant pressure transducers on the impulse lines to the flow distribution tank at 25,000 gpm, 35,000 gpm and full flow.
3. Raise safety rods to ULS in following order, one at a time at full flow, while quadrant pressures and ΔP 's are continuously recorded: NW; N; S; SW; SE.
4. When all 5 safety rods are ULS initiate a full scram while quadrant pressures and ΔP 's are recorded.
5. Withdraw SW safety rod to ULS and scram. Record quadrant pressures and ΔP 's.
6. Withdraw SE safety rod to ULS and record observations. Scram rod and record quadrant pressures and ΔP 's.
7. Withdraw S safety rod to ULS and scram. Record quadrant pressures and ΔP 's.

8. Withdraw NW safety rod to ULS and record observations. Leave at ULS.

9. Record ΔP between NE and SE quadrants.

10. Record set of readings for instrumented fuel elements in positions 10, 31, and 30.

11. Withdraw N, S, SW, and SE safety rods to ULS and lower flow to 35,000 gpm, then 25,000 gpm, and record the outlet pressures of all 4 quadrant pressure transducers on the impulse lines to the flow distribution tank.

12. Maintain primary coolant system temperature at $85^{\circ}\text{F} \pm 5^{\circ}$ if possible.

PCR

25,000 gpm — Traverse run with accelerometer in center IPT 86'0", 79'0", 72'0".

RCR

23,300 gpm

Accelerometer locations: center - 72'0"
SE - 83'0"

1650

25,000 gpm — No movement in center IPT through transit of top head plate.

31,000 gpm — Center loop - very slight - random movement through transit - questionable as to transit motion or loop!

SE and SW rods moving in seats - movement very slight, random.

35,000

	Loop	Rod				
NE	Steady					
N	"	Steady to just detectable				
NW	"	"	"	"	"	
W	"		--			
C	"		--	(Note: Very limited view.)		
E	"		--			
SE	"	Moving random, mild (CW)				
S	"	"	"	very mild (CW)		
SW	"	"	"	"	"	"

Note: Movement in center loop is barely observable in sub-pile room; however, a force of ~25# in a N to W (CCW) direction will stop motion. Force in any other direction will not stop motion.

From top head through transit with accelerometer at 74'0" movement ~1/4 dot peak to peak. "B" Baskets much improved!

39,000 gpm — Transit at top head, center tube accel at 79'0", movement 1/2 dot peak to peak; NE tube motion detectable.

40,000 gpm — Center tube as sub-pile room
.120" NS .075" EW

43,500 RCR	150 NS mils center inpile tube	} at elev. 79 feet
45,000 PCR	85 EW mils center inpile tube	
100 psi, Quad Δp		

SW	loop steady	safety rod steady
S	"	slight motion
SE	"	random slow motion-slight
W	"	none
E	"	none
NE	motion-slight	none
N	slight tube motion	very slight
NW	steady	steady
C	limited view (steady)	none

No noise in NE inpile tube - knocking sound has disappeared that was heard before when flow tube was inserted. B-hole flow restrictors steady!!!

Withdrawing NW Safety Rod —

@ 3" - motion easily detected.
@ 4" - rod more steady.
@ 5-1/2 - very slight motion.
@ 9" - motion increases.
@ 9-1/4" - motion decreased.
@ 12" - motion increased slightly, decreased infrequency.
@ 15" - motion medium, random, pulsing.
@ 24" - motion decreased slightly.
@ 31" - motion still random - mild, slight increase in frequency, decrease in amplitude.
@ 33.9" - everything moving - tube, tie, rod.
@ 32.7" - motion stopped and went back to same type motion observed previous.
@ 33.0" - no increase in motion.
@ 33.25" - no change.

@ 33.50" - Held steady for $\approx$ 10 to 15 seconds then started to vibrate with a large amplitude and high frequency. Locator tie, loop, and rod all vibrating worse than anything seen to date in any position.

Withdrawing SW Safety Rod —

- @ 4" - motion easily observed.
- @ 5" - motion decreased - relatively steady.
- @ 6" - motion increased.
- @ 8" - motion medium, random.
- @ 9" - tube motion - high frequency.
- @ 10" - and holding
- @ 11" - rod motion stopped - rod tilted to east-southeast - loop frequency decreased somewhat also.
- @ 13.5" - rod motion started - random.
- @ 21" - motion decreased - started - random; subpile room report "rattle" but not too bad!!
- @ 27" - locator tie motion increased.
- @ 29.7" - frequency increased.
- @ WLS - no change in amplitude or frequency seen when rod went on splines. (Motion is high frequency - low amplitude.) Motion considered unacceptable.

Ran NW Rod down to 25" and scrambled.

Withdrawing SE Safety Rod —

NE 50 mils EW 50 mils @ 83 ft elev. with rod @ 18.25"

- @ 2" - mild motion.
- @ 10" - tube motion detected.
- @ 11" - rod motion decreased. (rod tipped to NW)
- @ 13" - rod motion started.
- @ 27" - rod frequency increased.
- @ 30" - loop motion increased, low amplitude, high frequency in both loop and rod.
- @ 35" - rod motion decreased.
- @ ULS - low amplitude - high frequency; this is best we've seen in SE fractions.

Test No. 10

N - C - SW - SE - NE Prime tubes

A. The following modifications were made prior to Test No. 10.

1. Special flow restrictors designed by Roy Manoll of B&W installed inside safety rods located in NW and S position.
2. Special flow restrictor designed by Roy Manoll of B&W installed on center inpile tube immediately below upper splines on center inpile tube. (Square leading edge.)
3. 080 with square leading edge installed 19 inches above top of flux trap baffle on SW inpile tube and rod strapped.

B. Tests Performed

1. Closely observe SW rod as flow is increased. At full flow lower rod 2 inches and record observations.
2. Closely observe center inpile tube as flow is observed. Record accelerometer readings continuously as flow is increased.
3. At 22 psi Δp quadrant flow, withdraw SE rod to ULS, scram and record drop time. Determine velocity and record.
4. At 22 psi Δp quadrant flow, withdraw NW rod to ULS, scram and record drop time. Determine velocity and record.
5. At 22 psi Δp quadrant flow, withdraw S rod to ULS, scram and record drop time. Determine velocity and record.
6. Compare velocities of SE and NW, S rods and determine next flow step. At next flow step repeat items 3, 4, 5, and 6 until full flow has been obtained.
7. Record instrumented FE readings.
8. Record quadrant Δp as per Vince Walker assigned.
NE-SE
9. Record Statham output pressure from each quadrant flow orifice as requested by Vince Walker.

4/12/67

25,000 gpm, $\Delta p = 39$ psi — W/D NW rod from 6.5". Very slight and random motion to ULS - very good overall - dropped NW. Release - 27 msec, 12" drop time - 178 msec.

W/D SE rod —

Release 24 msec, drop time - 175 msec.

35,000 gpm, $\Delta p = 69$ psi — SW rod @ ULS - motion unacceptable, movement in loop and locator tie.

Lowered rod to 34" - motion remained unacceptable. Sub-pile room reports bad banging in SW tube lowering flow to drop SW rod to LLS.

Rod still pulsing at 16,000 gpm. Center tube @ 35,000 gpm - .016 N-S, .004 E-W.

45,000 gpm, $\Delta p = 100$ psi — Center IPT .020 N-S and E-W. HooRay!!! SE rod moving in seat.

@ 3" freq increases, small amplitude.

@ 10.5" freq increases, amplitude increases.

@ 12.4" motion stopped - can see in-pile tube motion - tube is high frequency.

@ 13.5" rod motion starts again, random and mild.

@ 16" - frequency increases - still low amplitude.

@ 18" - frequency increases - rod appears to be tipped to north.

@ 24" - rod motion judged acceptable, tube and rod high frequency, low amplitude. Sub-pile room reports clamp OFF (removed) from center & motion decreased to .012 NS/EW.

@ 29" - frequency & amplitude increase. Sub-pile room reports bang in SE.

@ 35" - frequency increases, amplitude decreases.

ULS - high frequency, very very low amplitude, considered acceptable.

Scram SE — release - 20 msec, drop - 142 msec.

W/D NW rod - rod motion detected in seat.

@ 5" - random movement.

@ 6" - pulsing motion.

@ 8" - rod gave a little shake (shudder).

@ 12" - rod steady !!

@ 13" - rod tipped (layed) to east.

@ 16" - rod shuddered

16 → 24" - rod pulses - shudders periodically.

@ 24" - continuous motion detected - mild, random motion, rod continues to lay toward east.

@ 28" - motion increased - mild, random.

@ 30" - frequency increased.

@ 33.5" - frequency increased, amplitude decreased.

@ 36" - rod motion considered acceptable all the way. Scrammed NW rod - release time - 11 msec, drop time - 137 msec. Sub-pile room reports sound and motion of NW - OK - pinging sound coming from NW position in sub-pile room.

W/D South rod —

@ 5" - motion detected in rod, random and mild.

@ 8" frequency increases and amp.

@ 9" amplitude increases.

@ 11" motion stopped.

@ 14" motion started, mild and random.

@ 17" frequency increased then started to pulse then stopped.

Continues this shudder (occasionally) all the way to 24".

@ 26" - frequency increased, amplitude very low.

@ 35" - Beautiful !!! motion stopped.

@ ULS - all motion stopped - completely acceptable.

Scram S rod — release - 15 msec, drop 152 msec.

Test No. 11

4/25/67

Ports 1, 3 and 4

		<u>Tube</u>	<u>Rod</u>
35,000 gpm	NW	Steady	Steady
	N	↓	Steady
	NE		--
	E		--
	C		--
	W		--
	SW		Steady
	S		Steady
	SE	↓	Steady

37,000 gpm — NE tube motion is barely detectable.

44,000 gpm — N tube motion high frequency, low amplitude.

44,800 gpm, 100 psi Δp — NE tube frequency increasing. SW tube motion high frequency, low amplitude. E tube motion high frequency, low amplitude.

Center inpile tube not tied down in subpile room - no knocking and considered acceptable. Motion approximately same as observed during Test No. 10. NE tube approximately same as Test No. 10 except it quivers every 10 or 20 seconds but is considered acceptable. All others approximately same as observed during Test No. 10.

W/D S Rod

- @ 7" - motion detected, very mild & random.
- @ 8" - frequency increases, amplitude mild.
- @ 11" - stopped motion.
- @ 13" - started mild, random motion.
- @ 16" - frequency increases slightly.
- @ 20" - light pulse, very mild.
- @ 24" - holding rod motion stops & pulses.
- @ 27" - frequency increases slightly.
- @ 35" - motion stopped.
- @ ULS - Everything Beautiful!

Scram S Rod — release - 15 msec, drop - 149 msec

Pulling N Rod

- @ 2" - very slight motion.
- @ 5" - frequency increase, very mild, low amplitude.
- @ 10" - motion stopped then pulsed.
- @ 11.9" - all motion stopped in rod.
- @ 11.9" - tube motion detected.

Rod motion is occasional shudder - majority of motion throughout withdrawal is mild & light.

- @ 19" - amplitude increases - still mild.
- @ 32" - tube frequency & amplitude slight increase.
- @ 35" - all motion stopped.
- @ ULS - Completely Acceptable.

Subpile reports north tube motion detectable - bumping could be felt with hand on tube, most pronounced @ 32"; @ ULS motion decreased.

N₂ - In Seat

Off west thimble 11" ~ 1' off top of reflector tank - ~80% of gas to I rods, ~20% sweeps to NW lobe in sprinkler-like action.

N - Wall Above Drop-Tube (11" above top of inset flow)

Much better diffusion of gas - without previously observed cross flow - diffusion (mixing) was much faster than previously observed & mixing more complete throughout vessel.

Inst Thimble #7 - gas shoots in (strut) of thimble directly to SW lobe going into baffle & surrounding F. E.

W/D NW Rod

Light motion in seat but increased slightly when withdrawal started.

- @ 4" - motion random - amplitude from one side of baffle to the other is slow motion.
- @ 6.5" - amplitude decreased, frequency decreased.
- @ 8" - motion more steady.
- @ 10" - motion remains random and mild.

@ 11" - rod leaned toward east and motion ceased.

@ 12.5" - tube motion detected.

@ 13.5" - rod motion erratic, mild.

@ 17 to 23" - rod motion random, erratic, and pulsing. Moves slowly with a large amplitude but generally laying toward east when motion stops. Motion considered mild and acceptable.

@ 23 to 24" - rod more concentric with tube and has low frequency. Small to medium amplitude motion but is considered acceptable. Motion is very slow.

* @ 33.5" - amplitude decreased.

@ 35" - all motion ceased.

@ ULS - rod, tube, locator ties all OK - considered acceptable.
Dropped rod - bad visicorder reading.

Subpile room could not detect any changes throughout entire rod withdrawal.

N₂ In Seat

NW - just below tie ~ at rod ULS location, bubbles sweep like sprinkler around tube to N&W lobe.

NW - at top of GBSB core - bubbles sweep directly into F.E. in NW lobe only converging.

NW - at top of GBSB core close to inpile thimble 11 - 50-50 split going from I hole to F.E. in NW lobe.

Pulling NW rod for Drop Time - release time - 9 msec, drop time - 189 msec

@ ULS - inserted N₂ from line on NW tube right at top of rod. 100% bubbles go directly down rod/loop annulus - sweep bubbles ~180° around tube ~90° each side of (Walker) bubble machine.

W/D SE Rod

@ LLS - no motion detected.

@ 0.5" - motion detected - very slight.

@ 4" - motion increasing slightly.

@ 7" - tube motion detected.

@ 8" - frequency increased.

@ 10" - tube motion increased - frequency.

@ 11" - rod motion stopped - layed toward west.
@ 13.3" - rod motion started - mild - low amplitude - low frequency.
@ 22" - tube motion increased - high frequency, low amplitude.
@ 24" - and holding.
@ 27" - motion detected in locator tie - mild - has to be studied to be detected.
@ 29" - rod frequency increased - low amplitude. Tube & rod vibrating, high frequency & low amplitude.
@ 32" - motion increased in locator tie.
@ 33 - 35" - motion considered marginal.
@ ULS - rod, inpile tube, and locator vibrating together. High frequency, amplitude decreased when rod went on inpile tube splines. Motion considered borderline to unacceptable. Sub-pile room observed SE motion and sounds slightly worse than center inpile tube; however, it is judged completely acceptable.

Rod scrambled — release time - 10 msec, drop time - 141 msec.

Information Needed to Complete Test Data Package for Test No. 11

1. Stator pressure of each quadrant in flow distribution tank.
2. Pressure of each quadrant at the orifice plates.
3. SW accelerometer.
4. Inlet plenum.
5. Outlet quadrant line on the NE elbow.
6. Reactor outlet line at elevation 40' on the outlet "T".

Data is to be taken as follows:

1. At 25,000 gpm with all rods at LLS.
2. At 35,000 gpm with all rods at LLS.
3. At full flow with all rods at LLS.
4. At full flow with all rods at ULS.

Test No. 12

4/20/67

A. The following changes were made in the vessel prior to running test No. 12.

1. Special flow restrictors as designed by B&W (12 inches long, roughened on the inside surface) installed on the inside of the safety rods in the following positions: NW, N, SW, S and SE.
2. Special flow restrictors as designed by B&W (12 inches long, roughened on the inside surface) installed on the inside of the standard flux trap fillers in the NE and E positions.
3. Special collar as designed by B&W (20 inches long by 3.297 in diameter) installed on center inpile tube immediately below the upper splines.
2.295
4. Removed dummy inpile tube from E position and replaced with a prime inpile tube.
5. Removed all flow tubes from prime inpile tubes.
6. Installed accelerometer in center inpile tube at elevation 79 feet.
7. Installed accelerometer in SW inpile tube at elevation 83 feet.
8. Changed instrumented fuel elements to positions 1, 2 and 3.
9. Installed the following instrumentation:
 - a. Three stain gauges on the flow distribution tank.
 - b. Three stain gauges on the core support tank.
 - c. One pressure transducer on NE Quadrant pressure top at flow distribution tank.
 - d. One pressure transducer in I-9 hole.
10. Special fuel element in position 14 and 18 (elements).

B. Tests Performed

1. Gradually increase flow to 100 psi quadrant ΔP while continuously recording the center and SW inpile tubes. Shutdown if vibration gets excessive.
 - a. Withdraw all rod and record stain gauge readings.At full flow visually inspect and record internals observations in detail.

Withdraw each of the following safety rods to ULS and record observations, scram, and record release and drop times. Run continuous recording of accelerometer in SE and SW while withdrawing.

NW, N SW, S, SE

At full flow run an accelerometer traverse in all prime inpile tubes and record results.

At completion of traverse install flow tubes in all prime in-pile tubes and record observations made in subpile room.

Maintain primary coolant system temperature as near 85° F as possible. $\pm 5^\circ$ F.

Take instrumented fuel element readings at flows as directed by V. A. Walker.

Record instrument readings at flows as directed by V. A. Walker.

Inject N₂ gas at completion of all instrument readings and record observations (V. A. Walker to be present for this test).

Depressurize reactor vessel and run drop times on the NW, N, SW, S and SE safety rods under no-flow conditions.

Note: Mark each scram brush recording with: Test No. _____
Date _____
Flow _____
Quadrant ΔP _____
Rod Dropped _____

and hand in to me.

C. Subpile Room Observations

RCR

Observations

Ports 1, 3 and 4
DPH
(top head dry)

42,500 gpm

P = 100 psi/quad.

PCR

44,000 gpm

Position	Tube	Rod
NW	Steady ↓	Mild & random - in seat
N		Mild & random - in seat
NE		
E		
C		
W		
SW		Very mild & random motion in seat
S		Very mild & random motion in seat
SE		Very mild & random motion in seat

Note: NW & N rods have more motion than SE, S or SW - all are acceptable.

SW tube has pronounced banging in subpile room - accelerometer at elevation 83' reading - .025 - .030".

By pulling SW temporary clamps in subpile room accelerometer reads .020.

Banging also heard in SE tube in subpile room.

Withdraw N Rod

Trouble with visicord at 3".

Withdraw SW Rod

From LLS mild and random motion

@ 12" - rod motion decreased in frequency and amplitude.

@ 25.5" - rod withdrawal stopped due to low magnet current.

@ ~35" - rod motion stopped.

@ ULS - rod and tube stable - no tube motion throughout SW withdrawal as viewed from top.

Rod acceptable from top.

Subpile room observations - SW tube reads .060" E-W direction banging can be heard over entire withdrawal. Banging is intermittent.

Center tube accelerometers - .012" NS and EW at elevation 79'.

Withdraw N Rod

Viewed from 18" - motion is mild and random

@ 31" - rod gave shudder - pulsed with more motion - then subsided.

@ 35" - motion stopped.

@ ULS - rod and tube steady.

Dropped N Rod

Release 14

Drop 141

Note: Amplifier changed from one used previously.
Trouble in setup for measuring drop time.

Withdraw NW Rod

Mild motion in seat - 4" motion decreased

@ 12" - rod leaned to east and decreased motion.

@ 18" - moved back to center - motion random and mild.

@ 32.5" - frequency increased.

@ 35.5" - motion stopped.

@ ULS - no motion - tube or rod.

Pulled N rod at same time as NW was withdrawn.

Scrammed N Rod

Release 13

Drop 151

Withdraw N Rod

Motion mild and random from LLS going up

@ 11" - motion decreased considerably.

@ 12 to 13" - rod stopped.

@ 13" - motion again - random.

@ 17" - slight tube motion - high frequency shudder.

@ 20" - rod much more steady.

@ 23" - rod pulsed but generally steady.

@ 24" - very slight motion.

@ 27" - motion increased slightly in frequency not amplitude.

@ 31" - rod motion decreased in frequency and amplitude.

@ 34" - slight increase in rod motion.

@ 35" - rod steady.

@ ULS - tube and rod steady.

Note: Motion of N rod as bad as or more than has been seen before with no flow restrictor.

Scrammed N Rod

Release 13

Drop 152

Motion of N rod is judged borderline to acceptable!

From subpile room N rod - no banging of tube "looks good!"

Withdraw NW Rod

LLS random motion

@ 12" - rod leaned to east and steady.

@ 13.5" - rod moved back some and moving. Rod not centered.

@ 17" - motion continues random and mild.

@ 18" - rod now back to center.

@ 31" - rod pulsed 2 or 3 times.

@ 33" - frequency increased slightly.

@ 35.5" - motion stopped.
@ ULS - tube and rod steady.

Rod Scrammed

Release 12
Drop 142

Note: Motion of NW rod about the same as test
when 10" flow restrictor was installed.

Withdraw SE Rod

LLS mild random motion

@ 10" - rod motion increasing.
@ 12" - slight movement of tube - rod steady.
@ 13" - subpile room said tube sounds better as rod is withdrawn.
@ 15" - rod motion started again random - to tube motion.
@ 16" - 20 mils in subpile.
@ 21" - very mild rod motion.
@ 24" - rod has an occasional pulse - generally steady.
@ 26.5" - tube motion detected - high frequency - low amplitude.
@ 35" - tube and rod motion decreased.
@ ULS - tube and rod steady.
@ ULS rod and tube acceptable.

From subpile room accelerometer at elevation 83 reading of rod
at ULS .020" NS and EW prior to ULS maximum reading .090" NS and
EW.

Scram SE Rod

Release 13
Drop 149

Withdraw SW Rod

From LLS mild and random motion

@ ~10" - motion decreases with occasional light pulse then con-
tinues very very slight.
@ 24" - only slight motion can be seen in rod.
@ 27" - frequency increased, amplitude decreased.
@ 31" - frequency increasing very small amplitude.
@ ~35" - motion stopped.

@ ULS - no motion detectable - completely acceptable at ULS.

From subpile - accelerometer readings

SW @ LLS .020" NS and EW.

@ ULS .020 NW .040 EW.

Also reports slight and intermittent bang throughout withdrawal.

Scrammed SW Rod

Release 12

Drop 143

Withdraw S Rod

Random, very mild motion from LLS

@ 11" - very mild to steady.

@ 13" - very mild.

@ 21" - very little motion detectable.

@ 27" - slight increase in frequency, low amplitude.

@ ~35" - rod steady - no motion.

@ ULS - no motion completely acceptable throughout travel.

Scram S Rod

Release 24

Drop

Note: Reading no good due to
slippage on tachometer!

Run Another Scram on S Rod

Release 12

Drop 149

From subpile room - center tube observation is basically same
as Test No. 11 or slightly improved.

General Observation (conclusions)

1. All positions are considered acceptable with rods at ULS
(both tubes and rods) based only upon view from top - (i.e.) all posi-
tions are acceptable at ULS.

2. No positions are considered unacceptable based on motion ob-
served from top head. Motion over the withdrawal range is generally
considered acceptable; however, the southeast is judged borderline to
marginal acceptable over a certain short range of travel (generally near
the upper region $\approx$ last 8 inches before spline).

3. The observations in the subpile room are:

- a. NW - Dummy - acceptable.
- b. N - prime - acceptable.
- c. NE - prime - acceptable.*
- d. E - prime - acceptable.
- e. C - prime - acceptable to marginal.*
- f. W - dummy - acceptable.
- g. SW - prime - unacceptable.*
- h. S - dummy - acceptable.
- i. SE - prime - unacceptable.*

- Note:
- c. NE tube as viewed from top head is quieter than on any other test to date.
 - e. C detectable noise - and movement. Although movement is slight the sound issuing merits further investigation.
 - g. SW - noise is metallic - intermittent and judged unacceptable.
 - i. SE - noise is metallic - however not as frequency as SW but when sound occurs it has sharper sound.

Last General Note: Top head and reactor room still dry.

D. Information Needed to Complete Test Data Package for Test No. 12.

- 1. Flow restrictor drawings for the five safety rods.
- 2. Flow restrictor drawings for the dummy flux trap fillers.
- 3. Drawing of the collar used on the center inpile tube.
- 4. Instrumented fuel element readings.
- 5. All instrument recordings.

IDAHO NUCLEAR CORPORATION

April 24, 1967

INTER-OFFICE CORRESPONDENCE/Subject

ATR Startup
Weekly Report No. 15
DPH-86-67A

Mr. F. R. Keller
MTR Wing C

This report covers progress in ATR Startup for the period April 16, 1967 to April 22, 1967.

1. Facility Transfers:

248(91) Primary Heat Exchanger area and Primary Emergency Pump Area.

248(92) PW Loop 1D - NR Loops 2A, 2B, 2C, 2D, 2E and all equipment as installed in Building ATR-670.

2. Completed a satisfactory hydrotest of the Bypass Demineralizer System.

3. Completed special hydrotest of loop 2E.

4. Chemistry approved and all loops in wet-layup conditions.

5. SO-101 Nuclear Instrumentation

Work completed except for source check of chambers.

6. Main Primary Coolant System Pumps

The oil samples collected this week indicate that discoloration is lessening but brass particles are still present. It is proposed to change all bearing oil prior to the hot-run next week and to change it immediately following.

7. Completed modifications to two more outer shim lower stop collar weldments and installed. Two more units will be delivered to the machine shop for modification on 4/24/67.

8. Thoroughly borescoped the NW and SE safety rod snubber tubes. Other than the scratches that was honed a year ago nothing of significance was found.

9. Removed and thoroughly cleaned the NW and SE safety rod drives.

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10. As-built measurements taken of the NW, SE, and prototype safety rods.
11. Made special scram test on SE safety rod, at normal operating flow and pressure, with the inflatable seal normal and at 80 psig. The release time for both tests was 11 milliseconds and the drop time for the first 12 inches with the seal inflated was 140 milliseconds vs 144 milliseconds when the seal was deflated.
12. Inserted long H-hole solid fillers for surveillance during vibration testing. See item 9A of Report No. 13.
13. Continued review and comments on Gas Cooled Loop drawings.
14. Core Vibration

The reactor was down most of the week for as-built measurements of the safety rods from the NW and SE positions. During this time the fixes proposed by B&W were fabricated and installed. The fixes consisted of 7 special flow restrictors identical to those installed on the NW and S safety rods during Test No. 10 except that these were 12 inches long with a rougher inside finish. They were installed on all five safety rods and in the NE and E flux trap fillers. In addition, a special flow restrictor 20 inches long by 3.297 ± 0.002 was fabricated and installed on the center inpile tube immediately below the upper splines.

Considerable instrumentation was also installed. Strain gauges were located on the flow distribution and core support tanks. A pressure transducer was installed on the spare pressure tap from the SE quadrant as close to the flow distribution tank as it could be placed.

Test No. 12 was run on 4/20/67 and 4/21/67. Results were disappointing in that motion was detected in all safety rods while still in their seats. This motion, however, was described as mild and random to very mild and random.

An intermittent light knocking noise was heard, in the subpile room, in the SW inpile tube. Tube vibration decreased when the subpile room tie clamp was removed.

SE safety rod vibration was judged borderline during withdrawal of the last few inches to ULS. Accelerometer readings reached 090" with the accelerometer located at elevation 83 feet.

Scram times were run on all safety rods as follows:

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<u>Rod Location</u>	<u>Release Time</u>	<u>Drop Time 1st 12"</u>
S	12	149
NW	12	142
SW	12	143
SE	13	149
N	14	141
N	13	151
N	13-1/2	152

The drop times listed above includes the release times.

The special pressure transducer installed near the flow distribution tank on the SE quadrant indicated a 22 psi pressure fluctuation. In addition, a special transducer installed on the SE quadrant flow transmitter indicated a 6 psi fluctuation. It is felt the excessive pressure fluctuations are originating in the core area and further work will be done in this area to try and determine what is causing this phenomenon. In addition, further work will be done to determine if the apparent flow oscillations are real.

Another test will be run with the system at temperature to see what effect, if any, temperature has on vibration.

On 4/21/67 flow tubes were installed in all prime inpile tubes and no change in vibration or noise could be detected from that noted without the flow tubes both with the safety rods at LLS and ULS.

A meeting will be held on 4/24/67 to determine the course of action to follow next week.

15. Program April 23 to April 29, 1967

- A. Continue Core Vibration Tests.
- B. Continue SO testing as time and conditions permit.
- C. Continue outer shim cylinder lower weldment modifications.
- D. Run PCS Hot Tests for hanger adjustments.

DPHalls:nh(jw)

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cc: C. H. Trent
F. H. Anderson
L. J. Weber
D. R. deBoisblanc
C. W. Bills (3) - ID
E. S. Brown
L. H. Jones
F. L. McMillan
J. P. Buerkle
R. J. Nertney
K. S. Dawson
J. D. Lawson
J. F. Sommers
S. Cohen
E. E. Burdick
J. W. Henscheid
D. P. Halls - 2

Test No. 13

4/25/67

Ports 1, 3 and 4

Reactor at Temperature of 169 F

RCR

45,300 gpm
 $\Delta P = 100$ psi

PCR

47,000 gpm

Position	Core survey	
	Loop	Rod
NW	Steady	Steady at LLS
N	↓	Steady at LLS
NE		--
E		--
C		--
W		--
SW	Mild motion	Mild motion
S	Steady	Steady
SE	Steady	Steady

W/D SE Rod

- @ LLS - no motion.
- @ 1.5" - motion detected in rod.
- @ 4" - motion increases in rod.
- @ 9" - tube motion easily detected - high freq., low amplitude.
- @ 11" - rod motion detected - tube motion continues.
- @ 13.5" - rod motion very mild occasional pulse type motion low frequency - medium amplitude.
- @ 24" - tube motion remains hi frequency low amplitude.
- @ 27" - rod motion very-very mild.
- @ 28" - frequency increased - low amplitude.
- @ 31" - amplitude of rod increased.
- @ 33" - amplitude and frequency decreased.
- @ 34" - frequency decreased.
- @ ULS - no motion detected in rod or tube.

W/D South Rod

- @ 2" - motion of rod detected - very very mild.
- @ 7" - freq. and ampl. increase slightly still con.
- @ 11" - motion of rod stopped.
- @ 13.5" - motion started again.

@ 16" - freq. increase - still very mild.
@ 20" - freq. decreased - (Note: motion observed is very very mild.)

@ 23" - freq. increase.

@ ~34" - all motion stopped.

@ ULS - no motion detected. Rod & tube acceptable throughout entire range of withdrawal; dropped 5 rod: release - 16 msec, drop - 151 msec.

W/D SW Rod

@ LLS - No motion.

@ 1" - rod & tube motion detected, tube & rod gave a pulse.

@ 3" - tube & rod motion increasing.

SE rod dropped to ~6.5" - stopped by clutch. Real decrease in tube motion between LLS and 6" W/D of safety rod as reported from sub-pile room.

@ 11" - rod motion stopped - tube motion high freq. - low ampl.

@ 13" - rod motion started - mild.

@ 14" - rod motion increased in frequency.

@ 15" - rod motion increased in frequency.

@ 18" - rod motion decreasing in frequency.

@ 19" - rod gives an occasional pulse with a large amplitude.

@ 21" - rod motion decreased dramatically - low freq., low amplitude - mild.

@ 30" - frequency of rod increased - motion still mild.

@ 31" - rod, tube, and tie motion - high frequency.

@ 31.7" - and holding - tube motion from top & subpile room as bad as we've seen to date.* (*I do not agree. J. James 4/26/67)

@ 33" - tube amplitude decreased.

@ 34" - rod and tube motion decreased between 34" and 35" then increased again.

@ 35" - tube and rod motion decreased.

@ ULS - tie motion stopped - tube and rod vibrating at high frequency, low-low amplitude - motion continued for approximately 5-15 seconds then stopped completely.

W/D N Rod

@ 2" - random motion - very mild.
@ 3" - freq. increase.
@ 5" - amplitude decrease, still very mild & random.
@ 8" - freq. increase.
@ ~9+" - tube motion detected - high freq. - low ampl.
@ 11" - rod motion decreased.
@ 14" - rod freq. increasing - still random & mild, binoculars necessary to determine tube motion - cannot view through tube with flashlight.

@ 22.4" - rod stopped moving - W/D stopped to observe - then rod started very mild random oscillation.

@ 26" - freq. increased.

@ ~35" - rod motion stopped.

@ ULS - high freq., very low amplitude in rod & tube - motion stops dead then starts very mild, high freq., very low amplitude movement.

Timing motion using wristwatch:

Motion starts & lasts	30	21	18 sec
Stops for	30	13	30 sec

Scrammed north rod: release - 14 msec, drop - 147 msec

W/D NW rod

@ LLS - no motion.

@ 0.5" - rod motion detected - rod drifting within limits of flux trap baffle.

@ 4.5" - motion stopped.

@ 5" - motion (freq.) increased.

@ 6" - frequency increases.

@ 9" - tube gives occasional shudder (pulse).

@ 10" - rod motion random - mild.

@ 12" - and holding - rod tipped toward east and all motion ceased.

@ 13" - tube motion high freq.

@ 14" - rod motion random - oscillating.

@ 17" - freq. increased on rod.

@ 17.5" - freq. decreased on rod to 28" - rod motion occasional pulse - random - mild. At end of each pulse rod lays toward west.

@ 28" - rod motion regular - mild.

@ 31" - freq. increased on rod.

@ 33" - freq. increased, amplitude decreased.

@ 35.5" - rod motion ceased.

@ ULS - rod & tube calm.

Note: Neck shim drive extensions at elev. ~56',
movement down from cold condition SW
5/16, other (3) - 1/4"
(SE, NE, NW)

A. There were no changes made inside the vessel from those itemized for Test No. 12. Flow tubes were in all prime tubes except the SE and the Primary Coolant System was operating at normal flow and pressure but at 170° F temperature.

B. Tests Performed.

1. Withdraw each safety rod to ULS and record observations.
2. Record Scram time on each rod.

C. Reactor Top Observations Ports 1, 3 and 4

Reactor at temperature of 169 °F

RCR	Core Survey		
	Position	Loop	Rod
45,300 gpm P = 100 psi	NW	Steady	Steady at LLS
PCR 47,000 gpm	N	Steady	Steady at LLS
	NE	Steady	
	E	Steady	
	C	Steady	
	W	Steady	
	SW	Mild motion	Mild motion
	S	Steady	Steady
	Se	Steady	Steady

Withdraw SE Rod

LLS - no motion.

@ 1.5" - motion detected in rod.

@ 4" - motion increases in rod.

@ 9" - tube motion easily detected.

@ High Frequency - low amplitude.

@ 11" - rod motion detected - tube motion continues.

@ 13.5" - rod motion very mild occasional pulse type motion low frequency - medium amplitude.

@ 24" - tube motion remains high frequency low amplitude.

@ 27" - rod motion very very mild.

@ 28" - frequency increased - low amplitude.

@ 31" - amplitude of rod increased.

@ 33" - amplitude and frequency decreased.

@ 34" - frequency decreased.

@ ULS - no motion detected in rod or tube.

Withdraw S Rod

@ 2" - motion of rod detected - very very mild.

@ 7" - frequency and amplitude increase slightly still continuing.

@ 11" - motion of rod stopped.

@ 13.5" - motion started again.

@ 16" - frequency increase - still very mild.

@ 20" - frequency decreased.

Note: Motion observed is very very mild.

@ 23" - frequency increase.

@ ~34" - all motion stopped.

@ ULS - no motion detected.

Rod and tube acceptable throughout entire range of withdrawal.

Dropped S Rod

Release 16

Drop 151

Withdraw SW Rod

LLS - no motion.

@ 1" - rod and tube motion detected tube and rod gave a pulse.

@ 3" - tube and rod motion increasing - real decrease in tube motion between LLS and 6" withdrawal of safety rod as reported from subpile room.

Note: SE rod dropped to a 6.5" and stopped by clutch.

@ 11" - rod motion stopped - tube motion high frequency low amplitude.

@ 13" - rod motion started - mild.

@ 14" - rod motion increased in frequency.

@ 15" - rod motion increased in frequency.

@ 18" - rod motion decreasing in frequency.

@ 19" - rod gives an occasional pulse with a large amplitude.

@ 21" - rod motion decreased dramatically - low frequency - low amplitude - mild

@ 30" - frequency of rod increased - motion still mild.

@ 31" - rod, tube, and tie motion - high frequency.

@ 31.7" - and holding - tube motion from top and subpile room (as bad as we've seen to date).

@ 33" - tube amplitude decreased.

@ 34" - rod and tube motion decreased between 34" and 35" then increased again.

@ 35" - tube and rod motion decreased.

@ ULS - tie motion stopped - tube and rod vibrating at high frequency low-low amplitude - motion continued for approximately 5-15 seconds then stopped completely.

Withdraw N Rod

@ 2" - random motion - very mild.

@ 3" - frequency increase.

@ 5" - amplitude decrease still very mild and random.

@ 8" - frequency increase.

@ ~9+ - tube motion detected - high frequency - low amplitude.

@ 11" - rod motion decreased.

@ 14" - rod frequency increasing - still random and mild.

Note: Binoculars necessary to determine tube motion - cannot thoroughly view through tube with flashlight.

@ 22.4" - rod stopped moving - withdrawal stopped to observe - then rod started very mild random oscillation.

@ 26" - frequency increased.

@ 35" - rod motion stopped.

@ ULS - high frequency very low amplitude in rod and tube - motion stops dead then starts very mild high frequency very low amplitude movement.

Timing motion using wristwatch

Motion starts & lasts	30	21	18 sec
stops for	30	13	30 sec

Scrammed N Rod

Release 14 ms

Drop 147 ms

Withdraw NW Rod

LLS - no motion.

@ 0.5" - rod motion detected - rod drifting within limits of flux trap baffle.

@ 4.5" - motion stopped.

@ 5" - motion (frequency) increased.

@ 6" - frequency increases.

@ 9" - tube gives occasional shudder (pulse).

@ 10" - rod motion random - mild and holding.

@ 12" - and holding - rod tipped toward east and all motion ceased.

@ 13" - tube motion high frequency.

@ 14" - rod motion random - oscillating.

@ 17" - frequency increased on rod.

@ 17.5" - frequency decreased on rod to 28 - rod motion occasional pulse - random - mild. At end of each pulse rod lays toward east.

@ 28" - rod motion regular - mild.

@ 31" - frequency increased on rod.

@ 33" - frequency increased, amplitude decreased.

@ 35.5" - rod motion ceased.

@ ULS - rod and tube calm.

Note: Neck shim drive extensions at elevation
~56' movement down from cold condition
SW - 5/16 other 3 (SE, NE, NW) - 1/4".

D. Subpile Room Observations.

System flow at 47,000 gpm, quadrant $\Delta P = 100$ psi and system temperature 170 °F.

Six prime tubes in loop positions N, NE, E, C, SE and SW. Flow tubes installed in all prime tubes except SE. Accelerometer installed in SE tube at elevation 83'.

All rods in seat:

Slight metal-to-metal contact detected in N, SW & SE - the SW is the loudest. No detectable noise in any of the remaining positions.

Withdrawing rods:

Pulling SE rod:

Slight increase in noise detected at 30-32", displacements recorded continuously on brush recorder during rod withdrawal - displacements decreased when rod reached ULS. With rod at ULS displacements were: N-S 24 mils, E-W 22 mils. Just before the safety rod engaged the inpile tube splines, maximum displacements were 80-90 mils in both N-S and E-W directions.

Pulling S rod:

No detectable vibration or noise during rod withdrawal.

Pulling SW rod:

Vibration noticeably decreased when rod reached 6-8", also noise stopped. At 14" vibration started to increase. At 31.7" stopped withdrawal for observation, tube vibration much worse and loud metal-to-metal contact noted. Continued withdrawal to ULS: vibration less but still easily detectable, noise still noticeable though not so loud. Note: all of a sudden vibration decreased considerably and noise became erratic and decreased considerably.

Pulling N rod:

Detectable slight increase in vibration - noise stopped when rod reached 6-8". Vibration started to increase when rod reached 14". No change in vibration or noise as rod engaged upper splines. At ULS vibration about the same as when rod was seated - slight random knocking noise.

Pulling NW rod:

No detectable change during rod withdrawal. Considerable noise in this position due to snubber tube flush water flow so small increases in vibration or knocking noise not easily detectable.

E. Information Needed to Complete Test Data Package
for Test No. 12.

1. All instrument recordings made.

Test No. 14

4/28/67

Changes For Vibration Test #14

1. Removed B&W stove pipe flow restrictor from SE rod and installed 80 mil tapered flow restrictor on inpile tube at elevation 19" above flux trap baffle. Rod at ULS and strapped.
2. Removed B&W stove pipe flow restrictor from NW rod and installed a 30 mil flow restrictor on IPT at elevation 7'-7-1/2" from top splines.
3. Inserted instrumented hafnium and filler plates in S rod to measure flow rate. (B&W stove pipe flow restrictor on safety rod.) Rod at ULS and strapped.
4. Installed pressure transducers in I-4, 9, 14 and 19.
5. Installed instrumentation to measure movement of reflector tank, flow distribution tank and outlet flow pipes.

Test No. 14

1. As flow is increased observe and record movement of SE rod. At full flow lower SE to 34" and record observations.
2. Observe and record movement of NW rod as flow is increased - at full flow raise NW rod to ~32" or where change in movement is shown. Record rod ΔP , continue raising rod and at various elevations around 32" if change in motion is seen record ΔP .
3. Observe and record movement of SW rod during withdraw to ULS.
4. Record flow readings on S rod at full flow.
5. Record readings of transducers and tank movement.
6. Record accelerometer measurements in SW and SE inpile tubes.
7. Raise N safety rod and record observations.

Ports 1, 4 and 5

25,200 gpm — SE & SW accelerometers located at elev. 83'-0". SE rod at ULS - moving with high freq., low amplitude. Tube movement can be observed by viewing through viewing port.

From subpile room

SE - { N-S - 50 mils } with spikes up to 70 mils
 { E-W - 40 mils } with pronounced banging

SW - { N-S - .006
 { E-W - .006

29,600 gpm —

From subpile room

SE - accelerometer instrumentation saturated
∴ >.100" movement

27,200 gpm — SE - .100" both N-S & E-W

View through tube from top head shows high frequency, low-amplitude, which changes with time (lc), builds up in freq, then dies down for ~1 sec, then builds up again.

Shut down flow & inched SE rod down past collar to LLS.

Starting flow

@ 27,500 gpm - view through tube at top - NO observable motion in tube.

@ 44,000 gpm, 100 psi Δp /quad. - Still no movement on SE from top port or through tube.

W/D N Rod

@ 2" - movement detected.

@ 24" - freq. increases & ampl. increases, very mild & random; motion observed in rod is in definite E-W direction, still random & mild.

@ 11" - freq. & amplitude decreased considerably.

@ 12" - very slight pulse to almost steady

@ 13.5" - regular motion (mild, random), Note: Rod gives occasional pulse.

@ 19" - motion decreased in freq. & ampl. - very very mild again, almost steady.

@ 23" - freq. increases very slightly.

@ 27" - freq. & amplitude increased.

@ 33" - freq. increased.

@ 34+ - ampl, decreasing.

@ 35+'' - rod stopped motion & stayed steady to ULS.

@ ULS - no motion.

Scrammed N rod - release - 8 msec, drop - 173 msec.

High freq., very low ampl, is observable in E & NE tubes as viewed through tube from top head.

W/D NW Rod

@ 4'' - rod motion very mild, low amplitude, must have binoculars to ascertain rod movement.

@ 13'' - motion increased - freq. slight increase, amplitude very slight.

@ 23'' - freq. & ampl. increases mild.

@ 29'' - strong pulse motion.

@ 31'' - strong pulse.

@ 32'' - rod motion stays med. freq. & med. ampl. - Q = 100 gpm on inner annulus.

@ 32.25'' - motion same, Q = 142 gpm on inner annulus.

@ 32.50'' - motion getting worse, then pulses & returns to medium freq. & ampl. Q = 230 gpm.

@ 32.75'' - med. ampl & freq. - motion is pulsing. Q = 280 gpm.

Note: During W/D motion increases.

@ 33.00'' - Very Severe Vibration! Shakes like hell. Had to lower rod to 32.75 to stop vibration; at 32.75, Q = 260 gpm. Bumping rod up at $\approx 32-7/8''$, Q = 275 gpm.

Note: Rod is concentric with tube even when vibration increases.

@ 32-15/16'' - Q = 280 gpm.

@ 33'' - Q $\approx$ 280 gpm.

@ 33.0'' - Bang! Took off again - shakes like hell - dropped to 32.75''. Rod held 1.5 $\rightarrow$ 2 min. then shook very bad again - Q = 260 gpm when shaking; dropped rod to 32.75''.

Lowered Flow

34,000 gpm, $\Delta p'$ = 61 psi —

@ 32-7/8'' - rod motion high freq., amplitude medium.

@ 33.0" - Q = 195 gpm.
@ 33.25" - Q = 195 gpm.
@ 33.50" - Q $\cong$ same.
@ 33.75" - Q = 203 gpm.
@ 34.00" - Q = 204 gpm.
@ 34.50" - Q = 208 gpm.

Raised Flow

40,000 gpm, Δp = 84 psi —

@ 32.75" - Q = 243 gpm.
@ 32-7/8" - motion increased, Q = 251 gpm.
@ 32-15/16" - Q = 251 gpm.
@ 33.0" - Q = 251 gpm.

Dropped to 32.75 to allow plant engr. to obtain data.

@ 33.0" - Q = 271 gpm.
@ 33.5" - holds steady for 20 sec, then violent shaking. Q = 271 gpm, then when violent shaking starts, Q decreases.

W/D SW rod

@ 3" - movement detected - very mild.
@ 6" - freq. increasing.
@ 8" - amplitude increases.
@ 10" - freq. & ampl. decrease.
@ 11" - freq. increase.
@ 12" - motion slowed down, pulsed, & rod assumes position to north - low amplitude, mild motion.
@ 13" - freq. increased - still considered mild.
@ 26" - freq. increased.
@ 28" - slight increase in ampl.
@ 30" - motion increased - high freq., low ampl.
@ 33" - tube motion detected.
@ 34" - high freq., low ampl.
@ ~35" - high freq., very low amplitude.
@ ULS - very mild to steady ampl., high freq.; 0.040 N-S & E-W from sub-pile room.

Lower rod - motion increased in amplitude, decreased freq.

@ 34-3/8" - holding for sub-pile readings — 0.080 E-W, 0.050 N-S

W/D NW Rod

34,400 gpm, $\Delta p = 61$ psi — holding at 34", increasing flow & rod motion increases in freq. & amplitude.

35,200	$Q_{rod} = 228$ gpm	in rod inner annulus
36,800	$Q_{rod} = 228$ gpm	in rod inner annulus
37,400	$Q_{rod} = 237$ gpm	rod motion very high freq.
38,200	$Q_{rod} = 240$ gpm	
38,600	$Q_{rod} = 252$ gpm	rod motion high freq., med. ampl.
39,300	$Q_{rod} = 259$ gpm	during flow increase rod & tube pulsed then settled down to med ampl., very high freq.
39,800	$Q_{rod} = 259$ gpm	
		Rod motion throughout previous readings has remained high freq., med. ampl., with pulses
39,900	$Q_{rod} = 259$ gpm	
40,000	$Q_{rod} = 258$ gpm	
40,150	$Q_{rod} = 259$ gpm	rod movement is increasing in ampl. & freq.; judged to be right on threshold of bad vibration

Test No. 15

5-4-67

A. The following changes were made in the vessel prior to test No. 15.

1. Installed special 40 inch sleeve, designed by B&W, on the SW inpile tube.
2. Special collar installed above top spline on center inpile tube.
3. Installed pressure transducer on static pressure top of SW and SE quadrant of Flow Distribution Tank.
4. SE safety rod run to ULS and strapped. Two accelerometers installed. A special 32" stovepipe type flow restrictor installed inside the safety rod. Accelerometer installed on inpile tube above rod of ULS. One installed on top of rod itself. One below the other in the exact south direction.
5. NW inpile tube moved to N position and N inpile tube moved to NW position. Stovepipe removed from N safety rod. Stovepipe in NW position.
6. Accelerometers installed at elevation 83' in SE and SW inpile tubes.

B. Tests Performed

1. Withdraw SW safety rod and record observations. Record scram times.
2. As flow is increased record accelerometer in SE & SW inpile tube. At full flow make a traverse.
3. Take readings at full flow of instrumented safety rod in S position.
4. Withdraw NW safety rod and record observations. Record scram times.
5. Withdraw N safety rod slowly and record observations. Record rod ΔP when change in rod vibration is detected (eg 32").
6. Tape the output of the microphone as it is lowered into the C, SW, NW, and SW inpile tube.
7. Make traverse of C - in pile tube at full flow.

C. Reactor Top Observations

0910 — Flow started - will go to 80 psi quadrant ΔP to check scram times on SW rod; ports 1, 3, 4.

38,700 flow, ΔP 80 — Withdraw SW rod - accelerometer at 83 feet in SW loop LLS no motion observed; high frequency, low-low amplitude, vibration detected in NE inpile tube with flashlight from top head as viewed down through tube - no motion observable as viewed through viewing port.

Pulling SW rod; at 4" still no motion on rod or tube - rod remains concentric with tube; at 22" occasional pulse was observed in rod - pulse described as very very low amplitude; at 24" and holding rod and tube very stable - view thru tube from top head has not revealed any motion to this point; withdraw from 24" to ULS very mild random motion (beautiful); at ULS rod and tube steady.

Scram SW rod, release time - 16, drop time - 143.

RCR, 43,300 — Withdraw SW rod, 100 psi at 26.5"; at 31" very very low amplitude random motion in rod - no tube motion either thru port of tube view; at ULS steady; dropped flow to 41,300 gpm.

RCR, 43,500 — Scrammed SW rod, 100 psi, release time - 11.5 ms, drop time 135 ms.

Withdraw NW safety rod; at LLS mild random motion; mild random continues; at 8" rod gives occasional pulse; at 9-1/2" tube motion detected - occasional shudder; at 11" rod motion stopped - tube frequency increased, rod leaned toward east; at 13.5" rod motion started - mild-random; at 15" rod amplitude increased - random; at 17" amplitude increased; at 19" motion pulsing - random motion for a period then it increases momentarily then slows down again - during slow motion rod leans toward east; at 34" tube and tie motion stopped; at 35" rod amplitude decreased; ULS high frequency - very low amplitude on rod - tube and tie steady, release time 12 ms, drop time 138 ms.

Withdraw N rod; just off LLS very slight motion; at 2.5 frequency increased - very mild and random and remained same; at 12" rod gave pulse; at 14" frequency in rod motion increased; at 16.5 rod motion stopped, inner flow annulus - 61 gpm; at 28.25 motion detected - rod gives occasional pulse, inner flow annulus - 80 gpm; at 29-3/8 and holding inner annulus 152 gpm; at 30-3/4 rod stopped motion - then gives

occasional pulse very very slight motion on pulse - must be studied to observe, inner flow - 151 gpm; at 31+ frequency increases on rod; at 32.5 rod motion - increased in amplitude - same medium frequency - motion, considered mild, inner flow - 274 gpm; at 33-3/4 frequency increased - medium and frequency and amplitude rod seem to oscillate around tube but does not change general concentricity with tube, inner flow - 368 gpm; at 34 frequency and amplitude decreased - marked decrease in amplitude; at 34-1/4, inner flow - 366 gpm; at 35.5 all motion stopped, inner flow - 376 gpm; at ULS - no motion in rod or tube, inner flow - 339 gpm; testing terminated.

D. Sub-pile Room Observations (Get Jack Clarks)

Accelerometers in SE and SW inpile tubes at elevation 83'. Outputs on brush recorder as follows:

<u>Channel</u>	<u>Reading</u>
1	N-S displacement SW tube
2	E-W displacement SW tube
3	N-S displacement SE tube
4	E-W displacement SE tube

Flow at 20,000 gpm - continuously recording accelerometer outputs while raising flow to 38,900 gpm. (SW safety rod in seat - SE safety rod at ULS)

At 38,900 gpm — SE tube, N-S - 16 mils, E-W - 12 mils; SW tube, N-S - 4 mils, E-W - 6 mils; withdraw SW rod to ULS while continuously recording SW displacement; at ULS, N-S - 10 mils, E-W - 6 mils.

SW tube had maximum displacement of 20 mils - just before safety rod engaged splines on inpile tube. Scrammed SW safety rod and re-recorded displacements with rod in seat; increased flow to 43,300 gpm - pulled SW safety rod to ULS, N-S - 14 mils, E-W - 12 mils.

SW tube had maximum displacement of 24 mils just before safety rod engaged splines on inpile tube. Scrammed SW safety rod and re-recorded displacements with rod in seat, N-S - 6 mils, E-W - 4 mils.

At 43,500 gpm — Pulling NW rod while observing subpile end of NW inpile tube: vibration decreased as rod started withdrawing, started to increase again at 8-10" withdrawn. At 13" noticed a detectable increase in tube vibration, however no knocking noise in tube. Just before safety

rod reached inpile tube splines the tube vibration increased again - noticed a shuddering type vibration. With safety rod at ULS the tube had less vibration than with the safety rod at LLS.

Note: At no time was the tube vibration excessive.

Made a traverse in the SE & SW inpile tubes with the accelerometers. Results were as follows: SW tube - safety rod in seat, elev. 72' - lower splines, N-S - 4 mils, E-W - 4 mils

Note: Acceleration of tube shown by recording.

Elev. 86'-4" - bottom locator tie, N-S - 2 mils, E-W - 2 mils

Note: Very slight acceleration noticed.

SE tube - safety rod at ULS, elev. 72' - lower splines, N-S - 4 mils, E-W - 4 mils

Note: Slight acceleration noticed.

Elev. 86'-4" - bottom locator tie, N-S - 2 mils, E-W - 2 mils

Note: Very slight acceleration noticed.

Center tube - elev. 72' - lower splines, N-S - 6 mils, E-W - 10 mils

Note: Slight acceleration noticed; no knocking.

Elev. 83', N-S - 4 mils, E-W - 4 mils; elev. 86'-4" - top of center flux trap baffle, N-S - 4-6 mils, E-W - 4-6 mils

Note: Tube motion random and slight acceleration noticed.

43,500 gpm — Pulling SW safety rod while listening for noise on subpile end of SW inpile tube. At 9" vibration increased - slight knocking noise detected. Noise stopped when rod withdrawn to 9.25". Could not get safety rod to vibrate on insertion past the 9" position - only on withdrawal past the 9" position. Continued withdrawal. Slight increase in tube vibration at 33-34", however no knocking evident. Raised rod to ULS and vibration decreased considerably to practically nothing. All other inpile tube positions quiet.

E. Information Needed to Complete Test Data

Package No. 15

1. Drawing of flow restrictor installed on SW inpile tube.
2. All instrument data taken.
3. Drawing of 32 inch stovepipe flow restrictor in SE safety rod.

Test No. 16

5-5-67

A. The following changes were made in the vessel prior to Test No. 16.

1. Removed intank accelerometers from SE safety rod and inpile tube.
2. Installed accelerometer at elevation 83' in SE inpile tube.
3. Removed subpile room inpile tube end fixity.

B. Tests Performed

1. Withdraw SE safety rod at 80 psi and full flow and record observations. Record scram times.
2. Record accelerometer readings on SE safety rod while raising flow. Made a traverse at full flow.
3. Make microphone traverse in SE, SW, C, and NW inpile tubes with safety rods at ULS and as requested by V. A. Walker.

C. Reactor Top Observations

38,000, 80 psi ΔP — S-Rod strapped at ULS; withdraw SE rod; rod motion detected as rod withdrawal started; at 6" amplitude decreased; at 12" rod motion stopped; at 13" rod motion started very mild and random; at 14.5 rod frequency increased; rod movement is described as oscillating motion around tube - rod tends to center itself concentric with tube; dropped rod.

Withdraw SE rod; at 2" rod motion - large amplitude - random; at 5" frequency decreases - small amplitude; at 12" motion stopped; at 13+" motion started; at 16" amplitude increases.

Note: View thru C tube at top head shows low frequency - large amplitude motion; in SE tube view - high frequency low amplitude motion - with amplitude increase in pulsing manner; no motion observed through ports.

at 24+ frequency increased slightly; at 26 amplitude decreased motion - med. frequency low amplitude; at 32 amplitude increased on rod; at 33.5 amplitude decreased; at 35 motion stopped; at ULS - no motion, rod steady; subpile room (0.008 N/S, 0.010 E/W) with spikes to 0.015 - 0.018.

Rod scrambled, release time - 11, drop time - 150.

Note: While SE rod held at 24" a scan through tubes at top was made as follows:

NE - High frequency low amplitude
N - Dummy
NW - High frequency low amplitude
W - Dummy
C - Low frequency high amplitude
E - Very high frequency low amplitude
SE - High frequency low amplitude - pulsing
S - Dummy
SW - High frequency low amplitude

Increasing flow; at 40,000 gpm SE rod motion started in seat.

43,500 gpm, 100 psi — Center tube ties placed back on due large amplitude motion as viewed thru tube at top head.

Survey at Full Flow

<u>Ports</u>			<u>Through Tubes</u>
	<u>Tube</u>		
NE	Steady		High frequency low amplitude
N	Steady	Moving in Seat	Dummy
NW	Steady	Steady	High frequency low amplitude
W	Steady	--	Dummy
C	Steady	--	Low amplitude low frequency
E	Steady	--	High frequency low amplitude
SE	Steady	Steady	Steady
S	Steady	Steady (at ULS)	Dummy
SW	Steady	Steady	Pulsing high frequency low amplitude

Note: Above survey made with all end fixity off in subpile room with exception of center which had temporary fix put back on.

Withdraw SE rod; at 3" - medium amplitude - random motion; at 6" - frequency increase amplitude decreased; at 11.5 - rod motion stopped; at 13" - started moving again - small amplitude - random;

at 17" - rod gives occasional pulse also frequency increased; at 24" - rod has random (lazy) motion with occasional pulse; at 26 - frequency increased amplitude still small easily detected with naked eye; rod stays concentric; at 34 - amplitude decreased; at 35 - all motion stopped; at ULS - everything steady.

From subpile room	.020	NS	Max at 34"	.028 NS
	.012	EW		.032 EW

Scrammed SE rod, release time - 10, drop time - 140.

Note: View thru SE pretty steady (small shudder occasionally).

D. Subpile Room Observations

Accelerometer in SE tube at elevation 83'. Output on brush recorder as follows:

<u>Channel</u>	<u>Reading</u>
1	N-S displacement SE tube
2	E-W displacement SE tube

No clamps on subpile end of prime inpile tubes. Flow at 38,000 gpm, quadrant P = 80 psi, SE safety rod at 15" when started recording accelerometer output on brush recorder. Continuously recorded SE tube displacement while safety rod was withdrawn to ULS.

SE safety rod at ULS, SE tube, N-S - 8 mils, E-W - 10 mils

Note: Occasional peak displacements of 15-18 mils.

Scrammed SE rod - recorded tube displacements with rod in seat, N-S - 12 mils, E-W - 8 mils

Note: Subpile room end of center tube vibrating with random radial motion - no knocking.

Increased flow to 43,500 gpm and quadrant P of 100 psi. Center tube now vibrating with radial random motion - maximum movement of lower end of tube in 1/8-3/16". Slight knocking noticed. Replaced clamp on subpile end of center tube and stopped vibration and knocking noise. Recorded accelerometer reading in SE tube with safety rod in seat, N-S - 6 mils, E-W - 12 mils

Note: Noticed slight intermittent noise - no metallic knocking.

Observed tube motion at 43,500 gpm in positions NE, E, SE, NW & SW as follows: SE & NW - slight vibration - slight noise; SW - no vibration or noise; E & NE - very slight vibration - no noise. Observed SE tube vibration on scope - motion random and predominantly radial. Vibration completely stops occasionally but no longer than for one second. Started withdrawing SE safety rod while continuously recording SE accelerometer output. Readings were as follows:

SE tube - accelerometer at 83'; safety rod in seat, N-S - 8 mils, E-W - 8 mils; safety rod at 34", N-S - 28 mils, E-W - 32 mils; safety rod at ULS, N-S - 20 mils, E-W - 12 mils.

Traversed SE & NW tubes with accelerometers:

SE tube - safety rod in seat, elevation 72' - lower splines, N-S - 20 mils, E-W - 24 mils; elevation 83', N-S - 12 mils, E-W - 12 mils; elevation 86'-4" - bottom locator tie, N-S - 4 mils, E-W - 4 mils.

NW tube - safety rod in seat, elevation 72' - lower splines, N-S - 8 mils, E-E - 8 mils; elevation 83', N-S - 12 mils, E-W - 12 mils; elevation 86'-4", - bottom locator tie, N-S - 12 mils, E-W - 8 mils.

SW withdraw with end fix removed as per Hal Larkin & D. P. Halls; LLS to 2+" OK; 2+ to 7" rough - metallic; at 9" metallic sounds (occasionally) then speeds up - cycles; at 9-1/2" sounds stopped - started and stopped again at 10-1/2"; at 28" sounds rougher but acceptable; at 32.6" occasional impact; at 33.5" impact frequency increased; at 34.2" impact frequency decreased; at 35" occasional impact ceased; at ULS OK.

E. Information Needed to Complete Test Data Package No. 16

1. Accelerometer traces.
2. Microphone traces, if available.

Test No. 17

5-8-67

A. The following changes were made in the vessel prior to Test No. 18.

1. Removed B&W flow restrictor from center position.
2. Interchanged E and C inpile tubes.
3. Lowered S instrumented safety rod to 32". Rod strapped.
4. Installed new flow restrictor in center position.
5. Filled SW, SE and NE inpile tubes with water.

B. Tests Performed

1. As flow is increased observe movement of SE, SW, C, E and NE inpile tubes and record accelerometer measurement in C and E in-pile tubes.
2. At full flow, observe and record movement of SE and SW rods during withdraw to ULS.
3. Record flow readings on S rod at full flow.
4. Drain SW inpile tube.
5. Make accelerometer traverse in SW and C at bottom locations on inpile tube at 72' and record.

C. Reactor Top Observations

RCR, 40,000 gpm, 1,500 — Ports 1, 3 and 5; NW rod at ULS - lowered to LLS; SW rod at 6"; S rod at 32" - slight random motion.

44,500 gpm, 100 psi core ΔP — Survey of internals:

	<u>Loop</u>	<u>Rod</u>
NE	Steady	
N	Steady	Very slight movement LLS
NW	Steady	Random movement at LLS more than N
W	Steady	--
C	Steady	--
E	Steady	--
SE	Steady	Random movement at LLS
S	Steady	Random movement at 32"
SW	Steady	Steady

In subpile room - with SW rod at 6" position knocking is easily heard. However, knocking is easily stopped by applying horizontal force to tube in any direction. Knocking only between 2" and 7" of SR withdraw - judged completely acceptable with force applied. SE rod at LLS - knocking and movement easily detected. However, movement can be reduced by applying more force in E/W direction; reduced significantly but not totally stopped by force in N/S direction judged completely acceptable with force applied. E - generally noisy - pulsing knocks. Even then knock can be stopped by application of horizontal force - release of force and knock starts again. Judged with force applied completely acceptable.

Note: This is the most noisy the E position has been - accelerometer .012 EW/NS.

C - at least as good or better than other tests.

Acceptable - Cook - James - Peters
Unacceptable - Larkin

NW - generally noisy with knocking - applying horizontal force in any direction stops knock. Completely acceptable with force applied. NE - beautiful - acceptable.

Pulling SW rod - 5.2" holding - noise and knocking easily detected in subpile room again stopped with horizontal force; at 8.2" holding - same knock stopped with force applied; at 10.75" - severe knocking but not steady - knocks come in pulsing fashion - cannot completely stop with horizontal force; 11.5 motion stopped. No motion observable from top head: from 11.5 - ULS - OK from subpile; very slight motion of rod during withdrawal - must be studied to see - From Top Head.

Withdraw SE rod - at 8" knocking can be stopped (easily) by horizontal force in any direction; at 21" knocking can be stopped by horizontal force in any direction; From Top Head. Rod motion mild and random on withdraw to ULS. No tube motion. At ULS no rod motion - no tube motion.

Note: Relative motion between insulating jacket and inpile tube is detected by movement in subpile room in insulating jacket closure.

Accelerometer traverse run in center tube at following points: 72'-8"; 74'-6"; 77'-6"; 82'-6"; and 85'-6". Purpose of traverse was to ascertain by brush trace any change in motion of inpile tube at these points. This could indicate striking between inpile tube and jacket (points of support). Only random spikes were detected and none were considered indicative of positive striking.

SW tube was drained to allow traverse; accelerometer elevation 72'; rod at 10.75" occasional steady pulses - swamps instruments; lowered rod to 6" - strong regular impulse, frequency - 1 cps with higher, frequency - 12 cps.

Holding rod at 6"; accelerometer at 74'-6" same strong regular impulses at same frequency; accelerometer at 77'-6" - same; at 80' (core mid plane), frequency same - magnitude less; at 82'-6" - no motion detected; at 85'-6" - minor motion detected.

Withdraw SW rod to 36"; accelerometer at 77'-6"; rod at 33" - bobble in EW direction; at ULS - no motion.

D. Subpile Room Observations

All clamps were removed from inpile tubes prior to starting primary system flow. Accelerometers installed in center inpile tube at elevation 79' and in East inpile tube at elevation 83'.

Accelerometer outputs connected to brush recorder as follows:

<u>Channel</u>	<u>Item</u>
1	Center tube N-S displacement
2	Center tube E-W displacement
3	East tube N-S displacement
4	East tube E-W displacement

Increased flow to 25,000 gpm while visually observing subpile end of inpile tubes. No detectable vibration or noise any position. Have instrument troubles on accelerometers so did not obtain any readings.

Slowly increased flow to 40,000 gpm - center tube started a slight random vibration - no noise. No vibration or noise in any other vibration.

Flow increased to 45,000 gpm - 100 psi quadrant ΔP . Center tube moving 1/8" to 3/16" on bottom end of inpile tube - slight intermittent

knocking noise. Put subpile clamps on center tube; still have slight vibration and very slight intermittent knocking noise. SW tube with safety rod in seat - have very slight vibration and slight knocking noise. SE tube with safety rod at ULS - very slight vibration and intermittent light knocking noise. Positions NW, N, NE, S and W have only flow noise - no knocking. East position has occasional slight rattling noise - no visible vibration. Ran accelerometer traverse in East tube with following results: elevation 72', N-S - 10-12 mils, E-W - 12 mils; elevation 83', N-S - 12 mils, E-W - 10 mils; elevation 86'-4", N-S - 12 mils, E-W - 8 mils. Very definite acceleration; spikes indicating tube is striking something.

Switched accelerometer from East tube to center tube and made a traverse in the center tube: elevation 72', N-S - 16 mils, E-W - 12 mils; elevation 79', N-S - 16 mils, E-W - 12 mils.

E. Information Needed to Complete Test Data Package No. 17

1. Accelerometer traces.

Test No. 18

5-10-67

A. The following changes were made in the vessel prior to Test No. 18.

1. Disconnect inst. leads from N dummy tube. Switch N end NW tubes - move stovepipe flow restrictor from NW to North safety rod. Reconnect inst. leads on dummy tube (now in NW position). Transfer constant magnet power supply from N to NW safety rod.
2. Remove stovepipe from SW safety rod, label and store in SS office.
3. Lower S safety rod to seat.
4. Install accelerometers on SE safety rod and inpile tube with safety rod at ULS and constant magnet power supply.
5. Drain water from SE and NE inpile tubes.
6. Accelerometers in SE tubes at elevation 83.

B. Tank Conditions for Test No. 18

1. NW position - instrumented dummy inpile tube with clamp on flow restrictor 7'-7-1/2" below upper spline. Safety rod with no flow restrictor. Clamp-on flow restrictor acts as flow control device for flow between inpile tube and safety rod as safety rod is raised and lowered. Constant magnet power supply on safety rod to prevent scram of rod.
2. N position - prime inpile tube and 12" stovepipe flow restrictor in safety rod. No constant magnet power supply on safety rod.
3. NE position - prime inpile tube with special 12" stovepipe flow restrictor in dummy flux trap filler. Dummy flux trap filler is modified to tighten clearance between flux trap filler and flux trap baffle.
4. W position - gas loop dummy tube with modified flux trap filler to tighten clearance between flux trap filler and flux trap baffle.
5. C position - prime inpile tube with KAFL clamp-on flow restrictor on inpile tube. Flow restrictor clamped on upper splines - tighten clearance between splines and center flux trap baffle flange, also acts as flow restrictor.
6. E position - prime tube with modified upper splines (splines on splines) and special 12" stovepipe flow restrictor in dummy flux trap

filler. Dummy flux trap filler is modified to tighten clearance between flux trap filler and flux trap baffle.

7. SW position - prime tube with special B&W 40" clamp on flow restrictor attached to the inpile tube. The 12" stovepipe flow restrictor was removed from the safety rod for this run.

8. S position - instrumented dummy inpile tube and instrumented safety rod with 12" stovepipe flow restrictor. Rod lowered to seat for additional flow measurements.

9. SE position - prime tube with Vince Walker type 32" stovepipe flow restrictor. Safety rod withdrawn to ULS and strapped with constant magnet power supply. Accelerometer attached to safety rod and inpile tube gas jacket.

C. Tests Performed

1. Observe and record movement inside the reactor vessel, the inpile tubes in the subpile room and the accelerometer readings in SE safety rod as flow is increased to 100 psi core ΔP .

2. Withdraw EW rod. Observe and record observations in subpile room and reactor tank. Record accelerometer readings as rod is withdrawn. Record scram time.

3. Record accelerometer reading in the SE at ULS and the SW safety rod at elevations 72', 74'-6", 77'-6", 82'-6", 85'-6" and 80' with the safety rod at LLS and ULS.

4. Tape I-4, 9, 14 and 19 transducer readings and SE and SW quadrant ΔP tape as directed by V. A. Walker.

5. Record SE safety rod and inpile tube accelerometer readings as requested by V. A. Walker.

6. Observer (listen) to SW rod in subpile room as safety rod is continuously withdrawn at full flow. Larkin of KAPL is to be the observer in the subpile room.

7. Withdraw NW as directed by R. A. Clemons and record data.

Caution: Don't let rod and tube rattle excessively.

D. Reactor Top Observations

RCR, 42,800, 100 psi ΔP — NW rod at 24" - rod is moving with large amplitude random motion. Rod lowered to LLS. Very hard to see!

Note: Only one intank light on - this is on "B" side of vessel; clear tank observations are limited to south side of tank and core region.

Core survey based on note above.

SE at LLS - steady

S at LLS - slight motion in rod

SW at LLS - slight motion in rod

Withdraw SW safety rod; LLS slight motion; at 4" motion increases considerably - pulsing motion; at 5" frequency increased - high frequency low amplitude; at 8" Larkin says sound better than at LLS; at 12" frequency increased rattling noise detected in subpile room - random motion; at 14" amplitude decreased; at 17" slight increase in noise (rattling); at 24" and holding - amplitude and frequency decreased; at 25" rod steady - no noise in subpile room occasional lazy movement; at 31" frequency and amplitude increased; at 32.5" noise from subpile room - hitting harder, high frequency low amplitude; at 33" noises increased; at 34" noises decreased; at ULS rod-tube vibration tie steady then gives occasional slight pulse!

Larkin: Some metal to metal sound all the way. Never as bad as heard during last test in 2 to 7" and 9 to 11" range. Worst position this run 32.5". Impact estimated twice that heard at LLS. All other ranges slightly less or slightly more than that heard at LLS; release time - 17 ms, drop time - 145 ms, release time - 10 ms, drop time - 136 ms.

SW at 6" and holding. Sounds same as when rod moving through position.

Withdraw NW safety rod; at LLS inner annulus flow - gpm; at 6" 82 gpm flow; at 7" movement detected random mild; at 10" motion stopped; at 12" rod gives occasional pulse; at 15 pulses start again; at 16 frequency increases, med.frequency amplitude can be seen with naked eye; at 19 frequency decreased med.amplitude - rod pulses; at 28" rod pulses with high frequency - med.amplitude; at 29" inner annulus - 103 gpm, inner annulus - 153 gpm; at 30" inner annulus - 158 gpm; at 31" inner annulus - 158 gpm (dropped SW rod to 11-1/4" from 33-1/2" - investigating cause for drop); at 32" inner annulus - 181 gpm; at 33

inner annulus - 354 gpm; at 33-1/4 inner annulus - 379 gpm; at 33-1/2 inner annulus - 398; at 33.8 rod lowered due to excessive vibration as rod approached 34.

Conclusion of Subpile Room Observations

The SW position over the entire range LLS to ULS is generally as good as that heard with both fixes as installed in Test No. 17. Noise is considered worse at LLS and all positions up to ULS. However, this noise is not the metallic knocking noise (i. e.) louder background noise. It is noticed during withdrawal and particularly at 32 to 33-1/2" that metallic noise is present but it is not as bad as heard at 10-3/4" in Test No. 17. At 33" knocking could be stopped with horizontal force applied. General consensus is that this fix alone is as good as compound fix of Test 17.

E. Subpile Room Observations

Accelerometer inside SE inpile tube at elevation 83'. SE safety rod at ULS and strapped with accelerometer strapped to outside of safety rod at top of flux trap baffle. Another accelerometer strapped to outside of SE tube gas jacket just above safety rod. Center inpile tube sub-pile vibration clamps installed - removed clamps from all other inpile tubes. Continuously recorded accelerometer readings as flow was increased.

43,000 gpm — Flow to 43,000 gpm and 100 psi quadrant ΔP . At 43,000 gpm, SE inpile tube displacements were: N-S - 16 mils, E-W - 16 mils

Visual observations at full flow on prime inpile tubes were as follows:

Note: All flow tubes removed.

SW tube - detectable vibration and slight rattling noise.

SE tube - slight vibration and rattling noise.

N tube - very slight vibration - no noise.

NE tube - no vibration - no noise.

E tube - no vibration, occasional very light rattle.

C tube - slight vibration, occasional light rattle.

Transferred accelerometer to inside SW inpile tube at elevation 83' - SW safety rod in seat: N-S - 8 mils, E-W - 8 mils. Occasional spikes to 12 mils. Raised safety rod to 24" and holding: N-S - 8 mils, E-W - 8 mils. Occasional spikes to 12 mils. Continued withdrawal of safety rod - at 32.5" observed maximum tube displacement of 16-20 mils both N-S and E-W. Raised safety rod to ULS: N-S - 12 mils, E-W - 12 mils.

Traversed inside of SE and SW inpile tubes at elevations 72', 74'-6", 77'-6", 80'-0", 82'-6" and 85'-6" to determine if gas jacket was hitting spacers on inpile tube. All measurements recorded on brush recorder. Did not observe any evidence of gas jacket hitting inpile tube spacers on either tube.

F. Information Needed to Complete Test Data Package No. 18

1. Instrument data from V. A. Walker and R. A. Clemons

Test No. 19

A. The following changes were made in the vessel prior to Test No. 19.

1. Removed the stovepipe flow restrictor from the SW safety rod and installed a 3" long flow restrictor in rod. The flow restrictor is the top 3" of a stovepipe restrictor. The 40" flow restrictor is installed on the inpile tube.
2. Removed the 32" stovepipe flow restrictor from the SE rod and the accelerometers from the rod and inpile tube. Installed a 40" flow restrictor on the inpile tube just below the upper splines. The flow restrictor is sized to give the same annulus as a B&W stovepipe and inpile tube flow restrictor combination.
3. Removed the inpile tube flow restrictor from the NW tube and installed a 12" stovepipe flow restrictor in the rod.
4. Accelerometers located in the SE and SW inpile tube.
5. Install eddy-current device in SW inpile tube.

B. Tests Performed

1. Observe and record observations from top head and subpile room as flow is increased to full flow.
2.
 - a. Withdraw the SE rod. Record observations and readings from the top head and subpile room. Get scram time.
 - b. Run an accelerometer traverse in the SE inpile tube.
 - c. Record rod drop time on SE rod.
3.
 - a. Withdraw the SW rod. Record observations and readings from the top head and subpile room. Get scram time.
 - b. Run an accelerometer traverse in the SW inpile tube.
 - c. Record rod drop time on SW rod.
4. Record flow readings on NW rod.

C. Tank Conditions for Test No. 19

1. NW Position — Instrumented dummy inpile tube. Safety rod with 12" stovepipe flow restrictor.
2. N Position — Prime inpile tube and 12" stovepipe flow restrictor in safety rod. No constant magnet power supply on safety rod.

3. NE Position — Prime inpile tube with special 12" stovepipe flow restrictor in dummy flux trap filler. Dummy flux trap filler is modified to tighten clearance between flux trap filler and flux trap baffle.

4. W Position — Gas loop dummy tube with modified flux trap filler to tighten clearance between flux trap filler and flux trap baffle.

5. C Position — Prime inpile tube with KAPL clamp-on flow restrictor on inpile tube. Flow restrictor clamped on upper splines - tightens clearance between splines and center flux trap baffle flange, also acts as flow restrictor.

6. E Position — Prime tube previously used in center with modified upper splines (splines on splines) and special 12" stovepipe flow restrictor in dummy flux trap filler. Dummy flux trap filler is modified to tighten clearance between flux trap filler and flux trap baffle.

7. SW Position — Prime tube with special B&W 40" clamp-on flow restrictor attached to the inpile tube. Safety rod with 3" stovepipe flow restrictor.

8. S Position — Instrumented dummy inpile tube and instrumented safety rod with 12" stovepipe flow restrictor. Rod lowered to seat for additional flow measurements.

9. SE Position — Prime tube with special 40" clamp-on flow restrictor to give same annulus as combination of B&W 40" clamp-on restrictor and 12" stovepipe restrictor. The 12" stovepipe was removed from the SE safety rod.

D. Reactor Top Observations

25,000 gpm, 40 psi ΔP — ports 1, 3, 4; only one tank light available - located in "S" side of tank. Core survey with naked eye; SE - rod at LLS and tube steady; S - rod at LLS possible movement, tube steady; SW - rod at LLS and tube steady. No movement detected in any other core positions. From top head as viewed through tube - NW and N tubes have high frequency very low amplitude movement - must have flashlight to detect.

35,000 gpm, 70 psi ΔP — Withdraw SE rod (6X binoculars used for observation). Subpile room reports slight knock on SE as rod removed from LLS .010 at 8" withdrawn.

Top head - from LLS - very low amplitude random motion; at 10" amplitude and frequency increased; at 12" amplitude and frequency decreased to previous level, i.e., low amplitude random; at 17" rod motion decreased - very slight movement; at 24" very slight motion holding for scram set; to ULS remained very slight motion until ULS; at ULS motion stopped - rod and tube steady. Lower rod to 33" to observe contact of rod and collar - very smooth operation; at ULS rod and tube steady, scram SE rod, release time 11, drop time 157.

RCR, 42,500 gpm, 100 psi ΔP - Core survey; rods NW, N, SE, S moving at LLS - NW moves most - no other movement detected in core.

42,500 gpm, 100 psi ΔP - Withdraw SE rod - very slight motion at 3"; at 5-1/2" rod motion same amplitude - same increase in frequency; at 8-1/2" some tube motion - rod same; at 10" more tube motion - rather severe - not high frequency, definitely rod driving tube as judged from top head. Lowered SE rod to LLS due to banging heard in subpile room which was determined as too severe to merit further withdrawal.

Withdraw SW rod; at 2" very slight random motion; at 10" motion very difficult to detect, must be studied; at 17" motion increased - gave "wobble" then back to mild random type motion; at 24" and holding - very very slight motion; at 32" frequency increased amplitude is same; at 35" all motion stopped; at ULS rod and tube steady.

Scram SW rod, release time 12, drop time 138.

Withdraw SW rod and ran accelerometer traverse, scram SW rod, release time 10, drop time 140.

General consensus of SW tube at various points of investigation (3", 4", 10+", and 33 to ULS) - Noise as detected from subpile room is judged as good as that during Test 17 with much less mechanical knocking than heard at 2" to 7" and 10+" locations during Test 17.

It was noted that of the two traverses run the second gave less noise than first run. First run was generally comparable to Test 18 whereas second resulted in less noise, i.e., comparable to quieter parts of Test 17.

Fixes incorporated are judged acceptable with horizontal force applied. Even noisiest points of second run were easily stopped with slight horizontal force.

E. Subpile Room Observations

Accelerometer installed in SE inpile tube at elevation 83'-0", SE safety rod in seat. Brush recorder channels hooked up as follows:

<u>Channel</u>	<u>Reading</u>
1	SE spare d/p tap - transducer
2	SW spare d/p tap - transducer
3	SE tube, N-S displacement
4	SE tube, E-W displacement
5	I-hole transducer No. 322
6	I-hole transducer No. 315
7	I-hole transducer No. 316
8	I-hole transducer No. 312

Increased flow to 25,500 gpm and started brush recorder. SE tube displacements were as follows: N-S - 4 mils, E-W - 4 mils. Increased flow to 30,000 gpm and recorded displacement readings on SE tube: N-S - 4 mils, E-W - 4 mils. Increased flow to 35,000 gpm and recorded displacement readings on SE tube: N-S - 4 mils, E-W - 6 mils.. At 35,000 gpm flow; very light occasional tap in SE tube - safety rod in seat; light occasional tap in SW tube - safety rod in seat; frequent light tap in N tube - safety rod in seat.

Pulling SE safety rod: slight knocking occurred as started with-draw. Have acceleration spikes at 5" and 9.7" - noticed steady increase in tube displacement. Stopped rod at 9.7" for displacement readings: N-S - 16-20 mils, E-W - 16-20 mils.

Note: Have occasional acceleration spikes while holding rod at 9.7".

Pulled rod to 24" and stopped: N-S - 12 mils, E-W - 8 mils. At 30" displacement started increasing again: average 20 mils with spikes to 28 mils. Rod at ULS: N-S - 12 mils, E-W - 16 mils

Note: Tube is quieter with rod at ULS than with rod at LLS.

Scrammed rod - tube displacements with rod seated: N-S - 4 mils, E-W - 4 mils.

Increased flow to 40,000 gpm - SE safety rod in seat - SE tube displacements were: N-S - 4 mils, E-W - 4 mils. Increased flow to 42,500 gpm; 100 psi core ΔP - SE safety rod in seat - SE tube displacements were: N-S - 4-8 mils, E-W - 4-8 mils.

42,500 gpm — Observed all tubes with full flow:

N tube - detectable knocking, slight motion of end of tube - no clamp on tube in subpile room.

NE tube - occasional light knock - no detectable motion of end of tube - no clamp on tube in subpile room.

E tube - occasional light knock - barely detectable motion of end of tube - no clamp on tube in subpile room.

SE tube - slight shuddering vibration with occasional sharp knock. No clamp on tube in subpile room. Slight motion of end of tube.

SW tube - very light steady tap - no clamp on tube in subpile room. Slight motion of end of tube.

C tube - same steady pulsing motion as observed during Test No. 18. Occasional light knock. Subpile clamp installed on end of tube to decrease motion and knock.

Started to withdraw SE safety rod at full flow - stopped at 10" due to severe knocking - lowered rod to seat.

Moved accelerometer to SW tube at elevation 83'-0". SW rod in seat - displacements were: N-S - 4 mils, E-W - 4 mils. Raised SW safety rod to ULS: N-S - 20 mils, E-W - 12-16 mils with occasional spikes to 24 mils. With SW safety rod at ULS: this tube sounds excellent, slight occasional tap, slight vibration of end of tube.

Detected slight knocking at 4" on first withdrawal so positioned rod at 4" and made traverse with accelerometer: elevation 83', N-S - 4 mils, E-W - 4 mils; elevation 72', N-S - 8 mils, E-W - 8 mils; elevation 85'-6", N-S - 4 mils, E-W - 4 mils.

Lowered accelerometer to 72' to observe tube motion while safety rod was withdrawn to ULS: displacement worse at 33-34" during withdrawal - not over 20 mils total.

Rod at ULS: N-S - 12 mils, E-W - 8 mils

F. Information Needed to Complete Test Data Package No. 19

1. Instrument data taken.

Test No. 20

A. The following changes were made in the vessel prior to Test No. 20.

1. Removed dummy inpile tube from NW position. Removed 12" stovepipe flow restrictor from NW safety rod and inserted a 3" stovepipe flow restrictor. Installed a 40" flow restrictor on a prime IPT just below the upper splines and inserted the inpile tube into NW.

2. Pulled N prime inpile tube and installed a 40" flow restrictor on inpile tube just below the upper splines. Removed 12" stovepipe flow restrictor from N safety rod and inserted a 3" stovepipe flow restrictor. Reinserted the inpile tube into N.

3. Removed the NE prime inpile tube. Installed a 40" flow restrictor on the dummy tube removed from NW (step 1) and inserted the dummy tube in NE.

4. Pulled center prime inpile tube and installed a 40" flow restrictor on inpile tube. Reinserted the inpile tube with flow restrictor in center.

Note: Left the KAPL type flow restrictor clamped on the center tube upper splines.

5. Removed the E prime inpile tube. Installed a 40" flow restrictor on a dummy tube and inserted the dummy tube in E.

6. Removed the S dummy tube. Removed 12" stovepipe flow restrictor from S safety rod and inserted 3" stovepipe flow restrictor. Installed a 40" flow restrictor on the prime inpile tube removed from the E (step 5) and inserted the inpile tube into the S.

7. Pulled SE prime inpile tube and removed a 40" flow restrictor from inpile tube. Installed a 40" flow restrictor on inpile tube of smaller OD than the one removed. Installed a 3" stovepipe flow restrictor in SE safety rod. Reinserted inpile tube into SE.

B. Tank Conditions for Test No. 20

1. NW Position - Prime inpile tube with 40" clamp-on flow restrictor attached to the tube just below the upper splines. Safety rod with 3" stovepipe flow restrictor.

2. N Position - Prime inpile tube with 40" clamp-on flow restrictor. Safety rod with 3" stovepipe flow restrictor.

3. NE Position - Instrumented dummy tube with 40" clamp-on flow restrictor. Special 12" stovepipe flow restrictor in dummy flux trap filler. Dummy flux trap filler is modified to tighten clearance between flux trap filler and flux trap baffle.

4. W Position - Gas loop dummy tube with modified flux trap filler to tighten clearance between flux trap filler and flux trap baffle.

5. C Position - Prime inpile tube with 40" clamp-on flow restrictor. KAPL clamp-on flow restrictor attached to upper splines to tighten clearance between splines and center flux trap baffle flange.

6. E Position - Instrumented dummy tube with 40" clamp-on flow restrictor. Special 12" stovepipe flow restrictor in dummy flux trap filler. Dummy flux trap filler is modified to tighten clearance between flux trap filler and flux trap baffle.

7. SW Position - Prime inpile tube with B&W 40" clamp-on flow restrictor. Safety rod with 3" stovepipe flow restrictor. Same as Test No. 19.

8. S Position - Prime inpile tube with 40" clamp-on flow restrictor. Safety rod with 3" stovepipe flow restrictor.

9. SE Position - Prime inpile tube with 40" clamp-on flow restrictor. Safety rod with 3" stovepipe flow restrictor.

C. Tests Performed

1. Observe and record observations, of all loops and safety rods, from top head and subpile room as flow is increased to full flow.

2. a. Withdraw SW rod. Record observations and readings from the top head and subpile room.

b. Record drop time on SE rod.

3. Transfer accelerometer to SE tube. Position at 83' elevation.

a. Withdraw SW rod. Record observations and readings from the top head and subpile room.

b. Record drop time on SW rod.

4. Withdraw N, NW and S safety rods. Record observations from the top head and subpile room. Record drop times on all three rods.

5. Record flow readings on NE and E dummy inpile tubes.
6. Record observations from top head and subpile room on center, NE, and E prime inpile tube.
7. Run eddy-current measurements in NW, N, SW, S and SE in-pile tubes with safety rods at ULS at full flow and no flow.

D. Reactor Top Observations

35,000 gpm — Core survey ports 1, 3, 4. All positions loop and rod (with naked eye) are steady through ports. High frequency very low amplitude pulse can be seen with flashlight shined into "S" tube.

41,700 gpm, 100 psi ΔP — Core survey - All positions loop and rod - Steady (naked eye). Withdraw SE rod; at 8" very slight random motion; at 22" rod gave pulse - low amplitude and low frequency then returned to steady with occasional slight hard to detect motion; at 25" motion less difficult to detect still very slight; at 28" frequency increased slightly; at ULS rod and tube steady; scrambled SE rod, release time - 10 m/sec, drop time - 140 m/sec.

Withdraw "South" rod; at 10" rod pulsed - then steady and remains steady - pulse was very mild; at 27" rod gave slight pulse. Other than two pulses noted above rod steady throughout withdrawal.

Note: With rod at LLS vibration can be felt intermittently by standing on tube closure at top head with rod being withdrawn, no vibration felt.

Scrammed South rod; release time - 12 m/sec, drop time - 145 m/sec.

South rod has loud noise with sharp metallic knocks as heard in subpile room with rod at LLS. Rod pulled to 7" where loop is completely steady. From top head S rod has mild movement at 7" position. (Loop has temporary ties on in subpile room.)

Withdraw SW rod; from LLS rod very steady; at 17+ rod gave slight pulse then returned to steady; at 26" rod again gave pulse and then returned to very mild occasional movements not the steady condition exhibited prior to 26" but judged very mild occasional movements; at ULS rod and tube steady.

Scram SW rod; release time - 11, drop time - 135.

Withdraw N rod; subpile room reports severe "banging" at 4" withdrawn; at 6" high frequency, low amplitude motion; at 10" motion decreased; at 11" motion stopped - rod and tube steady; at 14" mild motion started; at 17" motion stopped - tube and rod steady; at 28" mild motion started; at 33" high frequency - low amplitude motion; at 35" all motion stopped; at ULS rod and tube steady!

Scram N rod; release time - 11 m/sec, drop time - 148 m/sec.

Withdraw NW rod; very mild motion of rod at 8"; at 9" no motion; at 14" pulse then very mild motion; at 18" no motion detected; at 22" very mild motion; at 24" holding, motion mild; at 31" low amplitude high frequency; at ULS no motion tube or rod.

Scram NW rod; release time - 11 m/sec, drop time - 135 m/sec.

Top head observations on NE and E dummy tubes - both tubes and dummy flux trap fillers steady. Top head observation on center prime tube steady.

Conclusion

Due to the noise and metallic contact detected in the subpile room it was suggested and agreed by INC. ID, and KAPL to run another test May 23, 1967 with the same condition as existed for this test with the following change.

- a. Remove the 40" collars from the N & S positions.

This was agreed to based upon the KAPL statement that the "S" tube could not be stopped from metallic banging by the application of moderate horizontal force as was used on the SW during Test No. 17.

E. Subpile Room Observations

Accelerometer installed in SE tube at elevation 83'. Brush recorder inputs as follows:

<u>Channel</u>	<u>Input</u>
1	SE tube, N-S displacement
2	SE tube, E-W displacement
3	SE flow distribution tank P pressure transducer
4	SW flow distribution tank P pressure transducer
5	I-9 pressure transducer (SE)
6	I-14 pressure transducer (SW)
7	I-19 pressure transducer (NW)
8	I-4 pressure transducer (NE)

Started test with all safety rods at LLS.

Raised flow to 35,000 gpm: NW, C, SW & SE positions quiet; N - slight intermittent vibration and light knock; S - detectable vibration of subpile and of inpile tube, erratic light knock with loud knock approximately every 30 seconds.

Note: Subpile end clamps installed prime tubes
in NW, C, SW & SE - not installed on N & S.

Raised flow to 40,000 gpm: no change tube vibration over that observed at 35,000 gpm. Raised flow to 42,500 gpm (full flow).

SE tube displacements with safety rod seated were: N-S - 4 mils, E-W - 4 mils.

Pulled SE safety rod to ULS while continuously recording SE tube displacement. Had maximum of 8 mils displacement just before safety rod reached upper inpile tube splines: at ULS, N-S - 6 mils, E-W - 6 mils.

Traversed SE tube with accelerometer with safety rod at ULS. Results were as follows: elevation 72', N-S - 4-6 mils, E-W - 4-6 mils; elevation 73'-6", N-S - 8-12 mils, E-W - 8-10 mils; elevation 77'-6", N-S - 14 mils, E-W - 14 mils; elevation 80', N-S - 10 mils, E-W - 10 mils; elevation 82'-6", N-S - 8 mils, E-W - 8 mils; elevation 85'-6", N-S - 4 mils, E-W - 4 mils.

Installed subpile clamps on N & S tubes - stopped noise in N & S tubes.

Note: Approximately 10 minutes after installing clamp on S tube the knocking noise returned. Transferred accelerometer to S tube at elevation 77'-6" - recorded S tube displacements with safety rod in seat: N-S - 20 mils, E-W - 40 mils.

Have many acceleration spikes showing on recorder.

Raised S safety rod to ULS: N-S - 12-16 mils, E-W - 12-16 mils. Traversed S tube with accelerometer - results recorded on chart. Positioned S safety rod to 7" for remainder of test as there is no vibration or knocking observed at this point.

Transferred accelerometer to SW tube and positioned at elevation 77'-6". Safety rod in seat: N-S - 6 mils, E-W - 6 mils. Raised SW safety rod to ULS: N-S - 8-10 mils, E-W - 6-8 mils.

Note: With SW safety rod at 2" had maximum tube displacement in N-S direction of 30 mils. Tube displacement decreased to less than 10 mils when safety rod reached 4".

With safety rod at ULS lowered accelerometer to 80' and recorded maximum tube displacement of 12 mils. Observed occasional acceleration spikes with accelerometer at 80;

Transferred accelerometer to N tube and positioned at 77'-6".

Rod at LLS, N-S - 8 mils, E-W - 16 mils; rod at 4", N-S - 24 mils, E-W - 12 mils; rod at ULS, N-S - 12 mils, E-W - 20 mils.

Traversed N tube with accelerometer results are on chart.

Transferred accelerometer to NW tube and positioned at elevation 77'-6".

Rod at LLS, N-S - 8 mils, E-W - 8 mils; rod at ULS, N-S - 12 mils, E-W - 12-18 mils.

Note: With rod at 3'-6" observe occasional acceleration spikes and tube displacement of 40 mils maximum.

Transferred accelerometer to center tube and traversed tube: elevation 72', N-S - 8 mils, E-W - 8 mils; elevation 74'-6", N-S - 8 mils, E-W - 8 mils; elevation 77'-6", N-S - 8 mils, E-W - 8 mils;

elevation 80', N-S - 8 mils, E-W - 8 mils; elevation 82'-6", N-S - 4 mils, E-W - 8 mils; elevation 85'-6", N-S - 4 mils, E-W - 4 mils.

F. Information Needed to Complete Test Data Package No. 20

1. Instrument data taken.
2. NE and E ΔP readings.
3. Eddy-current measurements.

Test No. 21

5-23-67

A. The following changes were made in the vessel prior to Test No. 21.

1. Transferred instrumented dummy tube from NE to NW.
2. Transferred SW prime tube to NE.
3. Transferred prime tube removed from NW to SW.
4. Switched the E dummy tube with the center prime tube as set up for vibration test No. 20. Installed KAPL type flow restrictor on center dummy tube. The flow restrictor clamps on the upper splines.
5. Removed 40" flow restrictors from N & S prime inpile tubes and reinserted inpile tubes in their respective positions.

B. Tank Conditions for Vibration Test No. 21

1. NW Position - instrumented dummy tube with 40" clamped-on flow restrictor and 3" stovepipe flow restrictor in NW safety rod.
2. N Position - prime inpile tube and 3" stovepipe flow restrictor in N safety rod.

Note: The 40" inpile tube clamp-on flow restrictor was removed for this test.

3. NE Position - prime inpile tube with 40" B&W type clamp-on flow restrictor. Dummy flux trap filler with special 12" stovepipe flow restrictor.
4. W Position - gas loop dummy tube with modified flux trap filler to reduce clearance between flux trap filler and flux trap baffle.
5. C Position - instrumented dummy tube with 40" clamp-on flow restrictor and KAPL type flow restrictor clamped to upper splines.
6. E Position - prime inpile tube with 40" clamp-on flow restrictor. Dummy flow trap filler with special 12" stovepipe flow restrictor.
7. SW Position - prime inpile tube with 40" clamp-on flow restrictor and 3" stovepipe flow restrictor in SW safety rod.
8. S Position - prime inpile tube and 3" stovepipe flow restrictor in S safety rod.

Note: The 40" inpile tube clamp-on flow restrictor was removed for this test.

9. SE Position - prime inpile tube and 3" stovepipe flow restrictor in SE safety rod.

C. Tests Performed

1. Install accelerometer in S prime tube at elevation 77'-6".
Observe tube motion as flow is increased to full flow.
2. Observe all positions from top head and subpile room as flow is increased to full flow.
3. a. Withdraw S safety rod at full flow while continuously observing from top head and subpile room.
b. Scram S rod. Record scram time.
4. a. Transfer accelerometer to N tube and position at elevation 77'-6".
b. Withdraw N safety rod while continuously observing from top head and subpile room.
c. Scram N rod. Record scram time.
5. a. Transfer accelerometer to SW tube and position at elevation 77'-6".
b. Withdraw SW safety rod while continuously observing from top head and subpile room.
c. Scram SW rod. Record scram time.
6. Transfer accelerometer to NE tube and run traverse at 72', 74'-6", 77'-6", 80', 82'-6" and 85'-6".
7. Transfer accelerometer to E tube and run traverse at same elevations as those for NE tube in step 6.
8. Record ΔP readings on NW and C instrumented dummy tubes.

D. Reactor Top Observations

35,000 gpm — All top head observations unless otherwise noted are made with naked eye. Core survey - no detectable motion in rods or tubes as viewed from ports 1, 3, & 4. View through N tube with flashlight shows high frequency, low amplitude movement.

Note: At 40,000 gpm north tube is vibrating as viewed through window No. 1. Movement is high frequency low amplitude.

43,000 gpm, 100 psi ΔP — Top Head Observations

	Port View		Tube View
	Rod	Tube	
NW	Steady	Steady	--
N	Steady	High frequency, large amplitude*	High frequency, medium amplitude
NE	--	Steady	High frequency, low amplitude
E	--	Steady	High frequency, low amplitude
C	--	Steady	--
W	--	Steady	--
SW	Steady	Steady	High frequency, low amplitude
S	Steady	Steady	Frequency lower than SW
SE	Steady	Steady	Steady

* used 7 x 50 binoculars

Withdraw North rod; at 4" tube steady - rod mild random motion.

Withdraw S & SE; mod. random motion of S rod at 7.

S Rod	SE Rod
S near steady at 11"	No motion of SE to 13"
S random motion at 15"	Occasional strong pulse of SE 13 - 25
Frequency decreased at 18" a rod	Very low amplitude - high frequency - shake 13 - 27"
High frequency, low amplitude of S rod at 27" occasional strong pulse	Rod and tube steady at ULS, SE
Frequency of S rod increasing at 29"	Movement of rod very hard to detect except for occasional pulse
Frequency and amplitude decreased at 34" S rod	Rod and tube steady at ULS
Rod and tube steady at ULS S rod	

Scram S rod, release time - 10 m/sec, drop time - 156 m/sec.

Withdraw N rod; at 2" rod motion detected - random, mild; at 8" rod frequency and amplitude increased; at 11" rod motion stopped to

slight random; at 13" rod increased frequency and amplitude - motion mild & random; at 19" tube motion high frequency - low amplitude; at 24" holding - mild random motion with occasional pulse; at 25" frequency increases and amplitude decreases; at 29" rod motion judged - high frequency low amplitude; at 35" tube and rod both shake with high frequency - low amplitude; at ULS rod and tube shake together - very low amplitude, high frequency.

Scrammed N rod, release time - 10 m/sec, drop time - 151 m/sec.

Pulled N rod to 4" to reduce vibration of tube for remaining tests.

Withdraw SW rod; at 10" rod gave mild pulse; at 15" very mild motion detected - judged to be high frequency; at 24" frequency and amplitude of motion increased, rod gives occasional light pulse during withdrawal; at ULS rod and tube steady.

Scram SW rod, release time - 17 m/sec, drop time - 136 m/sec.

E. Subpile Room Observations

Accelerometer in S tube at elevation 77'-6". Brush recorder inputs as follows:

<u>Channel</u>	<u>Input</u>
1	N-S displacement, S tube
2	E-W displacement, S tube
3	Transducer - flow distribution tank SE ΔP tap
4	Transducer - flow distribution tank SW ΔP tap
5	I-9 pressure transducer (SE)
6	I-14 pressure transducer (SW)
7	I-19 pressure transducer (NW)
8	I-4 pressure transducer (NE)

All safety rods seated

Raised flow to 35,000 gpm. S tube displacement was: N-S - 8 mils, E-W - 8 mils.

Observed slight vibration in N & S tubes with E tube vibrating more than S. No knocking noise in either position. NE, E, SW & SE quiet - no detectable vibration.

Increased flow to 40,000 gpm. S tube displacements were: N-S - 4-16 mils, E-W - 4-16 mils. S tube had slight vibrations - no noise. N tube had detectable vibration and noise. No vibration or noise in NS, E, SW & SE.

Increased flow to 43,000 gpm. S tube displacements were: N-S - 8-24 mils, E-W - 8-20 mils. Slight occasional vibration and knock. N tube - detectable vibration and knock. Removed clamp from tube - can not stop vibration by pushing on tube. NE & E - are very good. SW - slight vibration (more than Test No. 20) - still acceptable. SE - occasional slight shudder - very acceptable.

Raising N rod to stop vibration. At 0.8" vibration decreased considerable - still have occasional light knock. Pulled rod to 4" - very little tube vibration and no knocking noise. Left rod at 4" while continuing test.

Raising S rod - LLS, N-S - 20 mils, E-W - 20 mils; 27", N-S - 80 mils, E-W - 80 mils; ULS, N-S - 20-88 mils, E-W - 20-44 mils. Occasional acceleration spikes.

Note: Raised SE rod with S rod for vibration and noise comparison - SE sounds real good (only occasional light tap) and no detectable vibration.

Transferred accelerometer to N tube and positioned at 77'-6". Rod at LLS, N-S - 60-80 mils, E-W - 60-80 mils; rod at 19.8", N-S - 6-30 mils, E-W - 6-30 mils; rod at ULS, N-S - 30-60 mils, E-W - 20-30 mils. Observed maximum tube displacement of 80-90 mils with rod at 35". Repositioned N rod to 4" for remainder of test.

Transferred accelerometer to SW tube and positioned at 77'-6". Rod at LLS, N-S - 8 mils, E-W - 8 mils. Occasional acceleration spike in E-W direction. Rod at 24", N-S - 12 mils, E-W - 12 mils; rod at ULS, N-S - 16 mils, E-W - 12 mils.

Traversed NE tube with accelerometer: elevation 72', N-S - 4 mils, E-W - 2 mils; elevation 74'-6", N-S - 4 mils, E-W - 2 mils; elevation 77'-6", N-S - 4 mils, E-W - 2 mils; elevation 80', N-S - 4 mils, E-W - 2 mils; elevation 82'-6", N-S - 4 mils, E-W - 2 mils; elevation 85'-6", N-S - 4 mils, E-W - 2 mils.

Traversed E tube with accelerometer: elevation 72', N-S - 4 mils, E-W - 4 mils; elevation 74'-6", N-S - 6-8 mils, E-W - 4-6 mils; elevation 77'-6", N-S - 4-8 mils, E-W - 4-6 mils; elevation 80', N-S - 4-8 mils, E-W - 4-6 mils; elevation 82'-6", N-S - 4-8 mils, E-W - 4-8 mils; elevation 85'-6", N-S - 4-6 mils, E-W - 4-6 mils.

F. Information Needed to Complete Test Data Package No. 21

1. Instrument data taken.
2. ΔP readings on NW and C instrumented dummy tubes.

Test No. 22

6-7-67

A. The following changes were made in the vessel prior to Test No. 22.

1. Remove instrumentation from S dummy tube and safety rod.
Remove 40" flow restrictor from S dummy tube and cut 12" off of bottom.
Install remaining 28" back on prime tube for insertion into S position.
2. Remove instrumentation pieces from S safety rod.
3. Install standard pieces on S safety rod and lower to seat.
4. Raise N prime tube and install 12" flow restrictor (from No. 1) beneath present 40" flow restrictor.
5. Insert N prime tube.

B. Tank Conditions for Vibration Test No. 22

1. NW Position - instrumented dummy tube with 40" clamped-on flow restrictor and 3" stovepipe flow restrictor in NW safety rod.
2. N Position - prime inpile tube with 52" flow restrictor (40" & 12") and 3" stovepipe flow restrictor in N safety rod.
3. NE Position - prime inpile tube with 40" B&W type clamp-on flow restrictor. Dummy flux trap filler with special 12" stovepipe flow restrictor.
4. W Position - gas loop dummy tube with modified flux trap filler to reduce clearance between flux trap filler and flux trap baffle.
5. C Position - instrumented dummy tube with 40" clamp-on flow restrictor and KAPL type flow restrictor clamped to upper splines.
6. E Position - prime inpile tube with 40" clamp-on flow restrictor. Dummy flux trap filler with special 12" stovepipe flow restrictor.
7. SW Position - prime inpile tube with 40" clamp-on flow restrictor and 3" stovepipe flow restrictor in SW safety rod.
8. S Position - prime inpile tube with 28" flow restrictor and 3" stovepipe flow restrictor in S safety rod.
9. SE Position - prime inpile tube and 3" stovepipe flow restrictor in SE safety rod.

C. Tests Performed

1. Install accelerometer in S prime tube at elevation 77'-6". Observe tube motion as flow is increased to full flow.
2. Observe N and S positions from top head and subpile room as flow is increased to full flow.
3. Withdraw S safety rod at full flow while continuously observing from top head and subpile room. Make traverse at worst vibrating condition, if possible.
4. Scram S rod. Record scram time.
5. Transfer accelerometer to N tube and position at elevation 77'-6".
6. Withdraw N safety rod while continuously observing from top head and subpile room.
7. Scram N rod. Record scram time.
8. Make traverse at worst vibrating condition, if possible.

D. Reactor Top Observations

Flow 35,000 - all rods and tubes steady on top; subpile room - N rod quiet; S same hydraulic noise.

100 Δ P quadrant - all rods and tubes steady on top.

43,000 flow - subpile room - N rod quiet; S same hydraulic noise.

Withdraw S rod; slight high frequency - vibration from 12" to 24". Occasional pulse; 24" to 35" occasional pulse (very good); at ULS no vibration rod or tube.

Scrammed rod, release time - 17, drop time - 145.

Withdraw N rod; at 18" - 24" very slight vibration - hard to detect; 24" to ULS very slight vibration - hard to detect (very good, even better than S rod); ULS no vibration rod or tube.

Scrammed rod, release time - 14, drop time - 145.

E. Subpile Room Observations

Installed accelerometer in S prime inpile tube at elevation 77'-6". Recorded accelerometer readings on brush recorder - channels 3 & 4.

Raised flow to 35,000 gpm and surveyed all prime tubes. All positions are quiet. S tube displacements were (safety rod in seat): N-S - .006", E-W - .008".

Raised flow to 43,000 gpm - quadrant P = 100 psi and recorded S tube displacements: N-S - .016", E-W - .020" average with occasional spikes to .024".

Checked all prime tubes visually, conclusions are:

1. S tube vibrating slightly more than N tube.
2. S tube vibrating same as SE & SW tubes
3. NE tube is the best.
4. E tube - no visible vibration but can hear occasional light knock.

Withdrew S safety rod while continuously recording S tube displacements on brush recorder: at 24", N-S - .020" maximum, E-W - .020" maximum. Average on both N-S and E-W was .008".

Per Larkin - some noise heard when rod was between 2'2" withdrawn.

Scrammed S rod and again recorded tube displacements: N-S - .012", E-W - .016.

Unclamped subpile end of S tube and traversed tube with accelerometer (results are on chart). Displacements recorded were slightly more with clamps removed.

Transferred accelerometer to N tube - positioned accelerometer at 77'. With rod seated tube displacements were: N-S - .020", E-W - .020"; at ULS, N-S - .008", E-W - .010" with occasional spike to .018".

Traversed N tube with clamps on tube. Results are on chart.

Transferred accelerometer to SW tube - at elevation 77'-6" (safety rod in seat): N-S - .004", E-W - .004".

Raised safety rod to 7": N-S - .020", E-W - .020".

Raised flow to obtain core ΔP of 115 psi - traversed N & S tubes - results are on chart.

F. Data Required to Complete Data Package for Test No. 22

1. Brush recorder data.

Test No. 23

A. The following changes were made in the vessel prior to Test No. 23.

1. Interchanged NW dummy inpile tube with the E prime tube.

Note: The prime tube now in the NW position has the modified upper splines.

2. Removed 40" and 12" flow restrictors from N tube. Cut the 40" flow restrictor to 37" and made 7.5° taper on bottom edge of flow restrictor. Removed 3" stovepipe flow restrictor from N safety rod and installed 12" stovepipe flow restrictor.

3. Removed 3" stovepipe flow restrictor from S safety rod and installed 12" stovepipe flow restrictor.

4. Pressure transducers reinstalled in I-4, 9, 14, and 19. Pressure transducers installed on NW and NE flow distribution tank (transducers are also installed on SW and SE taps). Pressure transducers installed on all 4 outlet pipe flow orifice upstream taps.

B. Tank Conditions for Vibration Test No. 23

1. NW Position - prime inpile tube (modified upper splines) with 40" clamp-on flow restrictor and 3" stovepipe flow restrictor in safety rod.

2. N Position - prime inpile tube with 37" clamp-on flow restrictor and 12" stovepipe flow restrictor in safety rod.

3. NE Position - prime inpile tube with 40" type clamp-on flow restrictor. Dummy flux trap filler with special 12" stovepipe flow restrictor.

4. Gas loop dummy tube with modified flux trap filler to reduce clearance between flux trap filler and flux trap baffle.

5. C Position - dummy tube with 40" clamp-on flow restrictor and KAPL type flow restrictor clamped to upper splines.

6. E Position - dummy tube with 40" clamp-on flow restrictor. Dummy flux trap filler with special 12" stovepipe flow restrictor.

7. SW Position - prime inpile tube with 40" clamp-on flow restrictor and 3" stovepipe flow restrictor in safety rod.

8. S Position - prime inpile tube with 28" clamp-on flow restrictor and 12" stovepipe flow restrictor in safety rod.

9. SE Position - prime inpile tube with 40" clamp-on flow restrictor and 3" stovepipe flow restrictor in safety rod.

C. Tests Performed

1. Install accelerometer in S prime tube at elevation 77'-6". Record accelerometer readings at no flow (system pressurized) and at 25%, 50%, 75% and 100% flow.

2. Observe all positions from top head and subpile room as flow is increased to full flow.

3. Pressure transducer outputs will be recorded on magnetic tape at 25% and 100% flow.

4. a. Raise S safety rod to ULS while continuously recording accelerometer output on brush recorder. (Observe from top head also.) From the recorder trace determine the rod position at which maximum tube displacement occurs; reposition the safety rod to that position and make traverse of tube with accelerometer as directed by Vince Walker.

b. Scram S rod. Record scram time.

5. a. Transfer accelerometer to N tube at elevation 77'-6".

b. Withdraw N safety rod to ULS while continuously recording accelerometer output (observe from top head also). Determine rod position for maximum tube displacements; position rod at this point and traverse tube as directed by Vince Walker.

c. Scram N rod. Record scram time.

6. Record pressure transducer outputs on magnetic tape with both N & S safety rods at ULS.

D. Reactor Top Observations

1. Filled and pressured to 200 lbs. - 0 flow. Pressure readings.

2. Established full flow - 100 psi P; SW and N rods noisy; Walker, Liebenenthal and Larkin observed and listened; lowered flow to 24,000 gpm - SW still rough; pulled SW rod; $\approx 7"$ smooth out; pulled to 36"; 30,000 gpm - OK; 35,000 gpm - SW - OK; N - started to get noisy; 40,000 gpm - SW - OK; N - noisy; full flow (100 P) - SW - OK; N - very noisy; pulling N rod; $\approx 1\frac{1}{2}"$ smoothed out; 7" some noise; $\approx 11"$

some vibration; $\approx 13''$ some knocking; $\approx 15 - 36''$ - OK; Walker ran accelerometer traverse on S rod; shut down and drained.

3. Changes made to core

a. Replaced 1 filler in SW rod and 3 in N rod that had loose handles.

b. No change in observation from previous test. Walker ran accelerometer traverse in SW and N rod.

Note: SW rod at LLS and 30,000 gpm accelerations up to 5 g measured with accelerometer located at 77'-6".

c. 20,000 - light knocking in N rod; SW rod quiet.

25,000 - SW rod very noisy; SW withdraw to 7-1/2" rod quiet; SW withdraw to ULS; N rod about the same.

30,000 - SW at ULS - OK; N - more noisy.

35,000 - SW at ULS - OK; N - getting very noisy; withdraw N rod knocking reduced as rod came up. Marked improvement at about 1' to 2". Some knocking to $\approx 13''$ then quiet.

d. 0-8

1. Ran all rods for Hal Larkin, E. J. Brunner.

2. System at temperature (150 - 140°F).

3. SW - lowered to 11", became very noisy. Raised back to ULS; N - lowered to 12", noise started about 22", became worse to 12", raised back to ULS; Clayton out to run traces on N and SW rods. SE - seemed OK over full travel; S - seemed OK over full travel; NW - lowered to LLS - noise started $\approx 10''$, became gradually worse to LLS.

E. Information Needed to Complete Test Data Package No. 23

1. Instrument data.

Test No. 23A

A. The following changes were made in the vessel prior to Test No. 23A.

1. Placed 40" clamp-on flow restrictors in pile tubes and 3" stovepipe flow restrictors in NW, SW, and SE positions.
2. Placed 37" clamp-on flow restrictors on inpile tube and 12" stovepipe flow restrictor in safety rod in N position.
3. Placed 40" clamp-on flow restrictors on inpile tube and 12" stovepipe flow restrictor in dummy flux trap fillers in NE and E positions.
4. Placed 40" clamp-on flow restrictor on prime inpile tube and KAPL type flow restrictor in C position.
5. Placed 28" clamp-on flow restrictor on inpile tube and 3" stovepipe flow restrictor in safety rod in S position.
6. Reinstalled pressure transducers in I-4, 9, 14 and 19. Pressure transducers in on NW, NE, SW, and SE taps of flow distribution tank. Pressure transducers and differential transducers installed on all 4 outlet flow orifices (elevation 40 ft.)

B. Tank Conditions for Vibration Test No. 23A

1. NW Position - prime inpile tube (modified upper splines) with 40" clamp-on flow restrictor and 3" stovepipe flow restrictor in safety rod.
2. N Position - prime inpile tube with 37" clamp-on flow restrictor and 12" stovepipe flow restrictor in safety rod.
3. NE Position - prime inpile tube with 40" type clamp-on flow restrictor. Dummy flux trap filler with special 12" stovepipe flow restrictor.
4. Gas loop dummy tube with modified flux trap filler to reduce clearance between flux trap filler and flux trap baffle.
5. C Position - prime tube with 40" clamp-on flow restrictor and KAPL type flow restrictor clamped to upper splines.
6. E Position - dummy tube with 40" clamp-on flow restrictor. Dummy flux trap filler with special 12" stovepipe flow restrictor.
7. SW Position - prime inpile tube with 40" clamp-on flow restrictor and 3" stovepipe flow restrictor in safety rod.

8. S Position - prime inpile tube with 28" clamp-on flow restrictor and 12" stovepipe flow restrictor in safety rod.

9. SE Position - prime inpile tube with 40" clamp-on flow restrictor and 3" stovepipe flow restrictor in safety rod.

C. Tests Performed

1. Install accelerometer in SW inpile tube.

2. Establish 25% flow.

a. Withdraw all rods; observe and record observations of all positions from top head and subpile room. Record ΔP readings of transducers.

b. If vibration exists, but not detrimental, scram SW safety rod and record scram time. Insert all rods.

3. Repeat 2 a & b at 50% flow.

4. Repeat 2 a & b at 75% flow.

5. Repeat 2 a & b at 100% flow.

Note: Testing will proceed to 100% flow only if vibration allows. If not, the rest of the test may be conducted at an acceptable flow rate.

6. a. Transfer accelerometer to N tube at elevation 77'-6".

b. Withdraw N safety rod to ULS while continuously recording accelerometer output (observe and record from top head also). Determine rod position for maximum tube displacements.

c. Scram N rod. Record scram time.

7. Repeat step 6 for S rod and tube.

8. During testing and before system shutdown insure that Dave Mousseau has taken readings on Butterfly valve. He is working with George Buchanen on getting data.

9. Record accelerometer readings at no flow (system pressurized) and at 25%, 50%, 75% and 100% flow.

D. Post Testing

1. Repeat measurements taken on steps 5 & 6 of DPH-164-67 (continued), July 12, 1967.

For No. 5

<u>Safety Rod</u>	<u>N-S/IPT</u>	<u>E-W/IPT</u>	<u>Initial/Date</u>
N	_____	_____	_____
NW	_____	_____	_____
SE	_____	_____	_____
S	_____	_____	_____
SW	_____	_____	_____

For No. 6

<u>Safety Rod</u>	<u>Hf. N-S</u>	<u>Diameter E-W</u>	<u>N-S/IPT</u>	<u>E-W/IPT</u>	<u>Initial/Date</u>
N	_____	_____	_____	_____	_____
NW	_____	_____	_____	_____	_____
SE	_____	_____	_____	_____	_____
S	_____	_____	_____	_____	_____
SW	_____	_____	_____	_____	_____

MEMORANDUM

July 12, 1967

Shutdown - Core Zero
CompletionDPH-164-67
Continued

To: Shift Supervisors

After the inpile tubes and safety rods are set up for vibration testing the following items must be done. Items 1 thru 4 are for V. Walder and his technicians will be available for details.

1. Install transducers in I-4, 9, 14 and 19.
2. Install 4 taps on flow distribution tank.
3. Install 4 pressure taps on upstream side of quadrant orifice plates at elevation 40 ft.
4. Install 4 pressure differential transducers of quadrant flows at elevation 40 ft.
5. All safety rods at LLS. Measure distance rods can travel with respect to inpile tube. Record data in N-S and E-W coordinates:

<u>Safety Rod</u>	<u>N-S/IPT</u>	<u>E-W/IPT</u>	<u>Initial/Date</u>
N	0.135	0.130/0.131	7/13/67
NW	0.119	0.105/0.106	7/13/67
SE	0.103	0.115/0.120	7/13/67
S	0.103	0.105/0.106	7/13/67
SW	0.119/0.120	0.128	7/13/67

6. All safety rods at ULS. Measure distance rod can travel with respect to inpile tube. Also measure diameter of hafnium as installed after insuring hafnium plates are latched properly. Check that pressure tube locator ties are secure.

Note: Measurements (step 5 & 6) can take place as soon as each position is ready for testing. Mr Roy Manoll would like to be notified. Maintenance will do the actual measuring.

<u>Safety Rod</u>	<u>Hf. N-S</u>	<u>Diameter E-W</u>	<u>N-S/IPT</u>	<u>E-W/IPT</u>	<u>Initial/Date</u>
N	5.035	5.037	0.156	0.151/ 0.153	7/13/67
NW	5.027	5.020	0.165	0.145/ 0.148	7/13/67
SE	5.025	5.031	0.160	0.147/ 0.152	7/13/67
S	5.021	5.032	0.148	0.120/ 0.120	7/13/67
SW	5.017	5.029	0.163/ 0.168	0.147	7/13/67

7. Install accelerometers in SW tube (77'-6") and N tube (77'-6").
8. Install scram instrumentation on SW safety rod.
9. Install subpile room vibration fixes on inpile tubes.
10. Upon completion of above items, fill and pressurize system.
11. Initiate flow, keeping very careful observation from reactor top and subpile room for excessive vibration. In reviewing Vibration Test No. 23 data, it looks like the SW rod may have to be raised to ULS to stop vibration. If vibration allows, bring primary flow to 25,000 gpm and degas system. It is planned that the system will be operating by 0800 July 13, 1967.

D. P. Halls

North Rod

Hafnium Plates Secure yes/yes Loose _____

Hafnium Plate Diameter $\frac{5.035}{5.037}$ to $\frac{5.037}{5.037}$

North West

Hafnium Plates Secure yes/yes Loose _____

Hafnium Plate Diameter $\frac{5.027}{5.031}$ to $\frac{5.020}{5.019}$

Locator Tie Tightest of Group Serial No. 1139

South East

Hafniurn Plate Secure yes/yes Loose _____

Hafniurn Plates Diameter $\frac{5.025}{5.029}$ to $\frac{5.031}{5.029}$

Locator Tie Excessively Loose Serial No. 1136

South Rod			
Hafnium Plates	Secure	Yes/Yes	Loose
Hafnium Plate	Diam	$\frac{5.021}{5.021}$	To $\frac{5.032}{5.032}$

South West

Hafnium Plates	Secure	<u>Yes/Yes</u>	Loose	<u> </u>
Hafnium Plate	Diam	$\frac{5.017}{5.024}$	To	$\frac{5.029}{5.030}$

Locator Tie Excessively Loose Serial No. 1137

MEMORANDUM

July 11, 1967

Shutdown - Core Zero
Completion

DPH-164-67

To: Shift Supervisor

At the completion of Core 0 testing, we will resume vibration testing with a re-run of Vibration Test No. 23 to duplicate data taken during that test. Consequently, a duplication of reactor internal positions must be made.

1. Fuel Loading - Discharge Core 0 elements to the working canal storage grid replacing each element, as it is removed, with a dummy element.
2. Remove source from C inpile tube.
3. Replace drop tube cover. Tank will be drained to top of core starting 0800 July 12. Insure that canal level is maintained. If radiation does not allow draining, start removal of in tank pieces remotely, providing H.P. approval is granted.
4. Remove solid fillers in B-1 thru 8 and return to ATRC. Replace with modified solid Al B hole fillers.
5. Remove fixed shims and poison sleeves from H-1, 5, 9 and 13. Remove short (16") H hole fillers from H-4, 6, 7, 8, 10, 12, 14, 15 and 16. Replace with long H hole fillers in H-1, 4, 5, 6, 7, 8, 9, 10, 12, 13, 14, 15 and 16. H-2 will contain special 4 ft. filler.
6. Remove A-10 and 11 fillers and return to ATRC. Replace with solid fillers.
7. Remove flow tubes from NW, N, NE, C, SW, S & SE inpile tubes.
8. Remove dummy inpile tube mockup from E and return to ATRC.
9. Replace 12" stovepipe flow restrictor in E flux trap filler and lockwire.
10. Insert dummy inpile tube with 40" clamp-on flow restrictor in E position.
11. Remove NE inpile tube and install a 40" clamp-on flow restrictor. Install special 12" stovepipe flow restrictor in dummy flux trap filler. Reinstall NE inpile tube.

12. Remove N inpile tube and install a 37" clamp-on flow restrictor. Install a 12" stovepipe flow restrictor (in N safety rod). Insure that rod has standard length fillers. Reinstall N inpile tube.

13. Remove NW inpile tube and install a 40" clamp-on flow restrictor. This inpile tube should have modified upper splines. Install a 3" flow restrictor in safety rod, after replacing the poison stops with standard length fillers. Reinstall inpile tube.

14. The W position should have the gas loop dummy inpile tube and the modified flux trap filler.

15. Remove C inpile tube and install 40" clamp-on flow restrictor and KAPL type flow restrictor to upper splines.

16. Remove SE inpile tube and install a 40" clamp-on flow restrictor. Remove poison stops from safety rod and install standard length fillers. Install a 3" flow restrictor in safety rod and reinstall inpile tube.

17. Remove S inpile tube and install a 28" clamp-on flow restrictor. Install a 3" flow restrictor in safety rod and insure that rod has standard length fillers. Reinstall inpile tube.

18. Remove SW inpile tube and install a 40" clamp-on flow restrictor. Install a 3" flow restrictor in safety rod and insure that rod has standard length fillers. Reinstall inpile tube.

19. Insure that all outer capsule positions have solid flow restrictors.

20. Replace flange on upper vessel drain line in nozzle trench (after tank level is lowered).

21. Drain inpile tubes in subpile room with H.P. coverage and remove plugged cans from bottom head.

22. Take measurements on safety rods and inpile tubes as requested by Roy Manoll of B&W.

July 13, 1967

Observations - (From data taken 2nd shift July 12)

1. North rod has the longest annulus between loop at 12 inches and rod and the longest diameter over the hafnium. At 25,000 gpm flow north rod had to be withdrawn 10" to stop metallic sounds.

Metallic sounds are emitting from the contact between the safety rod buttons and the 37 inch long loop restricting collar. (The south rod that had been transmitting sounds prior to test 23 has a 28 inch long collar installed which does not contact the buttons at lower limit of rod.)

2. South west has the next longest annulus at 12 inches withdrawal and one of the smallest hafnium diameters giving more flow in each channel.

3. Locator ties for north and south much more rigid and full of movement than corner positions, i.e., N.E., N.W., S.E., and S.W.

Conclusions From Test (To be checked out) - July 13, 1967

1. North rod metallic sounds emitting from hafnium plate button contact, i.e., south rod did same thing with long plate over loop.

2. Hafnium plates could have vibrated loose on S.W. safety rod since the buttons were performing a snubbing action against a 40 inch long collar (buttons strike approximately 5-1/2 from bottom of collar to button).

3. Handling extensions on filler could have vibrated loose.

4. Pad was on threshold of being stable and some slight shift of internals, possibly due to all components stabilizing around the fuel element clearances, etc., may have been just enough to trigger it off.

Data After Test of July 13, 1967 (Check out of conclusions)

1. South west hafnium plates were securely fastened after test.
2. Spring latches on hafnium plate latch were engaged.
3. South west pressure tube locator tie appears about the same as before the test, i.e., approximately the same motion.

S.W. Rod - SRF-9; loose (handle) NW quadrant of rod.

SRF-10; handle tight but seems to have a different radius or hump where it appears to have been straightened starting approximately 6 inches above filler SW quadrant of rod.

Flow 25,000 - N rod at 10" and banging; N rod lowered to 7" where banging stopped and started again at 3" to LLS. Other rods quiet - SW very quiet - NW some noise.

Flow to 30,000; N rod more banging. Others same as above. Withdrew N rod - banging stopped at 3" then started again at 8" to 18" where rod is again quiet.

Flow to 35,000; N rod banging at 18". Others no change. SW very quiet; N rod withdrew to 24" and is quiet again.

Note: After ~8 minutes at 35,000 the SW started to bang very bad. Withdrew SW rod - banging stopped at 9-10". Rod at 12" and quiet.

Flow to 40,000 - all rods quiet N at 24" and SW at 12" other at LLS.

Flow to 100 psi Core ΔP . 44,000 gpm - all rods quiet at above positions.

Vibration Test No. 24

7-20-67

A. The following changes were made in the vessel prior to Test No. 24.

1. Interchanged the NW and SW safety rod assemblies and inpile tubes. Drives not changed.
2. Modified the safety rod in the north position by boring and installation of a full length sleeve. The 37" flow restrictor was removed from the inpile tube.
3. Installed pressure transducers in the inlet plenum and on the second tap of the SW quadrant of the flow distribution tank. Other transducers used in Test No. 23A remained installed.
4. Installed flow balancing orifice plates upstream of the wye branch in all four quadrant outlet lines.

B. Tank Conditions

Tank conditions are the same as test 23A except as follows:

1. NW position contains the safety rod assembly and inpile tube from the SW position.
2. SW position contains the safety rod assembly and inpile tube from the NW position.
3. N position contains the modified safety rod bored with a liner installed.

C. Tests Performed

1. Install accelerometer - eddy current assembly in north inpile tube at elevation 77'-6".
2. Record all pressure transducer readings at 0 flow.
3. Establish 25% flow (11,000 gpm)
 - a. Record all transducer readings with all rods at LLS and ULS.
 - b. Tape record pressure transducer readings with rods at LLS and ULS.
4. Repeat 3 a at 50%, 75% and 100% flow.

Note: If vibration in any position limits further flow increase, run tests 5 and 6 below, and withdraw the rod to ULS during the higher flow rate tests.

5. If vibration of any rod or inpile tube limits further flow increase, tape record all transducer readings at that flow with all rods at LLS and ULS.
6. Run an accelerometer traverse in each of the N, NW and SW inpile tubes at the maximum flow obtained with that rod at LLS and ULS.
7. Observe vibration in the subpile room and top head at each flow and during flow changes. Record observations.
8. If the north rod vibration does not limit rod movement, (LLS to ULS) measure the scram time at full flow.

MEMORANDUM

July 13, 1967

Shutdown Letter -
Vibration Test 24

COK-54-67-N

To: Shift Supervisors

1. At the completion of vibration test 23A, shut down the primary system and drain the tank to core level.

2. Take measurements required by post testing portion of test 23A.

Note: Call Roy Manoll at 523-3229 ~1-1/2 hours before measurements are to be taken. Do not disturb any reactor internals until measurements are completed. Maintenance coverage is required.

3. Remove the hafnium plates from the N safety rod, the NW safety rod, and the SW safety rod. Label all plates so that they can be replaced on the same rod.

4. Drain the primary system to the "Y" branch of the outlet flow piping, so that maintenance can install orifice plates on the upstream side.

5. Remove N safety rod and crate for shipment to be modified. Retain and label fillers. Notify W. R. Cook when ready.

6. Interchange NW and SW safety rods and inpile tubes. Replace hafnium plates on rod they were removed from, and also flow restrictors.

7. Install modified spare safety rod in N position along with fillers from step 5. Replace hafnium plates.

Note: At present it is not known whether the modified spare safety rod will be ready for insertion over the weekend of on July 17 or July 18. If it is not available until July 17 or July 18, the weekend can be used to work on SO-111. The tank level can be raised after the orifice plate installation and the drop tube cover removed. Only the safety rod portion - 6E and 6H can be worked on at this time as movement of outer shim cylinders and Be blocks might alter fuel annulus. Only one hafnium

plate and one filler need be removed to satisfy SO-111; however, other portions of the test can be redone for training purposes if desired. The water level should be at the top of the core by 0800 July 17, 1967.

W. R. Cook

Subpile Room Observations

Flow increased to 25,000 gpm - after ~20 minutes the NW rod started banging. Withdrew NW to 9" and banging stopped. All other rods quiet.

Flow decreased to 20,000 - lowered NW rod to LLS - NW rod knocking. Other rods quiet.

Flow increased to 25,000 - NW knocking a little more. Other rods quiet.

Flow increased to 30,000 - NW knocking harder. Other rods the same.

Flow increased to 35,000 - NW rod banging. Withdrew NW rod - at 11" rod quiet; NW rod at 12" and quiet.

Flow increased to 40,000 - all rods quiet - NW at 12".

Flow increased to 44,000 - 100 psi ΔP .

All rods quiet and about the same; withdrew N rod; at ~25 tube knocking - held same to ULS. Rod from top some vibration observed. Scrammed rod - release time 9 ms, drop time 140 ms.

Vibration Test No. 25

7-23-67

A. The following changes are required in the vessel to prepare for
Test No. 25.

1. Remove hafnium plates and fillers from north and south safety rods. Label all pieces as to rod and position where they were removed.
2. Pull S inpile tube, label and store in hatch.
3. Remove 28" clamp-on flow restrictor from S inpile tube and 12" stovepipe flow restrictor from S safety rod. Label flow restrictors and store in SS office.
4. Pull S safety rod and store in box on west side main floor.
5. Pull N inpile tube, label and store in hatch.
6. Raise N safety rod and attach special handling tool to guide tube.

Note: Handling tool is stored in SS office.

7. Lower N safety rod to seat with tool attached. Maintenance will now remove the safety rod drive package.
8. Transfer the N safety rod to the S position, connect the drive package, raise the rod and remove the special handling tool.
9. Insert the inpile tube removed from the N position (step 5) into the S position. Inpile tube - safety rod combination to remain together.
10. Attach special safety rod handling tool to spare safety rod RT-6M and install the safety rod in the N position. Connect the N drive package, raise the rod and remove the special handling tool.
11. Insert the inpile tube removed from the S position (step 2) into the N position.
12. Reinstall fillers and hafnium plates as follows:
 - a. The fillers and plates removed from the previous N rod are to be inserted in the safety rod now in the S position.

Note: This is the rod transferred from the N position.

- b. The fillers and plates removed from the previous S rod are to be inserted in the spare safety rod now in the N position.

B. Tank Conditions

Tank conditions are the same as test 24 except as follows:

1. N position contains the spare safety rod bored with a liner installed and a "Dr. Rona" type flow restrictor inserted into the inside tapered portion of the connecting sleeve. No flow restrictor on inpile tube. The inpile tube was from the S position.

2. S position contains the modified safety rod bored with a liner installed and inpile tube from the N position.

C. Tests Performed

1. Install an accelerometer in the north inpile tube at elevation 77'-6".
2. Install the scram time measuring instrumentation on the N rod.
3. Pressurize the reactor and slowly increase flow observing rods/inpile tubes for vibration and recording results.

Note: If flow increase is limited by vibration of any rod or tube, withdraw that rod until vibration is sufficiently reduced prior to increasing flow.

4. a. At full flow, if not prevented by vibration, withdraw the north rod recording accelerometer readings and observations.
b. Scram the rod and record drop and release times.
5. Transfer the accelerometer to the south position and repeat 4 a and b for the south rod.

MEMORANDUM

July 21, 1967

Weekend Schedule

COK-58-67-N

To: Shift Supervisors

The spare safety rod (RT-6M) will be assembled on Saturday, July 22, 1967. If all goes well the assembly will be delivered to ATR sometime on Saturday swing shift.

Maintenance coverage has been scheduled for 0-8 shift, Sunday July 23 to make test changes as per attached instructions on Vibration Test No. 25.

You will be notified if the machine shop can NOT assemble the spare safety rod. In this case call Jess Momberger at 523-4429 to cancel maintenance coverage.

Note: Call Jess after 1700 Saturday.

In the event that the spare safety rod can NOT be assembled??????

W. R. Cook

Observations in Subpile Room

1. Flow at 21,000 - NW rod withdrawn to 15 to stop knocking - other rods quiet.
2. Flow at 30,000 - no change to above.
3. Flow at 35,000 - no change.
4. Flow at 40,000 - no change.
5. Flow at (100 psi ΔP) 43,000 - no change.
6. Withdrew N rod - quiet to ULS - very little increase in noise at ~34". No knocking. Scrammed rod, release time 8 ms, drop time 135 ms.
7. Ran an accelerometer traverse in N tube with rod at LLS and ULS.
8. Scrammed N rod again, release time 8 ms, drop time 137 ms.
9. Withdrew S rod. At ~28" vibration of rod/inpile tube increased. Vibration of inpile tube rather hard at ULS. Knocking not as bad as when rod was in N position but vibration seems to be worse. Scrammed rod, release time 16 ms, drop time 155 ms.

Vibration Test No. 25A

7-24-67

A. Changes for Vibration Test No. 25A.

1. Removed the fillers from the N rod and replaced with hafnium stops. No other changes.

Note: The N rod is the modified spare (RT-6M) with a Rona flow restrictor. This rod tested good during vibration test No. 25 with fillers.

B. Tank Conditions for Test 25A

Same as test 25 except as noted above.

C. Tests Performed

1. Pressurize the reactor, withdraw the NW rod to 15" and increase flow to 100 psi Core ΔP . Withdraw the N rod and observe vibration.

2. Install an accelerometer in the N inpile tube and record readings as rod is withdrawn.

Observations During Test 25A

Observations were the same as during Test 25.

Vibration Test No. 26

A. The following changes are to be made in preparation for vibration test #26.

1. Pull S inpile tube and safety rod.
 - a. Place inpile tube in storage hatch.
 - b. Place safety rod in box and prepare for shipment to CFA; must be ready by 0800 July 26, 1967.
2. Install normal safety rod, RT-7, presently in box, in south position.
3. Move N inpile tube to south position.
4. Install S inpile tube, removed in Step 1, in north position.
5. Switch NW and SW inpile tubes. Leave 40" flow restrictors on respective tubes.

B. Tank Conditions for Test No. 26

1. S position contains original unmodified safety rod RT-7. Original S inpile tube (test No. 23A) reinserted in S. No flow restrictor on inpile tube.
2. N position contains spare safety rod (RT-6M) - same as test No. 25. Original N inpile tube (Test No. 23A) reinserted in N position. No flow restrictor on inpile tube.
3. SW safety rod same as test No. 25. Inpile tube is same inpile tube that was in SW position (Test 23A). Flow restrictor on inpile tube (40").
4. NW safety rod same as test No. 25. Inpile tube is same inpile tube that was in NW position (Test 23A). FR on inpile tube (40").

Tests Conducted:

1. Install an accelerometer in the N inpile tube at elevation 77'-6".
2. Pressurize the reactor and increase flow to 100 psi Core ΔP . As flow is increased observe vibration of all positions. If vibration of any rod or inpile tube, other than the north position, limits further flow increase, withdraw the safety rod until vibration is reduced to an acceptable level.
3. If the north rod vibrates excessively prior to reaching full flow, reduce flow and withdraw the rod recording the accelerometer readings.

4. At full flow, vibrating permitting, withdraw.
 - A. North rod and observe vibration and record accelerometer readings.
 - B. NW rod and observe vibration.
 - C. SW rod and observe vibration.
5. Tape flow distribution tank transducer readings.

Observations:

1. Flow at 20,000 - all rods and tubes quiet.
2. Flow increased to 43,000 in steps of 5,000. No knocking or banging in any position.

Note: On previous tests the NW rod/inpile tube has been knocking at ~25,000 gpm. The only change in this position was to move the inpile tubes from NW to SW and SW to NW. The inpile now in the NW was quiet in the SW and is quiet in the NW. The inpile tube in the SW was knocking in the NW and is quiet in the SW.

NW and SW inpile tubes have 40" clamp on flow restrictors. Withdraw all rod - at 1" SW knocking

SW at 11" and knocking stopped.

S rod at 30 and knocking.

S rod knocking at ULS - scrambled rod and knocking stopped.

All rods up to ULS except S. Slight knocking in N rod - others quiet.

Accelerometer reading on N rod 28 mils - rod at ULS.

Lowered flow to 90 psi ΔP on quadrant.

Accelerometer reading on N rod 20 mils - rod at ULS.

Lowered flow to 80 psi ΔP on quadrant.

Accelerometer reading on a rod occasional 20 mils.

Increased flow to 113.5 ΔP - accelerometer about the same as 100.

Tank Preparation for Vibration Test 27

1. Remove N inpile tube, 820-2, to storage rack.
2. Remove S inpile tube, 820-4, and safety rod RT-7. Inventory, label and retain poison plates and fillers for insertion into RT-6M.
3. Remove N safety rod, RT-6(m), and install in south position, with fillers and hafnium plates from RT-7 after 5/8" orifice bushings are installed.
4. Start draining primary system for orifice plate change out.
5. Install inpile tube, 820-4, in south position.
6. Move SW inpile tube, 820-1, to storage rack. Remove 40" clamp on flow restrictor.
7. Move NW inpile tube, 820-6 (presently in storage), to southwest position.
8. Remove orifice plates presently installed in outlet flow pipes (elevation ~40') after system is drained. When plates are removed, fill vessel to core level.
9. Upon assembly install modified safety rod RT-4 with 7/8 inch orifices in northwest position with standard fillers and poison plates that were removed from it.
10. Install inpile tube, 820-1, in northwest position (was removed from SW).
11. Install modified safety rod RT-1 in north position using 7/8 inch orifices, and standard fillers and poison plates that were removed from it.
12. Install inpile tube, 820-2, in north position. Presently in S storage rack.
13. Install special clamp that goes between inpile tube and spring loaded button in the SE position pressure tube locator tie.
14. Install accelerometer on NW pressure tube locator tie.

Test 27 Positions

	<u>NW</u>	<u>N</u>	<u>NE</u>
Safety rod	RT-4	RT-1	FTF-
IPT	820-1	820-2	820-9
SRF			--
SRA			--
	<u>W</u>	<u>C</u>	<u>E</u>
IPT	GCL dummy	820-3	D-3632
	<u>SW</u>	<u>S</u>	<u>SE</u>
Safety rod	RT-2	RT-6M	RT-5
IPT	820-6	820-4	820-5
SRF			
SRA			

Vibration Test No. 27

1. Install an accelerometer in the N inpile tube at elevation 77'-6".
2. Pressurize the reactor and increase flow to 100 psi core ΔP continuously observing safety rod and inpile tube vibrations. If either NW, N or S safety rods vibrate excessively, reduce flow until vibration is acceptable and withdraw the rod(s) recording accelerometer readings.
3. If vibration in SW or SE positions limits flow increase, withdraw the safety rod(s) until acceptable vibration levels are attained, then increase flow to 100 psi core ΔP .
4. If full flow is attained, withdraw:
 - A. Northwest rod, observe vibration and record accelerometer readings.
 - B. North rod, observe vibration and record accelerometer readings.
 - C. South rod, observe vibration and record accelerometer readings.
 - D. Southeast rod, observe vibration and record accelerometer readings.
5. Obtain scram and release times for ~~NW~~, ~~N~~, and ~~S~~ rods.
6. ~~Tape all pressure transducer readings.~~ NO.
7. Record NW locator tie servo accelerometer readings.
 - a. Obtain inpile tube displacements at 77'6" of all IPT with safety rods at 0, 50, and 100% flow with safety rods at LLS and HLS.
 - b. Tape accelerometer at 100% flow on NW, N, and S with safety rods at LLS and HLS.
 - c. Tape noise?

Tank Conditions for Test No. 27

1. NW Position

Safety Rod RT-4, in SW on 23A

- a. 82" sleeve in guide tube.
- b. Rona internal flow restrictor (ss) square edged.
- c. 7/8" orifice bushings in connecting sleeve flow holes.

Inpile Tube 820-1, in SW (23A)

- a. No flow restrictor on tube.

2. N Position

Safety Rod RT-1, Same 23A

- a. 82" sleeve in guide tube.
- b. Rona internal flow restrictor (ss) square edged.
- c. 7/8" orifice bushings in connecting sleeve flow holes.

Inpile Tube 820-2

- a. No flow restrictor on tube.

3. NE Position

Dummy flux trap filler with special 12" stovepipe flow restrictor.
Inpile tube 820-9, in NE (23A) with 40" clamp-on flow restrictor.

4. W Position

GCL dummy tube with modified flux trap filler.

5. C Position

Inpile tube 820-3 in C (23A) with 40" clamp-on flow restrictor
and KAPL type flow restrictor on upper splines.

6. E Position

Dummy flux trap filler with special 12" stovepipe flow restrictor.
Dummy inpile tube 3632 with 40" clamp-on flow restrictor.
No chg (23A)

7. SW Position

Safety Rod RT-2, in NW (23A) - with 3" stovepipe flow restrictor.

Inpile Tube 820-6, in NW (23A) - with 40" clamp-on flow re-
strictor.

8. S Position

Safety Rod RT-6M (Spare)

- a. 82" sleeve in guide tube.
- b. Rona internal flow restrictor (Al) sharp edged.
- c. 5/8" "Rona" orifice bushings in connecting sleeve flow holes.

Inpile Tube 820-4, In S (23A)

- a. No flow restrictor on inpile tube.

9. SE Position

Safety Rod RT-5, no chg (23A) - with 3" stovepipe flow restrictor.

Inpile tube 820-5, in SE (23A) with 40" clamp-on flow restrictor.

Test 27

Hardware Available August 5, 1967

Test August 6th or 7th

Changes to Vessel

1. Install modified S.W. RT 4 safety rod with 7/8 orifices and standard fillers in N.W. position with loop combination which produced vibration.
2. Re-install N.W. RT 4 safety rod in S.W. position with same loop originally in that position. Use standard fillers and loop with 40" collar restrictor.
3. Install modified north safety rod RT 1 in N. position using 7/8" orifices - standard fillers with same loop combination used in previously.
4. Install modified spare RT-6M in south position using 5/8 inch orifice bushings - same fillers and loop as originally used.

If available, install pressure transducers in NSH using SNE-3, SSE-3, SSW-3, and SNW-3 positions (remove neck rods to permit transducer insertion). Following these insertions install flow restrictors in all except above NS rod inlet at top of NSH (restrictor provided by Jim McBride). Record and tape outputs of these and other previously installed pressure transducers (re-install malfunctioning "I" hole transducer).

SE safety rod and inpile tube remain unchanged except to add additional pre-load to locator tie spring buttons. Remove flow balancing orifice plates in discharge lines. Record acceleration and displacement in all five positions containing safety rods at elevations of pads upon pressure tube.

PITOT HEAD BODY

(Machine From SST Tube or Bar Stock)

PITOT HEAD ASSEMBLY - Step #1

PITOT HEAD ASSEMBLY Step #2

Filler ring

(will be furnished)

PITOT TUBE ASSEMBLY

(All tubing is SST and will be furnished)

Part #1

Part #2

Tail Fin Assembly

Dangling Pitot Vertical Layout

Locate Instrumented
Elements In:

NE - F3
SE - F13
SW - F23
NW - F33

Vibration Test No. 27

August 4, 1967

Accelerometer located in NW at 77'-6".

End fixes installed on all inpile tubes except NE tube.

Flow 20,000 gpm - all rods and tubes quiet - (Max 2 mils displacement)

Increased flow in 5000 gpm steps

25,000 gpm — NW 2 mils peak to peak

30,000 gpm — NW 4 mils peak to peak

35,000 gpm — NW (4 to 5) mils peak to peak

89 psi, 40,000 gpm — NW 8 mils peak to peak

100 psi, 42,500 gpm — NW 10 mils peak to peak

No knocking or banging noises heard in any position during flow increases.

W/D NW Rod

Maximum displacement up to 24 inches 20-24 mils. Max displacement between 32 and 34" at 30-32 mils.

No knocking or banging noises heard throughout withdrawal range.

Locator tie displacement 2 mils with rod at ULS.

Scram time 10 ms release
133 ms drop

Max 12 mils peak to peak at ULS

W/D S Rod

Peak to peak 6 mils at LLS.

Max displacement up to 24 inches 6-8 mils peak to peak.

15 mils peak to peak between 28 and 30 inches.

At 32 inches down to 8-10 mils peak to peak.

No knocking or banging noises heard throughout withdrawal range.

6-8 mils peak to peak at ULS

Release 14 ms
Drop 141 ms

W/D N Rod

Peak to peak displacement at LLS 8-10 mils.

Max displacement peak to peak up to 24" 8-10 mils.

Between 28 and 30" max peak to peak 14 to 20 mils displacement.

At 32 to 34" max peak to peak 26 to 30 mils displacement.

At ULS average maximum peak to peak displacement 10-12 mils - infrequent maximum peak to peak values of 16 mils were observed.

No knocking or banging noises heard throughout rod withdrawal.

Scram Release 10 ms.
 Drop 135 ms.

SE & SW W/D

No knocking or banging noises throughout withdrawal range.

Reactor Top Observations

<u>Steps</u>	<u>Flow</u>	<u>Observations</u>
1	20,000	None
2	25,000	None
3	30,000	None
4	35,000	None
5	40,000	None
6	42,500	None

<u>Step</u>	<u>Observations</u>
7 Pulling NW Rod	
4"	
6"	
8"	Very slight random movement
10"	Very slight random movement
12"	Very slight random movement
14"	Very slight random movement
16"	Motion increased slightly
18"	Very slight random movement
20"	Very slight random movement
22"	Very slight random movement
24" holding	Very slight random movement
26"	Very slight random movement
28"	
30"	
32"	

<u>Step</u>		<u>Observations</u>
7	34"	Motion stopped
	ULS	No motion
	Pulling S Rod	
	10"	No motion
	12"	No motion
	15"	No motion
	17"	Very slight random movement
	20"	
	22"	Very slight random movement
	24"	Very slight random movement
	26"	Very slight random movement - about same as NW
	28"	Very slight random movement - about same as NW
	30"	Very slight random movement - about same as NW
	32"	Very slight random movement - about same as NW
	34"	Stopped
	ULS	No movement

SE - No movement detected

SW - Slight - stopped at 20 to ULS

Pulling N Rod

4"	
6"	
8"	Very very slight random movement
10"	Very very slight random movement
12"	Very very slight random movement
14"	Very very slight random movement
16"	Very very slight random movement - almost stopped
18"	Very very slight random movement - almost stopped
20"	Very very slight random movement - almost stopped

<u>Step</u>	<u>Observations</u>
7	
22"	
24" & holding	No movement - like a rock (lava)
moving	
just detectable movement (random)	
26"	
28"	Slight increase (random)
30"	Slight increase (random)
32"	
34"	Stopped
ULS	No motion

Noises heard in S inpile tube had lower frequency than those heard in N and NW.

Test No. 27A

Hardware Available August 7

Changes to Vessel

Replace standard fillers in S. W. safety rod with modified fillers.

Replace standard fillers in N. safety rod with modified hafnium stops.

Hardware Available August 9

Changes to Vessel

Replace standard fillers in S. W. safety rod with modified fillers.

Replace standard fillers in N. safety rod with modified hafnium stops
per tel. conv. w/Marv Elder 8-1-67, delivery 8-9-67.

1. Two Rona FR's complete on 8-2-67 (Wednesday)
2. W/Manoll present start assembly of RT-1 on 8-3-67 - day shift (Thursday)
3. RT 4 (NW) rod delivered to CFA on 8-3-67 (start assembly - Thursday)
4. Both RT-1 and RT 4 to be assembled, and delivered to ATR by 1-12 on 8-3-67 (Thursday) or early morning on 8-4-67 (Friday)
5. Install on 8-4-67 complete swings (Friday)

MEMORANDUM

August 18, 1967

Reinstallation of Components
for Vibration Test No. 28

COK-65-67-N

To: Shift Supervisors

The following items must be completed to place the reactor vessel in an operating condition for vibration test No. 28.

1. Transfer inpile tube 820-1 from NW position to storage rack.
2. Transfer inpile tube 820-6 from storage rack to NW position.
3. Install safety rod RT-2 in SW position upon its return from the machine shop. Reconnect safety rod drive package.
4. Transfer inpile tube 820-1 from storage rack to SW position.
5. Install safety rod RT-7 in S position upon its return from the machine shop. Reconnect safety rod drive package.
6. Transfer inpile tube 820-4 from storage rack to S position.
7. Transfer inpile tube 820-10 from SE position to storage rack.
8. Install safety rod RT-5 in SE position upon its return from the machine shop. Reconnect safety rod drive package.
9. Transfer inpile tube 820-5 from storage rack to SE position.
10. The two dummy flux trap fillers will be returned from the machine shop late evening shift on Friday August 18. Reinstall the fillers in the NE and E positions.

Note: The dummy flux trap filler with the two instrumentation grooves on the top 3 feet of the O.D. is to be inserted in the NE position.

11. Transfer inpile tube 820-9 from storage rack to NE position.
12. Transfer inpile tube 820-10 from storage rack to E position.
13. Pressure transducers have been installed in all four No. 3 neck shim rod positions - to measure pressure fluctuations in the flow distribution tank. The instrumentation hookup will be completed on days August 18. Install aluminum plugs in top of remaining 20 neck shim rod sleeves. Plugs are in SS office.
14. Four instrumented dummy fuel elements have been temporarily installed in the reactor. Plant Engineering will utilize these elements

to obtain better information on suspected quadrant pressure unbalances. Nylon impulse tubing installation will be completed on days August 18. A short run will be made and readings obtained at 25, 50, 75, 100 and 115 psi quadrant ΔP 's.

15. Flow balancing orifices have been modified and reinstalled in all four quadrant outlet lines. The old gaskets were reused so some water leakage can probably be expected and tolerated.

16. Howard S. Wright is installing the 3-way 1" valve on the reactor fire water impulse line. This line should be observed when the system is initially pressurized.

Tank Conditions for Vibration Test No. 28

1. NW Position - prime inpile tube 820-6 (clamp-on flow restrictor removed).

Safety rod RT-4 with full length guide tube sleeve plus internal labyrinth flow restrictor.

2. N Position - prime inpile tube 820-2 (clamp-on flow restrictor removed).

Safety rod RT-1 with full length guide tube sleeve plus internal labyrinth flow restrictor.

3. NE Position - prime inpile tube 820-9 (clamp-on flow restrictor removed).

Dummy flux trap filler with internal labyrinth flow restrictor.

4. W Position - dummy gas loop inpile tube with integral dummy flux trap filler.

5. C Position - prime inpile tube 820-3 with 40" clamp-on flow restrictor and "KAPL" flow restrictor on upper splines.

6. E Position - prime inpile tube 820-10 (clamp-on flow restrictor removed).

Dummy flux trap filler with internal labyrinth flow restrictor.

7. SW Position - prime inpile tube 820-1 (clamp-on flow restrictor removed).

Safety rod RT-2 with full length guide tube sleeve plus internal labyrinth flow restrictor.

8. S Position - prime inpile tube 820-4 (clamp-on flow restrictor removed).

Safety rod RT-7 with full length guide tube sleeve plus internal labyrinth flow restrictor.

9. SE Position - prime inpile tube 820-5 (clamp-on flow restrictor removed).

Safety rod RT-5 with full length guide tube sleeve plus internal labyrinth flow restrictor.

Vibration Test No. 28

1. Install accelerometers in NW and N inpile tubes at elevation 77'-6".
2. Pressurize the reactor and increase flow to 100 psi core ΔP while continuously observing safety rod, dummy flux trap filler and in-pile tube vibrations. If any component vibrates excessively reduce flow until vibration is acceptable.
3. Perform the following tests at full flow:
 - a. Withdraw all safety rods individually, observe and record vibration and record accelerometer readings (accelerometer to be at 77'-6").
 - b. Obtain scram and release times for all 5 safety rods.
 - c. Obtain NE and E inpile tube displacements (accelerometer at 77'-6") at 100% flow.
4. Obtain all readings on attached data sheet (4 pages) from Plant Engineering at 25, 50, 75, 100 and 115 psi quadrant ΔP .
5. After weekend run; shutdown flow, drain to core level and remove 4 instrumented elements. Dick Clemons of Plant Engineering will assist in removal.
6. Install four dummy elements in place of instrumented elements.

DA-2C	F-3
DA-3C	F-13
DA-9C	F-23
DA-16A	F-33
7. Refill system and have it pressurized by 0800 Monday August 21, 1967. NO FLOW.

MEMORANDUM

August 14, 1967

Dummy Flux Trap Filler
Vibration Fix

JHC-37-67-N

To: Shift Supervisors

The two dummy flux trap fillers will be modified internally to eliminate the inpile tube vibration. This modification will consist of installing a labyrinth flow restrictor (inside of the dummy flux trap filler) similar to those presently installed in the modified safety rods.

Please remove the flux trap fillers and inpile tubes 820-9 and dummy tube 3632 from NE and E loop positions respectively. Label the flux trap fillers.

Store the dummy flux trap fillers on the main floor until the shipping boxes arrive from CF (boxes will arrive late Monday or early Tuesday).

Crate the fillers and ship to CF-640 (machine shop) for modification.

The modified safety rods and dummy flux trap fillers will return to ATR on August 17 or August 18. At this time all items will be reinstalled to prepare the vessel for Vibration Test No. 28.

In addition, inpile tube 820-10 was installed in the SE position on August 14. This tube may or may not be used for no flow vibration testing the week of August 14, pending results of a meeting today. Testing details will hopefully be transmitted later.

Drawings of "permanent" vibration fixes will be transmitted for your information as they become available.

J. H. Clark

Shutdown Letter - 8/7/67

Preparation for
Vibration Test 28

JHC-33-67

To: Shift Supervisors

1. Remove southwest 1PT-820-6, tag, and place in storage hatch. Remove 40" F.R. and store in S.S. office.

2. Remove southeast 1PT-820-5, tag, and place in storage hatch. Remove 40" F.R. and store in S.S. office.

3. Remove poison plates and fillers from southwest safety rod, RT-2, label as such and store in cage. Store 3" stovepipe F.R. in S.S. office. Remove safety rod RT-2 and box for shipment to CFA.

4. Remove poison plates and fillers from southeast safety rod, RT-5, label as such and store in cage. Store 3" stovepipe F.R. in S.S. office. Remove safety rod RT-5 and box for shipment to CFA.

J. H. Clark

RT-5

	0"	12"	24"	36"	40"	60"	72"
Side 3	0.000"	-0.015"	-0.005"	-0.010"	-0.003"	-0.006"	-0.013
Side 4	0.000"	-0.007"	+0.005"	+0.006"	+0.007"	+0.010"	-0.002"
Side 1	0.000"	-0.005"	+0.009"	0.000"	+0.004"	+0.008"	0.000"
Side 2	0.000"	-0.011"	0.000"	-0.012"	-0.006"	-0.002"	-0.011"

RT-2

Side 4	0.000"	-0.003"	+0.010"	-0.004"	+0.004"	+0.014"	+0.010"
Side 1	0.000"	-0.006"	-0.001"	-0.007"	-0.001"	+0.004"	-0.005"
Side 2	0.000"	-0.020"	-0.012"	-0.014"	-0.008"	-0.014"	-0.018"
Side 3	0.000"	-0.018"	0.000"	-0.013"	-0.009"	-0.007"	-0.008"

Vibration Run 28

Subpile Room Measurements

1. Initial Startup - place accelerometers in NW & N pressure tubes at elevation 77'-6". Record displacements as flow is increased to 100 psid. Mark charts showing: safety rod position, flow rate, N-S, E-W, displacement calibration. N.S. Hsg transducers to be put on Brush and recorded.
2. With 100 psid quadrant ΔP , safety rods at ULS, record displacements in all 5 safety rods, East and NE pressure tubes at elevation 77'-6".
3. Acceptance criterion - no observed motion greater than 0.025-inch.

Reactor Top Observations

NW Rod - some slight movement starting at 23 inches and continued until contact at upper splines.

N Rod - much more stable. Slight movement at 14-1/2" and 21-1/2". Stable the rest of the way up

SE Rod - very slight movement. Hardly detectable started at 30".

S Rod - no movement detected.

SW Rod - some slight movement at 17 to 18 inches, again at 21" and 29". Looked like inpile tube was moving some.

Note: All observations made with big beam light.
All tank lights burned out. Very difficult to see.

Subpile Room Observations

Flow 21,000 ΔP 28 psi, rods LLS - no noise heard in any inpile tube. Accelerometer in N & NW inpile tube - north accelerometer no good.

Flow 42,500 ΔP 100, LLS - no metallic noises heard both during the flow increase or at full flow: E-W - 8 mils peak to peak, N-S - 12 mils peak to peak.

W/D NW Rod - E-W - 18 mils peak to peak, N-S - 16 mils peak to peak. No metallic noises heard up to this point at ULS: E-W - 10

peak to peak, N-S - 14 mils peak to peak. No metallic noises heard up to this point: 28 mils - E-W at 30-1/2 inches, 34 mils - E-W at 32 inches, release time 8 ms, drop time 136 ms.

W/D N rod - at LLS; E-W 8 mils peak to peak, N-S 9 mils peak to peak, E-W 18 mils peak to peak at 14 to 15". At 24 inches and holding, E-W 18 mils peak to peak, N-S 10 mils peak to peak. At 27-1/2 inches - 020 - peak to peak - E-W. At 32-1/2 inches - 032 - peak to peak - E-W. At ULS, E-W - 016 - peak to peak, N-S - 012 - peak to peak. No metallic noise heard throughout. W/D range, release time 8 ms, drop time 136 ms.

Accelerometer installed in NE rod at 77'-6"; N-S maximum 014 mils peak to peak, E-W maximum 012 mils peak to peak.

W/D SE rod - at LLS, E-W 008 mils peak to peak, N-S 008 mils peak to peak. At 24", E-W 012 mils peak to peak, N-S 008 mils peak to peak. No metallic noises heard. At ULS, E-W 012 peak to peak, N-S 008 peak to peak. No noises heard through W/D. Maximum displacement at 31-1/2 - N-S - 022; at 32-1/2 - E-W - 022. Release time 10 ms, drop time 137 ms.

E inpile tube - E-W 012 peak to peak, N-S 009 peak to peak; at 77'-6".

W/D S rod - at LLS, E-W 014 mils peak to peak, N-S 008 peak to peak. At 24", E-W 012 mils peak to peak, N-S 012 mils peak to peak. No noises heard throughout W/D range. At ULS, E-W 010 mils peak to peak, N-S 008 mils peak to peak. No metallic noises heard throughout withdrawal range. Maximum peak to peak 014 mils at 27-1/2 inches in N-S direction. Release time 17 ms, drop time 143 ms.

PCS temperature 62° F at 1132 a.m.

PCS temperature 56° F at 0800 a.m.

W/D SW rod - at LLS, E-W 007 mils peak to peak, N-S 006 to 008 peak to peak. At 24", E-W 018 mils peak to peak, N-S 018 mils peak to peak; 18.5" 016 E-W, 20" 016 N-S; between 20-21" heard 1 knock. At ULS, E-W 018 mils peak to peak, N-S 018 mils peak to peak; 25.5" 024 E-W, 28" 020 N-S 026 EW. One metallic sound heard at 32". Release time 8 ms, drop time 125 ms.

Desired tapes - all sensor elevations equals 77'-6".

1. Accelerometers in SW & S PT's. All rods at ULS.

Tape record at each of following quadrant ΔP 's: 10, 40, 70, 100 and 113.5 psi. Brush read tape: E-W & N-S displacement (filtered) in each P.T. at each flow. Tape: E-W & N-S acceleration (unfiltered) in each P.T. at each flow.

2. At quadrant ΔP equals 40 and 100 psi and all rods at LLS repeat recordings.

3. Repeat 1 above with accelerometers mounted in NE and E P.T's.

Vibration Test No. 30

Changes

1. Remove dummy inpile tube from E position and move to storage.
2. Install inpile tube 820-10 in E position.
3. Remove inpile tube 820-4 from S position and move to storage.
4. Pull back S. drive.
5. Remove safety rod RT-6M.
6. Install safety rod RT-7 and reinstall drive.
7. Reinstall inpile tube 820-4 in S position.
8. Install accelerometer on E inpile tube above top locator tie at elevation 90'-0".
9. Startup and excite the E inpile tube as per item 1 of Vibration Test No. 29.
10. Shutdown and drain to core level.

Vibration Test No. 30A

Changes

8-29-67

1. Remove dummy inpile tube 3603 from the N position and move to storage.
2. Install inpile tube 820-2 in the N position.
3. Move insulation can accelerometer from E inpile tube to the insulation can of the S inpile tube and install above the top locator tie at elevation 90 feet.
4. Startup and excite the S inpile tube as per item 1 of Vibration Test No. 29 (up to 100 psid). Started 1400 8-29-67
5. Shutdown and drain to core level.

Vibration Test No. 30B

Changes

1. Remove inpile tube 820-4 from the S position and move to storage.
2. Transfer inpile tube 820-10 from the E position to the S position.
3. Transfer 820-1 from storage and insert in the E position.

Note: If trouble is encountered make the splines and compare to the measurements of dummy inpile tube 3603 which will be repaired at this time. If the dummy splines are smaller put dummy inpile tube in the E position.

4. Reinstall the insulation can accelerometer on the S inpile tube at elevation 90 feet.
5. Startup and excite the S inpile tube as per item 1 of Vibration Test No. 29. **
6. Shutdown and drain the core level.

** When 3rd pump (M-8) becomes available close surveillance should be maintained.

In addition, a head capacity curve is to be performed prior to starting the vibration test.

Note: When the hydraulic servo-actuator becomes available, install in subpile room and use it instead of air driven actuator.

Vibration Test No. 30C

Changes

1. Remove Dummy inpile tube 3632 from the SW position and move to storage.
2. Transfer inpile tube 820-10 from the S to the SW position.
3. Transfer 820-4 from storage to the S position.
4. Install accelerometer on the insulation can of the SW inpile tube at elevation 90 ffet.
5. Startup and excite the SW inpile tube as per item 1 of Vibration Test No. 29.
6. Install servo-actuator and record readings on N, SW, S, SE, and E tubes.

Note: The intank accelerometer is to be moved each time to the tube being vibrated.

7. Shutdown by 0800, 8-31-67 and drain to core level.

Vibration Test No. 30D

Changes

1. The dummy flux trap filler has to be removed from the NE and sent to CFA for the installation of the labyrinth flow restrictor.
 - a. Remove inpile tube 820-9 to storage. Remove 49" clamp on flow restrictor and mike and record lower spline diameter.
 - b. Send filler to CFA for modification.
 - c. Reinstall dummy flux trap filler in NE after modifications are completed.
 - d. Reinstall inpile tube 820-9 in the NE position.
2. Remove inpile tube 820-3 from the C position and move to storage.
3. Transfer inpile tube 820-10 from the SW to the C position after first installing the special flow restrictor in the groove in the upper splines.
4. Remove the 40 inch clamp-on flow restrictor from below the upper splines on inpile tube 820-3 and also the flow restrictor located on the splines.
5. Insert 820-3 in the SW position.
6. Install accelerometer on the insulation can of the C inpile tube at elevation 90 feet.
7. Remove Dummy 3631 from NW and move to storage.
8. Transfer inpile tube 820-6 from storage to the NW position.
9. Startup and excite C etc.
10. Continue with other tubes.

Vibration Test No. 31

Changes

1. Shutdown primary pumps, depressurize system, and drain reactor vessel.
2. Remove Center inpile tube, 820-10, and replace special flow restrictor in the groove in the upper splines with another special flow restrictor that is identical except for a smaller inside diameter.
3. Install inpile tube 820-10 in the center position.
4. Remove NW inpile tube 820-6 and move to storage.
5. After the drive unit is removed, pull the NW safety rod, RT-4 and move to main floor.
6. Locate and remove lost screw.
7. Reassemble NW position:
 1. Install safety rod RT-4 and replace drive unit.
 2. Install inpile tube 820-6.
8. Remove S safety rod drive unit and inspect for cause of difficulty experienced in removal and insertion of the drive.
9. Install 3" flow restrictor in S and SE safety rods, RT-5 and RT-7 after removing the 82" sleeves.
10. Install 12" stovepipe flow restrictor in NE flux trap filler.
11. Upon completion of above steps, fill system and start flow for Vibration Test No. 31.

Load cell here $\cong$ 1200 on 9-2-67

Operations Observations

0000 - 0800 - September 2, 1967

No intank lights were available - therefore no observations were taken from reactor top.

With all safety rods at LLS, 100 psi ΔP center tube showed a vibrator motion of ~4.5 cps with 17 mil displacement. Data were taken with 3 (three) pumps supplying the reactor. With two pumps supplying the reactor the low frequency vibration was still present but the 4.5 cps vibration was down to ~5 mil. This is with no support (tiedown) on the center inpile tube except the exciter.

Center tube was tied down (clamshell clamps) and excited at various frequencies, with all rods at LLS.

All rods except NW were raised to ULS and center tube excited at various frequencies and core ΔP 's.

Center inpile tube with 3 pumps 4-5 cps - 17 mils

Center inpile tube with 2 pumps 5 mils

Safety rod NW down

APPENDIX B
Consultant's Analytical Evaluation

CONTENTS

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1. Insulation Jacket Vibration Modes

Dimensions:

$$AB = 86'5'' - 68'0'' \rightarrow 221''$$

$$BC = 97'1'' - 86'5'' \rightarrow 128''$$

Effective lengths (assumed to account for changes in flexural inertia):

$$AB = 2L = 220''$$

$$BC = L = 110''$$

$$OD = 2.874''$$

$$ID = 2.634''$$

$$D = 2.754$$

$$A = \frac{\pi D}{2} (OD - ID) = 3.14 \times 2.754 \times 0.120 = 1.025 \text{ in.}^2$$

$$m = \frac{AW_m}{g} = \frac{1.025 \times 0.27}{386} = 7.20 \times 10^{-4} \text{ lb/in.}^{-2}\text{-sec}^2$$

$$I = \frac{1}{2} A \frac{D^2}{4} = 0.125 \times 1.025 \times 2.754^2 = 0.972 \text{ in.}^4$$

$$E = 2.85 \times 10^7 \text{ lb/in.}^{-2}$$

Natural frequency of simply supported BC span alone:

$$\omega = \frac{\pi^2}{L^2} \sqrt{\frac{EI}{m}} = \frac{9.86}{110^2} \left(\frac{2.85 \times 10^7 \times 0.972}{7.20 \times 10^{-4}} \right)^{1/2} = 160 \text{ rad/sec}^{-1} \text{ or } 25.6 \text{ cps}$$

It is known from reference 1 (section 4 references) that this is also the frequency of the first sinusoidal mode. The fundamental (which is not of sinusoidal shape) has a frequency defined by

$$\omega_0 = \left(\frac{9\pi^4}{16L} \right)^2 \sqrt{\frac{EI}{m}} \quad \text{or} \quad 0.316 \omega \rightarrow 50.5 \text{ rad/sec}^{-1} \text{ or } 8.13 \text{ cps.}$$

The fundamental mode shape is specified by (see reference 1, pp 93 through 95)

$$y_1 = C \left(\sin \frac{9\pi}{16L} x_1 + 0.0216 \sinh \frac{9\pi}{16L} x_1 \right) \quad \text{between A and B}$$

and

$$y_2 = C \left(-0.390 \sin \frac{9\pi}{16L} x_2 + 0.131 \sinh \frac{9\pi}{16L} x_2 \right) \quad \text{between B and C}$$

Note that the sinusoidal mode depends on the location of (B) but not on its transverse stiffness. The low-frequency component is expected to be very sensitive to both the location and the stiffness of the support in (B). With the mode shapes specified as above, we can compute the theoretical ratios of vibration amplitudes at the two pickup locations: (1) PT pickup at 77'6" and (2) IJ pickup at 90'0". It is not implied at this point that (1) is in contact with the insulation jacket.

$$L = 110'' \quad x_1 = 108'' \quad , \quad x_2 = 84''$$

$$\sin \frac{9\pi}{16L} x_1 = \sin 1.74 = 0.940 \quad \sinh 1.74 = 2.770$$

$$\sin \frac{9\pi}{16L} x_2 = \sin 1.35 = 0.985 \quad \sinh 1.35 = 1.760$$

$$y_1 = 0.940 + 0.0216 \times 2.77 = 0.9997$$

$$y_2 = -0.390 \times 0.985 + 0.131 \times 1.76 = -0.157$$

$$y_1/y_2 = 6.35$$

For the first sinusoidal mode,

$$y_1 = \sin \frac{x_1}{L} \pi \quad y_2 = \sin \frac{x_2}{L} \pi$$

$$y_1 = \sin \frac{108}{110} \pi \approx 0.0696 \quad y_2 = \sin \frac{84}{110} \pi \approx 0.68$$

$$y_1/y_2 = 0.101$$

2. Pressure Tube Vibration Modes

Dimensions:

$$DE = 97'1'' - 64'0'' \approx 397 \text{ in.}$$

Effective length, accounting for 6' top portion:

$$L = 360 \text{ in.}$$

$$OD = 2.530'' \quad ID = 2.124'' \quad D = 2.330''$$

$$A = \frac{\pi D}{2} (OD - ID) = 3.14 \times 2.330 \times 0.203 = 1.47 \text{ in.}^2$$

$$m = \frac{AW_m}{g} = \frac{1.47 \times 0.27}{386} = 1.03 \times 10^{-3} \text{ lb/in.}^{-2}\text{-sec}^2$$

$$I = \frac{1}{2} A \frac{D^2}{4} = 0.125 \times 1.47 \times 2.33^2 = 1.00 \text{ in.}^4$$

$$E = 2.85 \times 10^7 \text{ lb/in.}^{-2}$$

Natural (fundamental) frequency of simply supported DE span:

$$\omega_0 = \frac{\pi^2}{L^2} \sqrt{\frac{EI}{m}} = \frac{9.86}{360^2} \left(\frac{2.85 \times 10^7 \times 1.00}{1.03 \times 10^{-3}} \right)^{1/2} = 12.8 \text{ rad/sec}^{-1} \text{ or } 2.03 \text{ cps}$$

With clamped supports at both (D) and (E) this value may be increased by a factor of 2.3 or 4.65 cps.

3. Pressure Tube Superimposed on Insulation Jacket

Imagine now an assembly identical to and supported as the insulation jacket but with the inertia and mass properties of the pressure tube superimposed. No shear transmission between the two are assumed. This would be the case if, for example, the locator buttons on the pressure tube would be at all times in contact with the inside diameter of the insulation jacket. Then

$$I_{eq} = I_{PT} + I_{IJ} = 1.00 + 0.972 = 1.972 \text{ in.}^4$$

$$m_{eq} = m_{PT} + m_{IJ} = (1.03 + 0.720)10^{-3} \text{ lb/in.}^{-2}\text{-sec}^2$$

and the natural frequency of the span BC (which is also the first sinusoidal mode) becomes

$$\omega = \frac{\pi^2}{L^2} \sqrt{\frac{EI_{eq}}{m_{eq}}} = \frac{9.86}{110^2} \left(\frac{2.85 \times 10^7 \times 1.972}{1.75 \times 10^{-3}} \right)^{1/2} = 148 \text{ rad/sec}^{-1} \text{ or } 23.6 \text{ cps}$$

The fundamental mode in this case would be at 7.45 cps. Note how critically these frequencies depend on the assumptions of span length. A 10% reduction in the assumed span length would result in almost 8.9 cps fundamental; a reduction of the same amount would reduce this frequency to somewhat less than 6.0 cps.

4. Amplitudes Due to Parallel-Flow Excitation

Two specific computations are shown to illustrate the parallel-flow excitation mechanisms and to get a feel for the vibration amplitudes that

might be expected. Burgreen (section 4, reference 1), admittedly conservative, follows the computations given below:

$$\Gamma = \frac{\rho_w V^2 L^4}{EI} \left\{ \begin{array}{l} \rho_w = 0.98 \times 10^{-4} \text{ lb/in.}^{-4}\text{-sec}^2 \\ V = \text{flow velocity, here taken as} \\ \quad 420 \text{ in./sec}^{-1} (35 \text{ ft/sec}^{-1}) \\ L = 156 \text{ in.} \\ E = 2.85 \times 10^7 \text{ lb/in.}^{-2} \\ I = 0.972 \text{ in.}^4 \end{array} \right.$$

Values of L are taken as the distance between the top and bottom splines of the insulation jacket (85 and 72 ft levels, respectively).

$$V \text{ in./sec}^{-1} = \frac{3.86 \dot{Q}(\text{gpm})}{A_w(\text{in.}^2)} ; \text{ with } A_w = 2.35 \text{ in.}^2$$

$$\dot{Q} = \frac{2.35}{3.86} V \text{ with the units indicated} = 256 \text{ gpm.}$$

This would probably be on the high side with the flow restrictor and labyrinth arrangements now installed.

$$\Gamma = \frac{0.98 \times 420^2 \times 156^4}{2.85 \times 10^7 \times 0.972} = 5.04 \times 10^2$$

$$\Omega = \frac{\rho_w V^2}{\mu \omega} \left\{ \begin{array}{l} \rho_w = 0.98 \times 10^{-4} \text{ lb/in.}^{-4}\text{-sec}^2 \\ V = 420 \text{ in./sec}^{-1} \\ \mu = 16 \times 10^{-8} \\ \quad (\text{viscosity in sec, in. units water @ } 20^\circ \text{C}) \\ \omega = 46.7 \text{ rad/sec} \end{array} \right.$$

The value of ω in this case is the one corresponding to Appendix B, part 3, i.e., 7.45 cps insulation jacket fundamental.

$$\Omega = \frac{0.98 \times 10^{-4} \times 420^2}{16 \times 10^{-8} \times 46.7} \quad 2.32 \times 10^6$$

$$\left(\frac{\delta}{D_h}\right)^{1.30} = 4.15 \times 10^{-10} \Gamma^{1/2} \Omega$$

$$= 4.15 \times 10^{-10} (5.04 \times 10^2)^{1/2} \times 2.32 \times 10^6 = 2.18 \times 10^{-2}$$

$$\left(\frac{\delta}{D_h}\right) = \sqrt[1.30]{2.18 \times 10^{-2}} = \frac{1.82}{34.8} = 0.052$$

The hydraulic diameter

$$D_h = 4 \frac{\text{flow cross section}}{\text{wetted perimeter}} \approx \frac{4\pi(\text{OD}) \times 0.25}{2\pi(\text{OD})} = 0.5 \text{ in.}$$

Thus the vibration amplitude is found to be

$$\delta = 0.5 \times 0.052 = 0.026 \text{ inch}$$

The Burgreen amplitude will now be compared with the Westinghouse Correlation results, following the procedure outlined by Reavis (section 4, reference 2).

$$\frac{D_h}{L} = \frac{0.5}{156} = 0.00321 \therefore C \approx 3.0$$

is the ratio of actual to theoretical maximum deflection.

$$f = 7.45 \text{ cps}, \quad D = 2.874 \text{ in.}, \quad D_h = 0.5 \text{ in.}, \quad L = 156 \text{ in.}, \quad V = 420 \text{ in./sec}$$

$$\frac{fD}{V} = \frac{7.45 \times 2.874}{420} \quad \textcircled{A} \quad \frac{fD_h}{V} = \frac{7.45 \times 0.5}{420} \quad \textcircled{B} \quad \frac{fL}{V} = \frac{7.45 \times 156}{420}$$

$$= 0.049 \quad \quad \quad = 0.0089 \quad \quad \quad = 1.77$$

$$\eta_D = 1.01$$

$$\eta_L = 0.37$$

$$\eta_{D_h} = 0.80$$

The product $\eta_D \eta_L \eta_{D_h} = 0.295$

$\frac{W}{L}$ (unit weight of insulation jacket) = 0.300 lb/in.⁻¹
(including 15% water load)

ζ = damping ratio = 0.01

$\rho_w = 0.98 \times 10^{-4}$ lb/in.⁻⁴-sec² mass density of water

$\nu = \frac{\mu}{\rho_w} = \frac{16.10^{-8}}{0.98 \times 10^{-4}} = 16.3 \times 10^{-4}$ in.²-sec⁻¹ (kin. viscosity)

$$\delta = C \eta_D \eta_L \eta_{D_h} \frac{DV \rho_w \nu^{0.5}}{\left(\frac{W}{L}\right)^{1.5} \zeta^{0.5}} \text{ in.}$$

$$= \frac{3.0 \times 0.295 \times 2.874 \times 420 \times 0.98 \times 10^{-4} \times (16.3 \times 10^{-4})^{0.5}}{0.300 \times (7.45)^{1.5} \times (0.01)^{0.5}}$$

$\delta = 0.007$ in.

5. Damping Characteristics and Power Relationships

It is assumed now that a vibrator like that described in Appendix B, part 3, composed of the insulation jacket and pressure tube, is excited at its fundamental frequency $\omega_0 = 46.7$ rad/sec⁻¹ (7.45 cps). Our purpose is to determine the damping ratio from a steady-state response curve and obtain expressions for the power required to maintain vibrations at a specified level.

Consider a one-dimensional oscillator of mass M , natural frequency ω_0 and damping ratio ζ ; its response to an excitation force is, at frequency ω ,

$$Y = \frac{F}{M\omega_0} \frac{1}{[(1 - \beta^2)^2 + 4\zeta^2 \beta^2]^{1/2}} \quad \beta = \frac{\omega}{\omega_0}$$

At resonance Y is maximum by definition, $Y_{\max} = 1/2\zeta$. The bandwidth is specified by the difference in abscissas $\beta_2 - \beta_1$ of the two points where

$$Y = \frac{1}{\sqrt{2}} Y_{\max}$$

(the so-called half-power points are the response curve). For relatively small dampings,

$$\beta_2 - \beta_1 \cong 4\zeta \frac{\sqrt{1 + \zeta^2}}{2} \cong 2\zeta \therefore \zeta = \frac{\beta_2 - \beta_1}{2} = \frac{\omega_2 - \omega_1}{2\omega_0} = \frac{1}{2} \frac{f_2 - f_1}{f_0}$$

Note that in this expression f_0 is the resonant frequency in cps; f_2 and f_1 are the two half-power frequencies and thus can be measured for each response curve quite accurately as long as the damping is, say, less than 15%.

The work expended per cycle is found as

$$E_c = \pi F Y,$$

which at resonance becomes

$$2\pi \zeta M \omega_0^2 Y^2$$

The power consumption is

$$E_c f_0 = P_c = \zeta M \omega_0^3 Y^2$$

The power in the flow is

$$\frac{1}{2} \rho_w A_w V^3 = P_w$$

so that

$$\frac{P_c}{P_w} = \frac{\zeta}{2} \frac{M \omega_0^3 Y^2}{\rho_w A_w V^3}$$

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Numerical example:

$$M = \frac{1}{2} \frac{360 \text{ in.} \times 0.700 \text{ lb/in.}^{-1}}{388 \text{ in./sec}^{-2}} = 0.328 \text{ lb/in.}^{-1}\text{-sec}^2$$

$$\omega_0 = 46.7 \text{ sec}^{-1}; Y = 0.025 \text{ in.}$$

$$\zeta = 0.05, \quad \rho_w = 0.98 \times 10^{-4}, \quad A_w = 2.35 \text{ in.}^2, \quad V = 360 \text{ in./sec}^{-1}$$

$$\frac{P_c}{P_w} = \frac{0.05 \times 0.328 \times \overline{46.7^3} \times \overline{0.025^2}}{2 \times 0.98 \times 10^{-4} \times 2.35 \times \overline{360^3}} = 0.0047\%$$

With $V = 240 \text{ in./sec}^{-1}$ (145 gpm), and $\zeta = 0.1$, this ratio is 0.031%.

APPENDIX C
Thermal Calculations

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1. Determination of Outer Loop Gamma Heating Rate

In reference 1 the maximum heating rate at the outside surface of the pressure tube is reported to be 16.9 watts per gram. Applying a 1.25 uncertainty factor, the rate will be 21.73 watts per gram. Adjusting this value to the radial profile shown in reference 2, the radial distribution will be as follows:

<u>Location</u>	<u>Pressure tube, watts/gm</u>	<u>Insulation jacket, watts/gm</u>
I	21.73	19.86
III	17.16	15.42

At this point it should be noted that some experimental error may be present in the radial profile measurement. This error will be evaluated statistically. Assuming that axial gamma heating distribution is a true cosine, then the variance of the data can be determined from

$$\sigma^2 \cong \frac{1}{N-1} \sum_{i=1}^N (\bar{n} - n_i)^2$$

Only points above 10 watts per gram (extrapolated) will be included, because (1) the cosine assumption is not valid at the edge of the core, and (2) the error for small values may be different than that for larger values (may be % of point, response may be nonlinear, etc.).

Table C-1. Axial Heating Rate
Test Data

<u>i</u>	<u>$\bar{n}$</u>	<u>n_i</u>	<u>$\bar{n} - n_i$</u>	<u>$(\bar{n} - n_i)^2$</u>
1	14.2	13.4	+0.8	0.64
2	16.7	16.2	+0.5	0.25
3	18.2	17.8	+0.4	0.16
4	18.9	20.8	-1.9	3.61
5	18.5	19.3	-0.8	0.64
6	17.2	16.9	+0.3	0.09
7	15.1	14.3	+0.8	0.64
8	12.3	11.9	+0.3	0.09
Total				6.12

Table C-2. Radial Heating Rate
Test Data

<u>i</u>	<u>$\bar{n}$</u>	<u>n_i</u>	<u>$\bar{n} - n_i$</u>	<u>$(\bar{n} - n_i)^2$</u>
9	10.7	10.5	+0.2	0.04
10	12.4	12.9	-0.5	0.25
11	14.2	14.8	-0.6	0.36
12	14.0	14.0	0.0	0.00
13	13.2	13.3	-0.1	0.01
14	11.7	11.9	-0.2	0.04
Total				0.70
Grand total				6.82

$$\sigma^2 = \frac{6.82}{13} = 0.525 \text{ (W/gm)}^2$$

$$\text{standard deviation } \sigma = \sqrt{0.525} = 0.72 \text{ W/gm}$$

Limits, σ	Confidence level, %	One-sided confidence level, %
1	68	84
2	96	98
3	99.9	99.9

Applying an uncertainty factor to the radial profile based on this statistical evaluation of experimental data, and using a 99.0% confidence level, the resulting heat rates are as follows:

Location	Pressure tube, W/gm	Insulating jacket, W/gm
I	21.47	19.86
III	13.81	12.07

2. Determination of Center Loop Gamma Heating Rates

The radial profile in the center loop with a 60-40 power split has not been measured. For this reason a conservative estimate of the power split will be made. Assume that hot side heating rates will be 10% above average and cold side rates will be 10% below average. Average heat rates are based on core radial profiles listed in reference 3.

$$q''' = 16.47 \text{ W/gram}$$

Applying a 25% uncertainty factor and including the assumed radial profile, the heating rates will be as follows:

	Hot side	Cold side
$q''', \text{ W/gm}$	22.65	18.55

3. Determination of Flow Distribution in the Outer Loop

As noted in the hydraulics portion of the calculational results, thermal bow in the insulation jacket should tend to increase the coolant flow rate, as shown in reference 3. However, since the eccentricity of the insulation jacket varies with length, it would be expected that any derived benefits should be relatively small. Consequently, thermal calculations are performed with the flow distribution calculated for a no-bow condition.

4. Thermal Calculational Methods

To simplify the calculations, the hot and cold sides of the NR loop will be evaluated independently. This approach, in effect, assumes no azimuthal transfer of heat in either the insulation jacket or the pressure tube. The consequence of neglecting azimuthal heat transfer will be to increase the calculated radial temperature differentials and, thereby, to overestimate the thermal bow.

Consider a very narrow arc that encompasses the point of maximum or minimum power generation. Somewhere between the inner surface of the pressure tube and the outer surface of the insulation jacket will occur a point of maximum temperature. This point will act as a thermal insulated boundary so that all heat generated inside of this point must flow inward, and all heat generated outside of this point must flow outward radially. Assuming that the maximum temperature occurs somewhere inside of the pressure tube (this assumption can be verified through the calculations), and neglecting azimuthal heat transfer, the heat flux at the inner surface of the pressure tube will be predicted by the equation

$$Q/A = h_2(T_2 - T_1)$$

It follows, then, that the inner surface temperature of the pressure tube will be

$$T_2 = (Q/h_2A) + T_1 = \frac{q''' \pi (R_3^2 - R_2^2)}{2 \pi R_2 h_2} + T_1$$

The temperature at the outer surface of the pressure tube can then be found from the basic conduction equation

$$\frac{\partial T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{1}{r^2} \frac{\partial^2 T}{\partial \theta^2} + \frac{\partial^2 T}{\partial z^2} + \frac{q'''}{k} = \frac{C_p \rho}{k} \frac{\partial T}{\partial \phi}$$

Assuming radial, steady-state heat transfer,

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{q'''}{k} = 0$$

$$r \frac{dT}{dr^2} + \frac{dT}{dr} = \frac{-q'''r}{k}$$

$$r \frac{dT}{dr} = \frac{-r^2 q'''}{2k} + C$$

Boundary Condition at $R = R_3$, $dT/dr = 0$

$$R_3(0) = \frac{-R_3^2 q'''}{2k} + C$$

$$C = \frac{R_3^2 q'''}{2k}$$

$$r \frac{dT}{dr} = \frac{q'''}{2k} (R_3^2 - r^2)$$

$$dT = \frac{q'''}{2k} \left(\frac{R_3^2}{r} - r \right) dr$$

$$T = \frac{q'''}{2k} \left(R_3^2 \ln r - \frac{r^2}{2} \right) + C'$$

Boundary Condition at $R = R_2$, $T = T_2$

$$T_2 = \frac{q'''}{2k} \left(R_3^2 \ln R_2 - \frac{R_2^2}{2} \right) + C'$$

$$C' = T_2 - \frac{q'''}{2k} \left(R_3^2 \ln R_2 - \frac{R_2^2}{2} \right)$$

$$T = \frac{q'''}{2k} \left(\frac{R_2^2 - R^2}{2} + R_3^2 \ln \frac{R}{R_2} \right) + T_2$$

$$T_4 = q''' \left[\frac{1}{2k} \left(\frac{R_2^2 - R_4^2}{2} + R_3^2 \ln \frac{R_4}{R_2} \right) + \frac{R_3^2 - R_2^2}{2R_2 h_2} \right] + T_1$$

Referring to reference 2, the average temperature for this side of the pressure tube is

$$T_{avg} = \frac{q''' R_4^2}{4k_3} \left\{ \frac{1}{2} \left[1 + \left(\frac{R_2}{R_4} \right)^2 \right] - \frac{1 - \left(\frac{R_2}{R_4} \right)^2}{\ln \left(\frac{R_4}{R_2} \right)^2} \right\} + (T_4 - T_2) \left[\frac{1}{1 - \left(\frac{R_2}{R_4} \right)^2} - \frac{1}{\ln \left(\frac{R_4}{R_2} \right)^2} \right] + T_2$$

Since all heat generated outside of the point of maximum temperature must flow outward, the heat flux at the outer surface of the pressure tube is simply

$$q_4''' = \frac{V}{A} q'''$$

$$q_4''' = \frac{q''' \pi (R_4^2 - R_3^2)}{2\pi R_4}$$

Now the temperature distribution in the insulation jacket will be found. First we must find the coolant temperature around the insulation jacket; this calculation requires a knowledge of the heat transferred outward from both the hot and cold sides. Consequently, an iterative solution is necessary.

$$Q = Wc_p \Delta T$$

$$T_7 = \frac{Q}{Wc_p} + T_{in} = \frac{\frac{\bar{q}_4''}{(P^*/\bar{P})_r} 2\pi R_4 \frac{L_a}{2} + \frac{\bar{q}'''}{(P^*/\bar{P})_r} \pi (R_6^2 - R_5^2) \frac{L_a}{2}}{W_7 c_{p7}} + T_{in}$$

The following convective heat transfer model has been derived from methods and data in reference 3:

The Stien-Begell equation has been developed for convective heat transfer from concentric annuli where the inner annulus is heated.

$$h_0 = 97.7(1 + 0.0066 T_f) \frac{V^{0.8}}{De^{0.2}} \left(\frac{R_7}{R_8} \right)^{0.5}$$

so that

$$Nu_0 = 97.7(1 + 0.0066 T_f) \frac{V^{0.8} De^{0.8}}{k} \left(\frac{R_7}{R_8} \right)^{0.5}$$

However, for eccentric annuli, the Nusselt number decreases. On the basis of data contained in reference 3, the following correlation has been derived for the average Nusselt number.

$$Nu = 6.34 + 78.13 \epsilon - 122.70 \epsilon^2 + 0.959173 Nu_0 - 0.1839 Nu_0 \epsilon + 0.000041862 Nu_0^2$$

where ϵ , the eccentricity, is defined as the ratio of the bow of the inner annulus to the flow channel hydraulic diameter.

$$\epsilon = \frac{\text{bow}}{2(R_8 - R_6)}$$

and, by definition,

$$h_6 = \frac{Nuk}{De}$$

In accordance with the methods outlined in reference 3, the outside surface temperature of the insulated jacket is found from the following equation:

$$T_6 = T_7 \pm F_{\theta} (q_6''/h_6) = T_7 \pm F_{\theta} \left(\frac{q_4'' R_4}{h_6 R_6} + q_{pt}''' \frac{R_6^2 R_5^2}{2 R_6 h_6} \right)$$

where F_{θ} is obtained from a least-squares fit of experimental data.

$$F_{\theta} = 0.6574 \epsilon - 0.1356 \epsilon^2$$

The F_{θ} term will be positive on the hot side of the NR loop and negative on the cold side.

The temperature of the inner surface of the insulation jacket can be derived from the basic conduction equation, which was simplified earlier to

$$r \frac{dT}{dr} = \frac{-r^2 q'''}{2k} + C$$

$$\text{Boundary Condition at } R = R_5, \quad dT/dr = -q_5''/k = -q_4'' r_4 / k r_5$$

$$\frac{-R_4 q_4''}{k} = \frac{-R_5^2 q'''}{2k} + C$$

$$C = \frac{q''' R_5^2}{2k} - \frac{q_4'' R_4}{k}$$

$$r \frac{dT}{dr} = \frac{q''' (R_5^2 - r^2)}{2k} - \frac{q_4'' R_4}{k}$$

$$dT = \frac{q'''}{2k} \left(\frac{R_5^2}{r} - r \right) - \frac{q''R_4}{kr} dr$$

$$T = \frac{q'''}{2k} \left(R_5^2 \ln r - \frac{r^2}{2} \right) - \frac{q''R_4 \ln r}{k} + C'$$

Boundary Condition at $r = r_6$, $T = T_6$

$$T_6 = \frac{q'''}{2k} \left(R_5^2 \ln R_6 - \frac{R_6^2}{2} \right) - \frac{q''R_4 \ln R_6}{k} + C'$$

$$T = \frac{q'''}{2k} \left(\frac{R_6^2 - r^2}{2} + R_5^2 \ln \frac{r}{R_6} \right) + \frac{q''}{k} R_4 \ln \frac{R_6}{r} + T_6$$

$$T_5 = q''' \left[\frac{R_6^2 - R_5^2}{4k} - \frac{R_5^2 \ln \left(\frac{R_6}{R_5} \right)}{2k} \right] + \frac{q''}{k} R_4 \ln \frac{R_6}{R_5} + T_6$$

The average temperature of this side of the insulation jacket may be found from reference 2 using the following equation:

$$T_{avg I} = \frac{q'''R_6}{4k} \left\{ \frac{1}{2} \left[1 + \left(\frac{R_5}{R_6} \right)^2 \right] - \frac{1 - \left(\frac{R_5}{R_6} \right)^2}{\ln \left(\frac{R_6}{R_5} \right)^2} \right\} + (T_6 - T_5) \left[\frac{1}{1 - \left(\frac{R_5}{R_6} \right)^2} - \frac{1}{\ln \left(\frac{R_6}{R_5} \right)^2} \right] + T_6$$

At this point, the heat flux through the helium gap, the inner surface temperature of the insulation jacket, and the outer surface temperature of the pressure tube have been found. Knowing the thermal conductivity of helium, the corresponding helium gap is found as follows:

$$\frac{\frac{T_4 - T_5}{\ln (R_5/R_4)}}{2\pi k\ell}$$

$$q_4'' = \frac{\frac{T_4 - T_5}{2\pi R_4 \ell \ln (R_5/R_4)}}{2\pi k\ell} = \frac{(T_4 - T_5)k}{R_4 \ln (R_5/R_4)}$$

$$\ln (R_5/R_4) = \frac{k(T_4 - T_5)}{q_4'' R_4}$$

$$R_5/R_4 = a \log \left[\frac{k(T_4 - T_5)}{q_4'' R_4} \right]$$

$$R_5 - R_4 = R_4 \left\{ a \log \left[\frac{k(T_4 - T_5)}{q_4'' R_4} \right] \right\} - R_4$$

It should be noted that the point of maximum temperature for the hot and cold sides of the NR loop will occur at different radii. However, the two separate analytical solutions are connected through the helium gap. Knowing the helium gap for either side effectively fixes the gap for the other side.

5. Sample Thermal Calculations

The determination of the temperature distribution in the pressure tube and insulation jacket requires an iterative solution with the thermal bow conditions. The numbers used in the sample calculations are those used in the final iteration of the hot side conditions.

Since the heat flux is zero at the point of maximum temperature, this point acts as an insulated boundary against the radial transfer of heat. All heat generated inside of this point must flow inward, and all heat generated outside this point must flow outward. Consequently the heat transfer analysis can be divided into two simplified problems at the point of maximum temperature.

$$\text{Assume } R_3 = 0.10148$$

$$H_2 = 8960 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$$

It is now possible to solve for the temperature distribution inside the point of maximum temperature. The temperature of the inside surface of the pressure tube will be

$$\begin{aligned} T_2 &= \frac{q'''_{pt} \pi (R_3^2 - R_2^2)}{h_2 2\pi R_2} + T_1 \\ &= \frac{21.47 \text{ W/gm} \times 3413 \text{ Btu/kWh} \times 500.256 \text{ lb/ft}^3 (0.10148^2 - 0.0885^2) \text{ ft}}{2 \times 2.205 \text{ lb/kg} \times 0.0885 \text{ ft} \times 8960 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}} \\ &\quad + 650 \text{ F} = 682.27 \text{ F} \end{aligned}$$

Now, solving outward from the point of maximum temperature, the outer surface temperature of the pressure tube is

$$\begin{aligned} T_4 &= q''' \left[\frac{1}{2k_3} \left(\frac{R_2^2 - R_3^2}{2} + R_3^2 \ln \frac{R_4}{R_2} \right) + \frac{R_3^2 - R_2^2}{2R_2 H_2} \right] + T_1 \\ &= \frac{21.47 \text{ W/gm} \times 3413 \text{ Btu/kWh} \times 500.256 \text{ lb/ft}^3}{2.205 \text{ lb/kg}} \left[\frac{1}{2 \times 11.7 \text{ Btu/hr-ft-}^\circ\text{F}} \right. \\ &\quad \left(\frac{0.0885^2 - 0.10148^2}{2} + 0.10148^2 \ln \frac{0.10604}{0.0885} \right) \text{ ft} \\ &\quad \left. + \frac{0.10148^2 - 0.0885^2}{2 \times 0.0885 \times 8960 \text{ Btu/hr-ft}^2} \right] + 650 \text{ F} = 872.12 \text{ F} \end{aligned}$$

The average temperature on the cold side of the pressure tube, then, is

$$\begin{aligned}
 T_{pt} = & \frac{q''' R_4^2}{4k_3} \left\{ \frac{1}{2} \left[1 + (R_2/R_4)^2 \right] - \frac{1 - (R_2/R_4)^2}{\ln(R_4/R_2)^2} \right\} + (T_4 - T_2) \left[\frac{1}{1 - (R_2/R_4)^2} \right. \\
 & \left. - \frac{1}{\ln(R_4/R_2)^2} \right] + T_2 = \frac{21.47 \text{ W/gm} \times 3413 \text{ Btu/kWh} \times 500.256 \text{ lb/ft}^3}{2.205 \text{ lb/kg}} \\
 & \times \frac{0.10604^2 \text{ ft}^2}{4 \times 11.6 \text{ Btu/hr-ft-}^\circ\text{F}} \left\{ \frac{1}{2} \left[1 + \left(\frac{0.0885}{0.10604} \right)^2 \right] - \frac{1 - \left(\frac{0.0885}{0.10604} \right)^2}{\ln \left(\frac{0.10604}{0.0885} \right)^2} \right\} \\
 & + (872.12 - 682.27) \left[\frac{1}{1 - \left(\frac{0.0885}{0.10604} \right)^2} - \frac{1}{\ln \left(\frac{0.10604}{0.0885} \right)^2} \right] \\
 & + 682.27 = 806.7 \text{ F}
 \end{aligned}$$

Since all heat generated outside the point of maximum temperature must flow outward, the heat flux at the outside surface of the pressure tube is

$$\begin{aligned}
 q_4'' = & \frac{q''' (R_4^2 - R_3^2)}{2R_4} \\
 = & \frac{21.47 \text{ W/gm} \times 3413 \text{ Btu/kWh} \times 500.256 \text{ lb/ft}^3 (0.10604^2 - 0.10148^2) \text{ ft}^2}{2.205 \text{ lb/kg} (2 \times 0.10604 \text{ ft})} \\
 = & 29,375 \text{ Btu/ft}^2\text{-hr}
 \end{aligned}$$

At this point it is not possible to solve directly for the temperature gradient across the helium gap, because the corresponding gap thickness is unknown. Consequently, a different approach is taken. First, we must solve for the insulation jacket coolant temperature; then the temperature distribution within the insulation jacket can be found.

$$\begin{aligned}
T_7 &= \frac{(q_4'' + q_{4p}'') \pi R_4 (L_a/2) + \frac{q_{ij}''' + q_{ijp}'''}{2} (L_a/2) \pi (R_6^2 - R_5^2)}{(P^*/\bar{P})_a WC_p} + T_{in} \\
&= \left[(14,454 + 29,375) \text{ Btu/hr-ft}^2 \times \pi \times 0.10604 \text{ ft} \right. \\
&\quad + \frac{(19.86 + 12.07) \text{ W/gm} \times 3413 \text{ Btu/kWh}}{2 \times 0.002205 \text{ lb/gm} \times 1000 \text{ W/kW}} \\
&\quad \times \frac{500.256 \text{ lb/ft}^3 \times 4 \text{ ft} \times \pi (0.1198^2 - 0.010975^2) \text{ ft}^2}{2} \left. \right] \\
&\div (1.4 \times 185.0 \text{ gpm} \times 0.1337 \text{ ft}^3/\text{gal} \times 61.165 \text{ lb/ft}^3 \times 60 \text{ min/hr} \\
&\quad \times 1 \text{ Btu/lb-}^\circ\text{F}) + 130.0 \text{ F} = 131.58 \text{ F}
\end{aligned}$$

The average Nusselt number, as described by the Stein-Begell correlation for similarly dimensioned concentric annuli is

$$\begin{aligned}
Nu_0 &= 97.7 (1 + 0.0066 T_f) \frac{V^{0.8}}{k} D^{0.8} (R_8/R_6)^{0.5} \\
&= 97.7 \left[\frac{1 + 0.0066(131.58 + 163.73)}{2} \right] \\
&\quad \times \left[\frac{187 \text{ gpm} \times 0.1337 \text{ ft}^3/\text{gal}}{60 \text{ sec/min} \times \pi (0.13525^2 - 0.1198^2)} \right]^{0.8} \\
&\quad \times \frac{[2(0.13525 - 0.1198) \text{ ft}]^{0.8}}{0.3768 \text{ Btu/hr-ft-}^\circ\text{F}} \left(\frac{0.13525}{0.1198} \right)^{0.5} = 561.37
\end{aligned}$$

However, results from reference 3 indicate that this Nusselt number will be reduced by the insulation jacket eccentricity; the resulting Nusselt number will be

$$\begin{aligned}
Nu &= 6.337893639 + 78.13675028 \epsilon - 122.700393 \epsilon^2 \\
&\quad + 0.9591731445 Nu_0 - 0.1893880372 Nu_0 \epsilon + 0.00004186201650 Nu_0^2
\end{aligned}$$

where

$$\epsilon = \frac{\text{bow}}{R_8 - R_6} = \frac{0.1176/12}{0.13525 - 0.1198} = 0.64668$$

$$Nu = 484.75$$

In normal engineering practice, a 10% uncertainty factor is used with any empirically derived heat transfer correlation, so that the hypothetical average heat transfer coefficient will be

$$\bar{h} = \frac{Nuk}{D_e F_s} = \frac{484.75 \times 0.3768 \text{ Btu/hr-ft-}^\circ\text{F}}{2(0.13529 - 0.1198) \text{ ft} \times 1.1} = 5400 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$$

It should be noted that an average insulation jacket surface temperature was assumed in order to determine the convection coefficient. It is now possible to solve for this temperature, and if the calculated value does not agree with the assumed value, an iteration must be made.

$$\begin{aligned} \bar{T}_6 = \frac{q_4'' R_4}{h_6 R_6} + \frac{q_{1j}''' (R_6^2 - R_5^2)}{2R_6 h_6} + T_7 = \frac{29,375 \text{ Btu/hr-ft}^2 \times 0.10604 \text{ ft}}{5400 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F} \times 0.1198 \text{ ft}} \\ + \frac{19.86 \text{ W/gm} \times 3413 \text{ Btu/kWh} \times 500.256 \text{ lb/ft}^3 (0.1198^2 - 0.10975^2) \text{ ft}}{0.002205 \text{ lb/gm} \times 1000 \text{ W/kg} \times 2 \times 0.1198 \text{ ft} \times 5400 \text{ Btu/ft}^2\text{-hr-}^\circ\text{F}} \\ + 131.58 \text{ F} = 163.73 \text{ F} \end{aligned}$$

Including an additional 10% uncertainty factor on the temperature differential, the minimum insulation jacket surface temperature will be

$$T_6 = \bar{T}_6 + F_s F_\theta (\bar{T}_6 - T_7)$$

where F_θ is found from the following equation:

$$F_\theta = 0.6573950232 \epsilon - 0.1356373127 \epsilon^2 = 0.3684$$

$$T_6 = 163.73 \text{ F} + 1.1 \times 0.3684(163.73 - 131.58)^\circ\text{F} = 175.57 \text{ F}$$

Having found the outer surface temperature of insulation jacket and the heat flux at the inner surface, we find the inner surface temperature directly:

$$\begin{aligned}
T_5 &= q_{ij}''' \left[\frac{R_6^2 - R_5^2}{4k_{ij}} - \frac{R_5^2 \ln \left(\frac{R_6}{R_5} \right)}{2k_{ij}} \right] + \frac{q_4''}{k_{ij}} R_4 \ln \frac{R_6}{R_5} + T_6 \\
&= \frac{19.86 \text{ W/gm} \times 3413 \text{ Btu/kWh} \times 500.256 \text{ lb/ft}^3}{2 \times 2.205 \text{ lb/kg} \times 9.0 \text{ Btu/hr-ft-}^\circ\text{F}} \left[\frac{0.1198^2 - 0.10975^2}{2} \text{ ft}^2 \right. \\
&\quad \left. - 0.10975 \ln \frac{0.1198}{0.10975} \right] + \left(\frac{29,375 \text{ Btu/hr-ft}^2 \times 0.10604}{9.0 \text{ Btu/hr-ft-}^\circ\text{F}} \ln \frac{0.1198}{0.10975} \right) \\
&\quad + 175.57 \text{ F} = 259.48 \text{ F}
\end{aligned}$$

The average temperature of the insulation jacket will be

$$\begin{aligned}
T_{ij} &= q_{ij}''' \frac{R_6}{4k_{ij}} \left\{ \frac{1}{2} \left[1 + \left(\frac{R_5}{R_6} \right)^2 \right] - \frac{1 - (R_5/R_6)^2}{\ln (R_6/R_5)^2} + (T_6 - T_5) \right. \\
&\quad \left. \left[\frac{1}{1 - (R_5/R_6)^2} - \frac{1}{\ln (R_6/R_5)^2} \right] + T_6 \right\} \\
&= \left(\frac{19.86 \text{ W/gm} \times 3413 \text{ Btu/kWh} \times 500.256 \text{ lb/ft}^3}{2.205 \text{ lb/kg}} \right) \frac{0.1198}{4 \times 9 \text{ Btu/hr-ft-}^\circ\text{F}} \\
&\quad \left\{ \frac{1}{2} \left[1 + \left(\frac{0.10975}{0.1198} \right)^2 \right] - \frac{1 - (0.10975/0.1198)^2}{\ln (0.1198/0.10975)^2} \right\} + (259.48 - 175.57) \\
&\quad \left[\frac{1}{1 - (0.10975/0.1198)^2} - \frac{1}{\ln (0.1198/0.10975)^2} \right] + 175.57 = 225.05 \text{ }^\circ\text{F}
\end{aligned}$$

The helium gap corresponding to the assumed point of maximum temperature is

$$\begin{aligned}
R_5 - R_4 &= R_4 \left\{ a \log \left[\frac{k_{\text{He}} (T_4 - T_5)}{q_4'' R_4} \right] \right\} - R_4 \\
&= 0.10604 \text{ ft} \left\{ a \log \left[\frac{0.127 \text{ Btu/hr-ft-}^\circ\text{F} (872.12 - 259.48) \text{ }^\circ\text{F}}{29,375 \text{ Btu/ft}^2\text{-hr} \times 0.10604 \text{ ft}} \right] \right\} \\
&\quad - 0.10604 \text{ ft} = 0.002583 \text{ ft} = 0.031 \text{ in.}
\end{aligned}$$

6. List of Symbols

A	heat transfer area
bow	insulation jacket bow at midcore
C	integration constant
C'	integration constant
C_p	specific heat
D_e	hydraulic diameter
F_θ	factor on insulation jacket temperature distribution
$\bar{h}$	hypothetical average heat transfer coefficient
h_0	heat transfer coefficient for concentric geometry
h_2	heat transfer coefficient for pressure tube
h_6	heat transfer coefficient for insulation jacket
k	conduction coefficient
L_a	active fuel length
N	number of heating profile measurements
$\bar{n}$	true heating rate
n_i	measured heating rate
Nu	effective Nusselt number
Nu_0	concentric Nusselt number
$(P^*/\bar{P})_r$	radial power peaking ratio
Q	total heat produced
q'''	volumetric heat rate
q'''_{pt}	volumetric heat rate for pressure tube
q''_4	heat flux at outer surface of pressure tube
q''_6	heat flux at outer surface of insulation jacket
r	radius
R_2	inner radius of pressure tube

R_3	radius of maximum temperature
R_4	outer radius of pressure tube
R_5	effective inner radius of insulation jacket
R_6	effective outer radius of insulation jacket
R_8	effective outer radius of strongback
T_1	temperature of coolant inside pressure tube
T_2	temperature at pressure tube inner surface
T_3	maximum temperature
T_4	temperature at pressure tube outer surface
T_5	temperature at insulation jacket inner surface
T_6	temperature at insulation jacket outer surface
T_7	bulk temperature of coolant outside insulation jacket
T_{ij}	average temperature of insulation jacket
T_{pt}	average temperature of pressure tube
V	velocity
W	coolant flow rate
ϵ	eccentricity
θ	azimuthal ordinate
ρ	density
σ^2	variance of heating rate measurement
ϕ	time

Figure C-1. Temperature of the Outer NR Loop Insulation Jacket at Mid-Core With 187-gpm Flow and 0.120-Inch Bow

Figure C-2. Temperature of the Outer NR Loop Pressure Tube at Mid-Core With 187-gpm Flow and 0.120-Inch Bow

Figure C-3. Temperature of the Center NR Loop Insulation Jacket at Mid-Core With 117-gpm Flow and 0.118-Inch Bow

Figure C-4. Temperature of the Center NR Loop Pressure Tube at Mid-Core With 117-gpm Flow and 0.118-Inch Bow

REFERENCES

Appendix C

- ¹ Howard, J. O. to Croft, M. W., memo, 'NR Loop Pressure Tube Heating Rates, "The Babcock & Wilcox Company, Lynchburg, Virginia, January 17, 1964.
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- ³ Diskind, T., Heat Transfer and Pressure Drop in Eccentric Annuli, U.S. Atomic Energy Commission, NYO-9649, September 1961.

APPENDIX D
Hydraulic Calculations

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D.1. LABYRINTH FLOW RESTRICTOR DESIGN

It has been proposed that a labyrinth-type flow restrictor be incorporated at a point near the outlet of the NR loop coolant channel. Ideally, the flow restrictor will tend to perform as a hydraulic stabilizer, thereby reducing vibration in the safety rod assembly. A labyrinth flow restrictor has been designed and tested in place, in conjunction with an 82-inch "stove-pipe." The results of these tests indicate that vibration can be satisfactorily reduced through this design (see Figure D.1-1).

The performance of the labyrinth flow restrictor may be evaluated in accordance with the methods outlined in reference 1. The use of these methods, however, requires a knowledge of coolant flow conditions. For P/ϵ ratios of 2 or less, the coolant will tend to skim over the labyrinth teeth, failing to re-attach between restrictions.² The result is relatively low coolant pressure drops. When P/ϵ is about 8, there is enough valley length to permit the flow to become fully re-attached, and this flow regime is referred to as "wake interference flow." When the rib spacing is such that the boundary layer re-attaches just prior to reaching the following rib, the highest friction factor is attained.

$$P/\epsilon = \frac{1.16 - 0.329}{1.815 - 1.625} = 4.37$$

The P/ϵ ratios for the flow restrictor for the NR Loop fall somewhere between the skimming flow and the wake interference flow. Referring again to reference 2, it can be noted that the transition zone is smooth, producing no discontinuities. Consequently, it will be possible to interpolate results.

Figure D.1-1. Labyrinth Flow Restrictor

Flow Area A = 1.8039 in.², Wetted Perimeter = 19.24223 in.

Flow Area B = 3.6140 in.², Wetted Perimeter = 20.43604 in.

Figure D.1-2. Pressure Drop in Labyrinth

$$A_o = \pi(R_o^2 - R_i^2) = \pi(1.625^2 - 1.4375^2) = 1.80396 \text{ in.}^2$$

$$A_{ch} = \pi(R_{ch}^2 - R_i^2) = \pi(1.815^2 - 1.4375^2) = 3.8573032 \text{ in.}^2$$

$$\frac{A_o}{A_{ch}} = 0.4676738$$

$$Re = \frac{4\omega}{P_{W\mu}} = \frac{4 \times 187 \text{ gal/min} \times 0.1337 \text{ ft}^3/\text{gal} \times 61.5 \text{ lb/ft}^3 \times 60 \text{ min/hr} \times 12 \text{ in./ft}}{\pi(1.625 + 1.4375)\text{in.} \times 1.18818 \text{ lb/ft-hr}} = 387,376$$

$$D_H = \frac{4A_{ch}}{P_W} = \frac{4 \times 3.8573032 \text{ in.}^2}{\pi(1.625 + 1.4375)\text{in.}} = 1.6036816 \text{ in.}$$

$$\frac{P}{R_o - R_i} = \frac{1.16 - 0.329}{1.625 - 1.4375} = 4.432$$

$\frac{P}{\epsilon}$	c	d
2	0.28	1.27
8	1.10	2.30

$$\tau = cn + d = (0.603 \times 8) + 1.68 = 6.50$$

$$V_o = \frac{\omega}{PA_o} = \frac{187 \times 0.1337 \times 144}{1.8039 \times 60} = 33.26 \text{ fps}$$

$$\Delta P = \frac{\rho \tau V^2}{144 \times 2g_c} = 0.0439 V^2$$

ω	V_o	ΔP
100	17.79	13.64
125	22.23	21.31
150	26.68	30.69
175	31.13	41.76
200	35.57	54.55

Nomenclature

A_{ch}	coolant cross-sectional flow area between labyrinth teeth
A_o	coolant cross-sectional flow area through labyrinth teeth
c	labyrinth constant
d	labyrinth constant
D_H	hydraulic diameter
g_c	gravitational constant
P	labyrinth pitch
P_W	wetted perimeter
R_6	outside radius of insulation jacket
R_{ch}	outside radius of coolant flow channel between labyrinth teeth
Re	Reynolds number
R_o	inside radius of labyrinth teeth
V_o	coolant velocity through labyrinth
ω	coolant flow rate
ΔP	pressure drop across labyrinth
ϵ	height of labyrinth teeth
ρ	coolant density
τ	labyrinth coefficient

D. 2. SAFETY ROD CALCULATION WITH PROPOSED MODIFICATIONS

D. 2. 1. Calculation of Safety Rod Flow Rate With Labyrinth and "Stove Pipe" Flow Restrictors

Figure D. 2-1 shows the various safety rod flow channels and their numerical Designations in the up and down positions. The characteristics of flow rate versus pressure drop (Figures D. 2-2 and D. 2-3) were obtained using the CHATA computer code (see section 5 of the report, Hydraulic Analysis). The curves were used in an iteration by which the flow rates and pressure drops for each channel were obtainable (Figures D. 2-6 and D. 2-7). CHATA was then rerun with the resulting hydraulic information to obtain the incremental breakdown of the pressure drop along each flow channel. Figures D. 2-4 and D. 2-5 are plots of the constituent channel pressure drop as a function of the distance along the channel in the up and down safety rod positions, respectively.

Tables D. 2-1 through D. 2-6 are CHATA printouts for the inner channel (12+4+6) analysis. They contain the channel geometries, form loss coefficients, resulting flow rates, and the incremental breakdown of pressure drop. Figures D. 2-6 through D. 2-10 show the safety rod flow rates and pressure drops considering the flow annuli under the labyrinth and the stove pipe. Figure D. 2-11 illustrates flow rate as a function of pressure drop obtained with CHATA.

Table D.2-1. Channel 12+4+6 Up Position

CHANNEL SECTION INPUT
(INPUT OR CALCULATED)

X	AF	WP	FLUX	CONTK
DISTANCE ALONG CHANNEL, INCHES	FLOW AREA SQ. IN.	WETTED PERIMETER INCHES	AXIAL FLUX NORMALIZED TO AN AVERAGE OF 1.0	FORM LOSS COEFFICIENTS
0.	500.00000000	100.00000000	1.00000000	0.
0.0001	1.08500000	22.31000000	1.00000000	0.39913200
1.0010	1.03800000	22.00000000	1.00000000	0.01732719
1.7500	1.30000000	19.06000000	1.00000000	0.04061775
3.7500	1.77845000	19.22650000	1.00000000	0.07237520
85.7501	2.53400000	19.68000000	1.00000000	0.08890234
90.4500	3.61400000	20.43600000	1.00000000	0.35584000
90.4501	1.80390000	19.24223000	1.00000000	0.28416000
91.6201	3.61400000	20.43600000	1.00000000	0.35584000
91.6202	1.80390000	19.24223000	1.00000000	0.28416000
92.7902	3.61400000	20.43600000	1.00000000	0.35584000
92.7903	1.80390000	19.24223000	1.00000000	0.28416000
93.9603	3.61400000	20.43600000	1.00000000	0.35584000
93.9604	1.80390000	19.24223000	1.00000000	0.28416000
95.1304	3.61400000	20.43600000	1.00000000	0.35584000
95.1305	1.80390000	19.24223000	1.00000000	0.28416000
96.3005	3.61400000	20.43600000	1.00000000	0.35584000
96.3006	1.80390000	19.24223000	1.00000000	0.28416000
97.4706	3.61400000	20.43600000	1.00000000	0.35584000
97.4707	1.80390000	19.24223000	1.00000000	0.28416000
98.4608	3.61400000	20.43600000	0.	0.35584000
98.4609	1.80390000	19.24223000	0.	0.28416000
98.4610	3.61400000	20.43600000	0.	0.35584000

Table D.2-2. Channel 12+4+6 Up Position

CHATA S CHAT5

SEP. 5, 1967

CASE NO. 1

O U T P U T

THE FLOW SATISFYING THE GIVEN PRESSURE DROP.....W = 93806.306469

CHANNEL PRESSURE DROPS, PSI.....

TOTAL -88.7730169
 FRICTION -38.7829536
 ACCELERATION
 (CONSTANT AREA) -0.0000001

ELEVATION 3.5078059
 CONTRACTION AND EXPANSION
 (RECOVERABLE AND
 UNRECOVERABLE) -53.4978691

BULK COOLANT PARAMETERS AVERAGED OVER THE
 ACTIVE FUEL LENGTH.....

TEMPERATURE, DEG.F 129.2937267
 DENSITY, LB/CU.FT
 RHOA = F(ALPHA) 60.9420157

QUALITY, LB/HR.VAPOR PER
 LB/HR.MIXTURE 0.

VOID FRACTION 0.
 VELOCITY, FPS 30.1698898

Table D.2-3. Channel 12+4+6 Up Position

CASE NO.

1

-CHATA S CHAT5

SEP. 5, 1967

CHANNEL INCREMENTAL BREAKDOWN OF PRESSURE DROP, PSI.

DISTANCE ALONG CHANNEL (INCHES)	FRICTION	ACCELERATION (CONSTANT AREA)	ELEVATION	CONTRACTION AND EXPANSION (UNRECOVERABLE AND RECOVERABLE)	TOTAL
0.	0.	0.	0.	0.	0.
0.0001	-0.00000	-0.00000	0.00000	-29.31186	-29.31186
1.0010	-2.00676	0.00000	0.03566	-2.33679	-33.61975
1.7500	-1.69407	0.00000	0.02668	7.36704	-27.92010
3.7500	-1.89005	-0.00000	0.07125	5.73965	-23.99925
85.7501	-29.80805	-0.00000	2.92136	3.26350	-47.62243
90.4500	-0.59382	0.00000	0.16744	0.58586	-47.46295
90.4501	-0.00000	-0.00000	0.00000	-7.84455	-55.30751
91.6201	-0.40754	-0.00000	0.04168	2.99389	-52.67947
91.6202	-0.00000	-0.00000	0.00000	-7.84455	-60.52403
92.7902	-0.40754	0.00000	0.04168	2.99389	-57.89599
92.7903	-0.00000	-0.00000	0.00000	-7.84455	-65.74054
93.9603	-0.40754	0.00000	0.04168	2.99389	-63.11251
93.9604	-0.00000	-0.00000	0.00000	-7.84455	-70.95706
95.1304	-0.40754	-0.00000	0.04168	2.99389	-68.32903
95.1305	-0.00000	-0.00000	0.00000	-7.84455	-76.17358
96.3005	-0.40754	-0.00000	0.04168	2.99389	-73.54554
96.3006	-0.00000	-0.00000	0.00000	-7.84455	-81.39010
97.4706	-0.40754	0.00000	0.04168	2.99389	-78.76206
97.4707	-0.00000	-0.00000	0.00000	-7.84455	-86.60662
98.4608	-0.34488	-0.00000	0.03527	2.99389	-83.92233
98.4609	-0.00000	-0.00000	0.00000	-7.84455	-91.76688
98.4610	-0.00003	-0.00000	0.00000	2.99389	-88.77302

Table D.2-4. Channel 4+6 Down Position

X	CHANNEL SECTION INPUT (INPUT OR CALCULATED)			DOWN	
	AF	WP	FLUX	CONTK	
DISTANCE ALONG CHANNEL, INCHES	FLOW AREA SQ. IN.	WETTED PERIMETER INCHES	AXIAL FLUX NORMALIZED TO AN AVERAGE OF 1.0	FORM LOSS COEFFICIENTS	
0.	500.00000000	100.00000000	1.00000000	0.	
0.0001	2.53400000	19.68000000	1.00000000	0.39797280	
1.7500	2.53400000	19.68000000	1.00000000	0.	
1.7500	1.77845000	19.22650000	1.00000000	0.11926598	
85.7500	1.77845000	19.22650000	1.00000000	0.	
85.7501	2.53400000	19.68000000	1.00000000	0.08890234	
89.9500	2.53400000	19.68000000	1.00000000	0.	
90.4500	3.61400000	20.43600000	1.00000000	0.35584000	
90.4501	1.80390000	19.24223000	1.00000000	0.28416000	
91.6201	3.61400000	20.43600000	1.00000000	0.35584000	
91.6202	1.80390000	19.24223000	1.00000000	0.28416000	
92.7902	3.61400000	20.43600000	1.00000000	0.35584000	
92.7903	1.80390000	19.24223000	1.00000000	0.28416000	
93.9603	3.61400000	20.43600000	1.00000000	0.35584000	
93.9604	1.80390000	19.24223000	1.00000000	0.28416000	
95.1304	3.61400000	20.43600000	1.00000000	0.35584000	
95.1305	1.80390000	19.24223000	1.00000000	0.28416000	
96.3005	3.61400000	20.43600000	1.00000000	0.35584000	
96.3006	1.80390000	19.24223000	1.00000000	0.28416000	
97.4706	3.61400000	20.43600000	1.00000000	0.35584000	
97.4707	1.80390000	19.24223000	1.00000000	0.28416000	
98.4608	3.61400000	20.43600000	1.00000000	0.35584000	
98.4609	1.80390000	19.24223000	1.00000000	0.28416000	
			CHATA	\$ CHATS	SEP. 5, 1967.
98.4610	3.61400000	20.43600000	1.00000000	0.35584000	
98.4629	9.41000000	23.17000000	1.00000000	0.37938269	
99.0500	9.41000000	23.17000000	1.00000000	0.	
100.5500	2.40527000	7.55640000	0.	0.29775685	
100.8000	1.63000000	32.06000000	0.	0.12892856	

**** NOTE : FLUX WAS CALCULATED USING A POLYNOMIAL FIT, IAXFL=0 ****

Table D.2-5. Channel 4+6 Down Position

CHATA S CHAT5

SEP. 5, 1967

CASE NO. 1

O U T P U T

THE FLOW SATISFYING THE GIVEN PRESSURE DROP.....W = 109470.603424

CHANNEL PRESSURE DROPS, PSI.....

TOTAL -117.9471572

FRICTION -45.5619636

ACCELERATION
(CONSTANT AREA) -0.0000001

ELEVATION 3.5911359

CONTRACTION AND EXPANSION
(RECOVERABLE AND
UNRECOVERABLE) -75.9763294

BULK COOLANT PARAMETERS AVERAGED OVER THE
ACTIVE FUEL LENGTH.....

TEMPERATURE, DEG.F 129.3647102

DENSITY, LB/CU.FT

RHOA = F(ALPHA) 60.9757346

QUALITY, LB/HR.VAPOR PER
LB/HR.MIXTURE 0.

VOID FRACTION 0.
VELOCITY, FPS 14.0909222

D-10

Babcock & Wilcox

Table D. 2-6. Channel 4+6 Down Position

CASE NO.

1

CHATA S CHAT5

SEP. 5, 1967

CHANNEL INCREMENTAL BREAKDOWN OF PRESSURE DROP, PSI.

DISTANCE ALONG CHANNEL (INCHES)	FRICTION	ACCELERATION (CONSTANT AREA)	ELEVATION	CONTRACTION AND EXPANSION (UNRECOVERABLE AND RECOVERABLE)	TOTAL
0.	0.	0.	0.	0.	0.
0.0001	-0.00000	-0.00000	0.00000	-7.31230	-7.31230
1.7500	-0.29428	0.00000	0.06234	0.	-7.54424
1.7500	-0.00000	-0.00000	0.00000	-6.65501	-14.19925
85.7500	-40.73191	-0.00000	2.99261	0.	-51.93854
85.7501	-0.00005	-0.00000	0.00000	4.44442	-47.49417
89.9500	-0.70630	-0.00000	0.14963	0.	-48.05085
90.4500	-0.08409	-0.00000	0.01781	0.79785	-47.31927
90.4501	-0.00001	-0.00000	0.00000	-10.68315	-58.00241
91.6201	-0.54359	0.00000	0.04168	4.07725	-54.42707
91.6202	-0.00001	-0.00000	0.00000	-10.68315	-65.11021
92.7902	-0.54359	0.00000	0.04168	4.07725	-61.53486
92.7903	-0.00001	-0.00000	0.00000	-10.68315	-72.21801
93.9603	-0.54359	-0.00000	0.04168	4.07725	-68.64266
93.9604	-0.00001	-0.00000	0.00000	-10.68315	-79.32581
95.1304	-0.54359	0.00000	0.04168	4.07725	-75.75046
95.1305	-0.00001	-0.00000	0.00000	-10.68315	-86.43361
96.3005	-0.54359	-0.00000	0.04168	4.07725	-82.85826
96.3006	-0.00001	-0.00000	0.00000	-10.68315	-93.54141
97.4706	-0.54359	0.00000	0.04168	4.07725	-89.96606
97.4707	-0.00001	-0.00000	0.00000	-10.68315	-100.64921
98.4608	-0.46000	0.00000	0.03527	4.07725	-96.99669
98.4609	-0.00001	-0.00000	0.00000	-10.68315	-107.67984
98.4610	-0.00005	-0.00000	0.00000	4.07725	-103.60263
98.4629	-0.00011	-0.00000	0.00007	1.21666	-102.38602
99.0500	-0.00223	0.00000	0.02092	0.	-102.36733
100.5500	-0.00571	-0.00000	0.05344	-7.15498	-109.47458
100.8000	-0.01567	-0.00000	0.00891	-8.46582	-117.94716

D. 2. 2. Hydraulic Calculations — Effects of Thermal Bow on Flow Rate

Purpose: To determine the change (%) in the total inner channel flow rate (187 gpm) due to loop thermal bow.

Assumptions:

1. The pressure drop across the inner channel is 88.8 psi with the safety rod withdrawn.
2. The maximum loop bow is 122 mils at the core center line.
3. Water temperature is 130 F; isothermal flow exists throughout the channel.
4. The model used is that sketched below. The radii change according to the deflection at the incremental locations along the flow channel.

List of Symbols

D_H	hydraulic diameter, in.
W_p	wetted perimeter, in.
R_s	equivalent spline radius, in.
R_{tc}	inside radius of top safety rod collar, in.
t	thickness of annuli, in.
R	radius, in.

Note: Subscripts a and b designate sub-annuli.

A	flow area, in. ²
ΔP	pressure drop, psi
ω	flow rate, lb/hr

ρ bulk coolant density at 130 F (61.56 lb/ft³)
 K_c contraction coefficient
 K_e expansion coefficient
 σ area ratio
 V velocity, ft/sec
 f friction factor (Moody)
 L channel length, in.
 ϵ/D_H relative roughness (0.000063/ D_H)

Top collar radius = 1.687 in. = R_{tc}

Top collar flow area = 1.085 in.²

Top collar wetted perimeter = 22.31 in. = W_p

Effective spline radius at top collar:

$$D_H = \frac{4A}{W_p} = \frac{4(1.085)}{22.31} = 0.1945316 = 2t$$

$$t = 0.0972658 \text{ in.}$$

$$R_s = R_{tc} - t = 1.687 - 0.0972658 = 1.5897342 \text{ in.}$$

Entrance Loss ΔP_1

Bow at entrance = 0.020

$$R_a = 1.687 + 0.020 = 1.707 \text{ in.}$$

$$R_b = 1.687 - 0.020 = 1.667 \text{ in.}$$

$$D_{H_a} = 2t = 2(R_a - R_s) = 2(1.707 - 1.5897342) = 0.2346 \text{ in.}$$

$$D_{H_b} = 2(1.667 - 1.5897) = 0.1546 \text{ in.}$$

$$A_a = \frac{\pi}{2} (R_a^2 - R_s^2) = \frac{\pi}{2} (1.707^2 - 1.5897^2) = 0.607433 \text{ in.}^2$$

$$A_b = \frac{\pi}{2} (1.667^2 - 1.5897^2) = 0.39543 \text{ in.}^2$$

$$\frac{A_a}{A_b} = 1.53613$$

$$\frac{D_{H_a}}{D_{H_b}} = 1.51746$$

$$\Delta P_a = \Delta P_b$$

$$\frac{K_a \omega_a^2}{2g_c \rho A_a^2} = \frac{K_b \omega_b^2}{2g_c \rho A_b^2} = > \frac{K_a \rho V_a^2}{2g_c} = \frac{K_b \rho V_b^2}{2g_c}$$

$$\frac{K_a \omega_a^2}{A_a^2} = \frac{K_b \omega_b^2}{A_b^2} = > K_a V_a^2 = K_b V_b^2$$

The form losses, considering both permanent and recoverable, are:

$$K_a = 0.4(1 - \sigma) + 1 - \sigma^2 = 1.4 - 0.4 \left(\frac{0.607433}{500} \right) - \left(\frac{0.607433}{500} \right)^2 = 1.3995127$$

$$K_b = 1.4 - 0.4 \left(\frac{0.39543}{500} \right) - \left(\frac{0.39543}{500} \right)^2 = 1.3996831$$

$$V_a = \sqrt{\frac{K_b}{K_a}} V_b = \sqrt{\frac{1.3996831}{1.3995127}} V_b \approx V_a$$

$$\omega_a^2 = \frac{K_b}{K_a} \frac{A_a^2}{A_b^2} \omega_b^2$$

$$\omega_a = \sqrt{\frac{K_b}{K_a} \frac{A_a}{A_b}} \omega_b = 1.0000608(1.53613) \omega_b = 1.53622 \omega_b$$

$\omega_a = 1.53622 \omega_b \quad \text{at entrance}$

Friction Over First Inch — Nominal Bow = 20.75 mils

$$R_a = 1.687 + 0.02075 = 1.70775 \text{ in.}$$

$$R_b = 1.687 - 0.02075 = 1.66625 \text{ in.}$$

$$D_{H_a} = 2t = 2(R_a - R_s) = 2(1.70775 - 1.5897) = 0.2361 \text{ in.}$$

$$D_{H_b} = 2t = 2(R_b - R_s) = 2(1.66625 - 1.5897) = 0.1531 \text{ in.}$$

$$\frac{D_{H_a}}{D_{H_b}} = 1.542$$

$$A_a = \frac{\pi}{2} (R_a^2 - R_s^2) = \frac{\pi}{2} (1.70775^2 - 1.5897^2) = 0.6114558 \text{ in.}^2$$

$$A_b = \frac{\pi}{2} (R_b^2 - R_s^2) = \frac{\pi}{2} (1.66625^2 - 1.5897^2) = 0.3915109 \text{ in.}^2$$

$$\frac{A_a}{A_b} = 1.5618$$

$$\Delta P_{f_a} = \Delta P_{f_b}$$

$$\left(f \frac{L}{De} \frac{\rho V^2}{2g_c} \right)_a = \left(f \frac{L}{De} \frac{\rho V^2}{2g_c} \right)_b \Rightarrow f_a \frac{V_a^2}{De_a} = f_b \frac{V_b^2}{De_b}$$

$$V_a^2 = \frac{f_b}{f_a} \frac{De_a}{De_b} V_b^2 \Rightarrow V_a = \sqrt{\frac{f_b}{f_a} \frac{D_{H_a}}{D_{H_b}}} V_b$$

$$\left(f \frac{L}{De} \frac{W^2}{2g_c \rho A^2} \right)_a = \left(f \frac{L}{De} \frac{W^2}{2g_c \rho A^2} \right)_b \Rightarrow f_a \frac{\omega_a^2}{De_a A_a^2} = f_b \frac{\omega_b^2}{De_b A_b^2}$$

$$\omega_a^2 = \frac{f_b}{f_a} \frac{De_a}{De_b} \frac{A_a^2}{A_b^2} \omega_b^2 \Rightarrow \omega_a = \sqrt{\frac{f_b}{f_a} \frac{De_a}{De_b} \frac{A_a}{A_b}} \omega_b$$

$$\frac{\epsilon}{D_{H_a}} = \frac{0.000063}{0.2361} = 0.0002668 \Rightarrow f_a = 0.015$$

$$\frac{\epsilon}{D_{H_b}} = \frac{0.000063}{0.1531} = 0.0004114 \Rightarrow f_b = 0.018$$

Assuming that flow rate is ≈ 160 gal/min total,

$$V_a = \sqrt{\frac{0.018(1.542)}{0.015}} V_b = 1.36 V_b$$

$$\omega_t = \omega_a + \omega_b = \rho A_a V_a + \rho A_b V_b = \rho V_b \left(A_a \frac{V_a}{V_b} + A_b \right)$$

$$V_b = \frac{\omega_t}{\rho \left(A_a \frac{V_a}{V_b} + A_b \right)}$$

$$= \frac{160(500.22) \text{ lb/hr} (144) \text{ in}^2/\text{ft}^2}{61.56 \text{ lb/ft}^3 [0.6114558(1.36) + 0.3915109] \text{ in}^2 (3600 \text{ sec/hr})}$$

$$V_b = 42.519 \text{ ft/sec}$$

$$V_a = 57.826 \text{ ft/sec}$$

$$\text{Re}_b = \frac{V d \rho}{\mu} = \frac{42.519 \text{ ft/sec} (0.1531 \text{ in}) (61.56 \text{ lb/ft}^3) (3600 \text{ sec/hr})}{1.288 \text{ lb/ft-hr} (12 \text{ in./ft})} = 9.3338 \times 10^4$$

$$\text{Re}_a = \frac{V d \rho}{\mu} = \frac{57.826 (0.2316) (61.56) (3600)}{1.288 (12)} = 1.92028 \times 10^5$$

$$f_a = 0.018 \quad f_b = 0.0205$$

$$V_a = \sqrt{\frac{0.0210(1.542)}{0.018}} = 1.34 V_b$$

$$V_b = \frac{1.60(500.22)(144)}{61.56[0.6114558(1.34) + 0.3915109](3600)} = 42.9216 \text{ ft/sec}$$

$$V_a = 1.34 V_b = 57.514 \text{ ft/sec}$$

$$\text{Re}_b = \frac{42.9216(0.1531)(61.56)(3600)}{1.288(12)} = 9.42225 \times 10^4$$

$$\text{Re}_a = \frac{57.826(0.2316)(61.56)(3600)}{1.288(12)} = 1.92028 \times 10^5$$

$f_a = 0.018 \quad f_b = 0.021$

Contraction at 1 in. (1.085 → 1.038) in. (splines and buttons)

$$\text{Bow} = 0.0215 \text{ in.}$$

$$d_H = \frac{4A}{W_p} = \frac{4(1.038)}{22.00} = 0.18872 = 2t$$

$$\text{Effective spline radius} = 1.5897 \text{ in.} = R_s$$

$$d_H = 2t = 0.18872$$

$$t = 0.09436 \text{ in.}$$

$$t = R_b - R_s = 0.09436$$

$$R_b = 0.09436 + 1.5897 = 1.68406 \text{ in.}$$

$$R_a = 1.68406 + 0.0215 = 1.70556 \text{ in.}$$

$$R_b = 1.68406 - 0.0215 = 1.66256 \text{ in.}$$

$$D_{H_a} = 2(R_a - R_s) = 2(1.70556 - 1.5897) = 0.23172 \text{ in.}$$

$$= > \frac{D_{H_a}}{D_{H_b}} = 1.59017$$

$$D_{H_b} = 2(R_b - R_s) = 2(1.66256 - 1.5897) = 0.14572 \text{ in.}$$

$$A_a = \frac{\pi}{2} (R_a^2 - R_s^2) = \frac{\pi}{2} (1.70556^2 - 1.5897^2) = 0.59971 \text{ in.}^2$$

$$= > \frac{A_a}{A_b} = 1.61121$$

$$A_b = \frac{\pi}{2} (R_b^2 - R_s^2) = \frac{\pi}{2} (1.66256^2 - 1.5897^2) = 0.37221 \text{ in.}^2$$

$$\omega_a = \sqrt{\frac{K_b}{K_a} \frac{A_a}{A_b}} \omega_b$$

$$K_a = 0.4(1 - \sigma) + 1 - \sigma^2 = 1.4 - 0.4 \left(\frac{0.59971}{0.611456} \right) - \left(\frac{0.59971}{0.611456} \right)^2$$
$$= 1.4 - 0.4(0.98) - (0.98)^2$$

$$K_a = 0.0457348$$

$$K_b = 1.4 - 0.4 \sigma - \sigma^2 = 1.4 - 0.4 \left(\frac{0.37221}{0.3915109} \right) - \left(\frac{0.37221}{0.3915109} \right)^2$$
$$= 1.4 - 0.4(0.951) - (0.951)^2$$

$$K_b = 1.4 - 0.3802 - 0.904 = 0.115886$$

$$\omega_a = \sqrt{\frac{K_b}{K_a} \frac{A_a}{A_b}} \omega_b = \sqrt{\frac{0.115886}{0.0457348} (1.61121)} \omega_b = \sqrt{2.5338(1.61121)} \omega_b$$

$$\omega_a = 2.5647 \omega_b$$

$$V_a = \sqrt{\frac{K_b}{K_a}} V_b = \sqrt{2.5338} V_b$$

$$V_a = 1.5918 V_b$$

Friction at Elevation 1.001 → 1.7500

Bow = 21.5 - 23 mils

Avg bow = 22.25 mils

Area = 1.038 in.²

$$d_H = \frac{4A}{W_p} = \frac{4(1.038)}{22.00} = 0.18872 = 2t$$

$$t = 0.09436 \text{ in.}$$

Spline radius = 1.5897 in. = R_s

$$t = R_b - R_s = 0.09436$$

$$R_b = 0.09436 + 1.5897 = 1.68406 \text{ in.}$$

$$R_a = 1.68406 + 0.02225 = 1.70631$$

$$R_b = 1.68406 - 0.02225 = 1.66181$$

$$D_{H_a} = 2(R_a - R_s) = 2(1.70631 - 1.5897) = 0.23322$$

$$= > \frac{D_{H_a}}{D_{H_b}} = 1.6171127$$

$$D_{H_b} = 2(R_b - R_s) = 2(1.66181 - 1.5897) = 0.14422$$

$$A_a = \frac{\pi}{2} (R_a^2 - R_s^2) = \frac{\pi}{2} (1.70631^2 - 1.5897^2) = 0.6037335$$

$$= > \frac{A_a}{A_b} = 1.63924$$

$$A_b = \frac{\pi}{2} (R_b^2 - R_s^2) = \frac{\pi}{2} (1.66181^2 - 1.5897^2) = 0.3682998$$

$$V_a = \sqrt{\frac{f_b}{f_a} \frac{D_{H_a}}{D_{H_b}}} V_b$$

$$\frac{\epsilon}{D_{H_a}} = \frac{0.000063}{0.23322} = 0.00027 \Rightarrow f_a = 0.018$$

$$\frac{\epsilon}{D_{H_b}} = \frac{0.000063}{0.14422} = 0.0004368 \Rightarrow f_b = 0.021$$

$$V_a = \sqrt{\frac{0.021}{0.018}} (1.6171127) V_b = 1.373547 V_b$$

$$V_b = \frac{\omega_t}{\rho \left[A_a \frac{V_a}{V_b} + A_b \right]} = \frac{1.60(500.22)(144)}{61.56[0.6037(1.373547) + 0.3682998](3600)}$$

$$V_b = 43.43 \text{ ft/sec}$$

$$V_a = 59.65 \text{ ft/sec}$$

$$Re_b = \frac{V_b d_{H_b} \rho}{\mu} = \frac{43.43(0.4422)(61.56)(3600)}{1.288(12)} = 8.9806 \times 10^4$$

$$Re_a = \frac{V_a d_{H_a} \rho}{\mu} = \frac{59.65(0.23322)(61.56)(3600)}{1.288(12)} = 1.99469 \times 10^5$$

$f_a = 0.018$	$f_b = 0.021$
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Expansion at 1.175 inch (1.038 → 1.3) in.²

$$\text{Bow} = 0.023$$

$$d_H = \frac{4A}{W_p} = \frac{4(1.3)}{19.06} = 0.27282 \text{ in.} = 2t$$

$$t = 0.13641$$

$$R_s = 1.5897342 \text{ in.}$$

$$R_2 = R_s + t = 1.72614$$

$$R_a = 1.72614 + 0.023 = 1.74914$$

$$R_b = 1.72614 - 0.023 = 1.70314$$

$$D_{H_a} = 2(R_a - R_s) = 2(1.74914 - 1.5897) = 0.31888$$

$$= > \frac{D_{H_a}}{D_{H_b}} = 1.4055$$

$$D_{H_b} = 2(R_b - R_s) = 2(1.70314 - 1.5897) = 0.22688$$

$$A_a = \frac{\pi}{2} (R_a^2 - R_s^2) = \frac{\pi}{2} (1.74914^2 - 1.5897^2) = 0.8362$$

$$= > \frac{A_a}{A_b} = 1.425$$

$$A_b = \frac{\pi}{2} (R_b^2 - R_s^2) = \frac{\pi}{2} (1.70314^2 - 1.5897^2) = 0.5867$$

$$V_a = \sqrt{\frac{K_b}{K_a}} V_b \quad \omega_a = \sqrt{\frac{K_b}{K_a} \frac{A_a}{A_b}} \omega_b$$

$$K_a = 1 - \sigma^2 - (1 - \sigma)^2 = 2 \left(\frac{0.60373}{0.8362} \right) \left(1 - \frac{0.60373}{0.8362} \right) = 0.40144$$

$$K_b = 1 - \sigma^2 - (1 - \sigma)^2 = 2 \left(\frac{0.3683}{0.5867} \right) \left(1 - \frac{0.3683}{0.5867} \right) = 0.46736$$

$$V_a = \sqrt{\frac{0.46736}{0.40144}} V_b = 1.079 V_b = V_a$$

$$\omega_a = (1.079)(1.425) \omega_b$$

$$\omega_a = 1.53756 \omega_b$$

Friction From 1.75 → 3.75

$$\text{Bow} = 24.25 \text{ mils}$$

$$\text{Area} = 1.300 \text{ in.}^2$$

$$R_a = 1.72614 + 0.02425 = 1.75039 \text{ in.}$$

$$R_b = 1.72614 - 0.02425 = 1.70189 \text{ in.}$$

$$D_{H_a} = 2(R_a - R_s) = 2(1.75039 - 1.5897) = 0.32138$$

$$= > \frac{D_{H_a}}{D_{H_b}} = 1.4323$$

$$D_{H_b} = 2(R_b - R_s) = 2(1.70189 - 1.5897) = 0.22438$$

$$A_a = \frac{\pi}{2} (R_a^2 - R_s^2) = \frac{\pi}{2} (1.75039^2 - 1.5897^2) = 0.84307$$

$$= > \frac{A_a}{A_b} = 1.4534$$

$$A_b = \frac{\pi}{2} (R_b^2 - R_s^2) = \frac{\pi}{2} (1.70189^2 - 1.5897^2) = 0.58007$$

$$V_a = \sqrt{\frac{f_b}{f_a} \frac{D_{H_a}}{D_{H_b}}} V_b$$

$f_a = 0.018$	$f_b = 0.021$
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Expansion at 3.75 in.

Bow = 25.5 mils

Stove pipe ID = 3.246 in.

Radius = 1.623 in.

Insulation jacket OD = 2.875 in.

Radius = 1.4375 in.

$$R_a = 1.623 + 0.0255 = 1.6485 \text{ in.}$$

$$R_b = 1.623 - 0.0255 = 1.5975 \text{ in.}$$

$$R_s = 1.4375 \text{ in.}$$

$$D_{H_a} = 2(R_a - R_s) = 2(1.6485 - 1.4375) = 0.422$$

$$= > \frac{D_{H_a}}{D_{H_b}} = 1.31875 \text{ in.}$$

$$D_{H_b} = 2(R_b - R_s) = 2(1.5975 - 1.4375) = 0.320$$

$$A_a = \frac{\pi}{2} (R_a^2 - R_s^2) = \frac{\pi}{2} (1.6485^2 - 1.4375^2) = 1.02282$$

$$= > \frac{A_a}{A_b} = 1.3409$$

$$A_b = \frac{\pi}{2} (R_b^2 - R_s^2) = \frac{\pi}{2} (1.5975^2 - 1.4375^2) = 0.76278$$

$$V_a = \sqrt{\frac{K_b}{K_a}} V_b = > \omega_b = \sqrt{\frac{K_b}{K_a} \frac{A_a}{A_b}} \omega_b$$

$$K_a = 1 - \sigma^2 - (1 - \sigma)^2 = 2 \left(\frac{0.84307}{1.02282} \right) \left(1 - \frac{0.84307}{1.02282} \right) = 0.2897$$

$$K_b = 1 - \sigma^2 - (1 - \sigma)^2 = 2 \left(\frac{0.58007}{0.76278} \right) \left(1 - \frac{0.58007}{0.76278} \right) = 0.3693126$$

$$V_a = \sqrt{\frac{0.3643126}{0.2897}} V_b$$

$$V_a = 1.1214 V_b$$

Friction From 3.75 to 85.75 = 6.833 ft

Sector	Deflections, mils		
	$\beta_{\max}$	$\beta_{\min}$	$\bar{\beta}$
1	36	26	31
2	56	36	46
3	92	56	74
4	114	92	103
5	122	114	118
6	122	116	119
7	116	98	107
8	98	72	85

Sector 1

$$R_s = 1.4375$$

$$R_a = 1.623 + 0.031 = 1.654$$

$$R_b = 1.623 - 0.031 = 1.592$$

$$D_{H_a} = 2(R_a - R_s) = 2(1.654 - 1.4375) = 0.433$$

$$\Rightarrow \frac{D_{H_a}}{D_{H_b}} = 1.40129$$

$$D_{H_b} = 2(R_b - R_s) = 2(1.592 - 1.4375) = 0.309$$

$$A_a = \frac{\pi}{2} (R_a^2 - R_s^2) = \frac{\pi}{2} (1.654^2 - 1.4375^2) = 1.05135$$

$$\Rightarrow \frac{A_a}{A_b} = 1.42998$$

$$A_b = \frac{\pi}{2} (R_b^2 - R_s^2) = \frac{\pi}{2} (1.592^2 - 1.4375^2) = 0.73522$$

$$\frac{\epsilon}{D_{H_a}} = \frac{0.000063}{0.433} = 0.000145 \Rightarrow f_a = 0.016$$

$$\frac{\epsilon}{D_{H_a}} = \frac{0.00063}{0.309} = 0.0002038 \Rightarrow f_b = 0.019$$

$$V_a = \sqrt{\frac{f_b}{f_a} \frac{D_{H_a}}{D_{H_b}}} V_b = \sqrt{\frac{0.019}{0.016} (1.40129)} V_b$$

$$V_a = 1.2899 V_b$$

$$V_b = \frac{\omega_t}{\rho \left[A_a \frac{V_a}{V_b} + A_b \right]} = \frac{160(500.22)(144)}{61.56[1.05135(1.2899) + 0.73522](3600)} = 24.86$$

$$V_a = 32.75$$

$$Re_b = \frac{\rho d V}{\mu} = \frac{24.86(0.309)(61.50)(3600)}{1.288(12)} = 1.10144 \times 10^5$$

$$Re_a = \frac{\rho d V}{\mu} = \frac{32.75(0.433)(61.56)(3600)}{1.288(12)} = 2.0333 \times 10^5$$

$f_b = 0.019$	$f_a = 0.016$
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Sector 2

$$Bow = 0.046 \text{ in.}$$

$$R_a = 1.623 + 0.046 = 1.6690$$

$$R_b = 1.623 - 0.046 = 1.577$$

$$D_{H_a} = 2(R_a - R_s) = 2(1.699 - 1.4375) = 0.4630$$

$$\Rightarrow \frac{D_{H_a}}{D_{H_b}} = 1.65949$$

$$D_{H_b} = 2(R_b - R_s) = 2(1.577 - 1.4375) = 0.2790$$

$$A_a = \frac{\pi}{2} (R_a^2 - R_s^2) = \frac{\pi}{2} (1.669^2 - 1.4375^2) = 1.129648$$

$$\Rightarrow \frac{A_a}{A_b} = 1.71014$$

$$A_b = \frac{\pi}{2} (R_b^2 - R_s^2) = \frac{\pi}{2} (1.577^2 - 1.4375^2) = 0.660557$$

$$V_a = \sqrt{\frac{f_b}{f_a} \frac{D_{H_a}}{D_{H_b}}} V_b = \sqrt{\frac{0.021}{0.018} (1.65949)} V_b = 1.39142 V_b$$

$$V_b = \frac{160(500.22)(144)}{61.56[1.129648(1.39142) + 0.660557](3600)} = 23.296 \text{ ft/sec}$$

$$V_a = 32.41 \text{ ft/sec}$$

$$Re_b = \frac{\rho dV}{\mu} = \frac{23.296(0.279)(61.56)(3600)}{1.288(12)} = 9.3194 \times 10^4$$

$$Re_a = \frac{\rho dV}{\mu} = \frac{32.41(0.4630)(61.56)(3600)}{1.288(12)} = 2.15161 \times 10^5$$

$$\frac{\epsilon}{D_{H_a}} = \frac{0.000063}{0.463} = 0.000136 = > f_a = 0.0168$$

$$\frac{\epsilon}{D_{H_b}} = \frac{0.000063}{0.2790} = 0.0002258 = > f_b = 0.0195$$

$$V_a = \sqrt{\frac{0.0195}{0.0168} (1.65949)} V_b = 1.38787 V_b$$

$$V_b = \frac{160(500.22)(144)}{61.56[1.129648(1.38787) + 0.660557](3600)} = 23.3375$$

$$V_a = 32.389$$

$$Re_b \approx 9.3194 \times 10^4 \quad => \quad f_b = 0.0195$$

$$Re_a \approx 2.15161 \times 10^5 \quad => \quad f_a = 0.0168$$

Sector 3

$$Bow = 0.074 \text{ in.}$$

$$R_a = 1.623 + 0.074 = 1.697$$

$$R_b = 1.623 - 0.074 = 1.549$$

$$D_{H_a} = 2(R_a - R_s) = 2(1.697 - 1.4375) = 0.519$$

$$= > \frac{D_{H_a}}{D_{H_b}} = 2.32735$$

$$D_{H_b} = 2(R_b - R_s) = 2(1.549 - 1.4375) = 0.223$$

$$A_a = \frac{\pi}{2} (R_a^2 - R_s^2) = 1.27769$$

$$= > \frac{A_a}{A_b} = 2.44268$$

$$A_b = \frac{\pi}{2} (R_b^2 - R_s^2) = 0.52307$$

$$V_a = \sqrt{\frac{f_b}{f_a} \frac{D_{H_a}}{D_{H_b}}} V_b = \sqrt{\frac{0.021}{0.015} (2.32735)} V_b = 1.805 V_b$$

$$V_b = \frac{160(500.22)(144)}{61.56[1.27769(1.805) + 0.52307](3600)} = 18.38$$

$$V_a = 33.176$$

$$Re_b = \frac{\rho d V}{\mu} = \frac{18.38(0.223)(61.56)(3600)}{1.288(12)} = 5.877 \times 10^4$$

$$Re_a = \frac{\rho d V}{\mu} = \frac{33.176(0.519)(61.56)(3600)}{1.288(12)} = 2.46885 \times 10^5$$

$$\frac{\epsilon}{D_{H_a}} = \frac{0.000063}{0.519} = 0.0001213 = > f_a = 0.016$$

$$\frac{\epsilon}{D_{H_b}} = \frac{0.000063}{0.223} = 0.000285 = > f_b = 0.020$$

$$V_a = \sqrt{\frac{0.020}{0.016} (2.32735)} V_b = 1.705634 V_b$$

$$V_b = \frac{160(500.22)(144)}{61.56[1.27769(1.705634) + 0.53707](3600)} = 23.86 \text{ ft/sec}$$

$$V_a = 40.702 \text{ ft/sec}$$

$$Re_b = \frac{23.86(0.223)(61.56)(3600)}{1.288(12)} = 7.6304 \times 10^4$$

$$Re_a = \frac{40.702(0.519)(61.56)(3600)}{1.288(12)} = 3.0289 \times 10^5$$

$f_a = 0.016$	$f_b = 0.020$
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Sector 4

$$Bow = 0.103 \text{ in.}$$

$$R_a = 1.623 + 0.103 = 1.726$$

$$R_b = 1.623 - 0.103 = 1.520$$

$$D_{H_a} = 2(R_a - R_s) = 2(1.726 - 1.4375) = 0.577$$

$$= > \frac{D_{H_a}}{D_{H_b}} = 3.49696$$

$$D_{H_b} = 2(R_b - R_s) = 2(1.52 - 1.4375) = 0.165$$

$$A_a = \frac{\pi}{2} (R_a^2 - R_s^2) = 1.43362$$

$$= > \frac{A_a}{A_b} = 3.74049$$

$$A_b = \frac{\pi}{2} (R_b^2 - R_s^2) = 0.38327$$

$$V_a = \sqrt{\frac{f_b}{f_a} \frac{D_{H_a}}{D_{H_b}}} V_b = \sqrt{\frac{0.022}{0.014} (3.49696)} V_b = 2.344 V_b$$

$$V_b = \frac{160(500.22)(144)}{61.56[1.43362(2.344) + 0.38327](3600)} = 13.89$$

$$V_a = 32.56$$

$$Re_b = \frac{13.89(0.165)(61.56)(3600)}{1.288(12)} = 3.2862 \times 10^4$$

$$Re_a = \frac{32.56(0.577)(61.56)(3600)}{1.288(12)} = 2.69379 \times 10^5$$

$$\frac{\epsilon}{D_{H_a}} = \frac{0.000063}{0.577} = 0.000109 = > f_a = 0.016$$

$$\frac{\epsilon}{D_{H_b}} = \frac{0.000063}{0.165} = 0.0003818 \Rightarrow f_b = 0.023$$

$$V_a = \sqrt{\frac{0.023}{0.016}} (3.49696) V_b = 2.242 V_b$$

$$V_b = \frac{160(500.22)(144)}{61.56[1.43362(2.242) + 0.38327](3600)} = 14.4556 \text{ ft/sec}$$

$$V_a = 32.41 \text{ ft/sec}$$

$$Re_a \approx 2.69379 \times 10^5 \Rightarrow f_a = 0.016$$

$$Re_b \approx 3.2862 \times 10^4 \Rightarrow f_b = 0.023$$

Sector 5

$$\text{Bow} = 0.118 \text{ in.}$$

$$R_s = 1.4375$$

$$R_a = 1.623 + 0.118 = 1.741$$

$$R_b = 1.623 - 0.118 = 1.505$$

$$D_{H_a} = 2(R_a - R_s) = 0.607$$

$$\Rightarrow \frac{D_{H_a}}{D_{H_b}} = 4.4963$$

$$D_{H_b} = 2(R_b - R_s) = 0.135$$

$$A_a = \frac{\pi}{2} (R_a^2 - R_s^2) = 1.5153$$

$$\Rightarrow \frac{A_a}{A_b} = 4.8569$$

$$A_b = \frac{\pi}{2} (R_b^2 - R_s^2) = 0.31199$$

$$V_a = \sqrt{\frac{f_b}{f_a} \frac{D_{H_a}}{D_{H_b}}} V_b = \sqrt{\frac{0.026}{0.015}} (4.4963) V_b = 2.7917 V_b$$

$$V_b = \frac{160(500.22)(144)}{61.56[1.5153(2.7917) + 0.31199](3600)} = 11.449$$

$$V_a = 31.9624$$

$$Re_a = \frac{31.9624(0.607)(61.56)(3600)}{1.288(12)} = 2.78183 \times 10^5$$

$$Re_b = \frac{11.449(0.135)(61.56)(3600)}{1.288(12)} = 2.2161 \times 10^4$$

$$\frac{\epsilon}{D_{H_a}} = \frac{0.000063}{0.607} = 0.0001037$$

$$\frac{\epsilon}{D_{H_b}} = \frac{0.000063}{0.135} = 0.0004666$$

$$f_a = 0.0155$$

$$f_b = 0.026$$

Sector 6

Bow = 0.119 in.

Since the bow in this sector is only 1 mil greater than that of Sector 5, the relationship of Sector 5 will be used.

$$V_a = 2.7917 V_b$$

At Maximum Bow of 0.122 in.

$$R_s = 1.4375$$

$$R_a = 1.623 + 0.122 = 1.745$$

$$R_b = 1.623 - 0.122 = 1.501$$

$$D_{H_a} = 2(R_a - R_s) = 0.615$$

$$=> \frac{D_{H_a}}{D_{H_b}} = 4.8425$$

$$D_{H_b} = 2(R_b - R_s) = 0.127$$

$$A_a = \frac{\pi}{2} (R_a^2 - R_s^2) = 1.5372$$

$$=> \frac{A_a}{A_b} = 5.24462$$

$$A_b = \frac{\pi}{2} (R_b^2 - R_s^2) = 0.2931$$

$$V_a = \sqrt{\frac{f_b}{f_a} \frac{D_{H_a}}{D_{H_b}}} V_b = \sqrt{\frac{0.028}{0.015} (5.24462)} V_b = 3.12889 V_b$$

$$V_b = \frac{160(500.22)(144)}{61.56[1.5372(3.12889) + 0.2931](3600)} = 10.191$$

$$V_a = 31.887$$

$$Re_a = \frac{31.887(0.615)(61.56)(3600)}{1.288(12)} = 2.81185 \times 10^5$$

$$Re_b = \frac{10.191(0.127)(61.56)(3600)}{1.288(12)} = 1.8557 \times 10^4$$

$$\frac{\epsilon}{D_{H_a}} = \frac{0.000063}{0.615} = 0.0001024$$

$$\frac{\epsilon}{D_{H_b}} = \frac{0.000063}{0.127} = 0.000496$$

$$f_a = 0.0155$$

$$f_b = 0.028$$

Sector 7

The relationship of Sector 4 will be used.

$$V_a = 2.242 V_b$$

where $f_a = 0.016$ and $f_b = 0.023$. Elevation at end of Sector 7 is 78 ft.

Sector 8

$$\text{Bow} = (98 + 84)/2 = 91 \text{ mils}$$

$$\text{Area} = 2.534 \text{ in.}^2$$

$$W_p = 19.68 \text{ in.}$$

$$d_H = \frac{4A}{W_p} = \frac{4(2.534)}{19.68} = 0.515 = 2t$$

$$t = 0.2575 \text{ in.}$$

$$R_s = 1.4375$$

$$R_2 = R_s + 0.2575 = 1.695 \text{ in.}$$

$$R_a = 1.695 + 0.091 = 1.786$$

$$R_b = 1.695 - 0.091 = 1.604$$

$$D_{H_a} = 2(R_a - R_s) = 0.697$$

$$\Rightarrow \frac{D_{H_a}}{D_{H_b}} = 2.093$$

$$D_{H_b} = 2(R_b - R_s) = 0.333$$

$$A_a = \frac{\pi}{2} (R_a^2 - R_s^2) = 1.76462$$

$$\Rightarrow \frac{A_a}{A_b} = 2.21834$$

$$A_b = \frac{\pi}{2} (R_b^2 - R_s^2) = 0.79547$$

$$V_a = \sqrt{\frac{f_b}{f_a} \frac{D_{H_a}}{D_{H_b}}} V_b = \sqrt{\frac{0.020}{0.016} (2.093)} V_b = 1.61748 V_b$$

$$V_b = \frac{160(500.22)(144)}{61.56[1.76462(1.61748) + 0.79547](3600)} = 14.2489$$

$$V_a = 23.047$$

$$\frac{\epsilon}{D_{H_a}} = \frac{0.000063}{0.697} = 0.00009$$

$$\frac{\epsilon}{D_{H_b}} = \frac{0.000063}{0.333} = 0.000189$$

$$Re_a = \frac{23.047(0.697)(61.56)(3600)}{1.288(12)} = 2.3033 \times 10^5$$

$$Re_b = \frac{14.2489(0.333)(61.56)(3600)}{1.288(12)} = 6.8034 \times 10^4$$

$$f_a = 0.016$$

$$f_b = 0.020$$

Expansion of Sector 7 → 8

$$\text{Bow} = 98 \text{ mils, } A_a = 1.43362, A_b = 0.38327$$

$$\frac{D_{H_a}}{D_{H_b}} = \frac{0.697}{0.333} = 2.093$$

$$\frac{A_a}{A_b} = \frac{1.76462}{0.79547} = 2.21834$$

$$V_a = \sqrt{\frac{K_b}{K_a}} V_b$$

$$K_a = 1 - \sigma^2 - (1 - \sigma)^2 = 2 \left(\frac{1.43362}{1.76462} \right) \left(1 - \frac{1.43362}{1.76462} \right) = 0.30478$$

$$K_b = 2 \left(\frac{0.38327}{0.79547} \right) \left(1 - \frac{0.38327}{0.79547} \right) = 0.49933$$

$$V_a = \sqrt{\frac{0.49933}{0.30478}} V_b = 1.27998 V_b$$

Segment 9 Labyrinth

$$\text{Pitch} = 1.17 \text{ in.}$$

$$A_f = 3.614 \text{ in.}^2 \text{ at bottom of teeth and } 1.8039 \text{ in.}^2 \text{ at top}$$

$$W_p = 20.436 \text{ in. at bottom of teeth and } 19.24223 \text{ in. at top}$$

$$R_s = 1.4375$$

Assuming a constant bow of 0.077,

$$\text{Radius to top of tooth} = 1.623 = R_t$$

$$\text{Radius to bottom of tooth} = 1.813 = R_b$$

8 contractions and expansions

$$R_T \begin{cases} R_a = 1.623 + 0.077 = 1.70 \\ R_b = 1.623 - 0.077 = 1.546 \end{cases}$$

$$D_{H_a} = 2(1.70 - 1.4375) = 0.525$$

$$= > \frac{D_{H_a}}{D_{H_b}} = 2.41935$$

$$D_{H_b} = 2(1.546 - 1.4375) = 0.217$$

$$A_a = \frac{\pi}{2} (1.7^2 - 1.4375^2) = 1.2937$$

$$\Rightarrow \frac{A_a}{A_b} = 2.5442$$

$$A_b = \frac{\pi}{2} (1.546^2 - 1.4375^2) = 0.5084$$

$$R_B \begin{cases} R_a = 1.813 + 0.077 = 1.89 \\ R_b = 1.813 - 0.077 = 1.736 \end{cases}$$

$$D_{H_a} = 2(1.89 - 1.4375) = 0.905$$

$$\Rightarrow \frac{D_{H_a}}{D_{H_b}} = 1.5159$$

$$D_{H_b} = 2(1.736 - 1.4375) = 0.597$$

$$A_a = \frac{\pi}{2} (1.89^2 - 1.4375^2) = 2.3651$$

$$\Rightarrow \frac{A_a}{A_b} = 1.58947$$

$$A_b = \frac{\pi}{2} (1.736^2 - 1.4375^2) = 1.488$$

$$Kc_a = 0.4(1 - \sigma_a) + 1 - \sigma_a^2 = 1.4 - 0.4 \left(\frac{1.2937}{2.3651} \right) - \left(\frac{1.2937}{2.3651} \right)^2 = 0.8819973$$

$$Kc_b = 0.4(1 - \sigma_a) + 1 - \sigma_a^2 = 1.4 - 0.4 \left(\frac{0.5084}{1.488} \right) - \left(\frac{0.5084}{1.488} \right)^2 = 1.1465974$$

$$Ke_a = 1 - \sigma^2 - (1 - \sigma)^2 = 2 \left(\frac{1.2937}{2.3651} \right) \left(1 - \frac{1.2937}{2.3651} \right) = 0.4955827$$

$$Ke_b = 1 - \sigma^2 - (1 - \sigma)^2 = 2 \left(\frac{0.5084}{1.488} \right) \left(1 - \frac{0.5084}{1.488} \right) = 0.449861$$

Side A has 8 contractions and 8 expansions;

$$\therefore Kc_a(\text{total}) = 8(0.8819973) = 7.0559784$$

$$Ke_a(\text{total}) = 8(0.4955827) = 3.9646616$$

Side B

$$Kc_b(\text{total}) = 8(1.1465974) = 9.1727792$$

$$Ke_b(\text{total}) = 8(0.449861) = 3.5988$$

$$V_a = \sqrt{\frac{K_b}{K_a}} V_b = 1.4 V_b$$

$$\Delta p_T = 88.8 \cdot \Delta p_{c_{A-B}} + \Delta p_{f_B} + \Delta p_{c_{B-C}} + \Delta p_{f_C} - \Delta p_{e_{C-D}} + \Delta p_{f_D} - \Delta p_{e_{D-E}} + \Delta p_{f_E} - \Delta p_{e_{E-F}} + \Delta p_{f_F} + \Delta p_G - \Delta p_H$$

$$\Delta p_{c_{A-B}} = \frac{K(\omega)^2}{2g_c \rho A^2} \quad \omega = \omega_A + \omega_B = 1.53622 \omega_B + \omega_B = 2.53622 \omega_B = > \frac{K_B \omega^2}{2(2.53622)^2 g_c \rho A_B^2} = \frac{144 \omega^2}{2(32.174)(61.56)(3600)^2} \cdot \frac{1.4}{(2.53622)^2 (0.39543)^2}$$

$$\omega_B = \frac{\omega}{2.53622}$$

$$\Delta p_{f_B} = f \frac{L}{de} \frac{\omega_B^2}{2g_c \rho A^2} \quad \omega_A = 1.34 \frac{A_A}{A_B} \omega_B = 1.34(1.5618) \omega_B = 2.0928 \omega_B$$

$$\omega = \omega_A + \omega_B = 2.0928 \omega_B + \omega_B = 3.0928 \omega_B$$

$$\Delta p_{f_B} = f_B \frac{L_B \omega^2}{de_B (3.0928)^2 (2)(\mu_c)(A_B^2)} = \frac{144 \omega^2}{2(32.174)(61.56)(3600)^2} \cdot \frac{f_B L_B}{de_B A_B^2 (n)}$$

$$\Delta p_{c_{B-C}} = \frac{K \omega^2}{2\mu_c \rho A^2} \quad \omega = \omega_A + \omega_B = 2.5647 \omega_B + \omega_B = 3.5647 \omega_B = > \frac{K_B \omega^2}{(3.5647)^2 2g_c \rho A_B^2}$$

$$\omega_B = \frac{\omega}{3.5647}$$

$$\Delta p_{f_C} = f \frac{L}{de} \frac{\omega^2}{2g_c \rho A^2} \quad \omega = \omega_A + \omega_B = 1.373547(1.63924) \omega_B + \omega_B = 3.25157 \omega_B = > f_B \frac{L_B}{de_B} \frac{\omega^2}{(3.25157)^2 2g_c \rho A_B^2}$$

$$\omega_B = \frac{\omega}{3.25157}$$

$$\Delta p_{e_{C-D}} = \frac{K \omega}{2\mu_c \rho A^2} \quad \omega = \omega_A + \omega_B = 1.53756 \omega_B + \omega_B = 2.53756 \omega_B = > \frac{K_B \omega^2}{(2.53756)^2 2g_c \rho A_B^2}$$

$$\omega_B = \frac{\omega}{2.53756}$$

$$\Delta p_{fD} = f \frac{L}{de} \frac{\omega^2}{2g_c \rho A^2}$$

$$\omega = \omega_A + \omega_B = \sqrt{\frac{0.021}{0.018} (1.4323) (1.4534)} \omega_B + \omega_B = 1.8787782 \omega_B + \omega_B = 2.879 \omega_B = > \frac{f_B L_B \omega^2}{(2.879)^2 de_B^2 g_c \rho A_B^2}$$

$$\omega_B = \frac{\omega}{2.879}$$

$$\Delta p_{eD-E} = K \frac{\omega^2}{2g_c \rho A^2}$$

$$\omega = \omega_A + \omega_B = 1.1214(1.3409) \omega_B + \omega_B = 2.5037 \omega_B = > K_B \frac{\omega^2}{(2.5037)^2 2g_c \rho A_B^2}$$

$$\omega_B = \frac{\omega}{2.5037}$$

$$\Delta p_{fE} = \sum_{i=1}^8 \Delta p_{fi}$$

$$\text{Sector 1 } \omega_1 = \omega_A + \omega_B = 1.2899(1.42998) \omega_B + \omega_B = 2.8445 \omega_B = > \omega_B = \omega / 2.8445 = \omega / n$$

$$\text{Sector 2 } \omega_2 = \omega_A + \omega_B = 1.38787(1.71) \omega_B + \omega_B = 3.3733 \omega_B = > \omega_B = \omega / 3.3733$$

$$\text{Sector 3 } \omega_3 = \omega_A + \omega_B = 1.7056(2.4427) \omega_B + \omega_B = 5.1663 \omega_B = > \omega_B = \omega / 5.1663$$

$$\text{Sector 4 } \omega_4 = \omega_A + \omega_B = 2.242(3.74049) \omega_B + \omega_B = 9.386 \omega_B = > \omega_B = \omega / 9.386$$

$$\text{Sector 5 } \omega_5 = \omega_A + \omega_B = 2.7917(4.8596) \omega_B + \omega_B = 14.566 \omega_B = > \omega_B = \omega / 14.566$$

$$\text{Sector 6 } \omega_6 = \omega_A + \omega_B = 2.7917(4.8596) \omega_B + \omega_B = 14.566 \omega_B = > \omega_B = \omega / 14.566$$

$$\text{Sector 7 } \omega_7 = \omega_A + \omega_B = 2.242(3.74049) \omega_B + \omega_B = 9.386 \omega_B = > \omega_B = \omega / 9.386$$

$$\text{Sector 8 } \omega_8 = \omega_A + \omega_B = 1.617(2.21834) \omega_B + \omega_B = 4.587 \omega_B = > \omega_B = \omega / 4.587$$

$$\text{Sector}_{\max} = \omega_A + \omega_B = 3.13(5.245) \omega_B + \omega_B = 17.42 \omega_B = > \omega_B = \omega / 17.42$$

$$\Delta p_f = f \frac{L}{de} \frac{\omega^2}{2g_c \rho A^2} = f \frac{L(\text{in})(1b^2/\text{in}^2)(144 \text{ in}^2/\text{ft}^2) \omega^2}{de(\text{in})(2)(32.174 \text{ ft/sec}^2)(61.56 \text{ lb/ft}^3)(\text{in}^2)(A^2)(3600)^2 \text{ sec}^2/\text{hr}^2(n)^2}$$

$$\Delta p_{fE} = \frac{144 \omega^2}{2(32.174)(61.56)(3600)^2} \cdot \sum_{i=1}^8 \left(\frac{f_B L_B}{de A_B^2 n^2} \right)_i$$

$$\begin{aligned} \sum_{i=1}^8 \left(\frac{f_B L_B}{de A_B^2 n^2} \right)_i &= \left(\frac{0.019(8.25)}{0.1159851} \right)_1 + \left(\frac{0.0195(12)}{0.16892} \right)_2 + \left(\frac{0.020(12)}{0.1474} \right)_3 + \left(\frac{0.023(12)}{0.1292369} \right)_4 \\ &+ \left(\frac{0.026(12)(2)}{0.19918} \right)_{5,6} + \left(\frac{0.023(12)}{0.1292369} \right)_7 + \left(\frac{0.02(7)}{0.03157} \right)_8 + \left(\frac{0.028(1.0)}{0.0084571} \right)_{\max \text{ bow}} = 0.93 \end{aligned}$$

$$\Delta P_{fE} = \frac{144 \omega^2}{2(32.174)(61.56)(3600)^2} \sum_{i=1}^8 \left(\frac{f_B L_B}{d_{eB} A_B^2 n^2} \right)_i + \left(\frac{f_B L_B}{d_{eB} A_B^2 n^2} \right)_{\text{max bow}} = \frac{0.93(144) \omega^2}{2(32.174)(61.56)(3600)^2}$$

$$\Delta P_{eE-F} = K_e \frac{\omega^2}{2g_c \rho A^2} \quad \omega = \omega_A + \omega_B = 1.28(2.218) \omega_B + \omega_B = 3.84 \omega_B \Rightarrow \omega_B = \omega / 3.84$$

$$\Delta P_{eE-F} = \frac{K_e \omega^2}{(3.84)^2 2g_c \rho A^2} = \frac{0.49933(144 \text{ in}^2/\text{ft}^2) \omega^2 (\text{lb}^3/\text{ft}^3)}{(3.84)^2 (2)(32.174 \text{ ft/sec}^2)(61.56 \text{ lb/ft}^3)(0.79547)^2 \text{ in}^2 (3600)^2 \text{ sec}^2/\text{hr}^2} = \frac{144 \omega^2}{2(32.174)(61.56)(3600)^2} \cdot \frac{0.49933}{(3.84)^2 (0.79547)^2}$$

$$\Delta P_{fF} = f \frac{L}{d_e} \frac{\omega^2}{2g_c \rho A^2} = \left. \begin{array}{l} \text{This is Sector 8,} \\ \text{already accounted for.} \end{array} \right\}$$

$$\Delta P_G (\text{labyrinth}) = K \frac{\omega^2}{2g_c \rho A^2} \quad \omega = \omega_A + \omega_B = 1.14(2.5442) \omega_B + \omega_B = 3.9 \omega_B \Rightarrow \omega_B = \omega / 3.9$$

$$\Delta P_G = \frac{5.5}{(3.9)^2} \frac{\omega^2}{2g_c \rho A^2} = \frac{144 \omega^2}{2(32.174)(61.56)(3600)^2} \cdot \frac{5.5}{(3.9)^2 (0.5084)^2}$$

$$\Delta P_H = \rho \Delta H = \frac{61.56 \text{ lb/ft}^3 (98.461 \text{ in})}{1728 \text{ in}^3/\text{ft}^3} = 3.507 \text{ psi}$$

$$88.8 = \frac{144 \omega^2}{2(32.174)(61.56)(3600)^2} \left\{ \begin{array}{l} \frac{\Delta P_{CA-B}}{1.4} + \frac{\Delta P_{fB}}{(2.536)^2 (0.395)^2} + \frac{\Delta P_{CB-C}}{\{0.1531\} (0.392)^2 (3.093)^2} + \frac{\Delta P_{fC}}{(3.5647)^2 (0.372)^2} + \frac{\Delta P_{eC-D}}{(3.25)^2 (0.144) (0.368)^2} - \frac{0.46736}{(2.54)^2 (0.368)^2} \\ \frac{0.021(2)}{(2.879)^2 (0.2244) (0.58)^2} - \frac{\Delta P_{eD-E}}{(2.5)^2 (0.58)^2} + \frac{\Delta P_{fE}}{0.93} - \frac{\Delta P_{eE-F}}{(3.84)^2 (0.79547)^2} + \frac{\Delta P_G}{(3.9)^2 (0.5084)^2} \end{array} \right\} - 3.507$$

$$88.8 + 3.507 = \frac{144 \omega^2}{2(32.174)(61.56)(3600)^2} (3.08327) = 92.307$$

$$\omega^2 = \frac{92.307(2)(32.174)(61.56)(3600)^2}{144(3.083)}$$

$$\omega = 206 \text{ gal/min}$$

$$\text{Non-bow } \omega = 187 \text{ gal/min}$$

10% change

The previous calculations were repeated for a 146-mil maximum loop eccentricity; varying along the channel as follows:

<u>Elevation, ft</u>	<u>ε, mils</u>
86.5	0.00
85.5	14.7
84.5	34.0
83.5	58.5
82.5	85.6
81.5	116.0
80.0	146.5
78.5	128.0
77.5	99.7
74.5	42.5
71.5	13.2

The calculated flow rate with these eccentricities is 216.03 gpm under a 88.8 psi pressure differential. Figure 5.5 in reference 3 contains experimental data describing a friction factor ratio (f/f_0) as a function of eccentricity. These data were used to generate a curve describing the eccentric inner safety rod channel as a function of eccentricity (Figure D.2-14) using the 187 gpm concentric annuli flow rate (ω_0) and the maximum possible eccentricity (ϵ_m) of 186 mils as a base. The eccentric flow rate (ω_ϵ) is determined by the relationship

$$\omega_\epsilon = \frac{\omega_0}{\sqrt{f/f_0}}$$

where f and f_0 are the eccentric and concentric annuli friction factors, respectively, for an eccentricity based on a percentage of ϵ_m . For a 1-foot-long maximum eccentric annulus at the core midplane, the flow rate changes with eccentricity in the following manner:

ϵ , in.	% ϵ_m	f/f_0	$\sqrt{f/f_0}$	ω_ϵ , gpm
0.080	43	0.91	0.954	196
0.100	54	0.87	0.933	200
0.120	65	0.82	0.9055	206
0.140	75	0.78	0.8831	212
0.160	86	0.71	0.8426	222
0.170	92	0.67	0.8185	228
0.180	97	0.62	0.7874	238

The flow rates above are plotted as functions of eccentricity in Figure D.2-14. Indicated on this figure are the two points corresponding to the calculated flow rates of 206 and 216 gpm for the 122- and 146-mil eccentricities, respectively, and the percent of change in flow rate.

Figure D.2-1. Safety Rod Flow Channels and Numerical Designations

Figure D.2-2. Flow Rate Vs Pressure Drop, ATR Safety Rod in Up Position

Figure D.2-3. Flow Rate Vs Pressure Drop, ATR Safety Rod in Down Position

Figure D.2-4. Pressure Drop Vs Distance Along Channel,
ATR Safety Rod in Up Position

Figure D.2-5. Pressure Drop Vs Distance Along Channel,
ATR Safety Rod in Down Position

Figure D.2-6. Pressure Drops and Flow Rates, ATR Safety Rod in Full Up Position (12, 4, 6)

Figure D.2-7. Pressure Drops and Flow Rates, ATR Safety Rod in Down Position (4, 6)

Figure D.2-8. Pressure Drops and Flow Rates, ATR Safety Rod in Up Position (min 44, 66)

Figure D.2-9. Pressure Drops and Flow Rates, ATR Safety Rod in Up Position (max 44, 66)

Figure D.2-10. Pressure Drops and Flow Rates, ATR Safety Rod in Down Position (min 44, 66)

Figure D.2-11. Flow Rate Vs Pressure Drop as Obtained Using CHATA

Figure D.2-12. Eccentric Inner Safety Rod Channel

Figure D.2-13. Deflection of Insulation Jacket Vs Location Relative to Core Center

Figure D.2-14. Safety Rod - Up Position Inner Channel Flow Rate Vs Channel Eccentricity

D.3. HYDRAULIC CALCULATIONS — ATR CENTER LOOP FLOW RESTRICTOR — CONCEPT 5

These calculations were made to determine the flow rate that can be achieved in the center loop with flow restrictor concept 5 under a 100-psi pressure differential. Several basic factors remained constant for the work:

1. The flow restrictor has six parallel channels of identical geometry.

2. Flow areas per channel:

$$A_L = \text{unrestricted} = 0.10315 \text{ in.}^2$$

$$A_C = \text{restricted} = 0.07424 \text{ in.}^2$$

These areas were determined using Simpson's Rule (Figure D.3-2).

3. Wetted perimeters per channel:

$$W_{PL} = \text{unrestricted} = 1.84669 \text{ in.}$$

$$W_{PC} = \text{restricted} = 1.31459 \text{ in.}$$

4. Hydraulic diameters per channel:

$$D_{HL} = \text{unrestricted} = \frac{4A_L}{W_{PL}} = \frac{4(0.10315)}{1.84669} = 0.2234267 \text{ in.}$$

$$D_{HC} = \text{restricted} = \frac{4A_C}{W_{PC}} = \frac{4(0.07424)}{1.31459} = 0.2258955 \text{ in.}$$

5. Reynolds numbers, assuming a flow rate of 100 gpm total.
(This value must be divided by 6.):

$$Re_L = \frac{4}{6} \frac{\omega}{W_{PL}\mu} = \frac{4(100)(500.22)(12)}{1.84669 (1.288)(6)} = 1.68244 \times 10^5$$

$$Re_C = \frac{4}{6} \frac{\omega}{W_{PC}\mu} = \frac{4(100)(500.22)(12)}{1.31459 (1.288)(6)} = 2.36344 \times 10^5$$

6. Friction factors (Moody):

$$\frac{\epsilon}{D_{HL}} = \frac{0.000063}{0.2234267} = 0.0002819 = > f_L = 0.0175$$

$$\frac{\epsilon}{D_{HC}} = \frac{0.000063}{0.2258455} = 0.0002789 = > f_C = 0.0165$$

Pressure Drop Across Ribbed Area — Method 1 — Drag Approach

$$\Delta p = K \frac{\rho V^2}{2g_C} = K \frac{\omega^2}{2g_C \rho A^2} \text{ (per channel)}$$

$$K_D = nC + (n - 1) \left[\frac{f_C Z}{D_{HC}} + \frac{f_L (P - Z)}{D_{HL}} \right]$$

where

C = drag coefficient from reference 2, Figure 2-12 = 0.71

n = No. of restrictions

Z = length of restrictions = 0.125 in.

P = restriction pitch = 0.375 in.

f_C = restricted friction factor = 0.0165

f_L = unrestricted friction factor = 0.0175

D_{HC} = restricted hydraulic dia = 0.2258455 in.

D_{HL} = unrestricted hydraulic dia = 0.2234267 in.

therefore

$$K_D = 0.71n + (n - 1) \left[\frac{0.0165 (0.125)}{0.2258455} + \frac{0.25 (0.0175)}{0.2234267} \right]$$

$$= 0.71n + 0.0287(n - 1)$$

<u>n</u>	<u>K_D</u>	<u>n</u>	<u>K_D</u>
1	0.7100	9	6.6196
2	1.4487	10	7.3583
3	2.1874	11	8.0970
4	2.9261	12	8.8357
5	3.6648	13	9.5744
6	4.4035	14	10.3131
7	5.1422	15	11.0518
8	5.8809		

Restrictor Pitch — A restrictor pitch/height (P/ϵ) of 5.5 was selected as that which would give the highest frictional resistance.² The resistor height varies from 0.0 to 0.1 inch. A value of 2/3 (0.1) was chosen for ϵ ; then $\epsilon = 0.06667$. Therefore, $P = 5.5(0.06667) = 0.36667$ inches. The pitch used is 0.375 inch.

Pressure Drop Across Ribbed Area — Method 2 — Smeared Friction Approach

$$\Delta p = f \frac{L}{D_H} \frac{\rho V^2}{2g_C} = f \frac{L}{D_H} \frac{\omega^2}{2g_C \rho A^2}$$

$$f = f_{\text{smeared}} = \frac{W_{Ps} f_s + W_{Pr} f_r}{W_{Ps} + W_{Pr}}$$

where

f_s = friction factor—smooth—Moody = 0.0175

f_r = friction factor—roughened = 1.1*

(This value was obtained from Figure 2.3 of reference 2.) See Figures D.3-3 and D.3-4.

W_{Ps} = wetted perimeter—smooth = 1.84669 in.

W_{Pr} = wetted perimeter—rough = 1.31459 in.

Therefore,

$$f = \frac{1.84669(0.0175) + 1.31459(1.1)}{1.84669 + 1.31459} = 0.4676$$

$$\therefore \Delta p = 0.4676 \frac{L}{D_H} \frac{\omega^2}{2g_C \rho A^2}$$

$$K_f = f \frac{L}{D_{HL}} = \frac{0.4676 L}{0.2234267} = 2.09285 L$$

* Based on $\frac{\epsilon}{D} = \frac{0.06667}{0.2258} = 0.2952$ ($\frac{\epsilon}{D}$: restrictor height to hydraulic dia)

<u>n</u>	<u>L</u>	<u>K_f</u>
1	0.125	0.2616
2	0.500	1.0464
3	0.875	1.8312
4	1.250	2.6161
5	1.625	3.4009
6	2.000	4.1850
7	2.375	4.9705
8	2.750	5.7553
9	3.125	6.5402
10	3.500	7.3245
11	3.875	8.1098
12	4.250	8.8946

The graph K_D , K_f versus number of restrictions shows that there is a small difference between the coefficients determined by methods 1 and 2. The higher value, K_D , will be used in the flow rate calculation (Figure D.3-5).

Flow Rate Calculation

$$\Delta P_{\text{total}} = \sum \Delta P_{\text{contraction and expansion}} + \sum \Delta P_{\text{friction}} + \Delta P_H = 100 \text{ psi}$$

($\Delta P_{\text{acceleration}}$ will be neglected.)

$$\Delta P_c = K_c \frac{\omega^2}{2g_C \rho A^2} = K_c \frac{\omega^2 (\text{lb}^2/\text{hr}^2) (144 \text{ in.}^2/\text{ft}^2)}{2(32.174 \text{ ft/sec}^2)(61.56 \text{ lb/ft}^3)(A^2 \text{ in.}^4)(3600)^2 \text{ sec}^2/\text{hr}^2}$$

$$\Delta P_e = K_e \frac{\omega^2}{2g_C \rho A^2} = K_e \frac{\omega^2 (144)}{2(32.174)(61.56)(A^2)(3600)^2}$$

$$\Delta P_f = f \frac{L}{D_e} \frac{\omega^2}{2g_C \rho A^2} = \frac{0.18}{\text{Re}^{0.2}} \frac{L}{D_e} \frac{\omega^2 (144)}{2(32.174)(61.56)(A^2)(3600)^2}$$

Assuming $\omega \approx 100 \text{ gal/min}$,

$$\text{Re}_B = \left(\frac{4\omega}{\mu W_P} \right)_B^{0.2} = \left(\frac{4(100)(500.22)(12)}{1.288(22.09)} \right)^{0.2} = 9.666 = > f_B = \frac{0.18}{9.666} = 0.01862$$

$$\text{Re}_D = \left(\frac{4\omega}{\mu W_P} \right)_D^{0.2} = \left(\frac{4(100)(500.22)(12)}{1.288(22.29)} \right)^{0.2} = 9.649 = > f_D = \frac{0.18}{9.649} = 0.01865$$

$$Re_E = \left(\frac{4\omega}{\mu W_P} \right)_E^{0.2} = \left(\frac{4(100)(500.22)(12)}{1.288(19.63)} \right)^{0.2} = 9.897 = > f_E = \frac{0.18}{9.897} = 0.01818$$

($\Delta p_{\text{friction}}$ in section F will be neglected.)

$$de_B = \frac{4A}{W_{p_B}} = \frac{4(1.534)}{22.09} = 0.27777$$

$$de_D = \frac{4A}{W_{p_D}} = \frac{4(1.943)}{22.29} = 0.34867$$

$$de_E = \frac{4A}{W_{p_E}} = \frac{4(2.545)}{19.63} = 0.51859$$

$$\Delta p_T = 100 = \Delta p_{c_{A-B}} + \Delta p_{c_{B-C}} - \Delta p_{e_{C-D}} - \Delta p_{e_{D-E}} - \Delta p_{e_{E-F}} - \Delta p_{e_{F-G}} \\ + \Delta p_c^* + \Delta p_{f_B} + \Delta p_{f_D} + \Delta p_{f_E} + \Delta p_f^* - \Delta p_H$$

where

Δp_c = contraction pressure drop

Δp_e = expansion pressure drop

Δp_f = friction pressure drop

Δp_H = head pressure drop

Subscripts (capitals) designate sections

Δp_c^* = pressure drop across restrictor - ribbed area

Δp_f^* = friction pressure drop in restrictor before ribbed area = 3.5-L where L is the length of the ribbed area.

$$\Delta p_c^* = K_D \left(\frac{\omega}{6} \right)^2 \frac{1}{2g_C \rho A^2} = \frac{K_D}{36A^2} \left(\frac{144 \omega^2}{2(32.174)(61.56)(3600)^2} \right)$$

$$\Delta p_{f_c}^* = f \frac{(3.5 - L)(\omega/6)^2}{2g_C \rho A^2 de} = f \frac{(3.5 - L)}{36deA^2} \left(\frac{144 \omega^2}{2(32.174)(61.56)(3600)^2} \right)$$

$$\Delta p_H = \rho(\Delta H) = \frac{61.56 \text{ lb/ft}^3 (150 \text{ in.})}{1728 \text{ in.}^3/\text{ft}^3} = 5.34398 \text{ lb/in.}^2$$

$$100 = \frac{144 \omega^2}{2(32.174)(61.56)(3600)^2} \left[\frac{K_{c_{A-B}}}{(A_B)^2} + \frac{K_{c_{B-C}}}{(A_C)^2} - \frac{K_{e_{C-D}}}{(A_C)^2} - \frac{K_{e_{D-E}}}{(A_D)^2} \right. \\ \left. - \frac{K_{e_{E-F}}}{(A_E)^2} - \frac{K_{e_{F-G}}}{(A_F)^2} + \frac{f_B^L L_B}{de_B (A_B)^2} + \frac{K_D}{36(A_C)^2} + \frac{f_D^L L_D}{de_D (A_D)^2} + \frac{f_E^L L_E}{de_E A_E^2} \right. \\ \left. + \frac{f_c (3.5 - L)}{36 de_C (A_C)^2} \right] - 5.34398$$

$$K_c = 1.4 - 0.4\sigma - \sigma^2 \quad K_e = 2\sigma(1 - \sigma)$$

where σ = area ratio. K_e and K_c will predict the pressure change, both permanent and recoverable.

$$K_{c_{A-B}} = 1.4 - 0.4 \left(\frac{1.534}{500.00} \right) - \left(\frac{1.534}{500.00} \right)^2 = 1.39876$$

$$K_{c_{B-C}} = 1.4 - 0.4 \left(\frac{0.44548}{1.534} \right) - \left(\frac{0.44548}{1.534} \right)^2 = 1.1995038$$

$$K_{e_{C-D}} = 2 \left(\frac{0.44548}{1.943} \right) \left(1 - \frac{0.44548}{1.943} \right) = 0.3534152$$

$$K_{e_{D-E}} = 2 \left(\frac{1.943}{2.545} \right) \left(1 - \frac{1.943}{2.545} \right) = 0.3611802$$

$$K_{e_{E-F}} = 2 \left(\frac{2.545}{11.00} \right) \left(1 - \frac{2.545}{11.00} \right) = 0.355669$$

$$K_{e_{F-G}} = 2 \left(\frac{11.00}{500.00} \right) \left(1 - \frac{11.00}{500.00} \right) = 0.043032$$

$$\frac{K_{c_{A-B}}}{(A_B)^2} = \frac{1.39876}{(1.534)^2} = 0.5944$$

$$\frac{f_B^L L_B}{de_B A_B^2} = \frac{0.01621(0.5)}{0.278(1.534)^2} = 0.012389$$

$$\frac{K_{c_{B-C}}}{(A_C)^2} = \frac{1.995}{(0.44548)^2} = 6.0443$$

$$\frac{f_D^L D}{de_D A_D^2} = \frac{0.01624(14)}{0.3487(1.943)^2} = 0.1727$$

$$\frac{Ke_{C-D}}{(A_C)^2} = \frac{0.3534}{(0.44548)^2} = 1.7808$$

$$\frac{f_E^L E}{de_E A_E^2} = \frac{0.01583(132)}{0.5186(2.545)^2} = 0.62208$$

$$\frac{Ke_{D-E}}{(A_D)^2} = \frac{0.3612}{(1.943)^2} = 0.09567$$

$$\frac{K_D}{36(A_C)^2} = \frac{K_D}{36(0.07424)^2} = 5.0399K_D$$

$$\frac{Ke_{E-F}}{(A_E)^2} = \frac{0.35567}{(2.545)^2} = 0.054912$$

$$\frac{f_C(3.5 - L)}{36de_C(A_C)^2} = \frac{0.0165(3.5 - L)}{36de_C(A_C)^2} = \frac{0.0165(3.5 - L)}{36(0.2254)(0.07424)^2} = 1.28844 - 0.368125L$$

$$\frac{Ke_{F-G}}{(A_F)^2} = \frac{0.043032}{(11.0)^2} = 0.00035$$

$$100 = \frac{144 \omega^2}{2(32.174)(61.56)(3600)^2} (0.5944 + 6.0443 - 1.7808 - 0.9567 - 0.054912 \\ - 0.00035 + 0.012389 + 5.0399K_D + 0.1727 + 0.62208 + 1.28844 \\ - 0.368125L) - 5.34398$$

$$105.34398 = \frac{144 \omega^2}{2(32.174)(61.56)(3600)^2} (6.802577 + 5.0399K_D - 0.368125L)$$

$$\omega^2 = \frac{105.34398(2)(32.174)(61.56)(3600)^2}{144(6.802577 + 5.0399K_D - 0.368125L)} = \frac{37,550,448,000.00}{6.802577 + 5.0399K_D - 0.368125L}$$

$$\omega = \frac{193,779.37}{\sqrt{6.802577 + 5.0399K_D - 0.368125L}}$$

<u>n</u>	<u>K_D</u>	<u>L, in.</u>	<u>√</u>	<u>ω, lb/hr</u>	<u>ω, gal/min</u>
1	0.7100	0.125	3.214792	60277.41	120.501
2	1.4487	0.500	3.73093	51938.66	103.832
3	2.1874	0.875	4.18386	46315.85	92.591
4	2.9261	1.250	4.59235	42196.13	84.355
5	3.6648	1.625	4.96735	39010.59	77.987
6	4.4035	2.000	5.31597	36452.31	72.872
7	5.1422	2.375	5.64310	34339.18	68.648
8	5.8809	2.750	5.95225	32555.60	65.082
9	6.6196	3.125	6.24614	31023.84	62.020
10	7.3583	3.500	6.52681	29689.75	59.353
0	0.00	3.5	2.60817	74296.92	148.52

$$\text{For } n = 0, \omega = \frac{193,779.37}{\sqrt{6.802577}}$$

The flow rate through the center loop was plotted as a function of the number of restrictions in Figure D.3-6.

Pressure Drop Vs Flow Rate Across Restrictor

$$\Delta p_T = \Delta p_c (\text{entering}) + \Delta p^* (\text{across restrictions}) + \Delta p_f^* (\text{friction across nonrestricted area of restrictor}) - \Delta p (\text{exit}) - \Delta p_H$$

$$\Delta p_T = \frac{K_c \omega^2}{2g_C \rho A^2} + \frac{K_D (\omega/6)^2}{2g_C \rho A^2} + \frac{f_c (3.5 - L) (\omega/6)^2}{2g_C \rho A^2} - \frac{K_e \omega^2}{2g_C \rho A^2} - \Delta p_H$$

$$\Delta p_H = \rho (\Delta_H) = \frac{(61.56 \text{ lb/ft}^3) (3.5 \text{ in.})}{1728 \text{ in.}^3/\text{ft}^3} = 0.12468 \text{ psi}$$

$$\Delta p_c = \frac{\omega^2 (144) (1.1995)}{2(32.174)(61.56)(3600)^2 (0.44548)^2}$$

$$\Delta p^* = \frac{K_D (144) (\omega^2)}{36(0.07424)^2 (2)(32.174)(61.56)(3600)^2}$$

$$\Delta p_c = \frac{0.2197 \omega^2}{(3600)^2}$$

$$\Delta p^* = \frac{0.18326 K_D \omega^2}{(3600)^2}$$

$$\Delta p_f^* = \frac{0.0165(3.5 - L)\omega^2(144)}{36(0.2259)(0.07424)^2 2(32.174)(61.56)(3600)^2} = \frac{0.013382(3.5 - L)\omega^2}{(3600)^2}$$

$$\Delta p_e = \frac{0.3534\omega^2(144)}{2(32.174)(61.56)(3600)^2(0.44548)^2} = \frac{0.06473\omega^2}{(3600)^2}$$

$$\Delta p = \frac{0.2197\omega^2}{(3600)^2} + \frac{0.18326\omega^2 K_D}{(3600)^2} + \frac{0.013382(3.5 - L)\omega^2}{(3600)^2} - \frac{0.06473\omega^2}{(3600)^2} - 0.12468$$

$$\Delta p = \frac{\omega^2}{(3600)^2} [0.2197 + 0.18326K_D + 0.013382(3.5 - L) - 0.06473] - 0.12468$$

$$\omega^2 = \frac{(3600)^2(\Delta p - 0.12468)}{[0.2197 + 0.18326K_D + 0.013382(3.5 - L) - 0.06473]}$$

$$\omega^2 = \frac{(3600)^2(\Delta p - 0.12468)}{[0.15496 + 0.18326K_D + 0.013382(3.5 - L)]}$$

n	L, in.	K _D	[]	Δp, psi							
				10		30		60		100	
				W, gpm	V, ft/sec	W	V	W	V	W	V
0	0	0	0.201797	50.58	36.9	87.96	64.2	124.52	90.8	160.82	117.3
1	0.125	0.7100	0.330238	39.37	28.7	68.48	49.9	96.94	70.73	125.2	91.4
2	0.500	1.4487	0.460595	33.35	24.3	58.00	42.3	82.11	59.9	106.0	77.3
3	0.875	2.1874	0.59095	29.45	21.5	51.21	37.4	72.50	52.9	93.63	68.3
4	1.250	2.9261	0.72131	26.65	19.4	46.36	33.8	65.63	47.9	84.76	61.8
5	1.625	3.6648	0.85166	24.53	17.9	42.66	31.1	60.40	44.1	78.01	56.9
6	2.000	4.4035	0.98202	22.85	16.7	39.73	28.9	56.25	41.0	71.92	52.5
7	2.375	5.1422	1.11237	21.47	15.7	37.33	27.2	52.85	38.6	68.26	49.8
8	2.750	5.8809	1.24273	20.31	14.8	35.32	25.8	50.01	36.5	64.59	47.1
9	3.125	6.6196	1.37309	19.32	14.1	33.61	24.5	47.57	34.7	61.44	44.8
10	3.500	7.3583	1.50344	18.47	13.5	32.12	23.4	45.47	33.2	58.72	42.8

$$W = \sqrt{\frac{(3600)^2(\Delta p - 0.12468)}{[0.15496 + 0.18326K_D + 0.013382(3.5 - L)]}} = \frac{\text{lb/hr}}{500.22} = \text{gal/min}$$

Velocity in One Restrictor Channel ($\bar{V}$):

$$\bar{V} = \frac{\omega/6}{\rho A} = \frac{\omega(500.22)(144)}{6(61.56)(0.07424)(3600)} = \text{ft/sec}$$

The flow rate and velocity were plotted as functions of the number of flow restrictors for various Δp 's (see Figures D.3-7 and D.3-8).

Restrictor
Concept 5-A

(B&W Drawing SKM-832)

$$A_{A'} = A_{C'} = A_{E'} = 0.07424 \text{ in.}^2$$

$$Wp = Wp_{C'} = Wp_{E'} = 1.31459 \text{ in.}$$

$$D_{H_{A'}} = D_{H_{C'}} = D_{H_{E'}} = 0.2258955 \text{ in.}$$

$$f_{A'} = f_{C'} = f_{E'} = 0.0165$$

$$A_B = 1.534 \text{ in.}^2 \quad Wp_B = 22.9 \text{ in.}$$

$$A_D = 1.943 \text{ in.}^2 \quad Wp_D = 22.29 \text{ in.}$$

$$A_{B'} = A_{D'} = 0.10315 \text{ in.}^2$$

$$Wp_{B'} = Wp_{D'} = 1.84669 \text{ in.}$$

$$D_{H_{B'}} = D_{H_{D'}} = 0.2234267 \text{ in.}$$

$$f_{B'} = f_{D'} = 0.0175$$

$$Kc_{B-A'} = Kc_{B-C} = 1.1995038$$

$$Ke_{E'-D} = Ke_{C-D} = 0.3534152$$

Note: These values were obtained from previous calculations.

Pressure Drop Vs Flow Rate Across Restrictor 5-A (Proposed Design)

$$\Delta p_T = \Delta p_{c_{B-A'}} + \Delta p_{f_{A'}} - \Delta p_{e_{A'-B'}} + \Delta p_{f_{B'}} + \Delta p^* + \Delta p_{f_{D'}} + \Delta p_{c_{D'-E'}} \\ + \Delta p_{f_{E'}} - \Delta p_{e_{E'-D}} - \Delta p_H$$

$$\Delta p_{c_{B-A'}} = \frac{Kc\omega^2}{2g_C\rho(A')^2} = \frac{1.1995(144)(\omega^2)}{2(32.174)(61.56)(0.44548)^2(3600)^2} = \frac{0.2197\omega^2}{(3600)^2}$$

$$\Delta p_{f_{A'}} = f \frac{L}{De} \frac{(\omega/6)^2}{2g_C\rho(A')^2} = \frac{0.0165(1.125)(144)\omega^2}{36(0.2259)(2)(32.174)(61.56)(0.07424)^2(3600)^2} \\ = \frac{0.01504\omega^2}{(3600)^2}$$

$$\Delta p_{e_{A'-B'}} = \frac{K_e(\omega/6)^2}{2g_C \rho (A')^2}$$

$$K_{e_{A'-B'}} = 2\sigma(1 - \sigma) = 2\left(\frac{0.07424}{0.10315}\right)\left(1 - \frac{0.07424}{0.10315}\right) = 0.403438$$

Therefore

$$\Delta p_{e_{A'-B'}} = \frac{0.403438(144)\omega^2}{2(36)(32.174)(61.56)(0.07424)^2(3600)^2} = \frac{0.0739\omega^2}{(3600)^2}$$

$$\begin{aligned}\Delta p_{f_{B'}} &= f \frac{L}{De} \frac{(\omega/6)^2}{2g_C \rho A^2} = \frac{0.0175(1.0)(144)\omega^2}{36(0.2234)(2)(32.174)(61.56)(0.10315)^2(3600)^2} \\ &= \frac{0.007434\omega^2}{(3600)^2}\end{aligned}$$

$$\Delta p^* = \frac{K_D(\omega/6)^2}{2g_C \rho A^2} = \frac{0.71(144)\omega^2}{36(2)(32.174)(61.56)(0.07424)^2(3600)^2} = \frac{0.1300734\omega^2}{(3600)^2}$$

$$\begin{aligned}\Delta p_{f_{D'}} &= f \frac{L}{De} \frac{(\omega/6)^2}{2g_C \rho A^2} = \frac{0.0175(0.25)(144)\omega^2}{2(36)(0.2234)(32.174)(61.56)(0.10315)^2(3600)^2} \\ &= \frac{0.001852\omega^2}{(3600)^2}\end{aligned}$$

$$\Delta p_{c_{D'-E'}} = \frac{K_c(\omega/6)^2}{2g_C \rho A^2}$$

$$K_{c_{D'-E'}} = 1.4 - 0.4\sigma - \sigma^2 = 1.4 - 0.4\left(\frac{0.07424}{0.10315}\right) - \left(\frac{0.07424}{0.10315}\right)^2 = 0.5940995$$

Therefore,

$$\Delta p_{c_{D'-E'}} = \frac{0.5941(144)\omega^2}{2(36)(32.174)(61.56)(0.07424)^2(3600)^2} = \frac{0.1088451\omega^2}{(3600)^2}$$

$$\begin{aligned}\Delta p_{f_{E'}} &= f \frac{L}{De} \frac{(\omega/6)^2}{2g_C \rho A^2} = \frac{0.0165(1.0)(144)\omega^2}{0.2259(2)(36)(32.174)(61.56)(0.07424)^2(3600)^2} \\ &= \frac{0.01337\omega^2}{(3600)^2}\end{aligned}$$

$$\Delta p_{e_{E'-D}} = \frac{K_e \omega^2}{2g_C \rho A^2} = \frac{0.3534(144)\omega^2}{2(32.174)(61.56)(0.44548)^2(3600)^2} = \frac{0.06473\omega^2}{(3600)^2}$$

$$\Delta p_H = \rho(\Delta H) = \frac{61.56(3.5)}{1728} = 0.12468 \text{ psi}$$

$$\Delta p = \frac{\omega^2}{(3600)^2} \left[0.2197 + 0.01504 - 0.0739 + 0.007434 + 0.1300734 + 0.001852 \right. \\ \left. + 0.1088451 + 0.01337 - 0.06473 \right] - 0.12468$$

$$\Delta p = \frac{\omega^2}{(3600)^2} [0.3576845] - 0.12468$$

$$\omega^2 = \frac{(3600)^2(\Delta p - 0.12468)}{0.3576845}$$

Flow Rate Vs Pressure Drop Across Restrictor 5-A:

<u>Δp, psi</u>	<u>W, gpm</u>
10	37.70
20	53.48
30	65.56
40	75.74
50	84.71
60	92.81
70	100.26
80	107.20
90	113.71
100	119.87

Figure D.3-9 is a plot of these values.

Flow Rate Through Center Loop Under 100 psi Δp With Proposed Flow Restrictor

$$\Delta p_T = 100 = \Delta p_{c_{A-B}} + \Delta p_{f_B} + [\Delta p_c] + \Delta p_{f_D} - \Delta p_{e_{D-E}} + \Delta p_{f_E} - \Delta p_{e_{E-F}} \\ - \Delta p_{e_{F-G}} - \Delta p_H$$

$$100 = \frac{144\omega^2}{2(132.174)(61.56)(3600)^2} \left[\frac{K_{c_A}}{A_B^2} + \frac{f_B L_B}{d_{e_B} A_B^2} + \frac{f_D L_D}{d_{e_D} A_D^2} - \frac{K_{e_{D-E}}}{A_D^2} + \frac{f_E L_E}{d_{e_E} A_E^2} \right. \\ \left. - \frac{K_{e_{E-F}}}{A_E^2} - \frac{K_{e_{F-G}}}{A_F^2} \right] + \frac{\omega^2(0.3576845)}{(3600)^2} - 5.34398$$

$$100 = \frac{0.03635\omega^2}{(3600)^2} \left[0.5944 + 0.012389 + 0.1727 - 0.09567 + 0.62208 - 0.054912 - 0.00035 \right] + \frac{\omega^2(0.3576845)}{(3600)^2} - 5.34398$$

$$100 = \frac{0.0454606\omega^2}{(3600)^2} + \frac{0.3576845\omega^2}{(3600)^2} - 5.34398$$

$$105.34398 = \frac{4031451\omega^2}{(3600)^2}$$

$$\omega^2 = \frac{105.34398(3600)^2}{0.4031451}$$

$$\omega = 116.79 \text{ gal/min}$$

Velocity:

$$\bar{V} = \frac{W}{\rho A} = \frac{116.79(500.22) \text{ lb/hr} (144 \text{ in}^2/\text{ft}^2)}{61.56 \text{ lb/ft}^3 (0.07424 \text{ in}^2)(3600 \text{ sec/hr})(6)} = 85.2 \text{ ft/sec}$$

$$\Delta p_{c_{B-A'}} = \frac{0.2197(116.79)^2(500.22)^2}{(3600)^2} = 0.2197(263.25) = 57.83$$

$$\Delta p_{f_{A'}} = \frac{0.01504(116.79)^2(500.22)^2}{(3600)^2} = 3.959$$

$$\Delta p_{e_{A'-B'}} = \frac{0.0739(116.79)^2(500.22)^2}{(3600)^2} = 19.454$$

$$\Delta p_{f_{B'}} = 0.007434(263.25) = 1.9559^*$$

$$\Delta p^* = 0.1300734(263.25) = 34.24$$

$$\Delta p_{f_{D'}} = 0.001852(263.25) = 0.487$$

$$\Delta p_{c_{D'-E'}} = 0.1088451(263.75) = 28.65$$

$$\Delta p_{f_{E'}} = 0.01337(263.75) = 3.5196$$

$$\Delta p_{e_{E'-D}} = 0.06473(263.75) = 17.04$$

$$\Delta p_T = 94.14$$

Check:

$$\Delta p_{c_{A-B}} = \frac{Kc\omega^2}{2g_C\rho A^2} = \frac{1.39876(116.79)^2(500.22)^2(144)}{2(32.174)(61.56)(1.534)^2(3600)^2} = 5.6905$$

$$\Delta p_{e_{D-E}} = \frac{Kew^2}{2g_C\rho A^2} = \frac{0.36118(116.79)^2(500.22)^2(144)}{2(32.174)(61.56)(1.943)^2(3600)^2} = 0.91587$$

$$\Delta p_{e_{E-F}} = \frac{Kew^2}{2g_C\rho A_E^2} = \frac{0.355669(116.79)^2(500.22)^2(144)}{2(32.174)(61.56)(2.545)^2(3600)^2} = 0.52568$$

$$\Delta p_{e_{F-G}} = \frac{Kew^2}{2g_C\rho A_F^2} = \frac{0.043032(116.79)^2(500.22)^2(144)}{2(32.174)(61.56)(11)^2(3600)^2} = 0.0034$$

$$\Delta p_{f_B} = \frac{f(L/de)\omega^2}{2g_C\rho A_B^2} = \frac{0.01621(0.5)(116.79)^2(500.22)^2(144)}{2(32.174)(61.56)(1.534)^2(3600)^2(0.278)} = 0.11852$$

$$\Delta p_{f_D} = \frac{f_D L}{de} \frac{\omega^2}{2g_C\rho A_D^2} = \frac{0.01624(14)(116.79)^2(500.22)^2(144)}{0.3487(1.943)^2(2)(32.174)(61.56)(3600)^2} = 1.65338$$

$$\Delta p_{f_E} = \frac{f_E L_E}{de_E} \frac{\omega^2}{2g_C\rho A_E^2} = \frac{0.01583(132)(116.79)^2(500.22)^2(144)}{0.5186(2.545)^2(2)(32.174)(61.56)(3600)^2} = 5.95311$$

$$\Delta p^* = \frac{0.3576845(116.79)^2(500.22)^2}{(3600)^2} = 94.159$$

$$\Delta p = 5.6905 - 0.91587 - 0.52508 - 0.0034 + 0.11852 + 1.65338 + 5.95331 \\ + 94.159 - 5.34398 = 100.78$$

Incremental Breakdown of Pressure Drop Along Channel

	<u>L, in.</u>	<u>Δp_L, psi</u>	<u>Δp_H, psi</u>	<u>Δp_T, psi</u>
$\Delta p_{c_{A-B}}$	0.00	5.6905	0.0000	5.6905
Δp_{f_B}	0.50	0.9158	0.01781	6.5885
$\Delta p_{c_{B-A'}}$	0.50	57.8300	0.0000	64.4185
$\Delta p_{f_{A'}}$	1.625	3.959	0.04007	68.33742
$\Delta p_{e_{A'-B}}$	1.625	19.454	0.0000	48.8834
$\Delta p_{f_{B'}}$	2.625	1.9559	0.03562	50.8037
Δp^*	2.625	34.2400	0.0000	85.0437
$\Delta p_{f_{D'}}$	3.000	0.4870	0.01335	85.51735
$\Delta p_{c_{D'-E'}}$	3.000	28.6500	0.0000	114.65133
$\Delta p_{f_{E'}}$	4.000	3.5196	0.03562	117.65133
$\Delta p_{e_{E'-D}}$	4.000	17.0400	0.0000	100.61133
Δp_{f_D}	18.000	1.6534	0.49875	101.7659
$\Delta p_{e_{D-E}}$	18.000	0.91587	0.0000	100.85009
Δp_{f_E}	150.000	5.95311	4.720267	102.10053
$\Delta p_{e_{E-F}}$	150.000	0.52568	0.00000	101.57485
$p_{e_{F-G}}$	150.000	0.0034	0.00000	101.57145

Figure D.3-10 is a plot of these values.

Figure D.3-1. Layout of One Flow Channel in Collar
(Top View).

Scale — 6:1

Figure D.3-2. Determination of Areas in Flow Restrictor
Concept 5

Section	A_F , in. ²	W_p , in.	L , in.
A	500.00	100.00	0.00
B	1.534	22.90	0.50
C	0.10315/0.07424		3.50
D	1.943	22.29	14.00
E	2.545	19.63	132.00
F	11.000	23.63	1.00
G	500.00	100.00	151.00

Figure D.3-3. Friction Factor Vs Pitch/Height Ratio for Square Ribs²

Figure D.3-4. Friction Factor Vs Diameter/Height Ratio
for Square Ribs

Figure D.3-5. K_D , K_f Vs Number of Restrictions

Figure D.3-6. Flow Rate Through the Center Loop Vs
Number of Restrictions

Figure D.3-7. Flow Rate Vs Number of Restrictions

Figure D.3-8. Velocity Vs Number of Restrictions

Figure D.3-9. Flow Rate Vs Pressure Drop Across Restrictor 5-A

Figure D.3-10. Pressure Drop Vs Distance Along Channel

D.4. HYDRAULIC CALCULATIONS

(ATR NE Loop Position With Dummy Flux Trap Filler and Recommended Permanent Modifications)

Purpose: To determine the flow distribution of the ATR NE loop position with the dummy flux trap filler and the modifications as a function of the hydraulic characteristics of the constituent channels. The calculations are based upon the nominal dimensions found on the following drawings:

<u>Drawing No.</u>	<u>Title</u>
ATR-1075-MTR-670-M-229	- Loop dummy flux trap filler assembly
ATR-1075-MTR-670-M-197	- Outer flux trap baffle assembly and details
ATR-1075-MTR-670-M-460	- Outer snubber tube
ATR-1075-MTR-670-M-157	- Flow distribution tank guide tube
ATR-1075-MTR-670-M-1111	- Insulation jacket
I.N.C. No. 035777	- Labyrinth flow restrictor
I.N.C. No. 035800	- 12-inch internal sleeve

Assumptions:

1. A constant water temperature of 130 F.
2. All channels are concentric without considerations of thermal loop bow.
3. The total system pressure differential is 100 psi.

Method of Analysis: The breakdown of the system into constituent flow channels is shown in Figure D.4-1. Each channel is analyzed individually with the end result being an equation describing the pressure

drop of the channel as a function of its flow rate. The plot of these values is then used in an iterative method to establish the flow distribution of the system under the available pressure differential of 100 psi.

Channel I

The incremental geometric breakdown along the length of this channel is as follows:

Distance along channel, in.	R _{out} , in.	R _{in} , in.	A _F , in. ²	W _P , in.	D _e , in.	sm A _F ^σ /lg A _F
0.0000	--	--	500.000	100.00	--	0.003617
0.00001	1.6250	1.437	1.80848	19.239	0.376	
12.00000	1.6250		1.80848	19.239	0.376	0.73549
12.00001	1.6875		2.45888	19.6318	0.501	
71.12500	1.6875		2.45888	19.6318	0.501	
72.25000	1.8130		3.83903	20.42035	0.752	0.6405
Labyrinth						

The total pressure drop (ΔP_I) across this channel is the sum of the pressure drops occurring due to contractions (ΔP_C), expansions (ΔP_E), channel friction (ΔP_f), the head loss (ΔP_H), and the pressure drop across the labyrinth (ΔP_L). The loss (ΔP_H) in this case is actually a gain due to the downward fluid flow. The total pressure drop, neglecting acceleration effects and referring to Figure D.4-1, is

$$\Delta P_I = \Delta P_{C_{A-B}} + \Delta P_{f_B} + \Delta P_{E_{B-C}} + \Delta P_{f_C} + \Delta P_{E_{C-D}} + \Delta P_L - \Delta P_H$$

where

$$\Delta P_{C_{A-B}} = (1 - \sigma^2) \frac{\rho V^2}{2g_c} + K_C \frac{\rho V^2}{2g_c} = [1 - \sigma^2 + 0.4(1 - \sigma)] \frac{\rho V^2}{2g_c}$$

Since $\omega = \rho A_F V$,

$$\begin{aligned} \Delta P_{C_{A-B}} &= 1.39854 \frac{\omega^2}{2g_c \rho A_B^2} \\ &= 1.39854 \frac{\omega^2 \text{ lb}^2/\text{hr}^2 (144 \text{ in.}^2/\text{ft}^2)}{2(32.2 \text{ ft/sec}^2)(61.56 \text{ lb/ft}^3)(1.80848)^2 \text{ in.}^2 (3600)^2 \text{ sec}^2/\text{hr}^2} \end{aligned}$$

The values

$$\frac{144 \text{ in.}^2/\text{ft}^2}{2(32.2 \text{ ft/sec}^2)(61.56 \text{ lb/ft}^3)(3600 \text{ sec/hr})^2}$$

is common for most of the calculations. Therefore, it will be designated as E , then

$$\Delta P_{C_{A-B}} = 0.42761 E \omega^2$$

The friction pressure drop along the 12-inch sleeve (section B) is determined as follows:

$$\Delta P_{f_B} = f \frac{L}{D_e} \frac{\omega^2}{2g_c \rho A^2}$$

where

$$f = \frac{a}{R_e^n} = \frac{0.21}{(4\omega/\mu W_P)^{0.2}} \quad (\text{reference 4})$$

for $4 \times 10^4 \leq R_e \leq 4 \times 10^5$ and $\epsilon_R/D_e = 0.00017$. Then,

$$\Delta P_{f_B} = \frac{0.21}{(48)^{0.2}(4)} \frac{L \omega^{1.8} \mu^{0.2} W_P^{1.2}}{2g_c \rho A_B^3}$$

$$\Delta P_{f_B} = \frac{0.21(12 \text{ in.})(1.288 \text{ lb/ft-hr})^{0.2}(19.239 \text{ in.})^{1.2}}{2.17(4)(1.80848 \text{ in.}^2)^3} E \omega^{1.8}$$

$$\Delta P_{f_B} = 1.79447 E \omega^{1.8}$$

The pressure drop ($\Delta P_{E_{B-C}}$) resulting from the expansion from the 12-inch liner (section B), into the downstream section C is

$$\Delta P_{E_{B-C}} = (1 - \sigma^2) \frac{\rho V^2}{2g_c} - K_e \frac{\rho V^2}{2g_c} = (1 - \sigma^2 - K_e) \frac{\omega^2}{2g_c \rho A_B^2}$$

where $K_e = (1 - \sigma)^2$ (reference 6)

Then $1 - \sigma^2 - K_e = 0.389089$. The pressure drop is

$$\Delta P_{E_{B-C}} = \frac{0.389089}{(1.80848 \text{ in.}^2)^2} E \omega^2$$

$$\Delta P_{E_{B-C}} = 0.1189656 E \omega^2$$

The friction pressure drop (ΔP_{f_C}) in section C is

$$\Delta P_{f_C} = f \frac{L}{D_e} \frac{\omega^2}{2g_c \rho A_C^2}$$

where (again from reference 4),

$$f = \frac{a}{R_e^n} = \frac{0.20}{(4\omega/\mu W_P)^{0.2}}$$

for $4 \times 10^4 \leq R_e \leq 4 \times 10^5$ and $\epsilon_R/D_e = 0.00019$ using an average of the two surface finishes. Then,

$$\Delta P_{f_C} = \frac{0.20}{(48)^{0.2}(4)} \frac{L \omega^{1.8} \mu^{0.2} W_P^{1.2}}{2g_c \rho A_C^3}$$

$$\Delta P_{f_C} = \frac{0.21(59.125 \text{ in.})(1.288 \text{ lb/ft-hr})^{0.2}(19.6318 \text{ in.})^{1.2}}{2.17(4)(2.45888 \text{ in.}^2)^3} E \omega^{1.8}$$

$$\Delta P_{fC} = 3.43239 E \omega^{1.8}$$

The loss due to the expansion of section C into section D is

$$\Delta P_{E_{C-D}} = (1 - \sigma^2 - K_e) \frac{\omega^2}{2 g_c \rho A_C^2}$$

where K_e is the loss coefficient of an angled expansion of 30 degrees and $K_e = 0.09$ (reference 7). Then,

$$1 - \sigma^2 - K_e = 1 - (0.6405)^2 - 0.09 = 0.49976$$

and

$$\Delta P_{E_{D-E}} = \frac{0.49976}{(2.45888 \text{ in.}^2)^2} E \omega^2$$

$$\Delta P_{E_{D-E}} = 0.08265 E \omega^2$$

Calculation of Labyrinth Pressure Drop

$$\Delta P_L = K_T^1 \frac{\omega^2}{2 g_c \rho A^2}$$

where

$$K_T^1 = Y + [1 - \sigma^2 + 0.4(1 - \sigma)] + f \frac{L}{D_e}$$

The factor Y is the drag coefficient over the 8 labyrinth teeth; determined according to the data of reference 1, using the same method as in Appendix D. 1.

$$Y = nc_1 + d_1$$

For

$$S/\delta_0 = \frac{1.160 - 0.125}{0.376} = 2.7526$$

$$\sigma = 0.46576$$

P/ϵ	c	d
2	0.14	1.15
8	1.05	2.25

$$Y = 8(0.595) + 1.7 = 6.46$$

The constituents $1 - \sigma^2 + 0.4(1 - \sigma) + f \frac{L}{D}$ are the losses due to the additional contraction and friction of the extended 3.745-inch length to the centerline of the five holes. The friction factor f , based on a Reynolds number of 1.8×10^5 with an assumed flow rate of 185 gpm and a ϵ_R/D_e of 1.7×10^{-4} , is 0.017. Then if $\sigma = 0.466$,

$$1 - \sigma^2 + 0.4(1 - \sigma) + f \frac{L}{D_e} = 0.9964 + \frac{0.017(3.745 \text{ in.})}{0.372} = 1.16$$

Then the sum of the values above gives a total labyrinth loss coefficient of

$$K' = 7.567$$

The labyrinth pressure drop is

$$\Delta P_L = 7.567 \frac{\omega^2 \text{ lb}^2/\text{hr}^2 (144 \text{ in.}^2/\text{ft}^2)}{2(32.2 \text{ ft/sec}^2)(61.56 \text{ lb/ft}^3)(1.7881 \text{ in.}^2)^2(3600 \text{ sec/hr})^2}$$

$$\Delta P_L = 2.366 E \omega^2$$

The head pressure gain is

$$\Delta P_H = \rho \Delta H = \frac{61.56 \text{ lb/ft}^3 (72.25 + 13.25) \text{ in.}}{1728 \text{ in.}^3/\text{ft}^3} = 3.046 \text{ psi}$$

The total pressure drop is then

$$\Delta P_T + 3.046 = E(0.42761\omega^2 + 1.79447\omega^{1.8} - 0.1189656\omega^2 + 3.43239\omega^{1.8} - 0.08265\omega^2 + 2.366\omega^2)$$

Then

$$\Delta P_I = \frac{144}{2(32.2)(61.56)(3600)^2} (2.59\omega^2 + 5.22686\omega^{1.8}) - 3.046$$

The following tabulation gives the pressure drop as a function of various flow rates.

ω , gpm	ΔP_I , psi
50.0	2.51
60.0	3.23
75.0	6.77
100.0	18.61
150.0	44.97
200.0	81.46
250.0	127.94
300.0	183.84

A plot of these values is included in Figure D.4-2.

Channel II

The incremental geometric breakdown along the length of this channel is as follows:

Distance along channel, in.	R _{out} , in.	R _{in} , in.	A _F , in. ²	W _P , in.	D _e , in.	$\frac{A_S^\sigma}{A_L}$
00.000	--	--	500.00	100.00	--	
0.0000001	2.75	2.5625	3.129210	33.3794	0.375	0.002037
0.2165	2.625	↓	1.01856	32.594	0.125	
8.7500	2.625		1.01856	32.594	0.125	0.4940460
9.7500	2.6875		2.06167	32.9867	0.250	
58.375	2.6875		2.06167	32.9867	0.250	0.494046
59.375	2.625		1.01856	32.594	0.125	
61.7668	2.625	↓	1.01856	32.594	0.125	0.5060966
62.0000	2.625	2.50	2.01258	32.2013	0.250	
79.0000	2.625	2.50	2.01258	32.2013	0.250	

The total pressure drop (ΔP_{II}) across this channel is the sum of the pressure drops occurring due to contractions (ΔP_C), expansions (ΔP_E), channel friction (ΔP_f), and the head gain (ΔP_H). The total pressure drop across this channel, neglecting acceleration effects and referring to Figure D.4-1, is

$$\Delta P_{II} = \Delta P_{C_{1-2}} + \Delta P_{f_2} + \Delta P_{E_{2-3}} + \Delta P_{f_3} + \Delta P_{C_{3-4}} + \Delta P_{f_4} \\ + \Delta P_{E_{4-5}} + \Delta P_{f_5} - \Delta P_H$$

The pressure loss resulting from the contraction from the large upper plenum into Channel II is determined by

$$\Delta P_{C_{1-2}} = K_C \frac{\omega^2}{2g_c \rho A^2}$$

where K_C , the contraction coefficient is 0.5 (reference 7). Then,

$$\Delta P_{C_{1-2}} = \frac{0.5}{(1.01856 \text{ in.}^2)^2} E \omega^2$$

The value of E is defined in the Channel I calculations.

$$\Delta P_{C_{1-2}} = 0.48194 E \omega^2$$

The friction loss in section 2 is

$$\Delta P_{f_2} = f \frac{L}{D_e} \frac{\omega^2}{2 g_c \rho A^2}$$

where

$$f = \frac{a}{R_e^n} = \frac{0.21}{(4\omega/\mu W_P)^{0.2}} \quad (\text{reference 4})$$

for $2 \times 10^4 \leq R_e \leq 2 \times 10^5$ and $\epsilon_R/D_e = 1 \times 10^{-3}$ using the 125 μ inch dummy flux trap filler surface finish. Then,

$$\Delta P_{f_2} = \frac{0.21}{48^{0.2}(4)} \frac{L \omega^{1.8} \mu^{0.2} W_P^{1.2}}{2 g_c \rho A_2^3}$$

which becomes

$$\Delta P_{f_2} = \frac{0.21}{48^{0.2}(4)} \frac{(8.5335)(1.288)^{0.2}(32.594)^{1.2}}{(1.01856)^3} E \omega^{1.8}$$

$$\Delta P_f = 13.44562 E \omega^{1.8}$$

The expansion loss at elevation 14.75 inches is

$$\Delta P_{E_{2-3}} K_E \frac{\rho V^2}{2 g_c} = K_E \frac{\omega^2}{2 g_c \rho A_2^2}$$

The divergence angle is approximately 8 degrees with an area ratio of 0.494. From reference 1, Diagram 5-2, $K_E = 0.035$. Then

$$\Delta P_{E_{2-3}} = \frac{0.035}{(1.01856 \text{ in.}^2)^2} E \omega^2$$

$$\Delta P_{E_{2-3}} = 0.033736 E \omega^2$$

The friction pressure drop in section 3 is

$$\Delta P_{f_3} = f \frac{L}{D_e} \frac{\omega^2}{2 g_c \rho A_3^2}$$

where

$$f = \frac{0.20}{R_e^{0.2}} \quad (\text{reference 4})$$

Then

$$\Delta P_{f_3} = \frac{0.20}{48^{0.2}(4)} \frac{L \omega^{1.8} \mu^{0.2} W_P^{1.2}}{2 g_c \rho A_3^3}$$

Since $L = 48.625 \text{ in.}$, $\mu = 1.288 \text{ lb/ft-hr}$, $W_P = 32.9867 \text{ in.}$ and $A_3 = 2.06167 \text{ in.}^2$, the friction pressure drop is

$$\Delta P_{f_3} = 9.37317 E \omega^{1.8}$$

The contraction loss from section 3 to 4 is

$$\Delta P_{C_{3-4}} = K_C \frac{\omega^2}{2 g_c \rho A_4^2}$$

where K_C for an 8-degree convergence angle is 0.05 (reference 7). Then

$$\Delta P_{C_{3-4}} = \frac{0.05}{(1.01856 \text{ in.}^2)^2} E \omega^2$$

$$\Delta P_{C_{3-4}} = 0.04819 E \omega^2$$

The friction pressure drop in section 4 is

$$\Delta P_{f_4} = f \frac{L}{D_e} \frac{\omega^2}{2 g_c \rho A_4^3}$$

where $f = 0.21/R_e^{0.2}$ (reference 4), $L = 2.392$ in., $W_P = 32.594$ in., and $A_4 = 1.01856$ in.²; the pressure drop through this channel is then

$$\Delta P_{f_4} = 3.76877 E \omega^{1.8}$$

The pressure drop resulting from expanding from section 4-5 is

$$\Delta P_{E_{4-5}} = K_E \frac{\omega^2}{2 g_c \rho A_4^2}$$

where K_E for a 30-degree divergence angle and a σ of 0.5061 (according to reference 1, Diagram 5-2) is 0.17. Then

$$\Delta P_{E_{4-5}} = \frac{0.17}{(1.01856 \text{ in.}^2)^2} E \omega^2$$

$$\Delta P_{E_{4-5}} = 0.16386 E \omega^2$$

The friction pressure drop in section 5 is

$$\Delta P_{f_5} = f \frac{L}{D_e} \frac{\omega^2}{2 g_c \rho A_5^2}$$

where $f = 0.21/R_e^{0.2}$ (reference 4), $L = 17$ in., $W_P = 32.2013$ in., and $A_5 = 2.01258$ in.². Then

$$\Delta P_{f_5} = 3.42227 E \omega^{1.8}$$

The head pressure gain is

$$\Delta P_H = \rho(\Delta h) = \frac{61.56 \text{ lb/ft}^3 (79 \text{ in.})}{1728 \text{ in.}^3/\text{ft}^3} = 2.814 \text{ psi}$$

Considering the recoverable loss,

$$\Delta P_R = (1 - \sigma^2) \frac{\rho V^2}{2g_c} = (1 - \sigma^2) \frac{\omega^2}{2g_c \rho A_5^2}$$

where $1 - \sigma^2 = 1 - \left(\frac{2.01258}{500.0} \right)^2 \approx 1$. Then

$$\Delta P_R = 0.24688 E \omega^2$$

The total pressure drop across Channel II is the sum of the constituent pressure drops along the channel. Then

$$\begin{aligned} \Delta P_{II} = E[& 0.48194\omega^2 + 13.44652\omega^{1.8} + 0.033736\omega^2 + 9.37317\omega^{1.8} + 0.04819\omega^2 \\ & + 3.76877\omega^{1.8} + 0.16386\omega^2 + 3.42227\omega^{1.8} - 0.24688\omega^2] - 2.814 \end{aligned}$$

$$\Delta P_{II} = \frac{144}{2(32.2)(61.56)(3600)^2} [0.48084\omega^2 + 30.01\omega^{1.8}] - 2.814$$

Then the pressure drop for various flow rates is

ω , gpm	ΔP , psi
50.0	4.93
60.0	7.27
75.0	13.41
100.0	24.65
150.0	54.87
200.0	97.60
250.0	166.44

These values are plotted in Figure D.4-2.

Channel III

Channel III is the flow channel comprising the five labyrinth bushings that connect Channels I and II.

$ID = 0.875 \pm 0.002$
 $Length = 0.877 \text{ in.}$
 $A_F = 0.60132 \text{ in.}^2$
 $W_P = 2.749 \text{ in.}$
 (All dimensions are given in inches.)

Assuming that the total flow rate through the five bushings will distribute evenly,

$$W_T = \sum_{i=1}^5 W_i, \quad \text{where } W_i = f(\Delta P_i)$$

where i designates one bushing

The pressure drop through one bushing (ΔP_i) is composed of

$$\Delta P_i = K_I \frac{\rho V^2}{2g_c} + f \frac{L}{D_e} \frac{\rho V^2}{2g_c} + K_{II} \frac{\rho V^2}{2g_c}$$

(entrance) (friction) (exit)

The factor K_I is the loss due to contraction and a 90-degree turn. Assuming that one fifth of the labyrinth (minimum) area will feed the bushing,

$$A_I = \frac{1.788069 \text{ in.}^2}{5} = 0.3576138 \text{ in.}^2$$

$$A_{III} = 0.60132 \text{ in.}^2$$

$$\frac{A_{III}}{A_I} = 1.68$$

For this configuration, reference 1, Diagram 7-25 gives a 0.62 value for K_I . Using a similar method, the value for the exit coefficient, K_{II} , is -0.4 (reference 1, Diagram 7-7).

The pressure drop due to friction is

$$\Delta P_{f_{III}} = f \frac{L}{D_e} \frac{\omega^2}{2g_c \rho A_{III}^2}$$

where⁴

$$f = \frac{0.2}{R_e^{0.2}}$$

For $3.0 \times 10^4 \leq R_e \leq 4.0 \times 10^5$ and an $\epsilon_R/D_e = 7.2 \times 10^{-5}$

$$\Delta P_{f_{III}} = \frac{0.2 L \omega_T^{1.8} \mu^{0.2} W_P^{1.2}}{48^{0.2} (4)(2) g_c \rho A_{III}^{5^{1.8}}}$$

which becomes

$$\Delta P_f = 0.048 E \omega^{1.8}$$

The total pressure drop, then, is

$$\Delta P_T = E[19.44 \omega^2 + 0.048 \omega^{1.2} - 14.973 \omega^2]$$

$$\Delta P_T = \frac{144}{2(32.2)(61.56)(3600)^2} (4.472 \omega^2 + 0.048 \omega^{1.8})$$

The pressure drop through Channel III as a function of flow rate is as follows:

<u>W_T, gpm</u>	<u>ΔP, psi</u>
5.0	0.07
10.0	0.31
20.0	1.25
30.0	2.82
50.0	7.82
75.0	17.63
100.0	31.34
120.0	45.14

These values are plotted in Figure D.4-2.

Channel IV

(Expansion from labyrinth → first hole)

$$A_{F_I} = 1.788069 \text{ in.}^2$$

$$A_4 = \pi(R_o^2 - R_i^2) = \pi(2.25^2 - 1.437^2) = 9.417 \text{ in.}^2$$

$$W_{P_I} = 2\pi(R_o + R_i) = 2\pi(1.623 + 1.437) = 19.2265 \text{ in.}$$

$$W_{P_4} = 2\pi(2.25 + 1.437) = 23.1661 \text{ in.}$$

$$\sigma = \frac{A_{F_I}}{A_4} = \frac{1.788069}{9.417} = 0.189876$$

The total pressure drop considering both recoverable and unrecoverable losses is

$$\Delta P_{IV} = (1 - \sigma^2) \frac{V^2}{2g_c} - K_E \frac{V^2}{2g_c} = (1 - \sigma^2 - K_e) \frac{\rho V^2}{2g_c}$$

$$K_e = (1 - \sigma)^2 \Rightarrow K_T = 1 - \sigma^2 - (1 - \sigma)^2$$

$$K_T = 0.307647$$

Then

$$\Delta P_{IV} = K_T \frac{\omega^2}{2g_c \rho A_I^2}$$

$$= \frac{0.307647 \omega^2 \text{ lb}^2/\text{hr}^2 (144 \text{ in.}^2/\text{ft}^2)}{2(32.2 \text{ ft/sec}^2)(61.56 \text{ lb/ft}^3)(1.788069)^2 \text{ in.}^2 (3600)^2 \text{ sec}^2/\text{hr}^2}$$

$$\Delta P_{IV} = \frac{144}{2(32.2)(61.56)(3600)^2} [0.096224] \omega^2$$

$$\omega^2 = \frac{2(32.2)(61.56)(3600)^2}{144(0.096224)} \Delta P$$

$$\boxed{\omega = 59731.8 \sqrt{\Delta P}}$$

Then, the flow rate as a function of pressure drop is as follows:

ΔP , psi	ω , lb/hr	ω , gpm
1	59,731.8	119.41
3	103,336.01	206.58
4	119,463.60	238.82
5	133,201.91	266.28
7	157,691.95	315.24
10	188,752.48	377.33
2	84,221.83	168.36

These values are plotted in Figure D.4-2.

Channel IV-A

The total pressure loss (ΔP_T) through the 70 holes of the lower part of the dummy flux trap filler consists of contraction, friction, expansion, and bending. The friction loss will be neglected because of the geometry.

$$\Delta P_T = K_T \frac{\rho V^2}{2g_c}$$

where

$$K_T = K_{\text{contraction}} + K_{\text{bending}} + K_{\text{exit}} = K_C + K_B + K_E$$

$$\left. \begin{aligned} K_C &= 0.4(1 - \sigma) = 0.4 \\ K_E &= (1 - \sigma)^2 = 1 \end{aligned} \right\} \text{since } \sigma \rightarrow 0$$

K_B is determined using two 90-degree bend losses in a smooth pipe with a bend radius of 0.4 inch. $K_B = 1.3$ using Figure 4.7 of reference 5. Then

$$K_T = 0.4 + 2(1.3) + 1.0 = 4.0$$

Therefore, the pressure drop is

$$\Delta P_T = K_T \frac{\omega_T^2}{2g_c \rho A_C^2}$$

$$\Delta P = \frac{4.0(144 \text{ in.}^2/\text{ft}^2) \omega_T^2 (\text{lb}^2/\text{hr}^2)}{2(32.2 \text{ ft/sec}^2)(61.56 \text{ lb/ft}^3)(0.7854 \text{ in.}^2)^2(3600 \text{ sec/hr})^2(5^2)}$$

$$\omega = 37100.96 \sqrt{\Delta P}$$

ΔP , psi	ω , lb/hr	ω , gpm
1	37,100.96	74.16
4	74,201.92	148.33
9	111,302.88	222.50
16	148,403.84	296.67
25	185,504.80	370.84

Figure D.4-2 includes a plot of these values.

Channel V

The pressure drop through this channel consists of friction and the drag induced by the flow over the holes.

$$\Delta P_V = \Delta P_D + \Delta P_f - \Delta P_H$$

The drag pressure drop is determined as follows:

$$\Delta P_D = K_D \frac{\omega^2}{2g_c \rho A_V^2}$$

K_D (from reference 2, Figure 2.13) is $0.085(14) = 1.19$. Then,

$$\Delta P_D = \frac{1.19}{(3.2698 \text{ in.}^2)^2} E \omega^2$$

$$\Delta P_D = 0.1113E\omega^2$$

The friction loss is

$$\Delta P_{f_V} = f \frac{L}{D_e} \frac{\omega^2}{2g_c \rho A_V^2}$$

where $f = 0.21/R_e^{0.2}$, $A_V = 3.2698 \text{ in.}^2$, $W_P = 32.057 \text{ in.}$, $\mu = 1.288 \text{ lb/ft-hr}$ and $L = 31.0 \text{ in.}$ By substituting $R_e = (4\omega/\mu W_P)$ into the equation above, it becomes

$$\Delta P_{f_V} = \frac{0.21}{48^{0.2}(4)} \frac{L\omega^{1.8}\mu^{0.2}W_P^{1.2}}{2g_c \rho A_V^3}$$

$$\Delta P_{f_V} = 1.46E\omega^{1.8}$$

Then the total pressure drop is

$$\Delta P_V = \frac{144}{2(32.2)(61.56)(3600)^2} (1.46\omega^{1.8} + 0.1113\omega^2) - 1.1 \text{ psi}$$

where the 1.1 psi value is the head gain

ω , gpm	ΔP_V , psi
150.0	0.63
200.0	1.98
300.0	5.84
350.0	8.35

Exit Channel

Exit Channel

$$A_A = \pi(R_o^2 - R_i^2) = \pi(2.602^2 - 2.5^2) = 1.635 \text{ in.}^2$$

$$W_{P_A} = 2\pi(R_o + R_i) = 2\pi(2.602 + 2.5) = 32.05681 \text{ in.}$$

$$A_B = 1.44(1.307) + \frac{\pi}{4}(1.307)^2 = 3.2237 \text{ in.}^2$$

$$W_{P_B} = 2(1.44) + \pi(1.307) = 6.98606 \text{ in.}$$

The total exit pressure drop is defined as

$$\Delta P_T = \Delta P_{\text{bend}_{A-B}} + \Delta P_E$$

The bend or turning loss is determined as follows:

$$\Delta P_{\text{bend } A-B} = \Delta P_{B_{A-B}} = K_B \frac{\omega_B^2}{2g_c \rho A_B^2}$$

The bend loss coefficient K_B is determined by using Figure 4.7 of reference 5. K_B (for $\frac{R}{D_e} \approx 2$) = 0.2, based on the assumption that one fourth of A_A feeds A_B ; then

$$\Delta P_{B_{A-B}} = 0.2 \frac{\omega^2}{2g_c \rho (A_A/4)^2}$$

$$\Delta P_{B_{A-B}} = \frac{0.2}{(0.40875 \text{ in.}^2)^2} E \omega^2$$

The expansion loss is

$$\Delta P_{E_{A-B}} = K_E \frac{\omega^2}{2g_c \rho (A_A/4)^2}$$

Again, assuming that one fourth of A_A feeds A_B , then the expansion loss is

$$K_E = (1 - \sigma)^2 = \left[1 - \frac{1.635}{4(3.2237)} \right]^2 = 0.7625$$

Therefore,

$$\Delta P_{E_{A-B}} = \frac{0.7625}{(0.40875 \text{ in.}^2)^2} E \omega^2$$

$$\Delta P_{E_{A-B}} = 4.5638 E \omega^2$$

The total pressure drop is then

$$\Delta P_T = (4.5638 + 1.2)E\omega^2$$

but this flow rate is only one fourth of the total. Considering this, the pressure drop equation becomes

$$\Delta P_T = \left(\frac{5.7638}{16} \right) E\omega_T^2$$

Then,

$$\omega_T = \sqrt{\frac{2(32.2)(61.56)(3600)^2(16)}{144(5.7638)} \Delta P_T} = 31,481.78 \sqrt{\Delta P_T}$$

Due to the minor height change, a negligible head gain will result. The flow rate varies with pressure drop as follows:

ΔP_T , psi	ω , lb/hr	ω , gpm
16	125,927.12	251.74
25	157,408.90	314.67
36	188,890.08	377.61
64	251,854.24	503.48
81	283,336.02	566.42
100	314,817.80	629.35

Figure D.4-2 includes a plot of these values.

Calculations of Incremental Pressure Drops Occurring
Along Each Channel With the Resulting Flow Rates

Channel I: $\omega = 177$ gpm, $\Delta P = 64$ psi

$$\Delta P_{C_{A-B}} = \frac{1.39854(177)^2(500.22)^2(144)}{2(32.2)(61.56)(1.80848)^2(3600)^2} = 9.49 \text{ psi}$$

$$\Delta P_{f_B} = 1.79447 E \omega^{1.8} = 4.02 \text{ psi}$$

$$\Delta P_{E_{B-C}} = 0.1189656 E \omega^2 = 2.63 \text{ psi}$$

$$\Delta P_{f_C} = 3.43239 E \omega^{1.8} = 7.72 \text{ psi}$$

$$\Delta P_{E_{C-D}} = 0.08265 E \omega^2 = 1.75 \text{ psi}$$

$$\Delta P_L = 2.2634 E \omega^2 = 49.65 \text{ psi}$$

$$\Delta P_H = 3.046 \text{ psi}$$

$$\Sigma \Delta P = 63.45 \text{ psi}$$

Channel II: $\omega = 166$ gpm, $\Delta P = 68$ psi

$$\Delta P_{C_{1-2}} = 0.482 E \omega^2 = 9.27 \text{ psi}$$

$$\Delta P_{f_2} = 13.45 E \omega^{1.8} = 26.97 \text{ psi}$$

$$\Delta P_{E_{2-3}} = 0.034 E \omega^2 = 0.57 \text{ psi}$$

$$\Delta P_{f_3} = 9.37 E \omega^{1.8} = 18.79 \text{ psi}$$

$$\Delta P_{C_{3-4}} = 0.05 E \omega^2 = 0.96 \text{ psi}$$

$$\Delta P_{f_4} = 3.77 E \omega^{1.8} = 7.56 \text{ psi}$$

$$\Delta P_{E_{4-5}} = 0.164 E \omega^2 = 3.09 \text{ psi}$$

$$\Delta P_{f_5} = 3.42 E \omega^{1.8} = 6.85 \text{ psi}$$

$$\Delta P_R = 0.247 E \omega^2 = 4.83 \text{ psi}$$

$$\Delta P_H = 2.81 \text{ psi}$$

$$\Sigma = 66.42 \text{ psi}$$

Channel III: $\Delta P = 4 \text{ psi}$, $\omega = 36 \text{ gpm}$

$$\left. \begin{array}{l} \Delta P_{IN} = 19.44 E \omega^2 = \\ \Delta P_f = 0.05 E \omega^{1.8} = \\ \Delta P_E = -14.973 E \omega^2 = \end{array} \right\} 4.0 \text{ psi}$$

Channel IV: $\omega = 141 \text{ gpm}$

$$\Delta P = 1.55 \text{ psi} + 1.1 \text{ psi (head)}$$

Channel IV-A: $\omega = 141 \text{ gpm}$

$$\Delta P = 3.7 \text{ psi} +$$

Channel V: $\omega = 202$ gpm

$$\Delta P = 2.0 \text{ psi}$$

EXIT: $\omega = 343$ gpm

$$\Delta P = 30 \text{ psi}$$

The pressure drop characteristics of the system investigated are plotted as a function of the distance from the top of the dummy flux trap filler in Figure D.4-4.

Figure D.4-1. ATR NE Loop Position With Dummy Flux Trap Filler and Modifications

Figure D.4-2. Flow Rate Vs Pressure Drop of Various Flow Channels

Figure D.4-3. Flow Distribution of ATR NE Loop Position With Dummy Flux Trap Filler and Modifications

Figure D.4-4. ATR NE Loop Position With Dummy Flux Trap Filler and Modifications

D.5. CONFIGURATIONS INVESTIGATED IN ADDITION TO PROPOSED MODIFICATIONS

We performed the following hydraulic analyses of configurations other than those pertaining to the recommended safety rod and center loop modifications:

1. Safety Rod Assembly

A number of combinations of sleeves (mounted below the upper insulation jacket splines) and stove pipes (mounted on the inside surface of the guide tube assembly) have been investigated. The resulting flow rates for the two extreme limits of safety rod travel are as follows:

Flow restrictor combination	Flow rate, gpm			
	Inner channel		Total	
	Up position	Down position	Up position	Down position
40-inch sleeve and 10-inch stove pipe	140	200	542	482
37-inch sleeve and 12-inch stove pipe	140	187	543	512
12-inch sleeve and 84-inch stove pipe	128	208	530	538

The inner channel refers to the annuli between the insulation jacket and the guide tube.

An analysis was performed to determine the effects of combining the labyrinth with an 84-inch stove pipe and a 12-inch sleeve located as cited above. The resulting flow rates for the two extreme limits of safety rod travel are as follows:

<u>Safety rod position</u>	<u>Inner channel flow rate, gpm</u>	<u>Total flow rate, gpm</u>
Up	116	520
Down	167	493.5

We analyzed an arrangement wherein the flux trap filler outside diameter was enlarged by 100 mils from the as-built condition; both without flow restrictors in the channel between the insulation jacket and the safety rod guide tube. The enlargement of the filler diameter resulted in a 53-gpm and a 142-gpm decrease in the total outer channel flow rate in the up and down safety rod positions, respectively. The total safety rod flow rate decreased by 42 and 172 gpm in the up and down positions.

An analysis was performed to determine the hydraulic feasibility of extending the proposed labyrinth flow restrictor into the rack tube area. Feasibility is based on the attainment of the same heat transfer characteristics that are obtained with the proposed safety rod modifications. The results of the analysis indicate that an extension would require such a reduction of the stove pipe inside diameter that it is not practicable from a mechanical standpoint.

2. Center Flux Trap Assembly

The flow rate through this assembly without flow restrictors was calculated as 349.25 gpm under the available pressure differential of 100 psi. An analysis has shown that the installation of a 20-inch sleeve with an outside diameter of 3.296 inches, mounted below the upper insulation jacket splines, results in a flow rate of 60 gpm; a flow rate of this magnitude is too low from a thermal standpoint. A series of calculations was performed to obtain a curve showing the relationship between the total center loop flow rate and the outside sleeve diameter. The flow rates obtained for various sleeve outside diameters are as follows:

<u>Sleeve OD, in.</u>	<u>Total flow rate, gpm</u>
3.10	285
3.15	240
3.20	183
3.25	118

A configuration consisting of a 7/8-inch-long collar located at the extreme top of the flux trap baffle was also investigated. The flow restrictor is designed so that its outside diameter contacts the inside diameter of the flux trap baffle. The effective flow passage is between the flow restrictor inside diameter and the upper insulation jacket splines. Total center loop flow rates were calculated for restrictor inside diameters of 3.100 inch and 3.024 inch (Figures D.4-1 and D.4-2). The following flow rates are obtainable with these configurations:

<u>Flow restrictor ID, in.</u>	<u>Total center loop flow rate, gpm</u>
3.100	242
3.024	163

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Appendix D

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APPENDIX E
Stress Calculations and Thermal Bowing of the Loops

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E.1. THERMAL BOW CALCULATION PROCEDURE
FOR THE
INNER/OUTER LOOP POSITION

The solution of the thermal bow problem has been programmed on a computer to increase the speed of calculation and the accuracy of results. The computer would go through the following steps in solving for the bow in an inner/outer loop position.

Gamma heating rates for the hot and cold sides of both the pressure tube and insulation jacket are input along with the coolant flow rate in the channel between the insulation jacket and the safety rod. The insulation jacket is assumed to have an initial bow of 0.100 inch. The temperature profiles for the hot and cold sides of the pressure tube and insulation jacket are calculated for various helium gaps between the tube and the jacket at the core midplane. The variation of helium gap size would be due to unequal thermal deflections of the two tubes.

Initially, the gap is assumed to be 0.030 inch, and temperature differentials (from hot to cold sides) are picked off of the aforementioned temperature profiles. The forces at each of the spacer rings between the two tubes are a function of the temperature differentials. Since there were six spacers assumed in the bow models (actually, there are more than six, but the remaining spacers are out of the core region and were felt to contribute little to the restraint of the thermal bow), the solution for the loads is a system of six simultaneous equations with six unknowns. The equations form a matrix as follows:*

- - - - -

* All of the equations in this section are from Appendixes E.5 and E.6.

$$\begin{aligned}
1.114639P_1 - 1.207526P_2 + 1.209557P_3 + 1.036699P_4 - .848482P_5 + .606900P_6 &= K_1 \\
1.213405P_1 - 1.377243P_2 + 1.400885P_3 + 1.254146P_4 - 1.034220P_5 + .752301P_6 &= K_2 \\
1.218362P_1 - 1.423584P_2 + 1.543269P_3 + 1.418873P_4 - 1.185125P_5 + .864993P_6 &= K_3 \\
1.037584P_1 - 1.253220P_2 + 1.418014P_3 + 1.450943P_4 - 1.261742P_5 + .937011P_6 &= K_4 \\
.84916P_1 - 1.034017P_2 + 1.184478P_3 + 1.261393P_4 - 1.142800P_5 + .871999P_6 &= K_5 \\
.616043P_1 - .751375P_2 + .868161P_3 + .945734P_4 - .883315P_5 + .710037P_6 &= K_6
\end{aligned}$$

The known conditions for a given set of temperature differentials are as follows:

$$\begin{aligned}
K_1 &= .17776 \Delta T \text{ P.T.} + .011316 \Delta T \text{ I.J.} \\
K_2 &= .22283 \Delta T \text{ P.T.} - .007845 \Delta T \text{ I.J.} \\
K_3 &= .26789 \Delta T \text{ P.T.} - .045185 \Delta T \text{ I.J.} \\
K_4 &= .25534 \Delta T \text{ P.T.} - .059740 \Delta T \text{ I.J.} \\
K_5 &= .19486 \Delta T \text{ P.T.} - .035315 \Delta T \text{ I. J.} \\
K_6 &= .13439 \Delta T \text{ P.T.} - .018595 \Delta T \text{ I. J.}
\end{aligned}$$

(P.T. and I.J. stand for pressure tube and insulation jacket. ΔT s are the temperature differentials from hot to cold sides for each tube.)

In the inner/outer loop position, the splines at the snubber tube assembly have been machined so that a radial gap of 0.015 inch exists between the splines and the inner snubber tube. (The load coefficient matrix applies until that gap has been closed; then a second set of equations describes the deflections of the tubes. This will be covered later.)

The deflection at the snubber tube assembly is calculated by the following equation:

$$\begin{aligned}
\Delta_{ST} &= [(-16106.78 P_1 - 10969.70 P_2 + 57476.84 P_3 \\
&\quad + 134353.54 P_4 - 153707.27 P_5 - 26876.69 P_6) \\
&\quad \times \frac{1}{26.8} + (766.90) (\Delta T_{\text{I.J.}})] \times 10^{-6}
\end{aligned}$$

The ΔT for the insulation jacket to deflect .015" is found by the ratio

$$\Delta T_{I.J.}' = \Delta T_{I.J.} \left(\frac{.015}{\Delta S T} \right)$$

since the ratio of $\Delta T_{P.T.}$ to $\Delta T_{I.J.}$ will remain the same

$$\Delta T_{P.T.}' = \Delta T_{P.T.} \left(\frac{\Delta T_{I.J.}'}{\Delta T_{I.J.}} \right)$$

(The ΔT in excess of ΔT 's will be $\Delta T_{P.T.}''$ and $\Delta T_{I.J.}''$ and handled by a second model to be discussed later).

Each of the loads that were calculated for the full ΔT must now be ratioed by

$$P_i' = P_i \left(\frac{\Delta T_{I.J.}'}{\Delta T_{I.J.}} \right)$$

and the deflection at mid-core for each of the tubes is calculated by the following equations:

$$\begin{aligned} \Delta I.J. &= (-893.74 P_1' - 557.13 P_2' + 2803.25 P_3' \\ &+ 5080.23 P_4' - 4757.26 P_5' + 3400.46 P_6' \\ &+ 2860.26 \Delta T_{I.J.}') \times 10^{-6} \end{aligned}$$

$$\begin{aligned} \Delta P.T. &= (-48484 P_1' + 56130 P_2' + 59990 P_3' \\ &- 55642 P_4' + 46736 P_5' - 34426 P_6' \\ &+ 12099.43 \Delta T_{P.T.}') \times 10^{-6} \end{aligned}$$

Since this only covers up to and including the ΔT 's for closing the .015" gap at the snubber tube assembly, the second model now applies.

The system of simultaneous equations are as follows:

$$\begin{aligned} 1.1052 P_1'' - 1.2094 P_2'' + 1.2164 P_3'' + 1.0524 P_4'' - .8658 P_5'' + .6078 P_6'' &= K_1'' \\ 1.2101 P_1'' - 1.3765 P_2'' + 1.4196 P_3'' + 1.2433 P_4'' - 1.0223 P_5'' + .7144 P_6'' &= K_2'' \\ 1.2165 P_1'' - 1.4188 P_2'' + 1.5169 P_3'' + 1.3614 P_4'' - 1.1200 P_5'' + .7786 P_6'' &= K_3'' \\ 1.0522 P_1'' - 1.2422 P_2'' + 1.3615 P_3'' + 1.3167 P_4'' - 1.1094 P_5'' + .7689 P_6'' &= K_4'' \\ .8665 P_1'' - 1.0216 P_2'' + 1.1204 P_3'' + 1.1100 P_4'' - .9706 P_5'' + .6791 P_6'' &= K_5'' \\ .6305 P_1'' - .7414 P_2'' + .8116 P_3'' + .8116 P_4'' - .7277 P_5'' + .5852 P_6'' &= K_6'' \end{aligned}$$

The equations for the known conditions for a set of temperature differentials are as follows:

$$K_1'' = .17776 \Delta T \text{ P.T.}'' + .00850 \Delta T \text{ I.J.}''$$

$$K_2'' = .22282 \Delta T \text{ P.T.}'' - .00589 \Delta T \text{ I.J.}''$$

$$K_3'' = .26789 \Delta T \text{ P.T.}'' - .03508 \Delta T \text{ I.J.}''$$

$$K_4'' = .25534 \Delta T \text{ P.T.}'' - .03654 \Delta T \text{ I.J.}''$$

$$K_5'' = .19486 \Delta T \text{ P.T.}'' - .00989 \Delta T \text{ I.J.}''$$

$$K_6'' = .13439 \Delta T \text{ P.T.}'' + .00081 \Delta T \text{ I.J.}''$$

(The ΔT 's'' above are those remaining after the insulation jacket has deflected .015").

Deflection of each tube is calculated at mid-core using the loads from the above solution and the ΔT 's'' involved by the following equations:

$$\begin{aligned} \Delta \text{ I. J.} = & (-412.387 P_1'' - 259.304 P_2'' + 1215.000 P_3'' \\ & + 1350.361 P_4'' - 550.061 P_5'' - 33.691 P_6'' \\ & + 2201.03 \Delta T \text{ I.J.}'') \times 10^{-6} \end{aligned}$$

$$\begin{aligned} \Delta \text{ P. T.} = & (-48373 P_1'' + 56096 P_2'' - 60021 P_3'' \\ & - 55646 P_4'' + 46733 P_5'' - 32833 P_6'' \\ & + 12298.224 \Delta T \text{ P.T.}'') \times 10^{-6} \end{aligned}$$

The gap is now calculated from the deflections from both models

$$\text{GAP} = .0475 + \sum \Delta \text{I. J.} - \sum \Delta \text{P. T.}$$

This calculated gap is compared to the gap that was assumed in the beginning of the iteration when the temperature differentials were found and, if they are not equal, a new gap is assumed. This new gap is the average of the old assumed gap and the calculated gap.

Once the gap calculation converges, the mid-core deflection of the insulation jacket is compared to the assumed bow and, if they are not equal, a new bow is assumed and the iteration is repeated. The new bow is assumed equal to the calculated mid-core insulation jacket deflection. As a new bow is assumed, the temperature profiles must be recalculated and the iteration for the helium gap, etc., is started anew.

Once the iterations for gap and bow have been completed, deflections at the six spacer rings are calculated. The spacers can be identified in the reactor by their elevations and are here identified by number for ease in notation.

<u>Elevation</u>	<u>Spacer Number</u>
88' 6"	1
85' 6"	2
82' 6"	3
77' 6"	4
74' 6"	5
71' 6"	6

The deflections at these six points are described in the three support model by the following equations:

$$\Delta 1 = \left[(12742 P_1' + 5069 P_2' - 16850 P_3' - 22772 P_4' + 19807 P_5' - 14100 P_6') \div 26.8 - (8.3895)(50.328) \Delta T \text{ I.J.} \right] \times 10^{-6}$$

$$\Delta 2 = \left[(-5595 P_1' - 3318 P_2' + 11561 P_3' + 15743 P_4' - 14152 P_5' + 9657 P_6') \div 26.8 + (5.8165)(50.328) \Delta T \text{ I.J.} \right] \times 10^{-6}$$

$$\Delta 3 = \left[(-18600 P_1' - 11559 P_2' + 55423 P_3' + 81750 P_4' - 74347 P_5' + 52164 P_6') \div 26.8 + (33.5006)(50.328) \Delta T \text{ I.J.} \right] \times 10^{-6}$$

$$\Delta_4 = \left[\begin{aligned} &(-25137 P_1' - 15740 P_2' + 81751 P_3' \\ &+ 170880 P_4' - 168901 P_5' + 124056 P_6') \div 26.8 \\ &+ (44.2906)(50.328) \Delta_T \text{ I.J.} \end{aligned} \right] \times 10^{-6}$$

$$\Delta_5 = \left[\begin{aligned} &(-22136 P_1' - 13880 P_2' + 73451 P_3' \\ &+ 167688 P_4' - 182927 P_5' + 142558 P_6') \div 26.8 \\ &+ (26.1828)(50.328) \Delta_T \text{ I.J.} \end{aligned} \right] \times 10^{-6}$$

$$\Delta_6 = \left[\begin{aligned} &(-15564 P_1' - 10642 P_2' + 55910 P_3' \\ &+ 132584 P_4' - 154706 P_5' + 137823 P_6') \div 26.8 \\ &+ (13.7863)(50.328) \Delta_T \text{ I.J.} \end{aligned} \right] \times 10^{-6}$$

The deflections at the six spacers are described in the four support model by the following equations:

$$\Delta_1 = \left[\begin{aligned} &(9500 P_1'' + 3800 P_2'' - 10200 P_3'' \\ &- 7100 P_4'' + 2500 P_5'' + 200 P_6'') \div 26.8 \\ &- (6.3)(50.238) \Delta_T \text{ I.J.} \end{aligned} \right] \times 10^{-6}$$

$$\Delta_2 = \left[\begin{aligned} &(-4200 P_1'' - 2500 P_2'' + 6900 P_3'' \\ &+ 4900 P_4'' - 2100 P_5'' - 100 P_6'') \div 26.8 \\ &+ (4.365)(50.328) \Delta_T \text{ I.J.} \end{aligned} \right] \times 10^{-6}$$

$$\Delta_3 = \left[\begin{aligned} &(-11200 P_1'' - 6900 P_2'' + 29100 P_3'' \\ &+ 24200 P_4'' - 9000 P_5'' - 600 P_6'') \div 26.8 \\ &+ (26.005)(50.328) \Delta_T \text{ I.J.} \end{aligned} \right] \times 10^{-6}$$

$$\Delta_4 = \left[\begin{aligned} &(-7800 P_1'' - 5000 P_2'' + 24300 P_3'' \\ &+ 35900 P_4'' - 16000 P_5'' - 1100 P_6'') \div 26.8 \\ &+ (27.095)(50.328) \Delta_T \text{ I.J.} \end{aligned} \right] \times 10^{-6}$$

$$\begin{aligned}\Delta_5 = & \left[(-2800 P_1'' - 1800 P_2'' + 8900 P_3'' \right. \\ & + 15800 P_4'' - 10200 P_5'' - 800 P_6'') \div 26.8 \\ & \left. + (7.335)(50.328) \Delta_T \text{ I.J.}'' \right] \times 10^{-6}\end{aligned}$$

$$\begin{aligned}\Delta_6 = & \left[(300 P_1'' + 200 P_2'' - 800 P_3'' \right. \\ & - 1600 P_4'' + 1200 P_5'' + 200 P_6'') \div 26.8 \\ & \left. - (.604)(50.328) \Delta_T \text{ I.J.}'' \right] \times 10^{-6}\end{aligned}$$

The total deflection at each of the spacers will be the sum of the respective Δ 's from the three support model and the four support model.

E.2. THERMAL BOW CALCULATION PROCEDURE FOR THE CENTER LOOP POSITION

As with the inner/outer loop position, the center loop thermal bow problem has been programmed on a computer. The following procedure is used for the center loop position.

Gamma heating rates for the hot (60-watt) and cold (40-watt) sides of both the pressure tube and insulation jacket are input along with the coolant flow rate in the channel between the insulation jacket and the center flux trap baffle. The insulation jacket is assumed to have an initial bow of 0.100 inch. The temperature profiles for the hot and cold sides of both the pressure tube and the insulation jacket are calculated for various helium gaps between the tube and jacket at the core midplane. The variation of helium gap size would be due to unequal thermal deflections of the two tubes.

Initially, the gap is assumed to be 0.030 inch, and temperature differentials (from hot to cold sides) are picked off of the aforementioned temperature profiles. The forces at each of the spacer rings between the two tubes are a function of the temperature differentials. Since there were six spacers assumed in the bow models (actually, there are more than six, but the remaining spacers are out of the core region and were felt to contribute little to the restraint of the thermal bow), the solution for the loads is a system of six simultaneous equations with six unknowns. The equations form a matrix as follows:*

- - - - -

* All of the equations in this section are from Appendix E.5.

$$\begin{aligned}
1.114639P_1 - 1.207526P_2 + 1.209557P_3 + 1.036699P_4 - .848482P_5 + .606900P_6 &= K_1 \\
1.213405P_1 - 1.377243P_2 + 1.400885P_3 + 1.254146P_4 - 1.034220P_5 + .752301 P_6 &= K_2 \\
1.218362P_1 - 1.423584P_2 + 1.543269P_3 + 1.418873P_4 - 1.185125P_5 + .864993P_6 &= K_3 \\
1.037584P_1 - 1.253220P_2 + 1.418014P_3 + 1.450943P_4 - 1.261742P_5 + .937011P_6 &= K_4 \\
.84916P_1 - 1.034017P_2 + 1.184478P_3 + 1.261393P_4 - 1.142800P_5 + .871999P_6 &= K_5 \\
.616043P_1 - .751375P_2 + .868161P_3 + .945734P_4 - .883315P_5 + .710037 P_6 &= K_6
\end{aligned}$$

The known conditions for a given set of temperature differentials are as follows:

$$\begin{aligned}
K_1 &= .17776 \Delta T \text{ P.T.} + .011316 \Delta T \text{ I.J.} \\
K_2 &= .22283 \Delta T \text{ P.T.} - .007845 \Delta T \text{ I.J.} \\
K_3 &= .26789 \Delta T \text{ P.T.} - .045185 \Delta T \text{ I.J.} \\
K_4 &= .25534 \Delta T \text{ P.T.} - .059740 \Delta T \text{ I.J.} \\
K_5 &= .19486 \Delta T \text{ P.T.} - .035315 \Delta T \text{ I. J.} \\
K_6 &= .13439 \Delta T \text{ P.T.} - .018595 \Delta T \text{ I. J.}
\end{aligned}$$

(P.T. and I.J. stand for pressure tube and insulation jacket. ΔT s are the temperature differentials from hot to cold sides for each tube.)

The deflection of each tube at midcore is calculated from the following equations:

$$\begin{aligned}
\Delta_{\text{I.J.}} &= (-893.74 P_1 - 557.13 P_2 + 2803.25 P_3 + 5080.23 P_4 \\
&\quad - 4757.26 P_5 + 3400.46 P_6 = 2860.26 \Delta T_{\text{I.J.}}) \times 10^{-6} \\
\Delta_{\text{P.T.}} &= (-48484 P_1 + 56130 P_2 + 59990 P_3 - 55642 P_4 \\
&\quad + 46736 P_5 - 34426 P_6 + 12099.43 \Delta T_{\text{P.T.}}) \times 10^{-6}
\end{aligned}$$

From these deflections, the helium gap is calculated by

$$\text{Gap} = 0.0475 + \Delta_{\text{I.J.}} - \Delta_{\text{P.T.}}$$

This calculated gap is compared with the gap that was assumed in the beginning of the iteration when the temperature differentials were found, and, if the two are not equal, then a new gap is assumed. This new gap is the average of the old, assumed gap and the calculated gap.

Once the gap calculation converges, the midcore deflection of the insulation jacket is compared with the assumed bow, and if these two are not equal, then a new bow is assumed, and the iteration is repeated. The new bow is assumed to be equal to the calculated midcore insulation jacket deflection. As a new bow is assumed, the temperature profiles must be recalculated and the iteration for the helium gap, etc., is started anew.

Once the iterations for gap and bow have been completed, deflections at the six spacer rings are calculated. The spacers can be identified in the reactor by their elevations and are identified here by number for easier notation.

<u>Elevation, ft/in.</u>	<u>Spacer number</u>
88/6	1
85/6	2
82/6	3
77/6	4
74/6	5
71/6	6

The deflections at these six points are described in the three support model by the following equations:

$$\begin{aligned}
 \Delta 1 &= \left[(12742 P_1 + 5069 P_2 - 16850 P_3 \right. \\
 &\quad - 22772 P_4 + 19807 P_5 - 14100 P_6) \div 26.8 \\
 &\quad \left. - (8.3895)(50.328) \Delta T \text{ I.J.} \right] \times 10^{-6} \\
 \\
 \Delta 2 &= \left[(-5595 P_1 - 3318 P_2 + 11561 P_3 \right. \\
 &\quad + 15743 P_4 - 14152 P_5 + 9657 P_6) \div 26.8 \\
 &\quad \left. + (5.8165)(50.328) \Delta T \text{ I.J.} \right] \times 10^{-6} \\
 \\
 \Delta 3 &= \left[(-18600 P_1 - 11559 P_2 + 55423 P_3 \right. \\
 &\quad + 81750 P_4 - 74347 P_5 + 52164 P_6) \div 26.8 \\
 &\quad \left. + (33.5006)(50.328) \Delta T \text{ I.J.} \right] \times 10^{-6} \\
 \\
 \Delta 4 &= \left[(-25137 P_1 - 15740 P_2 + 81751 P_3 \right. \\
 &\quad + 170880 P_4 - 168901 P_5 + 124056 P_6) \div 26.8 \\
 &\quad \left. + (44.2906)(50.328) \Delta T \text{ I.J.} \right] \times 10^{-6} \\
 \\
 \Delta 5 &= \left[(-22136 P_1 - 13880 P_2 + 73451 P_3 \right. \\
 &\quad + 167688 P_4 - 182927 P_5 + 142558 P_6) \div 26.8 \\
 &\quad \left. + (26.1828)(50.328) \Delta T \text{ I.J.} \right] \times 10^{-6} \\
 \\
 \Delta 6 &= \left[(-15564 P_1 - 10642 P_2 + 55910 P_3 \right. \\
 &\quad + 132584 P_4 - 154706 P_5 + 137823 P_6) \div 26.8 \\
 &\quad \left. + (13.7863)(50.328) \Delta T \text{ I.J.} \right] \times 10^{-6}
 \end{aligned}$$

E.3. STRESS CALCULATIONS FOR THE INNER AND
OUTER LOOP POSITIONS —
RECOMMENDED PERMANENT MODIFICATIONS

1. 82-Inch-Long Safety Rod Stove Pipe
2. Safety Rod Extension Sleeve Labyrinth

ATR SAFETY ROD FLOW RESTRICTOR

(Ref: Idaho Nuclear Corp. Dwg. No. 035761)

ATR SAFETY ROD FIX - 82" "STOVE PIPE"

CONSIDERING A ΔP ACROSS THE TUBE WALL, THE ΔP NECESSARY TO YIELD (19000 PSI) WILL BE

$$\frac{PR}{t} = \sigma = 19000 \text{ PSI}$$

$$P = \left(\frac{t}{R} \right) 19000 \text{ PSI} = \left(\frac{.071}{1.69} \right) 19000 = \underline{\underline{798 \text{ PSI}}}$$

THIS IS MUCH GREATER THAN THE MAX. SYSTEM PRESS. OK.

CONSIDERING THE TUBE AS A COLUMN, THE CRITICAL BUCKLING PRESSURE WILL BE

$$L = 82 \quad 7 \quad 4.90 \sqrt{\frac{E}{t}} = (4.90)(1.69) \sqrt{\frac{1.69}{.071}} = 40.4$$

$$P_{CR} = \frac{Et^3}{4(1-\mu^2)L^3} = \frac{(10 \times 10^6)(.071)^3}{4(1-.33^2)(1.69)^3} = 208 \text{ PSI}$$

MAX. ΔP ACROSS THE CORE IS 100 PSI < 208 PSI OK

CUSTOMER	EDASCO	JOB No.	059-3063-06
SUBJECT	ATR 82" STOVEPIPE SAFETY ROD FIX		
		BY	WILLIAMSON
		DATE

MAT'L. 17-4 PH

ATTACHING PLUG

(RELIEF: .109 WIDE X .95 DIA)

4 REQ'D

ATR SAFETY ROD
LABYRINTH FLOW RESTRICTOR

FIGURE NO. 1

Considering a pressure across the minimum thickness,

$$PR/t = \sigma_{\max}$$

$$\sigma_{\text{yield}} > 80,000 \text{ psi}$$

$$P = \left(\frac{t}{R} \right) 80,000 = \left(\frac{0.125}{2.178} \right) 80,000 = 4,600 \text{ psi} \gg \text{maximum system pressure}$$

Considering a full 100 psi ΔP across the labyrinth, the force will be exerted on the attaching plugs.

$$\text{Minimum area} = \frac{\pi}{4} (0.992^2 - 0.95^2) = 0.064 \text{ in}^2 - \text{one plug}$$

$$\text{Shear stress} = \frac{P}{A} = \frac{(100 \text{ psi}) \pi/4 (4.355)^2}{(0.064)} = 23,300 \text{ psi},$$

assuming only one plug holds the labyrinth.

It is more realistic to say that three plugs will take the force; then

$$\tau \approx 8,000 \text{ psi}$$

E.4. STRESS CALCULATIONS FOR THE 3.5-INCH- LONG FLOW RESTRICTOR COLLAR FOR THE CENTER LOOP POSITION

Memo to R. E. Manoll (B&W) from R. P. Williamson (B&W), dated
October 3, 1967:

"The center NR loop flow restrictor as per B&W Drawing SKM-832 has been checked for stresses and has been found acceptable. The following is a summary of the conditions checked and the results thereof.

The maximum shear on the .093" diameter pins at assembly equals 10,400 psi due to the preload of 283 lbs. The preload will lessen to 176 lbs when the loop and collar are subjected to system pressure. During operation, the differential expansion between the loop and the collar will increase the load on the pins to 482 lbs for a shear stress of 17,700 psi in the pins. Under operating conditions, the maximum stresses will be 19,600 psi tension in the collar, 7,600 psi compression in the loop insulation jacket, and 9,000 psi shear on the plug welds in the collar assembly. The bearing stress on the lower land of the collar has been calculated at 2,700 psi for the 100 psi downward pressure across the collar. All of the above stresses are less than the respective allowables and are, therefore, acceptable.

RPW:js

R. P. Williamson"

OUTER LOOP POSITION

USING THE LOADS FROM THE ITERATED SOLUTION (PAGE 5-8), THE MOMENT ALONG BOTH THE INSULATION JACKET AND PRESSURE TUBE ARE CALCULATED CONSIDERING THE SUPPORT AT THE SNUBBER TUBE ASSEMBLY TO BE NON EXISTANT. THIS IS INTENDED TO BE A CHECK OF THE WORST CASE FOR THE RESTRAINT OF THE THERMAL BOW, (ESTIMATE OF THE ORDER OF MAGNITUDE)

INSULATION JACKET

$P_1 =$	1.06 #	↓
$P_2 =$	5.76 #	↓
$P_3 =$	1.46 #	↑
$P_4 =$	.41 #	↑
$P_5 =$	3.25 #	↓
$P_6 =$	.19 #	↓

MOMENT OF INERTIA
IS CONSIDERED TO BE
CONSTANT AND EQUAL TO
THAT OF THE MINIMUM
SECTION.

LOADS ARE IN THE DIRECTIONS SHOWN ABOVE.

REACTIONS AT A, B, & C.

LOAD P_1

$$\sum M_B^+ = 0 = 6.785P_1 - 25P_1 + 167R_A$$

$$R_A = .109 P_1 \uparrow$$

$$\sum M_A^+ = 142P_1 - 167R_B + 6.785P_1$$

$$R_B = .891 P_1 \uparrow$$

$$\sum M_B^+ = -6.785P_1 - 240R_C$$

$$R_C = -.028 P_1 \downarrow$$

$$\therefore R_A = .109 P_1 \uparrow$$

$$R_B = .891 P_1 + .028 P_1 = .919 P_1 \uparrow$$

$$R_C = -.028 P_1 \downarrow$$

$$\sum M_C^+ = 0 = -6.785P_1 + 240R_B$$

$$R_B = .028 P_1 \uparrow$$

$$\sum M_B^+ = 0 = 6.718P_2 + 167R_A$$

$$R_A = -.040 P_2 \downarrow$$

$$\sum F_y = 0 = R_A + R_B$$

$$\therefore R_B = .040 P_2 \uparrow$$

$$\begin{aligned}\sum M_B^+ &= 0 = -6.718 P_2 \\ &\quad + 11 P_2 - 240 R_C \\ R_C &= .018 P_2 \uparrow\end{aligned}$$

$$\therefore R_A = -.040 P_2 \downarrow$$

$$R_B = .040 P_2 + .952 P_2 = 1.022 P_2 \uparrow$$

$$R_C = .018 P_2 \uparrow$$

$$\begin{aligned}\sum M_C^+ &= 0 = -229 P_2 - 6.718 P_2 \\ &\quad + 240 R_B \\ R_B &= .952 P_2 \uparrow\end{aligned}$$

LOAD P_3

$$\begin{aligned}\sum M_B^+ &= 0 = -22.332 P_3 + 167 R_A \\ R_A &= .134 P_3 \uparrow\end{aligned}$$

$$\sum F_y = 0 = R_A + R_B$$

$$\therefore R_B = -.134 P_3 \downarrow$$

$$\begin{aligned}\sum M_B^+ &= 0 = 22.332 P_3 - 47 P_3 \\ &\quad - 240 R_C \\ R_C &= -.103 P_3 \downarrow\end{aligned}$$

$$\therefore R_A = .134 P_3 \uparrow$$

$$R_B = -.134 P_3 - .897 P_3 = -1.031 P_3 \downarrow$$

$$R_C = -.103 P_3 \downarrow$$

$$\begin{aligned}\sum M_C^+ &= 22.332 P_3 + 240 R_B \\ &\quad + 193 P_3 \\ R_B &= -.897 P_3 \downarrow\end{aligned}$$

LOAD P_4

$$\sum M_B^+ = 0 = 30.181 P_4 + 167 R_A$$

$$R_A = -.181 P_4 \downarrow$$

$$\sum F_y = 0 = R_A + R_B$$

$$\therefore R_B = .181 P_4 \uparrow$$

$$\sum M_B^+ = -30.181 P_4 + 107 P_4 - 240 R_C$$

$$R_C = .320 P_4 \uparrow$$

$$\therefore R_A = -.181 P_4 \downarrow$$

$$R_B = .181 P_4 + .680 P_4 = .861 P_4 \uparrow$$

$$R_C = .320 P_4 \uparrow$$

$$\sum M_C^+ = 0 = -133 P_4 + 240 R_B - 30.181 P_4$$

$$R_B = .680 P_4 \uparrow$$

LOAD P_5

$$\sum M_B^+ = 0 = 167 R_A - 26.251 P_5$$

$$R_A = .157 P_5 \uparrow$$

$$\sum F_y = 0 = R_A + R_B$$

$$R_B = -.157 P_5 \downarrow$$

$$\begin{aligned} \sum \vec{M}_B^+ &= 0 = 26.251 P_5 - 143 P_5 \\ &\quad - 240 R_C \\ R_C &= -.486 P_5 \downarrow \end{aligned}$$

$$\therefore R_A = .157 P_5 \uparrow$$

$$R_B = -.157 P_5 - .514 P_5 = -.671 P_5 \downarrow \quad R_B = -.514 P_5 \downarrow$$

$$R_C = -.486 P_5 \downarrow$$

$$\begin{aligned} \sum \vec{M}_C^+ &= 0 = 97 P_5 + 26.251 P_5 \\ &\quad + 240 R_B \end{aligned}$$

LOAD P_6

$$\begin{aligned} \sum \vec{M}_B^+ &= 0 = 18.687 P_6 + 167 R_A \\ R_A &= -.112 P_6 \downarrow \\ \sum F_y = 0 &= R_A + R_B \\ R_B &= .112 P_6 \uparrow \end{aligned}$$

$$\begin{aligned} \sum \vec{M}_B^+ &= 0 = -18.687 P_6 + 179 P_6 \\ &\quad - 240 R_C \end{aligned}$$

$$R_C = .668 P_6 \uparrow$$

$$\begin{aligned} \sum \vec{M}_C^+ &= 0 = -61 P_6 - 18.687 P_6 \\ &\quad + 240 R_B \end{aligned}$$

$$R_B = .332 P_6 \uparrow$$

$$\therefore R_A = -.112 P_6 \downarrow$$

$$R_B = .112 P_6 + .332 P_6 = .444 P_6 \uparrow$$

$$R_C = .668 P_6 \uparrow$$

SUMMATION:

$$R_A = .109 P_1 - .040 P_2 + .134 P_3 + .181 P_4 - .157 P_5 \\ - .112 P_6$$

SUBSTITUTING VALUES FOR $P_1, \dots, P_6$;

$$R_A = .3765 \# \downarrow$$

$$R_B = .919 P_1 + 1.022 P_2 - 1.031 P_3 - .861 P_4 + .671 P_5 \\ + .444 P_6$$

SUBSTITUTING;

$$R_B = 7.2677 \# \uparrow$$

$$R_C = -.028 P_1 + .018 P_2 - .103 P_3 - .304 P_4 + .486 P_5 \\ + .668 P_6$$

SUBSTITUTING;

$$R_C = 1.5054 \# \uparrow$$

MAX MOMENT = $+138 \text{ IN-LB}$

MAX STRESS = $\frac{(138 \text{ IN-LB})(1.4375 \text{ IN})}{.995 \text{ IN}^3} \approx \underline{200 \text{ PSI}}$

PRESSURE TUBE

$$\begin{aligned} P_1 &= 1.06 \# \uparrow \\ P_2 &= 5.76 \# \uparrow \\ P_3 &= 1.46 \# \downarrow \\ P_4 &= .41 \# \downarrow \\ P_5 &= 3.25 \# \uparrow \\ P_6 &= .19 \# \uparrow \end{aligned}$$

MOMENT OF INERTIA
IS CONSIDERED TO BE
CONSTANT AND EQUAL
TO THAT OF THE MINIMUM
SECTION.

$$\sum M_A^+ = 0 = -(1.06)142 - (5.76)178 + (1.46)214 + (.41)274 - (3.25)310 - (.19)346 + 426 R_C$$

$$R_C = 4.2823 \# \downarrow$$

$$\sum M_C^+ = 0 = (.19)80 + (3.25)116 - (.41)152 - (1.46)212 + (5.76)248 + (1.06)284 - 426 R_A$$

$$R_A = 4.1077 \# \downarrow$$

MAX. MOMENT = -693 IN-LB

$$\text{MAX. STRESS} = \frac{(693 \text{ IN-LB})(1.270 \text{ IN})}{1.029 \text{ IN}^3} \approx 856 \text{ PSI}$$

CUSTOMER	EBASCO SERVICES INC.
SUBJECT	ATC CENTER LOOP FLOW RESTRICTOR
BY	KILLIAMSON
DATE	9-28-67
JOB NO.	57-3063-06

AT ASSEMBLY, .001 ON DIA. IS INTERFERENCE BETWEEN LOOP & COLLAR.

ASSUME .001 TAKEN ONLY BY COLLAR

$$\Delta R = \frac{PR^2}{Et} \left(1 - \frac{\nu}{2}\right) = .0005 = \frac{P(1.4355)^2}{(28 \times 10^6)(.046)} (1 - .15)$$

$$P = 368 \text{ PSI}$$

HOOP STRESS IN COLLAR

$$\sigma = \frac{PR}{t} = \frac{(368)(1.4355)}{.046} = 11500 \text{ PSI} < \underset{348}{30,000 \text{ PSI}}$$

$$\text{HOOP LOAD} = PA = (368)(3.5)(.2195) = 283 \# = F$$

TWO PINS ON EACH SIDE - EACH IN DOUBLE SHEAR

$$\tau = \frac{F}{2A} = \frac{283}{2(2)(\pi/4)(.093)^2} = 10400 \text{ PSI} < 50000 \text{ PSI INCONEL X}$$

CUSTOMER	JOB No.
SUBJECT	
	BY
	DATE

CHANGE IN RADIUS DUE TO SYSTEM PRESSURE

$$\Delta P = 100 \text{ PSI ACROSS COLLAR \& LOOP}$$

$$\text{GENERAL FORMULA: } \Delta R = \frac{R}{E} \left(\frac{PR}{2} - \frac{\nu PR}{2E} \right)$$

REF: FORMULAS FOR STRESS AND STRAIN, 4TH ED., RAYMOND J. ROARK, PG. 29B, CASE 1

$$\Delta R_{IJ} = \frac{PR^2}{Et} \left(1 - \frac{\nu}{2} \right) = \frac{(100 \text{ PSI})(1.436)^2}{(28 \times 10^6)(.118)} (.85) = 5.3050 \times 10^{-5}$$

$$\Delta R_c = \frac{(100)(1.436)^2}{(28 \times 10^6)(.046)} (.85) = 13.6086 \times 10^{-5}$$

$$\begin{aligned} \text{PRELOAD REMAINING} &= .0005 - \Delta R_{IJ} - \Delta R_c \\ &= .0005 - .00005305 - .000136086 = .000310864 \end{aligned}$$

$$\text{LOAD REMAINING} = \left(\frac{.000310864}{.0005} \right) (368)(3.5)(.2195) = \frac{176}{2} \#$$

CUSTOMER	JOB No.
SUBJECT	
	BY
	DATE

AS THE LOOP HEATS UP, THE ΔT IN THE COLLAR FROM RT ASSEMBLY TO OPERATION = 60°F & ΔT FOR THE INSULATION JACKET = 100°F

$$\Delta R = \alpha L \Delta T = \alpha R \Delta T$$

$$\alpha = 9.3 \times 10^{-6} \frac{\text{IN}}{\text{IN}^{\circ}\text{F}}$$

$$\Delta R_{IJ} = (9.3 \times 10^{-6})(1.4360)(100^{\circ}\text{F}) = 1.335 \times 10^{-3} \text{ IN.}$$

$$\Delta R_C = (9.3 \times 10^{-6})(1.4355)(60^{\circ}\text{F}) = .801 \times 10^{-3} \text{ IN.}$$

$$\text{NET DIFFERENCE} = .534 \times 10^{-3} \text{ IN.}$$

TEMP. CHANGE PLUS PRESS. CHANGE & PRELOAD

$$\Delta R_{C \text{ TOTAL}} = .000534 + .000311 = .000845 \text{ IN.}$$

$$P = \frac{(.000845)(28 \times 10^6)(.046)}{(1.4355)(.85)} = 628 \text{ PSI}$$

LOAD ON PINS

$$F = (628)(3.5)(.2195) = 482 \#$$

SHEAR STRESS

$$\tau = \frac{482}{(2)(2)(\pi/4)(.093)^2} = 17700 \text{ PSI} < 50000 \text{ PSI}$$

INCONEL X

STRESS IN COLLAR

$$\sigma_c = \frac{PR}{E} = \frac{(628)(1.4355)}{.046} = 19600 \text{ PSI} < 30,000 \text{ PSI}$$

348

CUSTOMER	JOB No.
SUBJECT	
	BY
	DATE

STRESS IN INSULATION JACKET

$$\tau_{ij} = \frac{(620)(1.436)}{.118} = 7600 \text{ PSI} < 30,000 \text{ PSI}$$

348

SHEAR STRESS ON PLUG WELDS

$$\text{AREA} = \frac{\pi}{4} \left(\frac{3}{32} \right)^2 = .0069 \quad \text{ONE WELD}$$

$$\text{FORCE ON WELDS} = 482 \#$$

$$\text{SHEAR STRESS} = \tau = \frac{482}{8(.0069)} = 9000 \text{ PSI}$$

NOTE: CONSIDER ONLY $\frac{2}{3}$ OF WELDS ARE TAKING LOAD

CUSTOMER	JOB No.
SUBJECT	
	BY
	DATE

TOTAL FORCE ON COLLAR = 482# HOOP

STRESS IN ONE MALE TAB

$$\sigma = \frac{P}{A} = \frac{482}{(3/8)(.172)} = 7500 \text{ PSI}$$

NOTE: CONSIDERS
ONLY ONE TAB
TAKING ALL THE LOAD

CENTER FLUX
TRAP BAFFLE

NR LOOP INSULATION JACKET
2.872 $\pm .002$ AT COLLAR

CENTER LOOP FLOW RESTRICTOR
LOOD O.D. MINUS .001 AS I.D.
3.310 $\pm .002$ O.D.

INSULATION JACKET SPINES
3.211 $\pm .001$

CUSTOMER	JOB No.
SUBJECT	
	BY
	DATE

$$\text{MIN. BEARING AREA} = \left(\frac{3.211 - 2.967}{2} \right) \cdot .370 = .0451 \text{ IN}^2$$

$$\text{TOTAL LAND AREA FOR 8 SPLINES} = .3608 \text{ IN}^2$$

HYDRAULIC LOADING = 100 PSI DOWNWARD

$$F = PA = (100)(3.310)^2 \left(\frac{\pi}{4} \right) = 860 \#$$

$$\text{BEARING STRESS} = \frac{860}{.3608} = 2700 \text{ PSI} < 15000 \text{ PSI}$$

348

CUSTOMER	JOB No.
SUBJECT	
	BY
	DATE

CENTER LOOP POSITION

USING THE LOADS FROM THE ITERATED SOLUTION (PAGE 5-9), THE MOMENT ALONG BOTH THE INSULATION JACKET AND PRESSURE TUBE ARE CALCULATED. THIS IS INTENDED TO BE AN ESTIMATE OF THE ORDER OF MAGNITUDE OF THE STRESSES INVOLVED IN RESTRAINING THE BOW.

INSULATION JACKET

$$\begin{aligned} P_1 &= 3.36 \# \downarrow \\ P_2 &= 8.27 \# \downarrow \\ P_3 &= 4.32 \# \uparrow \\ P_4 &= 11.88 \# \uparrow \\ P_5 &= 12.10 \# \downarrow \\ P_6 &= 1.59 \# \uparrow \end{aligned}$$

MOMENT OF INERTIA
IS CONSIDERED TO BE
CONSTANT AND EQUAL TO
THAT OF THE MINIMUM
SECTION.

REACTIONS AT A, B, & C.

LOAD P_1

$$\sum M_B^+ = 0 = 6.785P_1 - 25P_1 + 167R_A$$

$$R_A = .109 P_1 \uparrow$$

$$\sum M_A^+ = 142P_1 - 167R_B + 6.785P_1$$

$$R_B = .891 P_1 \uparrow$$

$$\sum M_B^+ = -6.785P_1 - 240R_C$$

$$R_C = -.028 P_1 \downarrow$$

$$\therefore R_A = .109 P_1 \uparrow$$

$$R_B = .891 P_1 + .028 P_1 = .919 P_1 \uparrow$$

$$R_C = -.028 P_1 \downarrow$$

$$\sum M_C^+ = 0 = -6.785P_1 + 240R_B$$

$$R_B = .028 P_1 \uparrow$$

$$\sum M_B^+ = 0 = 6.718P_2 + 167R_A$$

$$R_A = -.040 P_2 \downarrow$$

$$\sum F_y = 0 = R_A + R_B$$

$$\therefore R_B = .040 P_2 \uparrow$$

$$\begin{aligned}\sum M_B^+ &= 0 = -6.718 P_2 \\ &\quad + 11 P_2 - 240 R_C \\ R_C &= .018 P_2 \uparrow\end{aligned}$$

$$\therefore R_A = -.040 P_2 \downarrow$$

$$R_B = .040 P_2 + .952 P_2 = 1.022 P_2 \uparrow$$

$$R_C = .018 P_2 \uparrow$$

$$\begin{aligned}\sum M_C^+ &= 0 = -229 P_2 - 6.718 P_2 \\ &\quad + 240 R_B \\ R_B &= .982 P_2 \uparrow\end{aligned}$$

LOAD P_3

$$\begin{aligned}\sum M_B^+ &= 0 = -22.332 P_3 + 167 R_A \\ R_A &= .134 P_3 \uparrow\end{aligned}$$

$$\sum F_y = 0 = R_A + R_B$$

$$\therefore R_B = -.134 P_3 \downarrow$$

$$\begin{aligned}\sum M_B^+ &= 0 = 22.332 P_3 - 47 P_3 \\ &\quad - 240 R_C \\ R_C &= -.103 P_3 \downarrow\end{aligned}$$

$$\therefore R_A = .134 P_3 \uparrow$$

$$R_B = -.134 P_3 - .897 P_3 = -1.031 P_3 \downarrow$$

$$R_C = -.103 P_3 \downarrow$$

$$\begin{aligned}\sum M_C^+ &= 22.332 P_3 + 240 R_B \\ &\quad + 193 P_3 \\ R_B &= -.897 P_3 \downarrow\end{aligned}$$

LOAD P_4

$$\sum M_B^+ = 0 = 30.181 P_4 + 167 R_A$$

$$R_A = -.181 P_4 \downarrow$$

$$\sum F_y = 0 = R_A + R_B$$

$$\therefore R_B = .181 P_4 \uparrow$$

$$\sum M_B^+ = -30.181 P_4 + 107 P_4$$

$$- 240 R_C$$

$$R_C = .320 P_4 \uparrow$$

$$\therefore R_A = -.181 P_4 \downarrow$$

$$R_B = .181 P_4 + .680 P_4 = .861 P_4 \uparrow$$

$$R_C = .320 P_4 \uparrow$$

$$\sum M_C^+ = 0 = -133 P_4 + 240 R_B$$

$$- 30.181 P_4$$

$$R_B = .680 P_4 \uparrow$$

LOAD P_5

$$\sum M_B^+ = 0 = 167 R_A - 26.251 P_5$$

$$R_A = .157 P_5 \uparrow$$

$$\sum F_y = 0 = R_A + R_B$$

$$R_B = -.157 P_5 \downarrow$$

$$\begin{aligned} \sum \vec{M}_B^+ &= 0 = 26.251 P_5 - 143 P_5 \\ &\quad - 240 R_C \\ R_C &= -.486 P_5 \downarrow \end{aligned}$$

$$\therefore R_A = .157 P_5 \uparrow$$

$$R_B = -.157 P_5 - .514 P_5 = -.671 P_5 \downarrow \quad R_B = -.514 P_5 \downarrow$$

$$R_C = -.486 P_5 \downarrow$$

$$\begin{aligned} \sum \vec{M}_C^+ &= 0 = 97 P_5 + 26.251 P_5 \\ &\quad + 240 R_B \end{aligned}$$

LOAD P_6

$$\begin{aligned} \sum \vec{M}_B^+ &= 0 = 18.687 P_6 + 167 R_A \\ R_A &= -.112 P_6 \downarrow \\ \sum F_y = 0 &= R_A + R_B \\ R_B &= .112 P_6 \uparrow \end{aligned}$$

$$\begin{aligned} \sum \vec{M}_B^+ &= 0 = -18.687 P_6 + 179 P_6 \\ &\quad - 240 R_C \end{aligned}$$

$$R_C = .668 P_6 \uparrow$$

$$\begin{aligned} \sum \vec{M}_C^+ &= 0 = -61 P_6 - 18.687 P_6 \\ &\quad + 240 R_B \end{aligned}$$

$$\therefore R_A = -.112 P_6 \downarrow$$

$$R_B = .112 P_6 + .332 P_6 = .444 P_6 \uparrow$$

$$R_C = .668 P_6 \uparrow$$

$$R_B = .332 P_6 \uparrow$$

SUMMATION:

$$R_A = .109 P_1 - .040 P_2 + .134 P_3 + .181 P_4 - .157 P_5 + .112 P_6$$

SUBSTITUTING IN VALUES FOR $P_1, P_2, \dots, P_6$;

$$R_A = 1.04^\# \uparrow$$

$$R_B = .919 P_1 + 1.022 P_2 - 1.031 P_3 - .861 P_4 + .671 P_5 - .444 P_6$$

SUBSTITUTING;

$$R_B = 4.27^\# \uparrow$$

$$R_C = -.028 P_1 + .018 P_2 - .103 P_3 - .304 P_4 + .486 P_5 - .668 P_6$$

SUBSTITUTING;

$$R_C = .82^\# \uparrow$$

$$\text{MAX. MOMENT} = 239 \text{ IN-LB}$$

$$\text{MAX. STRESS} = \frac{(239 \text{ IN-LB})(1.4375 \text{ IN})}{.995 \text{ IN}^3} = 345 \text{ PSI}$$

PRESSURE TUBE

$P_1 = 3.36$	#	↑	MOMENT OF INERTIA IS CONSIDERED TO BE CONSTANT AND EQUAL TO THAT OF THE MINIMUM SECTION.
$P_2 = 8.27$	#	↑	
$P_3 = 4.32$	#	↓	
$P_4 = 11.88$	#	↓	
$P_5 = 12.10$	#	↑	
$P_6 = 1.59$	#	↓	

$$\sum M_A^+ = 0 = -(3.36)(142) - (8.27)(178) + (4.32)(214) + (11.88)(274) - (12.10)(310) - (1.59)(346) + 426 R_C$$

$$R_C = 2.20 \text{ #} \downarrow$$

$$\sum M_C^+ = 0 = -(1.59)(80) + (12.10)(116) - (11.88)(152) - (4.32)(212) + (8.27)(248) + (3.36)(284) - 426 R_A$$

$$R_A = 3.66 \text{ #} \downarrow$$

$$\text{MAX. MOMENT} = 531 \text{ IN. LB}$$

$$\text{MAX. STRESS} = \frac{(531 \text{ IN. LB})(1.270 \text{ IN.})}{1.028 \text{ IN.}^4} = 656 \text{ PSI}$$

E.5. THE THREE-SUPPORT THERMAL BOW MODEL

PRESSURE TUBE
INITIAL DEFLECTIONS DUE TO A ΔT ACROSS THE
TUBE (NON-UNIFORM HEAT FLUX) IN THE CORE

$$\Delta'_1 = 142(0.854\theta_1) = 121.268\theta_1'$$

$$\Delta'_2 = 178(0.854\theta_1) = 152.012\theta_1'$$

$$\Delta'_3 = 214(0.854\theta_1) = 182.756\theta_1'$$

$$\Delta'_0 = 184.474\theta_1' + \Delta_{PT}'' \quad \text{SEE NEXT PAGE}$$

$$\Delta'_4 = 152(1.146\theta_1) = 174.192\theta_1'$$

$$\Delta'_5 = 116(1.146\theta_1) = 132.736\theta_1'$$

$$\Delta'_6 = 80(1.146\theta_1) = 91.680\theta_1'$$

WITH REFERENCE TO PT. 3

$$\Delta'_0 = 220 (0.854 \theta'_1) + \Delta''PT_0 - 24 (0.146 \theta'_1)$$

$$\Delta'_0 = 189.376 \theta'_1 + \Delta''PT_0$$

WITH REFERENCE TO PT. 4

$$\Delta'_0 = 152 (1.146 \theta'_1) + \Delta''PT_0 + 24 (0.146 \theta'_1)$$

$$\Delta'_0 = 184.572 \theta'_1 + \Delta''PT_0$$

$$\text{AVG.} = \frac{189.376 + 184.572}{2} = \underline{\underline{184.474 \theta'_1 + \Delta''PT_0}}$$

INSULATION JACKET LOADINGS

$$I_1 = \pi/64(4.0^4 - 3.625^4) = 4.091 \text{ IN}^4$$

$$I_2 = \pi/64(2.875^4 - 2.633^4) = 0.995 \text{ IN}^4$$

$$I_3 = \pi/64(3.122^4 - 2.633^4) = 2.309 \text{ IN}^4$$

INSULATION JACKET - INITIAL DEFLECTION
DUE TO A ΔT ACROSS THE TUBE (NON-
UNIFORM HEAT FLUX)

Δ^+

$$\theta'_B = \theta'_{ic} + \theta''_{ic} \\ = 1.358 \theta'_{ic}$$

E-46

$$\theta''_{ic} = \frac{133 \theta'_{ic} - 47 \theta'_{ic}}{240} \\ = 0.358 \theta'_{ic}$$

$$\Delta_c = 133 \theta'_{ic}$$

$$\theta'_c = \theta'_{ic} - 0.358 \theta'_{ic} = 0.642 \theta'_{ic}$$

$$\Delta'_{ic2} = 11 (1.358 \theta'_{ic}) = 14.938 \theta'_{ic}$$

$$\Delta'_{ic3} = 47 (1.358 \theta'_{ic}) = 63.826 \theta'_{ic}$$

$$\Delta'_{ic0} = 80.606 \theta'_{ic} + \Delta''_{ic} \quad \text{SEE NEXT PAGE}$$

$$\Delta'_{ic4} = 133 (0.642 \theta'_{ic}) = 85.386 \theta'_{ic}$$

$$\Delta'_{ic5} = 97 (0.642 \theta'_{ic}) = 62.274 \theta'_{ic}$$

$$\Delta'_{ic6} = 61 (0.642 \theta'_{ic}) = 39.162 \theta'_{ic}$$

WITH REF. TO PT. 3

$$\Delta'_0 = (47+6)(1.3589\theta''_c) + \Delta''_{c_0} + 24(0.3589\theta''_c)$$

$$\Delta'_0 = 80.566\theta''_c + \Delta''_{c_0}$$

WITH REF. TO PT. 4

$$\Delta'_0 = (133+6)(0.6429\theta''_c) + \Delta''_{c_0} - 24(0.3589\theta''_c)$$

$$\Delta'_0 = 80.646\theta''_c + \Delta''_{c_0}$$

$$\text{Avg.} = \frac{80.566 + 80.646}{2} = 80.606\theta''_c + \Delta''_{PT_0}$$

DETERMINE THE "EQUIVALENT" I TO BE
USED IN MOMENT DISTRIBUTION SOLUTION
(HARDY CROSS) — INSULATION JACKET

$$I_1 = 4.091 \text{ IN}^4$$

$$I_2 = .995 \text{ IN}^4$$

AREAS:

$$A_1 = \left(\frac{1}{2} \right) (52) (.311 M_B) = 8.086 M_B$$

$$A_2 = (52) (.689 M_B) = 35.828 M_B$$

$$A_3 = \left(\frac{1}{2} \right) (115) (.168 M_B) = 9.660 M_B$$

$$\Sigma A = 53.574 M_B$$

$$\bar{X}_A = \left[(9.660 M_B) \left(\frac{2}{3} (115) \right) + (35.828 M_B) \left(115 + \frac{52}{2} \right) + (8.086 M_B) \left(115 + \frac{2(52)}{3} \right) \right] \div 53.574 M_B$$

$$= \frac{7002.6 M_B}{53.574 M_B} = 130.7"$$

$$F_A = 53.574 \text{ MB} \left(\frac{167 - 130.7}{167} \right) = 11.645 \text{ MB}$$

$$F_B = 53.574 \text{ MB} \left(\frac{130.7}{167} \right) = 41.929 \text{ MB}$$

$$\phi_B = \frac{41.929 \text{ MB}}{EI_L}$$

FOR CONSTANT I

$$\phi = \frac{ML}{3EI}$$

$$\frac{ML}{3EI} = \frac{41.929 \text{ MB}}{EI_L}$$

SOLVING FOR "I"

$$I = \frac{L I_2}{3(41.929)} = \frac{(167)(.995)}{3(41.929)} = 1.321 \text{ IN}^4$$

EQUIVALENT I

AREA:

$$A_1 = \left(\frac{1}{2}\right)(186)(.775 \text{ MB}) = 72.095 \text{ MB}$$

$$A_2 = (186)(.225 \text{ MB}) = 41.850 \text{ MB}$$

$$A_3 = \left(\frac{1}{2}\right)(54)(.097 \text{ MB}) = 2.619 \text{ MB}$$

$$\Sigma = 116.564 \text{ MB}$$

$$\bar{x}_c = \left[(2.619 \text{ MB})\left(\frac{2}{3}\right)(54) + (41.850 \text{ MB})\left(54 + \frac{186}{2}\right) + (72.095 \text{ MB})\left(54 + \frac{2(186)}{3}\right) \right] \div 116.564$$

$$\bar{x}_c = 163.5''$$

$$F_c = (116.564 \text{ MB})\left(\frac{163.5}{240}\right) = 79.409 \text{ MB}$$

$$F_B = (116.564 \text{ MB})\left(\frac{240 - 163.5}{240}\right) = 37.155 \text{ MB}$$

$$\checkmark \quad 79.409 + 37.155 = 116.564$$

$$\phi_c = \frac{79.409 \text{ MB}}{EI_2}$$

FOR CONSTANT I

$$\phi = \frac{ML}{3EI}$$

$$\therefore \frac{79.409 \text{ MB}}{EI_2} = \frac{ML}{3EI}$$

SOLVE FOR I

$$I = \frac{I_2 L}{3(79.409)} = \frac{(0.995)(240)}{3(79.409)} = 1.002 \text{ IN}^4$$

EQUIVALENT I

$$\begin{aligned}
 I_{EQ} &= 1.321 \text{ IN}^4 \\
 L &= 16.7 \text{ IN} \\
 K = \frac{I}{L} &= \frac{1.321}{16.7} = 0.0079101 \\
 \text{DIST.} &= \frac{0.0079101}{0.0079101 + 0.0041750} = 0.655
 \end{aligned}$$

$$\begin{aligned}
 I_{EQ} &= 1.002 \text{ IN}^4 \\
 L &= 240 \text{ IN} \\
 K = \frac{I}{L} &= \frac{1.002}{240} = 0.0041750 \\
 \text{DIST.} &= \frac{0.0041750}{0.0079101 + 0.0041750} = 0.345
 \end{aligned}$$

$$\begin{aligned}
 \frac{M_B L}{3EI} + \frac{M_C L}{6EI} &= 1.358 \theta'_C \\
 \frac{M_B L}{6EI} + \frac{M_C L}{3EI} &= 0.642 \theta'_C \\
 M_C &= 618 \times 10^{-6} E \theta'_C \quad \text{BY SIML. SOLUTION} \\
 M_B &= 17318 \times 10^{-6} E \theta'_C
 \end{aligned}$$

DIST.	0.655	0.345	
FEM	0	17318	618
D	0	-5975	-618
CO	-5672	-309	-2987
D	+5672	107	+2987
CO	+101	1494	+53
D	-101	-1494	-53
	-11741	+11141	0

$$M_B = 11141 \times 10^{-6} E \theta'_{ic} = 11119 \times 10^{-6} EI_2 \theta'_{ic}$$

I.C.

$$\Delta = \frac{MB}{6EI} \left(3x^2 - \frac{x^3}{L} - 2Lx \right)$$

$$\Delta'_{ic2} = \frac{11119 \times 10^{-6} E \theta'_{ic}}{6E} \left[3(11)^2 - \frac{(11)^3}{240} - 2(240)11 \right] = -9.1215 \theta'_{ic}$$

\$x=11\$

$$\Delta'_{ic3} = \frac{11119 \times 10^{-6} E \theta'_{ic}}{6E} \left[3(47)^2 - \frac{(47)^3}{240} - 2(240)47 \right] = -30.3254 \theta'_{ic}$$

\$x=47\$

$$\Delta'_{ic0} = \frac{11119 \times 10^{-6} E \theta'_{ic}}{6E} \left[3(77)^2 - \frac{(77)^3}{240} - 2(240)77 \right] = -39.0524 \theta'_{ic}$$

\$x=77\$

$$\Delta'_{ic4} = \frac{11119 \times 10^{-6} E \theta'_{ic}}{6E} \left[3(107)^2 - \frac{(107)^3}{240} - 2(240)107 \right] = -40.9534 \theta'_{ic}$$

\$x=107\$

$$\Delta'_{ic5} = \frac{11119 \times 10^{-6} E \theta'_{ic}}{6E} \left[3(143)^2 - \frac{(143)^3}{240} - 2(240)143 \right] = -36.0912 \theta'_{ic}$$

\$x=143\$

$$\Delta'_{ic6} = \frac{11119 \times 10^{-6} E \theta'_{ic}}{6E} \left[3(179)^2 - \frac{(179)^3}{240} - 2(240)179 \right] = -25.3757 \theta'_{ic}$$

\$x=179\$

THERE IS NO EFFECT FROM \$I_{ic}\$ SINCE IT IS CONSIDERED
• BEING DUE TO SIMPLE SUPPORTS.

DEFLECTIONS ON INSULATION JACKET DUE TO
INITIAL BOW OF JACKET FROM A GRADIENT (ΔT)
ACROSS DIA. (SUMMATION OF Δ 's FROM PPS E II)

<u>+ Δ ↓</u>	<u>PAGE 5</u>	<u>+</u>	<u>PAGE 11</u>	<u>-</u>	<u>SUMMATION</u>
Δ'_{1C_2}	14,935 θ'_{1C}	+	9,1215 θ'_{1C}	+	5,8165 θ'_{1C}
Δ'_{1C_3}	63,826 θ'_{1C}	-	30,3254 θ'_{1C}	=	33,5006 θ'_{1C}
Δ'_{1C_0}	80,606 θ'_{1C} + Δ''_K	-	39,0524 θ'_{1C}	=	41,5536 θ'_{1C} + Δ''_{1C_0}
Δ'_{1C_4}	85,274 θ'_{1C}	-	40,9834 θ'_{1C}	=	44,2906 θ'_{1C}
Δ'_{1C_5}	62,274 θ'_{1C}	-	36,0912 θ'_{1C}	=	26,1828 θ'_{1C}
Δ'_{1C_6}	39,162 θ'_{1C}	-	25,3757 θ'_{1C}	=	13,7863 θ'_{1C}

$$M_1 = P_1 \frac{(142)(25)^2}{(167)^2} = 3.1823 P_1$$

$$M_2 = -P_1 \frac{(142)^2(25)}{(167)^2} = -18.075 P_1$$

D.F.	.655	.345	
FEM	3.1823 P ₁	-18.075 P ₁	0
D	3.1823 P ₁	+11.839 P ₁	+6.236 P ₁
CO	15.920 P ₁	-1.591 P ₁	0
D	-5.920 P ₁	+1.042 P ₁	+0.549 P ₁
CO	+0.521 P ₁	-2.960 P ₁	-1.559 P ₁
D	-0.521 P ₁	+2.960 P ₁	+1.559 P ₁
	0	-6.785 P ₁	+6.785 P ₁

D.F.	.655	.345	
FEM	0	0	-10.015 P ₂
D	0	+6.560 P ₂	+3.455 P ₂
CO	+3.280 P ₂	0	-1.241 P ₂
D	-3.280 P ₂	+1.158 P ₂	+0.83 P ₂
CO	+0.079 P ₂	-1.640 P ₂	-0.864 P ₂
D	-0.079 P ₂	+1.640 P ₂	+0.864 P ₂
	0	+6.718 P ₂	-6.718 P ₂

$$M_1 = \frac{Pab^2}{L^2} = \frac{(-P_2)(11)(229)^2}{(240)^2} = -10.015 P_2$$

$$M_2 = -\frac{Pa^2b}{L^2} = \frac{P_2(11)^2(229)}{(240)^2} = 0.481 P_2$$

$$M_1 = \frac{P_3(47)(193)^2}{(240)^2} = 30.394 P_3$$

$$M_2 = -\frac{P_3(47)^2(193)}{(240)^2} = -7.402 P_3$$

D.F.	.655	.345	
FEM	0	0	$+30.394 P_3$
D	0	$-19.908 P_3$	$-10.486 P_3$
CO	$-9.954 P_3$	0	$+3.701 P_3$
D	$+9.954 P_3$	$-2.424 P_3$	$-1.277 P_3$
CO	$-1.212 P_3$	$+4.977 P_3$	$+2.622 P_3$
D	$+1.212 P_3$	$-4.977 P_3$	$-2.622 P_3$
	0	$-22.332 P_3$	$+22.332 P_3$
			0

D.F.	.655	.345	
FEM	0	0	$+32.860 P_4$
D	0	$-21.523 P_4$	$-11.337 P_4$
CO	$-10.762 P_4$	0	$+13.218 P_4$
D	$+10.762 P_4$	$-8.658 P_4$	$-4.560 P_4$
CO	$-4.329 P_4$	$+5.381 P_4$	$+2.834 P_4$
D	$+4.329 P_4$	$-5.381 P_4$	$-2.834 P_4$
	0	$-30.181 P_4$	$+30.181 P_4$
			0

$$M_1 = \frac{Pab^2}{L^2} = \frac{P_4(107)(133)^2}{(240)^2} = 32.860 P_4$$

$$M_2 = -\frac{Pa^2b}{L^2} = -\frac{P_4(107)^2(133)}{(240)^2} = -26.436 P_4$$

$$M_1 = \frac{P_5 (143)(97)^2}{(240)^2} = 23.359 P_5$$

$$M_2 = -\frac{P_5 (143)^2 (97)}{(240)^2} = -34.437 P_5$$

D.F.	.655	.345		
FEM	0	0	+23.359 P ₅	-34.437 P ₅
D	0	-15.300 P ₅	-8.059 P ₅	+33.437 P ₅
CO	-7.650 P ₅	0	+16.719 P ₅	-4.029 P ₅
D	+7.650 P ₅	-10.951 P ₅	-5.768 P ₅	+4.029 P ₅
CO	-5.475 P ₅	+3.825 P ₅	+2.015 P ₅	-2.884 P ₅
D	+5.475 P ₅	-3.825 P ₅	-2.015 P ₅	+2.884 P ₅
	0	-26.251 P ₅	+26.251 P ₅	0

NOTE: SIGNS WRONG

+26.251 P₅ - 26.251 P₅

D.F.	.655	.345		
FEM	0	0	+11.564 P ₆	-33.932 P ₆
D	0	-7.574 P ₆	-3.990 P ₆	+33.932 P ₆
CO	-3.787 P ₆	0	+16.966 P ₆	-1.995 P ₆
D	+3.787 P ₆	-11.113 P ₆	-5.853 P ₆	+1.995 P ₆
CO	-5.556 P ₆	+1.894 P ₆	+.998 P ₆	-2.927 P ₆
D	+5.556 P ₆	-1.894 P ₆	-.998 P ₆	+2.927 P ₆
	0	-18.687 P ₆	+18.687 P ₆	0

$$M_1 = \frac{P a b^2}{L^2} = \frac{P_6 (179)(61)^2}{(240)^2} = 11.564 P_6$$

$$M_2 = -\frac{P a^2 b}{L^2} = -\frac{P_6 (179)^2 (61)}{(240)^2} = -33.932 P_6$$

$$\begin{aligned}
 A_1 &= \left(\frac{1}{2}\right)(25)(21.257 P_1) = 265.713 P_1 \\
 A_2 &= \left(\frac{1}{2}\right)(27)(4.042 P_1) = 54.567 P_1 \\
 A_3 &= (27)(17.215 P_1) = 464.805 P_1 \\
 A_4 &= \left(\frac{1}{2}\right)(115)(4.103 P_1) = 240.523 P_1
 \end{aligned}$$

$$\Sigma = 1025.608 P_1$$

$$\begin{aligned}
 V_A &= \left[(265.713 P_1) \left(\frac{2}{3} \right) (25) + (54.567 P_1) \left(25 + \frac{27}{3} \right) + (464.805 P_1) \left(25 + \frac{27}{2} \right) \right. \\
 &\quad \left. + (240.523 P_1) \left(52 + \frac{115}{3} \right) \right] \div 167 \\
 &= 274.887 P_1
 \end{aligned}$$

$$\begin{aligned}
 V_B &= \left[(240.523 P_1) \left(\frac{2}{3} \right) (115) + (464.805 P_1) \left(115 + \frac{27}{2} \right) \right. \\
 &\quad \left. + (54.567 P_1) \left(115 + \frac{2}{3} (27) \right) + (265.713 P_1) \left(142 + \frac{25}{3} \right) \right] \div 167 \\
 &= 750.721 P_1
 \end{aligned}$$

$$274.887 P_1 + 750.721 P_1 = 1025.608 P_1$$

$$\Delta_1 = \frac{(750.721 P_1)(25) - (265.713 P_1) \left(\frac{25}{3} \right)}{EI_2} = \frac{16636.93 P_1}{E}$$

$$A_1 = (42)(4.678 P) = 196.467 P$$

$$A_2 = \left(\frac{1}{2}\right)(42)(2.111 P) = 44.331 P$$

$$A_3 = \frac{1}{2}(115)(1.137 P) = 65.377 P$$

$$E = 306.186 P$$

$$V_A = \frac{(196.467 P)(52)(\frac{1}{2}) + (44.331 P)(\frac{52}{3}) + (65.377 P)(52 + \frac{115}{3})}{167}$$

$$V_A = 70.553 P$$

$$V_B = \frac{(65.377 P)(\frac{2}{3})(115) + (44.331 P)(115 + (\frac{2}{3})(52)) + (196.467 P)(115 + \frac{52}{2})}{167}$$

$$V_B = 235.633 P \quad 70.553 + 235.633 = 306.186$$

$$\Delta_1 = \frac{(235.633 P)(25) - (25)(5.773 P)(\frac{25}{2}) - (\frac{1}{2})(25)(1.016 P)(\frac{2}{3})(25)}{EI_2}$$

$$\Delta_1 = \frac{-3894.57 P}{E}$$

$$(.850)(6.789 P) = 5.773 P$$

$$\Delta_{TOTAL} = \frac{16636.93 P - 3894.57 P}{E}$$

$$\Delta_{TOTAL} = \frac{12742.36}{E}$$

Δ_1 'S DUE TO LOADS $P_1, P_3, \dots, P_6$

$$\frac{I_2}{I_1} = \frac{.995}{4.091} = .243$$

$$A_1 = \left(\frac{1}{2}\right)(52)(.311M) = 8.086M$$

$$A_2 = (52)(.689M) = 35.828M$$

$$A_3 = \left(\frac{1}{2}\right)(115)(.167M) = 9.603M$$

$$\Sigma = 53.517M$$

$$V_B = \frac{(9.603M)\left(\frac{2}{3}(115)\right) + (35.828M)\left(115 + \frac{52}{2}\right) + (8.086M)\left(115 + \left(\frac{2}{3}\right)52\right)}{167}$$

$$V_B = 41.905M$$

$$V_A = \frac{(8.086M)\left(52\left(\frac{1}{3}\right)\right) + (35.828M)\left(52\left(\frac{1}{2}\right)\right) + (9.603M)\left(52 + \frac{115}{2}\right)}{167}$$

$$V_A = 11.612M$$

$$41.905 + 11.612 = 53.517$$

$$\Delta_1 = \frac{(41.905M)(25) - (.850M)\left(\frac{(25)^2}{2}\right) - \left(\frac{1}{2}\right)(.150M)\left(\frac{2}{3}(25)^2\right)}{EI_2}$$

$$\Delta_1 = \frac{754.523M}{E}$$

GENERAL EQ.
FOR DEFL. AT
POINT 1 DUE
TO LOADS AT
POINTS 2-6

$$\Delta_1 = 754.523 \text{ MB} / E$$

See Pp 13, 14, & 15 FOR VALUES OF MB

$$\Delta_1 = \frac{754.523}{E} (6.718 P_2) = \frac{5068.986}{E} P_2$$

$$\Delta_1 = \frac{754.523}{E} (-22.332 P_3) = -\frac{16850.008}{E} P_3$$

$$\Delta_1 = \frac{754.523}{E} (-30.181 P_4) = -\frac{22772.259}{E} P_4$$

$$\Delta_1 = \frac{754.523}{E} (26.251 P_5) = \frac{19806.993}{E} P_5$$

$$\Delta_1 = \frac{754.523}{E} (-18.687 P_6) = -\frac{14099.771}{E} P_6$$

$$\Delta'_{1c} = \frac{754.523}{E} (111.19 \times 10^{-6} E \theta'_{1c}) = -8.3895 \theta'_{1c}$$

DEFLECTION AT
OTHER POINTS DUE TO LOAD AT P_1

$$\Delta L = \frac{M}{6EI_2} \left(3x^2 - \frac{x^3}{L} - 2Lx \right) \quad \Delta \text{'S DUE TO END MOMENT AT B}$$

$$\Delta_2 = \underset{X=1}{(6.785 \text{ P}_1)} \underset{E}{(-824.547)} = -5594.551 \underset{E}{\text{P}_1}$$

$$\Delta_2 = \frac{(6.785 \text{ P})(-2741.304)}{E} = -18599.748 \frac{\text{P}}{E}$$

$$\Delta_0 = (6.785 \text{ P})(\frac{-3530.187}{E}) = -23952.39 \frac{\text{P}}{E}$$

$$\Delta_1 = (6.785 \frac{P_1(-3704.746)}{E}) = -25136.702 \frac{P_1}{E}$$

$$\Delta G = (6.785 \text{ P}) \left(- \frac{3262.510}{E} \right) = -22136.130 \frac{\text{P}}{E}$$

$x=143$

$$\Delta_s = (6.705 \text{ P}) - \frac{2293.844}{E} = -15563.732 \text{ P}$$

DEFLECTION AT
OTHER POINTS DUE TO LOAD AT P_2

$$\Delta = \frac{M}{6EI_2} \left(3x^2 - \frac{x^3}{L} - 2Lx \right) \quad \Delta \text{'s DUE TO END MOMENT AT B}$$

$$\Delta_2 = \frac{(-6.718 P_2)(-824.547)}{E} = 5539.307 \frac{P_2}{E}$$

$x = 11$

$$\Delta_3 = \frac{(-6.718 P_2)(-2741.304)}{E} = 18416.080 \frac{P_2}{E}$$

$x = 41$

$$\Delta_0 = \frac{(-6.718 P_2)(-3530.187)}{E} = 23715.796 \frac{P_2}{E}$$

$x = 77$

$$\Delta_4 = \frac{(-6.718 P_2)(-3704.746)}{E} = 24888.484 \frac{P_2}{E}$$

$x = 107$

$$\Delta_5 = \frac{(-6.718 P_2)(-3262.510)}{E} = 21917.542 \frac{P_2}{E}$$

$x = 143$

$$\Delta_6 = \frac{(-6.718 P_2)(-2293.844)}{E} = 15410.044 \frac{P_2}{E}$$

$x = 179$

DEFLECTION AT
OTHER POINTS DUE TO LOAD AT P_2

$$I_2 = 995 \text{ in}^4$$

$$L = 240 \text{ in}$$

$$\textcircled{1} \text{ (B TO } P_2) \Delta = \frac{Pbx}{6EIL} [2L(L-x) - b^2 - (L-x)^2]$$

$$\textcircled{2} \text{ (} P_2 \text{ TO C)} \Delta = \frac{Pa(L-x)}{6EIL} [2Lb - b^2 - (L-x)^2]$$

$$\text{Eq. } \textcircled{1} \Delta_2 = -\frac{P_2(229)(11)}{(6)(995)(240)E} [(480)(229) - (229)^2 - 52441] = -8857.208 \frac{P_2}{E}$$

$x=11$

$$\textcircled{2} \Delta_3 = -\frac{P_2(11)(193)}{1432.80E} [(480)(229) - (229)^2 - 37249] = -29974.993 \frac{P_2}{E}$$

$x=47$

$$\textcircled{3} \Delta_4 = -\frac{P_2(11)(163)}{1432.80E} [(480)(229) - (229)^2 - 26596] = -38646.859 \frac{P_2}{E}$$

$x=77$

$$\textcircled{4} \Delta_5 = -\frac{P_2(11)(133)}{1432.80E} [(480)(229) - (229)^2 - 17689] = -40623.678 \frac{P_2}{E}$$

$x=107$

$$\textcircled{5} \Delta_6 = -\frac{P_2(11)(97)}{1432.80E} [(480)(229) - (229)^2 - 9409] = -35797.522 \frac{P_2}{E}$$

$x=143$

$$\textcircled{6} \Delta_7 = -\frac{P_2(11)(61)}{1432.80E} [(480)(229) - (229)^2 - 1849] = -26052.296 \frac{P_2}{E}$$

$x=179$

DEFLECTION AT
OTHER POINTS DUE TO LOAD AT P_3

$$\Delta_L = \frac{M}{6EI_2} \left(3x^2 - \frac{x^3}{L} - 2Lx \right) \quad \Delta's \text{ DUE TO END MOMENT AT B}$$

$$\Delta_2 = \left(22,332 P_3 \right) \left(\frac{-824.547}{E} \right) = -18413.784 \frac{P_3}{E}$$

$x = 11$

$$\Delta_3 = \left(22,332 P_3 \right) \left(\frac{-2741.304}{E} \right) = -61218.801 \frac{P_3}{E}$$

$x = 47$

$$\Delta_4 = \left(22,332 P_3 \right) \left(\frac{-3530.187}{E} \right) = -78836.136 \frac{P_3}{E}$$

$x = 77$

$$\Delta_5 = \left(22,332 P_3 \right) \left(\frac{-3704.746}{E} \right) = -82734.398 \frac{P_3}{E}$$

$x = 107$

$$\Delta_6 = \left(22,332 P_3 \right) \left(\frac{-3262.510}{E} \right) = 72858.373 \frac{P_3}{E}$$

$x = 143$

$$\Delta_7 = \left(22,332 P_3 \right) \left(\frac{-2293.844}{E} \right) = 51226.124 \frac{P_3}{E}$$

$x = 179$

DEFLECTION AT
OTHER POINTS DUE TO LOAD AT P_3

$$I_2 = 995 \text{ in}^4$$

$$L = 240 \text{ in}$$

$$\textcircled{1} \text{ (B TO P)} \quad \Delta = \frac{Pbx}{6EIL} [2L(L-x) - b^2 - (L-x)^2]$$

$$\textcircled{2} \text{ (P TO C)} \quad \Delta = \frac{Pa(L-x)}{6EIL} [2Lb - b^2 - (L-x)^2]$$

$$\textcircled{1} \Delta_2 = \frac{P_3(193)(11)}{(6)(995)(240)E} [(480)(229) - (193)^2 - 52441] = \frac{29975.077}{E} P_3$$

$x=11$

$$\textcircled{1} \Delta_3 = \frac{P_3(193)(47)}{1432.80E} [(480)(193) - (193)^2 - 37249] = \frac{116641.613}{E} P_3$$

$x=47$

$$\textcircled{2} \Delta_4 = \frac{P_3(47)(163)}{1432.80E} [(480)(193) - (193)^2 - 26596] = \frac{153963.215}{E} P_3$$

$x=77$

$$\textcircled{2} \Delta_5 = \frac{P_3(47)(133)}{1432.80E} [(480)(193) - (193)^2 - 17609] = \frac{104485.763}{E} P_3$$

$x=107$

$$\textcircled{2} \Delta_6 = \frac{P_3(47)(97)}{1432.80E} [(480)(193) - (193)^2 - 9409] = \frac{146309.281}{E} P_3$$

$x=143$

$$\textcircled{2} \Delta_6 = \frac{P_3(47)(61)}{1432.80E} [(480)(193) - (193)^2 - 1849] = \frac{107136.316}{E} P_3$$

$x=179$

DEFLECTION AT
OTHER POINTS DUE TO LOAD AT P_4

$$\Delta_L = \frac{M}{6EI_2} \left(3x^2 - \frac{x^3}{L} - 2Lx \right) \quad \Delta's \text{ DUE TO END MOMENT AT B}$$

$$\Delta_2 = \left(30.181 P_4 \right) \left(\frac{-824.547}{E} \right) = -24885.653 \frac{P_4}{E}$$

$x=11$

$$\Delta_3 = \left(30.181 P_4 \right) \left(\frac{-2741.304}{E} \right) = -82735.296 \frac{P_4}{E}$$

$x=47$

$$\Delta_0 = \left(30.181 P_4 \right) \left(\frac{-3530.187}{E} \right) = -106544.574 \frac{P_4}{E}$$

$x=77$

$$\Delta_4 = \left(30.181 P_4 \right) \left(\frac{-3704.746}{E} \right) = -111812.939 \frac{P_4}{E}$$

$x=107$

$$\Delta_5 = \left(30.181 P_4 \right) \left(\frac{-3262.510}{E} \right) = -98465.814 \frac{P_4}{E}$$

$x=143$

$$\Delta_6 = \left(30.181 P_4 \right) \left(\frac{-2293.844}{E} \right) = -69230.506 \frac{P_4}{E}$$

$x=179$

DEFLECTION AT
OTHER POINTS DUE TO LOAD AT P_4

$$I_2 = 995 \text{ IN}^4$$

$$L = 240 \text{ IN}$$

$$\textcircled{1} \text{ (B TO P)} \quad \Delta = \frac{Pbx}{6EIL} [2L(L-x) - b^2 - (L-x)^2]$$

$$\textcircled{2} \text{ (P TO C)} \quad \Delta = \frac{Pa(L-x)}{6EIL} [2Lb - b^2 - (L-x)^2]$$

Eq

$$\textcircled{1} \quad \Delta_2 = \frac{P_4(133)(11)}{(6)(995)(240) E} [(480)(229) - (133)^2 - 52441] = \frac{40628.678}{E} \frac{P_4}{E}$$

$x=11$

$$\textcircled{1} \quad \Delta_3 = \frac{P_4(133)(47)}{1432.80 E} [(480)(193) - (133)^2 - 37249] = \frac{164485.713}{E} \frac{P_4}{E}$$

$x=47$

$$\textcircled{1} \quad \Delta_4 = \frac{P_4(133)(77)}{1432.80 E} [(480)(163) - (133)^2 - 26596] = \frac{242694.832}{E} \frac{P_4}{E}$$

$x=77$

$$\textcircled{1} \quad \Delta_4 = \frac{P_4(133)(107)}{1432.80 E} [(480)(133) - (133)^2 - 17689] = \frac{282693.133}{E} \frac{P_4}{E}$$

$x=107$

$$\textcircled{1} \quad \Delta_5 = \frac{P_4(107)(97)}{1432.80 E} [(480)(133) - (133)^2 - 9409] = \frac{266153.837}{E} \frac{P_4}{E}$$

$x=143$

$$\textcircled{1} \quad \Delta_6 = \frac{P_4(107)(61)}{1432.80 E} [(480)(133) - (133)^2 - 1849] = \frac{201814.038}{E} \frac{P_4}{E}$$

$x=179$

DEFLECTION AT
OTHER POINTS DUE TO LOAD AT P_5

$$I_2 = .995 \text{ in}^4$$

$$L = 240 \text{ in}$$

$$\Delta_1 = \frac{M}{6EI_2} \left(3x^2 - \frac{x^3}{L} - 2Lx \right) \quad \Delta \text{'s DUE TO END MOMENT AT B}$$

$$\Delta_2 = \frac{(-26.251 P_5)(-824.547)}{E} = \frac{21645.183 P_5}{E}$$

$x = 11$

$$\Delta_3 = \frac{(-26.251 P_5)(-2741.304)}{E} = \frac{71961.971 P_5}{E}$$

$x = 47$

$$\Delta_4 = \frac{(-26.251 P_5)(-3530.187)}{E} = \frac{92670.939 P_5}{E}$$

$x = 77$

$$\Delta_5 = \frac{(-26.251 P_5)(-3704.746)}{E} = \frac{97253.287 P_5}{E}$$

$x = 107$

$$\Delta_6 = \frac{(-26.251 P_5)(-3262.510)}{E} = \frac{85644.150 P_5}{E}$$

$x = 143$

$$\Delta_7 = \frac{(-26.251 P_5)(-2293.844)}{E} = \frac{60215.699 P_5}{E}$$

$x = 179$

DEFLECTION AT
OTHER POINTS DUE TO LOAD AT P_5

$$I_2 = .995 \text{ in}^4$$

$$L = 240 \text{ in}$$

$$\textcircled{1} (B \text{ to } P) \quad \Delta = \frac{Pbx}{6EIL} [2L(L-x) - b^2 - (L-x)^2]$$

$$\textcircled{2} (P \text{ to } C) \quad \Delta = \frac{Pa(L-x)}{6EIL} [2Lb - b^2 - (L-x)^2]$$

$$\textcircled{1} \Delta_2 = \frac{P_5(97)(11)}{(6)(.995)(240)E} [(480)(229) - (97)^2 - 52441] = \frac{-35797.522}{E} P_5$$

$$\textcircled{2} \Delta_3 = \frac{P_5(97)(47)}{1432.80E} [(480)(193) - (97)^2 - 37249] = \frac{146309.280}{E} P_5$$

$$\textcircled{3} \Delta_4 = \frac{P_5(97)(77)}{1432.80E} [(480)(163) - (97)^2 - 26596] = \frac{220165.560}{E} P_5$$

$$\textcircled{4} \Delta_5 = \frac{P_5(97)(107)}{1432.80E} [(480)(133) - (97)^2 - 17689] = \frac{266153.837}{E} P_5$$

$$\textcircled{5} \Delta_6 = \frac{P_5(97)(143)}{1432.80E} [(480)(97) - (97)^2 - 9409] = \frac{268571.525}{E} P_5$$

$$\textcircled{6} \Delta_7 = \frac{P_5(143)(61)}{1432.80E} [(480)(97) - (97)^2 - 1849] = \frac{214921.374}{E} P_5$$

DEFLECTION

AT OTHER POINTS DUE TO LOAD AT P_6

Δ

$$\Delta_L = \frac{M}{6EI_2} \left(3x^2 - \frac{x^3}{L} - 2Lx \right) \quad \Delta \text{'s DUE TO END MOMENT AT B}$$

$$\Delta_2 = \left(18.687 P_6 \right) \left(\frac{-824.547}{E} \right) = -15408.310 \frac{P_6}{E}$$

$x=11$

$$\Delta_3 = \left(18.687 P_6 \right) \left(\frac{-2741.304}{E} \right) = -51226.748 \frac{P_6}{E}$$

$x=47$

$$\Delta_0 = \left(18.687 P_6 \right) \left(\frac{-3530.187}{E} \right) = -65968.604 \frac{P_6}{E}$$

$x=77$

$$\Delta_4 = \left(18.687 P_6 \right) \left(\frac{-3704.746}{E} \right) = -69230.589 \frac{P_6}{E}$$

$x=107$

$$\Delta_5 = \left(18.687 P_6 \right) \left(\frac{-3262.510}{E} \right) = -60966.524 \frac{P_6}{E}$$

$x=143$

$$\Delta_6 = \left(18.687 P_6 \right) \left(\frac{-2293.844}{E} \right) = -42865.063 \frac{P_6}{E}$$

$x=179$

DEFLECTION

AT OTHER POINTS DUE TO LOAD AT P_0

$$I_2 = 995 \text{ in}^4$$

$$L = 240 \text{ in}$$

$$\textcircled{1} (B \text{ TO } P) \Delta = \frac{P_0 b x}{6 E I L} [2 L (L - x) - b^2 - (L - x)^2]$$

$$\textcircled{2} (P \text{ TO } C) \Delta = \frac{P_0 a (L - x)}{6 E I L} [2 L b - b^2 - (L - x)^2]$$

$$\textcircled{1} \Delta_2 = \frac{P_0 (61) (11)}{(6) (995) (240) E} \left[(480) (229) - (61)^2 - 52441 \right] = \frac{25175.613}{E} P_0$$

$x = 11$

$$\textcircled{1} \Delta_3 = \frac{P_0 (61) (47)}{1432.80 E} \left[(480) (193) - (61)^2 - 37249 \right] = \frac{103390.487}{E} P_0$$

$x = 47$

$$\textcircled{1} \Delta_0 = \frac{P_0 (61) (77)}{1432.80 E} \left[(480) (163) - (61)^2 - 26596 \right] = \frac{157101.012}{E} P_0$$

$x = 77$

$$\textcircled{1} \Delta_4 = \frac{P_0 (61) (107)}{1432.80 E} \left[(480) (133) - (61)^2 - 17689 \right] = \frac{193286.299}{E} P_0$$

$x = 107$

$$\textcircled{1} \Delta_5 = \frac{P_0 (61) (143)}{1432.80 E} \left[(480) (97) - (61)^2 - 9409 \right] = \frac{203524.490}{E} P_0$$

$x = 143$

$$\textcircled{1} \Delta_6 = \frac{P_0 (61) (179)}{1432.80 E} \left[(480) (61) - (61)^2 - 1849 \right] = \frac{180637.807}{E} P_0$$

$x = 179$

INSULATION JACKET DEFLECTION
DUE TO LOAD AND MOMENTS.

	LOAD AT						INITIAL
	P ₁	P ₂	P ₃	P ₄	P ₅	P ₆	DEFL
LOAD	16636.93	-	-	-	-	-	
MOM.	-3894.51	5068.89	-16850.01	-22772.26	19806.98	-14099.77	
$\Delta_1 E$	12742.36	5068.89	-16850.01	-22772.26	19806.98	-14099.77	-8.38950%
LOAD	-	8857.29	29975.08	40628.68	-35797.52	25175.61	
MOM.	-5594.55	5539.31	-18413.78	-24885.65	21645.18	-15408.31	
$\Delta_2 E$	-5594.55	-3317.98	11561.30	15743.03	-14152.34	9767.30	5.81650%
LOAD	-	-29974.99	116641.61	164485.76	-146309.28	103390.49	
MOM.	-18599.75	18416.08	-61218.80	-82735.30	71961.97	-51226.75	
$\Delta_3 E$	-18599.75	-11558.91	55422.81	81750.46	-74347.31	52163.74	33.50060%
LOAD	-	-40628.68	164485.76	282693.13	-266153.84	193286.30	
MOM.	-25136.70	24888.48	-82734.39	-111812.94	97253.29	-69230.59	
$\Delta_4 E$	-25136.70	-15740.20	81751.37	170880.19	-168900.55	124055.71	44.29060%
LOAD	-	-35797.52	146309.28	266153.84	-268571.53	203524.49	
MOM.	-22136.13	21917.54	-72858.37	-98465.81	85644.15	-60966.52	
$\Delta_5 E$	-22136.13	-13879.98	73450.91	167688.03	-182927.38	142557.97	26.18280%
LOAD	-	-26052.30	107136.32	201814.04	-214921.37	180687.81	
MOM.	-15563.73	15410.04	-51226.12	-69230.51	60215.70	-42865.06	
$\Delta_6 E$	-15563.73	-10642.26	55910.20	132583.53	-154705.67	137822.75	13.78630%
							Pc. 12
LOAD	-	-38646.86	153963.22	242694.83	-220165.56	157101.01	
MOM.	-23952.32	23715.80	-78836.14	-106544.57	92670.94	-65968.60	
$E \Delta_0$	-23952.32	-14931.06	75127.08	136150.26	-127494.62	91132.41	41.55360%
							+ Δ''_{1c}

LOAD COEFFICIENTS FOR PRESSURE TUBE LOAD AT P_1

$$L = 426''$$

$$\frac{I_2}{I_1} = \frac{1.028}{4.013} = .256$$

$$\frac{(P)(142)(284)}{426} = 94.7P$$

NOTE: MOM. DIAG.
INVERTED

$$(94.7P) \left(\frac{110}{142} \right) = 73.4P$$

$$(.256)(73.4P) = 18.8P$$

$$\begin{aligned} A_1 &= \left(\frac{1}{2} \right) (284) (94.7P) = 13447.4P \\ A_2 &= \left(\frac{1}{2} \right) (32) (21.3P) = 304.8P \\ A_3 &= \left(\frac{1}{2} \right) (32) (73.4P) = 2348.8P \\ A_4 &= \left(\frac{1}{2} \right) (110) (18.8P) = 1034.0P \\ \Sigma &= 17171.0P \end{aligned}$$

$$\begin{aligned} \bar{X}_B &= \left[(13447.4P) \left(\frac{2}{3} \right) (284) \right] + \left(304.8P \right) \left(284 + \frac{32}{3} \right) \\ &+ \left(2348.8P \right) \left(284 + \frac{32}{2} \right) + \left(1034.0P \right) \left(284 + 32 + \frac{110}{3} \right) \div 17171.0P \\ &= 215.8 \end{aligned}$$

$$V_A = \frac{(17171.0P)(215.8)}{426} = 8698.4P$$

$$V_B = \frac{(17171.0P)(426 - 215.8)}{426} = 8472.6P$$

DEFLECTION AT OTHER POINTS DUE TO LOAD AT P_1

$$A_2 = \left(\frac{1}{2}\right)(94.7P_1)(284) = 13447.4P_1$$

$$\Delta_1 = \frac{[(8472.6P_1)(284) - (13447.4P_1)(94.7)]}{1.028E}$$

$$= -1.101897 \times 10^6 \frac{P_1}{E}$$

$$A_2 = \left(\frac{1}{2}\right)(82.7P_1)(248) = 10254.8P_1$$

$$\Delta_2 = \frac{[(8472.6P_1)(248) - (10254.8P_1)(82.7)]}{1.028E}$$

$$= -1.219000 \times 10^6 \frac{P_1}{E}$$

$$A = \left(\frac{1}{2}\right)(71.0P_1)(212) = 7420.0P_1$$

$$\Delta_3 = \frac{[(8472.6P_1)(212) - (7420.0P_1)(70.7)]}{1.028E}$$

$$= -1.236962 \times 10^6 \frac{P_1}{E}$$

$$A = \left(\frac{1}{2}\right)(60.9 P)(182) = 5541.9 P$$

$$\Delta_0 = - \left[\frac{(8472.6 P)(182) - (5541.9 P)(60.6)}{1.028 E} \right]$$

$$= - 1.173321 \times 10^6 \frac{P}{E}$$

$$A_2 = \left(\frac{1}{2}\right)(50.7 P)(152) = 3853.2 P$$

$$\Delta_4 = - \left[\frac{(8472.6 P)(152) - (3853.2 P)(50.7)}{1.028 E} \right]$$

$$= - 1.062721 \times 10^6 \frac{P}{E}$$

$$A = \left(\frac{1}{2}\right)(38.7 P)(116) = 2244.6 P$$

$$\Delta_5 = - \left[\frac{(8472.6 P)(116) - (2244.6 P)(38.7)}{1.028 E} \right]$$

$$\Delta_5 = - .871552 \times 10^6 \frac{P}{E}$$

$$A_2 = \left(\frac{1}{2}\right)(26.7 P)(80) = 1068.0 P$$

$$\Delta_6 = - \left[\frac{(8472.6 P)(80) - (1068.0 P)(26.7)}{1.028 E} \right] = -.631607 \times 10^6 \frac{P}{E}$$

LOAD COEFFICIENTS FOR PRESSURE TUBE LOAD AT P_2

$$L = 426''$$

$$\frac{(P_2)(178)(248)}{426} = 103.6 P_2$$

$$\left(\frac{110}{178}\right) 103.6 P_2 = 64.0 P_2$$

$$(0.256)(64.0 P_2) = 16.4 P_2$$

$$\begin{aligned} A_1 &= \left(\frac{1}{2}\right) (103.6 P_2) (248) = 12846.4 P_2 \\ A_2 &= \left(\frac{1}{2}\right) (39.6 P_2) (68) = 1346.4 P_2 \\ A_3 &= (64.0 P_2) (68) = 4352.0 P_2 \\ A_4 &= \left(\frac{1}{2}\right) (16.4 P_2) (110) = 902.0 P_2 \\ \Sigma &= 19446.8 P_2 \end{aligned}$$

$$\begin{aligned} \bar{X}_B &= \left[(12846.4 P_2) \left(\frac{2}{3}\right) (248) + (1346.4 P_2) \left(248 + \frac{68}{3}\right) \right. \\ &\quad \left. + (4352.0 P_2) \left(248 + \frac{68}{2}\right) + (902.0 P_2) \left(248 + 68 + \frac{110}{3}\right) \right] \div 19446.8 P_2 \\ &= 207.4 \end{aligned}$$

$$V_A = \frac{(19446.8 P_2)(207.4)}{426} = 9467.8 P_2$$

$$V_B = \frac{(19446.8 P_2)(426 - 207.4)}{426} = 9979.0 P_2$$

DEFL. AT OTHER POINTS DUE TO LOAD AT P_2

$$A_1 = \left(\frac{1}{2}\right)(18.6 P_2)(32) = 297.6 P_2$$

$$A_2 = (64.0 P_2)(32) = 2048.0 P_2$$

$$A_3 = \left(\frac{1}{2}\right)(16.4 P_2)(110) = 902.0 P_2$$

$$\Delta_1 = \left[(9467.8 P_2)(142) - (297.6 P_2)\left(\frac{32}{3}\right) - (2048.0 P_2)\left(\frac{32}{2}\right) - (902.0 P_2)\left(32 + \frac{110}{3}\right) \right] \div 1.028 E$$

$$\Delta_1 = 1.212595 \times 10^6 \frac{P_2}{E}$$

$$\left(\frac{142}{178}\right) 103.6 P_2 = 82.6 P_2$$

$$A_2 = \left(\frac{1}{2}\right)(103.6 P_2)(248) = 12846.4 P_2$$

$$\Delta_2 = \left[(9979.0 P_2)(248) - (12846.4 P_2)(82.7) \right] \div 1.028 E$$

$$= 1.3713925 \times 10^6 \frac{P_2}{E}$$

$$\left(\frac{212}{248}\right) 103.6 P_2 = 88.6 P_2$$

$$A_2 = \left(\frac{1}{2}\right)(212)(88.6 P_2) = 9391.6 P_2$$

$$\Delta_3 = \left[(9979.0 P_2)(212) - (9391.6 P_2)(70.7) \right] \div 1.028 E$$

$$= 1.412025 \times 10^6 \frac{P_2}{E}$$

$$A = \left(\frac{1}{2}\right)(182)(76.0 P_2) = 6916.0 P_2$$

$$\Delta_0 = \frac{[(9979.0 P_2)(182) - (6916.0 P_2)(60.2)]}{1.028 E}$$

$$= 1.358343 \times 10^6 \frac{P_2}{E}$$

$$A = \left(\frac{1}{2}\right)(152)(63.5 P_2) = 4826.0 P_2$$

$$\Delta_4 = \frac{[(9979.0 P_2)(152) - (4826.0 P_2)(50.7)]}{1.028 E}$$

$$= 1.237480 \times 10^6 \frac{P_2}{E}$$

$$A = \left(\frac{1}{2}\right)(116)(48.5 P_2) = 2813.0 P_2$$

$$\Delta_5 = \frac{[(9979.0 P_2)(116) - (2813.0 P_2)(38.7)]}{1.028 E}$$

$$= 1.020132 \times 10^6 \frac{P_2}{E}$$

$$A = \left(\frac{1}{2}\right)(80)(34.5 P_2) = 1380.0 P_2$$

$$\Delta_6 = \frac{[(9979.0 P_2)(80) - (1380.0 P_2)(26.7)]}{1.028 E} = 740733 \times 10^6 \frac{P}{E}$$

LOAD COEFFICIENTS FOR PRESSURE TUBE LOAD AT P_3

$$L = 426''$$

$$\frac{(P_3)(214)(212)}{426} = 106.5P_3$$

$$\frac{I_2}{I_1} = \frac{1.028}{4.013} = .256$$

$$\text{NOTE: MOM } \left(\frac{110}{214}\right) 106.5P_3 = 54.7P_3$$

$$(.256)(54.7P_3) = 14.0P_3$$

$$\begin{aligned} A_1 &= \left(\frac{1}{2}\right)(212)(106.5P_3) = 11289.0 P_3 \\ A_2 &= \left(\frac{1}{2}\right)(104)(51.8P_3) = 2693.6 P_3 \\ A_3 &= (104)(54.7P_3) = 5688.8 P_3 \\ A_4 &= \left(\frac{1}{2}\right)(110)(14.0P_3) = 770.0 P_3 \\ \Sigma &= 20441.4 P_3 \end{aligned}$$

$$\begin{aligned} \bar{X}_B &= \left[(11289.0 P_3) \left(\frac{2}{3}\right)(212) + (2693.6 P_3) \left(212 + \frac{104}{3}\right) \right. \\ &\quad \left. + (5688.8 P_3) \left(212 + \frac{104}{2}\right) + (770.0 P_3) \left(212 + 104 + \frac{110}{3}\right) \right] \div 20441.4 P_3 \\ &= 197.3 \end{aligned}$$

$$V_A = \frac{(20441.4 P_3)(197.3)}{426} = 9467.3 P_3$$

$$V_B = \frac{(20441.4 P_3)(426 - 197.3)}{426} = 10974.1 P_3$$

DEFL AT OTHER POINTS DUE TO LOAD AT P_3

$$A_1 = \left(\frac{1}{2}\right)(32)(16.0 P_3) = 256.0 P_3$$

$$A_2 = (32)(54.7 P_3) = 1750.4 P_3$$

$$A_3 = \left(\frac{1}{2}\right)(110)(14.0 P_3) = 770.0 P_3$$

$$\Delta_1 = - \left[(9467.3 P_3)(142) - (256.0 P_3)\left(\frac{32}{3}\right) - (1750.4 P_3)\left(\frac{32}{2}\right) - (770.0 P_3)\left(32 + \frac{110}{3}\right) \right] - 1.028E$$

$$\left(\frac{142}{214}\right) 106.5 P_3 = 70.7 P_3$$

$$= -1.226407 \times 10^6 \frac{P_3}{E}$$

$$A_1 = \left(\frac{1}{2}\right)(68)(33.9 P_3) = 1152.6 P_3$$

$$A_2 = (68)(54.7 P_3) = 3719.6 P_3$$

$$A_3 = \left(\frac{1}{2}\right)(110)(14.0 P_3) = 770.0 P_3$$

$$\Delta_2 = - \left[(9467.3 P_3)(178) - (1152.6 P_3)\left(\frac{68}{3}\right) - (3719.6 P_3)\left(\frac{68}{2}\right) - (770.0 P_3)\left(68 + \frac{110}{3}\right) \right] - 1.028E$$

$$\left(\frac{178}{214}\right) 106.5 P_3 = 88.6 P_3$$

$$= -1.412446 \times 10^6 \frac{P_3}{E}$$

$$A = \left(\frac{1}{2}\right)(212)(106.5 P_3) = 11289.0 P_3$$

$$\Delta_3 = - \frac{[(10974.1 P_3)(212) - (11289.0 P_3)(70.6)]}{1.028E}$$

$$= -1.487846 \times 10^6 \frac{P_3}{E}$$

$\left(\frac{182}{212}\right) 106.5 = 91.4 P_3$
 $A = \frac{1}{2} (182) (7407.4 P_3) = 6717.4 P_3$
 $\Delta_0 = \frac{[(10974.1 P_3)(182)] - (6717.4 P_3)(60.7)}{1.028 E}$
 $= -1.45177 \times 10^6 \frac{P_3}{E}$

$\left(\frac{152}{212}\right) 106.5 P_3 = 76.4 P_3$
 $A = \frac{1}{2} (152) (5806.4 P_3) = 4404.8 P_3$
 $\Delta_4 = \frac{[(10974.1 P_3)(152)] - (4404.8 P_3)(50.7)}{1.028 E}$
 $= -1.336263 \times 10^6 \frac{P_3}{E}$

$\left(\frac{116}{212}\right) 106.5 P_3 = 58.3 P_3$
 $A = \frac{1}{2} (116) (1608.0 P_3) = 940.8 P_3$
 $\Delta_5 = \frac{[(10974.1 P_3)(116)] - (940.8 P_3)(38.7)}{1.028 E}$
 $= -1.11027 \times 10^6 \frac{P_3}{E}$

$\left(\frac{80}{212}\right) 106.5 P_3 = 40.2 P_3$
 $A = \frac{1}{2} (80) (1608.0 P_3) = 643.2 P_3$
 $\Delta_6 = \frac{[(10974.1 P_3)(80)] - (643.2 P_3)(26.7)}{1.028 E} = -812251 \times 10^6 \frac{P_3}{E}$

LOAD COEFFICIENTS FOR PRESSURE TUBE LOAD AT P_4

$$L = 426''$$

$$\frac{(P_4)(152)(274)}{426} = 97.8 P_4$$

$$\left(\frac{110}{274}\right) 97.8 P_4 = 37.3 P_4$$

$$0.256(37.3 P_4) = 10.1 P_4$$

NOTE! MOM. DIAG.
INVERTED

$$\begin{aligned} A_1 &= \left(\frac{1}{2}\right) (97.8 P_4) (152) = 7432.8 P_4 \\ A_2 &= \left(\frac{1}{2}\right) (58.5 P_4) (164) = 4797.0 P_4 \\ A_3 &= (37.3 P_4) (164) = 6445.2 P_4 \\ A_4 &= \left(\frac{1}{2}\right) (10.1 P_4) (110) = 555.5 P_4 \\ \Sigma &= 19230.5 P_4 \end{aligned}$$

$$\begin{aligned} \bar{X}_B &= \left[(7432.8 P_4) \left(\frac{2}{3}\right) (152) \right] + \left(4797.0 P_4 \right) \left(152 + \frac{164}{3} \right) \\ &+ \left(6445.2 P_4 \right) \left(152 + \frac{164}{2} \right) + \left(555.5 P_4 \right) \left(152 + 164 + \frac{110}{3} \right) \div 19230.5 P_4 \\ &= 179.3 \end{aligned}$$

$$V_A = \frac{(19230.5 P_4)(179.3)}{426} = 8094.0 P_4$$

$$V_B = \frac{(19230.5 P_4)(426 - 179.3)}{426} = 11136.5 P_4$$

DEFLECTION AT
OTHER POINTS DUE TO LOAD AT P_4

$$A_1 = \left(\frac{1}{2}\right)(32)(11.4 P_4) = 182.4 P_4$$

$$A_2 = (32)(39.3 P_4) = 1257.6 P_4$$

$$A_3 = \left(\frac{1}{2}\right)(110)(10.1 P_4) = 555.5 P_4$$

$$\Delta_1 = - \left[(8094.0 P_4)(142) - (182.4 P_4)\left(\frac{32}{3}\right) - (1257.6 P_4)\left(\frac{32}{2}\right) - (555.5 P_4)\left(32 + \frac{110}{3}\right) \right] \div 1.028 E$$

$$\left(\frac{142}{274}\right) 97.8 P_4 = 50.7 P_4$$

$$= -1.059471 \times 10^6 \frac{P_4}{E}$$

$$A_1 = \left(\frac{1}{2}\right)(68)(24.2 P_4) = 822.8 P_4$$

$$A_2 = (68)(39.3 P_4) = 2672.4 P_4$$

$$A_3 = \left(\frac{1}{2}\right)(110)(10.1 P_4) = 555.5 P_4$$

$$\Delta_2 = - \left[(8094.0 P_4)(178) - (822.8 P_4)\left(\frac{68}{3}\right) - (2672.4 P_4)\left(\frac{68}{2}\right) - (555.5 P_4)\left(68 + \frac{110}{3}\right) \right] \div 1.028 E$$

$$\left(\frac{178}{274}\right) 97.8 P_4 = 63.5 P_4$$

$$= -1.238403 \times 10^6 \frac{P_4}{E}$$

$$A_1 = \left(\frac{1}{2}\right)(37.1 P_4)(104) = 1929.2 P_4$$

$$A_2 = (39.3 P_4)(104) = 4087.2 P_4$$

$$A_3 = \left(\frac{1}{2}\right)(110)(10.1 P_4) = 555.5 P_4$$

$$\Delta_3 = - \left[(8094.0 P_4)(214) - (1929.2 P_4)\left(\frac{104}{3}\right) - (4087.2 P_4)\left(\frac{104}{2}\right) - (555.5 P_4)\left(104 + \frac{110}{3}\right) \right] \div 1.028 E$$

$$\left(\frac{214}{274}\right) 97.8 P_4 = 76.4 P_4$$

$$= -1.337123 \times 10^6 \frac{P_4}{E}$$

$$A_1 = \frac{1}{2}(134)(47.8P_4) = 3202.6 P_4$$

$$A_2 = (134)(39.3P_4) = 5266.2 P_4$$

$$A_3 = \frac{1}{2}(110)(10.1P_4) = 555.5 P_4$$

$$\left(\frac{244}{274}\right) 97.8P_4 = 87.1P_4$$

$$\Delta_0 = - \left[\frac{(8094.0P_4)(244) - (3202.6P_4)\left(\frac{134}{3}\right) - (5266.2P_4)\left(\frac{134}{2}\right) - (555.5P_4)\left(134 + \frac{40}{3}\right)}{1.028E} \right]$$

$$= -1.346543 \times 10^6 \frac{P_4}{E}$$

$$A = \left(\frac{1}{2}\right)(152)(97.8P_4) = 7432.8 P_4$$

$$\Delta_4 = - \left[\frac{(11136.5P_4)(152) - (7432.8P_4)(50.7)}{1.028E} \right]$$

$$= -1.280063 \times 10^6 \frac{P_4}{E}$$

$$A = \left(\frac{1}{2}\right)(116)(74.6P_4) = 4326.8 P_4$$

$$\Delta_5 = - \left[\frac{(11136.5P_4)(116) - (4326.8P_4)(38.7)}{1.028E} \right]$$

$$= -1.093705 \times 10^6 \frac{P_4}{E}$$

$$A = \left(\frac{1}{2}\right)(80)(51.5P_4) = 2060.0 P_4$$

$$\Delta_6 = - \left[\frac{(11136.5P_4)(80) - (2060.0P_4)(26.7)}{1.028E} \right] = -813150 \times 10^6 \frac{P_4}{E}$$

LOAD COEFFICIENTS FOR PRESSURE TUBE LOAD AT P_5

$$L = 426''$$

$$\frac{(P_5)(116)(310)}{426} = 84.4 P_5$$

$$\left(\frac{116}{310}\right) 84.4 P_5 = 29.9 P_5$$

$$(.256)(29.9 P_5) = 7.7 P_5$$

$$A_1 = \left(\frac{1}{2}\right)(116)(84.4 P_5) = 4895.2 P_5$$

$$A_2 = \left(\frac{1}{2}\right)(200)(54.5 P_5) = 5450.0 P_5$$

$$A_3 = \left(\frac{1}{2}\right)(200)(29.9 P_5) = 5980.0 P_5$$

$$A_4 = \left(\frac{1}{2}\right)(110)(7.7 P_5) = 423.5 P_5$$

$$\Sigma = 16748.7 P_5$$

$$\begin{aligned} \bar{X}_B = & \left[(4895.2 P_5) \left(\frac{2}{3} (116) \right) + (5450.0 P_5) \left(116 + \frac{200}{3} \right) \right. \\ & \left. + (5980.0 P_5) \left(116 + \frac{200}{2} \right) + (423.5 P_5) \left(116 + 200 + \frac{110}{3} \right) \right] \div 16748.7 P_5 \\ = & 168.1 \end{aligned}$$

$$V_A = \frac{(16748.7 P_5)(168.1)}{426} = 6609.1 P_5$$

$$V_B = \frac{(16748.7 P_5)(426 - 168.1)}{426} = 10139.6 P_5$$

DEFLECTION AT OTHER POINTS DUE TO LOAD AT P_5

$$A_1 = \left(\frac{1}{2}\right)(32)(8.8 Ps) = 140.8 Ps$$

$$A_2 = (32)(29.9 Ps) = 956.8 Ps$$

$$A_3 = \left(\frac{1}{2}\right)(110)(7.7 Ps) = 423.5 Ps$$

$$\Delta_1 = \left[\frac{(6609.1 Ps)(142) - (140.8 Ps)\left(\frac{32}{3}\right) - (956.8 Ps)\left(\frac{32}{2}\right) - (423.5 Ps)\left(32 + \frac{110}{3}\right)}{1.028 E} \right]$$

$$= 0.868289 \times 10^{-6} \frac{Ps}{E}$$

$$A_1 = \left(\frac{1}{2}\right)(68)(18.6 Ps) = 632.4 Ps$$

$$A_2 = (68)(29.9 Ps) = 2033.2 Ps$$

$$A_3 = \left(\frac{1}{2}\right)(110)(7.7 Ps) = 423.5 Ps$$

$$\Delta_2 = \left[\frac{(6609.1 Ps)(178) - (632.4 Ps)\left(\frac{68}{3}\right) - (2033.2 Ps)\left(\frac{68}{2}\right) - (423.5 Ps)\left(68 + \frac{110}{3}\right)}{1.028 E} \right]$$

$$= 1.020068 \times 10^{-6} \frac{Ps}{E}$$

$$A_1 = \left(\frac{1}{2}\right)(104)(28.4 Ps) = 1476.8 Ps$$

$$A_2 = (104)(29.9 Ps) = 3109.6 Ps$$

$$A_3 = \left(\frac{1}{2}\right)(110)(7.7 Ps) = 423.5 Ps$$

$$\Delta_3 = \left[\frac{(6609.1 Ps)(214) - (1476.8 Ps)\left(\frac{104}{3}\right) - (3109.6 Ps)\left(\frac{104}{2}\right) - (423.5 Ps)\left(104 + \frac{110}{3}\right)}{1.028 E} \right]$$

$$= 1.110778 \times 10^{-6} \frac{Ps}{E}$$

$$A_1 = \left(\frac{1}{2}\right)(134)(36.5 \text{ Ps}) = 2445.5 \text{ Ps}$$

$$A_2 = (134)(29.9 \text{ Ps}) = 4006.6 \text{ Ps}$$

$$A_3 = \left(\frac{1}{2}\right)(110)(7.7 \text{ Ps}) = 423.5 \text{ Ps}$$

$$\Delta_0 = \left[(6609.1 \text{ Ps})(244) - (2445.5 \text{ Ps})\left(\frac{134}{3}\right) - (4006.6 \text{ Ps})\left(\frac{134}{2}\right) - (423.5 \text{ Ps})\left(134 + \frac{110}{3}\right) \right] \div 1.028 \text{ E}$$

$$= 1.131001 \times 10^6 \frac{\text{Ps}}{\text{E}}$$

$$A_1 = \left(\frac{1}{2}\right)(164)(44.7 \text{ Ps}) = 3665.4 \text{ Ps}$$

$$A_2 = (164)(29.9 \text{ Ps}) = 4903.6 \text{ Ps}$$

$$A_3 = \left(\frac{1}{2}\right)(110)(7.7 \text{ Ps}) = 423.5 \text{ Ps}$$

$$\Delta_4 = \left[(6609.1 \text{ Ps})(274) - (3665.4 \text{ Ps})\left(\frac{164}{3}\right) - (4903.6 \text{ Ps})\left(\frac{164}{2}\right) - (423.5 \text{ Ps})\left(164 + \frac{110}{3}\right) \right] \div 1.028 \text{ E}$$

$$= 1.092841 \times 10^6 \frac{\text{Ps}}{\text{E}}$$

$$A_2 = \left(\frac{1}{2}\right)(116)(84.4 \text{ Ps}) = 4895.2 \text{ Ps}$$

$$\Delta_5 = \left[(10139.6 \text{ Ps})(116) - (4895.2 \text{ Ps})(38.7) \right] \div 1.028 \text{ E}$$

$$= .959873 \times 10^6 \frac{\text{Ps}}{\text{E}}$$

$$A_2 = \left(\frac{1}{2}\right)(80)(58.2 \text{ Ps}) = 2328.0 \text{ Ps}$$

$$\Delta_6 = \left[(10139.6 \text{ Ps})(80) - (2328.0 \text{ Ps})(26.7) \right] \div 1.028 \text{ E} = .728609 \times 10^6 \frac{\text{Ps}}{\text{E}}$$

LOAD COEFFICIENTS FOR PRESSURE TUBE LOAD AT P_0

$$L = 426''$$

NOTE: MOM. DIAG.
INVERTED

$$\begin{aligned} A_1 &= \left(\frac{1}{2}\right) \times 80 \times \left\{ \begin{matrix} 65.0 P_0 \\ 44.3 P_0 \end{matrix} \right\} = 2600.0 P_0 \\ A_2 &= \left(\frac{1}{2}\right) \times 236 \times \left\{ \begin{matrix} 44.3 P_0 \\ 20.7 P_0 \end{matrix} \right\} = 5227.4 P_0 \\ A_3 &= \left(\frac{1}{2}\right) \times 236 \times \left\{ \begin{matrix} 20.7 P_0 \\ 5.3 P_0 \end{matrix} \right\} = 4885.2 P_0 \\ A_4 &= \left(\frac{1}{2}\right) \times 110 \times \left\{ \begin{matrix} 5.3 P_0 \end{matrix} \right\} = 291.5 P_0 \\ \Sigma &= 13004.1 P_0 \end{aligned}$$

$$\begin{aligned} \bar{X}_B &= \left[(2600.0 P_0) \left(\frac{2}{3} \times 80 \right) + (5227.4 P_0) \left(80 + \frac{236}{3} \right) \right. \\ &\quad \left. + (4885.2 P_0) \left(80 + \frac{236}{2} \right) + (291.5 P_0) \left(80 + 236 + \frac{110}{3} \right) \right] \div 13004.1 P_0 \\ &= 156.7 \end{aligned}$$

$$V_A = \frac{(13004.1 P_0)(156.7)}{426} = 4783.4 P_0$$

$$V_B = \frac{(13004.1 P_0)(426 - 156.7)}{426} = 8220.7 P_0$$

DEFL. AT OTHER POINTS DUE TO LOAD AT P_0

$$A_1 = \left(\frac{1}{2}\right)(32)(6.0 P_0) = 96.0 P_0$$

$$A_2 = (32)(20.7 P_0) = 662.4 P_0$$

$$A_3 = \left(\frac{1}{2}\right)(110)(5.3 P_0) = 291.5 P_0$$

$$\Delta_1 = - \left[(4783.4 P_0)(142) - (96.0 P_0)\left(\frac{32}{3}\right) - (662.4 P_0)\left(\frac{32}{2}\right) - (291.5 P_0)\left(32 + \frac{110}{3}\right) \right] \div 1.028 E$$

$$= - .621000 \times 10^6 \frac{P_0}{E}$$

$$A_1 = \left(\frac{1}{2}\right)(68)(12.7 P_0) = 431.8 P_0$$

$$A_2 = (68)(20.7 P_0) = 1407.6 P_0$$

$$A_3 = \left(\frac{1}{2}\right)(110)(5.3 P_0) = 291.5 P_0$$

$$\Delta_2 = - \left[(4783.6 P_0)(178) - (431.8 P_0)\left(\frac{68}{3}\right) - (1407.6 P_0)\left(\frac{68}{2}\right) - (291.5 P_0)\left(68 + \frac{110}{3}\right) \right] \div 1.028 E$$

$$= - .742534 \times 10^6 \frac{P_0}{E}$$

$$A_1 = \left(\frac{1}{2}\right)(104)(19.5 P_0) = 1014.0 P_0$$

$$A_2 = (104)(20.7 P_0) = 2152.8 P_0$$

$$A_3 = \left(\frac{1}{2}\right)(110)(5.3 P_0) = 291.5 P_0$$

$$\Delta_3 = - \left[(4783.6 P_0)(214) - (1014.0 P_0)\left(\frac{104}{3}\right) - (2152.8 P_0)\left(\frac{104}{2}\right) - (291.5 P_0)\left(104 + \frac{110}{3}\right) \right] \div 1.028 E$$

$$= - .812829 \times 10^6 \frac{P_0}{E}$$

$$A_1 = \left(\frac{1}{2}\right)(134)(25.1 P_0) = 1681.7 P_0$$

$$A_2 = (134)(20.7 P_0) = 2773.8 P_0$$

$$A_3 = \left(\frac{1}{2}\right)(110)(5.3 P_0) = 291.5 P_0$$

$$\Delta_0 = - \left[(4783.4 P_0)(244) - (1681.7 P_0) \left(\frac{134}{3} \right) - (2773.8 P_0) \left(\frac{134}{2} \right) - (291.5 P_0) \left(134 + \frac{44}{3} \right) \right] \div 1.028 E$$

$$= - .833113 \times 10^6 \frac{P_0}{E}$$

$$A_1 = \left(\frac{1}{2}\right)(164)(30.8 P_0) = 2525.6 P_0$$

$$A_2 = (164)(20.7 P_0) = 3394.8 P_0$$

$$A_3 = \left(\frac{1}{2}\right)(110)(5.3 P_0) = 291.5 P_0$$

$$\Delta_4 = - \left[(4783.4 P_0)(274) - (2525.6 P_0) \left(\frac{164}{3} \right) - (3394.8 P_0) \left(\frac{164}{2} \right) - (291.5 P_0) \left(164 + \frac{44}{3} \right) \right] \div 1.028 E$$

$$= - .812955 \times 10^6 \frac{P_0}{E}$$

$$A_1 = \left(\frac{1}{2}\right)(200)(37.5 P_0) = 3750.0 P_0$$

$$A_2 = (200)(20.7 P_0) = 4140.0 P_0$$

$$A_3 = \left(\frac{1}{2}\right)(110)(5.3 P_0) = 291.5 P_0$$

$$\Delta_5 = - \left[(4783.4 P_0)(310) - (3750.0 P_0) \left(\frac{200}{3} \right) - (4140.0 P_0) \left(\frac{200}{2} \right) - (291.5 P_0) \left(200 + \frac{110}{3} \right) \right] \div 1.028 E$$

$$= - .729441 \times 10^6 \frac{P_0}{E}$$

$$8220.7 P_0$$

$$A = \left(\frac{1}{2}\right)(65.0 P_0)(60) = 2600.0 P_0$$

$$\Delta_6 = \left[(8220.7 P_0)(60) - (2600.0 P_0)(26.7) \right] \div 1.028 E = .572214 \times 10^6 \frac{P_0}{E}$$

Continuity Equations

Insulation Jacket							Pressure Tube							
T = 300 F E = 26.8 × 10 ⁶ psi							T = 800 F E = 24.2 × 10 ⁶ psi							
$\Delta_1 + \Delta_1'$							=	$\Delta_1 + \Delta_1'$						
$\Delta_2 + \Delta_2'$							=	$\Delta_2 + \Delta_2'$						
$\Delta_3 + \Delta_3'$							=	$\Delta_3 + \Delta_3'$						
$\Delta_4 + \Delta_4'$							=	$\Delta_4 + \Delta_4'$						
$\Delta_5 + \Delta_5'$							=	$\Delta_5 + \Delta_5'$						
$\Delta_6 + \Delta_6'$							=	$\Delta_6 + \Delta_6'$						
P ₁	P ₂	P ₃	P ₄	P ₅	P ₆		P ₁	P ₂	P ₃	P ₄	P ₅	P ₆		
12,742.36	+ 5,068.89	- 16,850.01	- 22,772.26	+ 19,806.98	- 14,099.77	- 8.38958 _{IC} ^E	- 1,101,897	+ 1,212,595	- 1,226,407	- 1,059,471	+ 868,289	- 621,000	+ 121.2688 _{PT} ^E	
- 5,594.55	- 3,317.98	+ 11,561.30	+ 15,743.03	- 14,152.34	+ 9,767.30	+ 5.81658 _{IC} ^E	- 1,219,000	+ 1,373,925	- 1,412,446	- 1,238,403	+ 1,020,068	- 742,534	+ 152.0128 _{PT} ^E	
- 18,599.75	- 11,558.91	+ 55,422.81	+ 81,750.46	- 74,347.31	+ 52,163.74	+ 33.50068 _{IC} ^E	- 1,236,962	+ 1,412,025	- 1,487,846	- 1,337,123	+ 1,110,778	- 812,829	+ 182.7568 _{PT} ^E	
- 25,136.70	- 15,740.20	+ 81,751.37	+ 170,880.19	- 168,900.55	+ 124,055.71	+ 44.29068 _{IC} ^E	- 1,062,721	+ 1,237,480	- 1,336,263	- 1,280,063	+ 1,092,841	- 812,955	+ 174.1928 _{PT} ^E	
- 22,136.13	- 13,879.93	+ 73,450.91	+ 167,688.03	- 182,927.38	+ 142,557.97	+ 26.18288 _{IC} ^E	- 871,552	+ 1,020,137	- 1,111,027	- 1,093,705	+ 959,873	- 729,441	+ 132.9368 _{PT} ^E	
- 15,563.73	- 10,642.26	+ 55,910.20	+ 132,583.53	- 154,705.67	+ 137,822.75	+ 13.78638 _{IC} ^E	- 631,607	+ 740,733	- 812,251	- 813,150	+ 728,609	- 572,214	+ 91.6808 _{PT} ^E	
Rearranging,														
1,114,639	- 1,207,526	+ 1,209,557	+ 1,036,699	- 848,482	+ 606,900		=	121.2688 _{PT} ^E	+ 8.38958 _{IC} ^E					
1,213,405	- 1,377,243	+ 1,400,885	+ 1,254,146	- 1,034,220	+ 752,301		=	152.0128 _{PT} ^E	- 5.81658 _{IC} ^E					
1,218,362	- 1,423,584	+ 1,543,269	+ 1,418,873	- 1,185,125	+ 864,993		=	182.7568 _{PT} ^E	- 33.50068 _{IC} ^E					
1,037,584	- 1,253,220	+ 1,418,014	+ 1,450,943	- 1,261,742	+ 937,011		=	174.1928 _{PT} ^E	- 44.29068 _{IC} ^E					
849,416	- 1,034,017	+ 1,184,478	+ 1,261,393	- 1,142,800	+ 871,999		=	132.9368 _{PT} ^E	- 26.18288 _{IC} ^E					
616,043	- 751,375	+ 868,161	+ 945,734	- 883,315	+ 710,037		=	91.6808 _{PT} ^E	- 13.78638 _{IC} ^E					
Simplifying,														
1.114639	- 1.207526	+ 1.209557	+ 1.036699	- 0.848482	+ 0.606900		=	2,934.6868 _{PT} ^E	+ 224.8398 _{IC} ^E	= K ₁				
1.213405	- 1.377243	+ 1.400885	+ 1.254146	- 1.034220	+ 0.752301		=	3,678.6908 _{PT} ^E	- 155.8828 _{IC} ^E	= K ₂				
1.218362	- 1.423584	+ 1.543269	+ 1.418873	- 1.185125	+ 0.864993		=	4,422.6958 _{PT} ^E	- 897.8168 _{IC} ^E	= K ₃				
1.037584	- 1.253220	+ 1.418014	+ 1.450943	- 1.261742	+ 0.937011		=	4,215.4468 _{PT} ^E	- 1186.9888 _{IC} ^E	= K ₄				
0.849416	- 1.034017	+ 1.184478	+ 1.261393	- 1.142800	+ 0.871999		=	3,217.0518 _{PT} ^E	- 701.6998 _{IC} ^E	= K ₅				
0.616043	- 0.751375	+ 0.868161	+ 0.945734	- 0.883315	+ 0.710037		=	2,218.6568 _{PT} ^E	- 369.4738 _{IC} ^E	= K ₆				

ASSUMING THE GRADIENT ALONG THE IN-CORE REGION VARIES AS A SINE FUNCTION AND THE ΔT ACROSS THE TUBE WALL IS LINEAR,

$$\theta'_{ic} = \frac{\alpha L \Delta T_{ic}}{\pi D}$$

$$\text{WHERE } \alpha @ 300^\circ\text{F} = 9.47 \times 10^{-6}$$

$$L = 48$$

$$D = 2.875$$

$$\theta'_{ic} = \frac{(9.47 \times 10^{-6})(48)(\Delta T_{ic})}{\pi(2.875)} = 50.328 \times 10^{-6} \Delta T_{ic}$$

$$\theta'_{PT} = \frac{(10.05 \times 10^{-6})(48)(\Delta T_{PT})}{\pi(2.875)} = 60.572 \times 10^{-6} \Delta T_{PT}$$

$$K_1 = (2934.686)(60.572 \times 10^{-6}) \Delta T_{PT} + (224.839)(50.328 \times 10^{-6}) \Delta T_{ic}$$

$$= .17776 \Delta T_{PT} + .011316 \Delta T_{ic}$$

$$K_2 = (3678.690)(60.572 \times 10^{-6}) \Delta T_{PT} - (155.882)(50.328 \times 10^{-6}) \Delta T_{ic}$$

$$= .22283 \Delta T_{PT} - .007845 \Delta T_{ic}$$

$$K_3 = (4422.695)(60.572 \times 10^{-6}) \Delta T_{PT} - (897.816)(50.328 \times 10^{-6}) \Delta T_{ic}$$

$$= .26789 \Delta T_{PT} - .045185 \Delta T_{ic}$$

$$K_4 = (4215.446)(60.572 \times 10^{-6}) \Delta T_{PT} - (1186.988)(50.328 \times 10^{-6}) \Delta T_{ic}$$

$$= .25534 \Delta T_{PT} - .05974 \Delta T_{ic}$$

$$K_5 = (3217.051)(60.572 \times 10^{-6}) \Delta T_{PT} - (701.699)(50.328 \times 10^{-6}) \Delta T_{ic}$$

$$= .19486 \Delta T_{PT} - .035315 \Delta T_{ic}$$

$$K_6 = (2218.656)(60.572 \times 10^{-6}) \Delta T_{PT} - (369.473)(50.328 \times 10^{-6}) \Delta T_{ic}$$

$$= .13439 \Delta T_{PT} - .018595 \Delta T_{ic}$$

THREE-SUPPORT CONDITION

For $\frac{\Delta T_{PT}}{\Delta T_{IC}} = 0.50$ WITH $\Delta T_{PT} = 100^\circ F$
THEN $\Delta T_{IC} = 200$

$$K_1 = 17.776 + (0.011316)(200) = 20.039$$

$$K_2 = 22.283 - (0.007845)(200) = 20.713$$

$$K_3 = 26.789 - (0.045185)(200) = 17.751$$

$$K_4 = 25.534 - (0.05974)(200) = 13.586$$

$$K_5 = 19.486 - (0.035315)(200) = 12.422$$

$$K_6 = 13.439 - (0.018595)(200) = 9.719$$

THE SOLUTION FOR THE 6-BY-7 MATRIX IS OBTAINED BY THE
"MATRX" SIMULTANEOUS EQUATION COMPUTER CODE.

THE FOLLOWING SOLUTIONS ARE FROM SET NUMBER

X(1) = 0.1546049599+02
X(2) = -0.3762303855+02
X(3) = -0.2195498390+02
X(4) = -0.6352409421+02
X(5) = -0.6569429367+02
X(6) = -0.9810389380+01

$$\frac{\Delta T_{PT}}{\Delta T_{IC}} = 0.50$$

$$\Delta T_{PT} = 100^{\circ}F$$

$$\Delta T_{IC} = 200^{\circ}F$$

$$K_1 = 20.039$$

$$K_2 = 20.713$$

$$K_3 = 17.751$$

$$K_4 = 13.586$$

$$K_5 = 12.422$$

$$K_6 = 9.719$$

$$P_1 = 15.46050$$

$$P_2 = -37.62304$$

$$P_3 = -21.95498$$

$$P_4 = -63.52409$$

$$P_5 = -65.69429$$

$$P_6 = -9.81039$$

THREE-SUPPORT CONDITION

FOR $\frac{\Delta T_{PT}}{\Delta T_{IC}} = 0.75$ WITH $\Delta T_{PT} = 100^\circ F$
THEN $\Delta T_{IC} = 133^\circ F$

$$K_1 = 17.776 + (.011316)(133) = 19.280$$

$$K_2 = 22.283 - (.007845)(133) = 21.240$$

$$K_3 = 26.789 - (.045185)(133) = 20.780$$

$$K_4 = 25.534 - (.05974)(133) = 17.589$$

$$K_5 = 19.486 - (.035315)(133) = 14.790$$

$$K_6 = 13.439 - (.018595)(133) = 10.967$$

SOLUTION FOR THE 6 BY 7 MATRIX IS OBTAINED BY
THE "MATRIX" SIMULTANEOUS EQUATION COMPUTER CODE

THE FOLLOWING SOLUTIONS ARE FROM SET NUMBER (1):

X(1) = 0.7566004607+01
X(2) = -0.1915331137+02
X(3) = -0.6967592178+01
X(4) = -0.1493503543+02
X(5) = -0.1387537439+02
X(6) = -0.2367021015+00

$$\frac{\Delta TPT}{\Delta TIC} = .75$$

$$\Delta TPT = 100 \text{ } ^\circ F$$

$$\Delta TIC = 133 \text{ } ^\circ F$$

$$K_1 = 19.280$$

$$K_2 = 21.240$$

$$K_3 = 20.780$$

$$K_4 = 17.589$$

$$K_5 = 14.790$$

$$K_6 = 10.967$$

$$P_1 = 7.56600$$

$$P_2 = -19.15331$$

$$P_3 = -6.96759$$

$$P_4 = -14.93504$$

$$P_5 = -13.87537$$

$$P_6 = -.23670$$

THREE-SUPPORT CONDITION

For $\frac{\Delta T_P}{\Delta T_C} = 1.00$ WITH $\Delta T_P = 100^\circ F$ THEN $\Delta T_C = 100^\circ F$

$$K_1 = 17.776 + (.011316) \left(\frac{100}{100} \right) = 18.908$$

$$K_2 = 22.283 - (.007645) \left(\frac{100}{100} \right) = 21.498$$

$$K_3 = 26.789 - (.045185) \left(\frac{100}{100} \right) = 22.270$$

$$K_4 = 25.534 - (.05974) \left(\frac{100}{100} \right) = 19.560$$

$$K_5 = 19.486 - (.035315) \left(\frac{100}{100} \right) = 15.954$$

$$K_6 = 13.439 - (.018595) \left(\frac{100}{100} \right) = 11.579$$

SOLUTION FOR THE 6 BY 7 MATRIX IS OBTAINED BY THE "MATRIX" SIMULTANEOUS EQUATION COMPUTER CODE

THE FOLLOWING SOLUTIONS ARE FROM SET NUMBER (1):

$X(1) = 0.3789109644+01$
 $X(2) = -0.9923097266+01$
 $X(3) = 0.4028516302+00$
 $X(4) = 0.9119896336+01$
 $X(5) = 0.1174225297+02$
 $X(6) = 0.4487301912+01$

$$\frac{\Delta T_{PT}}{\Delta T_{IC}} = 1.00$$

$$\Delta T_{PT} = 100^{\circ}F$$

$$\Delta T_{IC} = 100^{\circ}F$$

$$K_1 = 18.908$$

$$K_2 = 21.498$$

$$K_3 = 22.270$$

$$K_4 = 19.560$$

$$K_5 = 15.954$$

$$K_6 = 11.579$$

$$P_1 = 3.78911$$

$$P_2 = -9.92310$$

$$P_3 = .40285$$

$$P_4 = 9.11990$$

$$P_5 = 11.74225$$

$$P_6 = 4.48730$$

THREE-SUPPORT CONDITION

FOR $\frac{\Delta T_{PT}}{\Delta T_{IC}} = .91$ WITH $\Delta T_{PT} = 100^\circ\text{F}$
THEN $\Delta T_{IC} = 109.9^\circ\text{F}$

$$K_1 = 17.776 + (.011316)(109.9) = 19.0189$$

$$K_2 = 22.283 - (.007845)(109.9) = 21.4215$$

$$K_3 = 26.789 - (.045185)(109.9) = 21.8242$$

$$K_4 = 25.534 - (.05974)(109.9) = 18.9692$$

$$K_5 = 19.486 - (.035315)(109.9) = 15.6058$$

$$K_6 = 13.439 - (.018595)(109.9) = 11.3962$$

SOLUTION FOR THE 6 BY 7 MATRIX IS OBTAINED BY
THE "MATRIX" SIMULTANEOUS EQUATION COMPUTER CODE

THE FOLLOWING SOLUTIONS ARE FROM SET NUMBER (1):

$$X(1) = 0.4868778003+01$$

$$X(2) = -0.1275427338+02$$

$$X(3) = -0.1801650777+01$$

$$X(4) = 0.1846783499+01$$

$$X(5) = 0.4006254914+01$$

$$X(6) = 0.3056070715+01$$

$$\Delta TPT = .91$$

$$\Delta TIC$$

$$P_1 = 4.86878$$

$$P_2 = -12.75427$$

$$\Delta TPT = 100^\circ F$$

$$P_3 = -1.80165$$

$$\Delta TIC = 109.9^\circ F$$

$$P_4 = 1.84678$$

$$P_5 = 4.00625$$

$$K_1 = 19.0189$$

$$P_6 = 3.05607$$

$$K_2 = 21.4215$$

$$K_3 = 21.8242$$

THREE - SUPPORT CONDITION

$$K_4 = 18.9692$$

$$K_5 = 15.6058$$

$$K_6 = 11.3962$$

MID-CORE DEFLECTIONS

$$\Delta_{IC_0} + \Delta'_{IC_0} = \frac{-23952.32 P_1}{E_{IC}} - \frac{14931.06 P_2}{E_{IC}} + \frac{75127.08 P_3}{E_{IC}} \\ + \frac{136150.26 P_4}{E_{IC}} - \frac{127494.62 P_5}{E_{IC}} + \frac{91132.41 P_6}{E_{IC}}$$

$$+ 41.5536 \theta'_{IC} + \Delta''_{IC_0}$$

$$\Delta_{PT_0} + \Delta'_{PT_0} = \frac{-1173321 P_1}{E_{PT}} + \frac{1358343 P_2}{E_{PT}} - \frac{1451770 P_3}{E_{PT}} \\ - \frac{1346543 P_4}{E_{PT}} + \frac{1131001 P_5}{E_{PT}} - \frac{933113 P_6}{E_{PT}}$$

$$+ 194.474 \theta'_{PT} + \Delta''_{PT_0}$$

$$\Delta''_{IC_0} = \frac{\alpha L^2 \Delta T_{IC}}{\pi^2 D} = \frac{(9.47 \times 10^{-6} (48))^2 \Delta T_{IC}}{\pi^2 (2.875)} = 768.947 \times 10^{-6} \Delta T_{IC}$$

$$\Delta''_{PT_0} = \frac{\alpha L^2 \Delta T_{PT}}{\pi^2 D} = \frac{(10.05 \times 10^{-6} (48))^2 \Delta T_{PT}}{\pi^2 (2.535)} = 925.468 \times 10^{-6} \Delta T_{PT}$$

$$E_{IC} = 26.8 \times 10^6$$

$$E_{PT} = 24.2 \times 10^6$$

$$\theta'_{IC} = 50.328 \times 10^{-6} \Delta T_{IC}$$

$$\theta'_{PT} = 60.572 \times 10^{-6} \Delta T_{PT}$$

$$\Delta_{IC_0} = \left[-893.14 P_1 - 557.13 P_2 + 2803.25 P_3 + 5080.23 P_4 \right. \\ \left. - 4757.26 P_5 + 3400.46 P_6 + 7860.26 \Delta T_{IC} \right] \times 10^{-6}$$

$$\Delta_{PT_0} = \left[-48484 P_1 + 56130 P_2 - 59990 P_3 - 55642 P_4 \right. \\ \left. + 46736 P_5 - 34426 P_6 + 12099.43 \Delta T_{PT} \right] \times 10^{-6}$$

EVALUATE THE DEFL. AT THE SNUBBER TUBE
ASSEMBLY. (ELEV 71'-11") $\Delta_{ST} = 0.025"$

INITIAL DEFL. PAGE 5

$$\Delta'_{ST} = 66(4.642 \theta'_{IC}) = 42.372 \theta'_{IC}$$

RESTRAINING MOMENT AT B, PAGE 11

$$\Delta'_{ST} = \frac{11119 \times 10^{-6} E \theta'_{IC}}{6E} \left[\frac{3(174)^2 - (174)^3}{240} - 2(240)(174) \right]$$

$$= -27.134 \theta'_{IC}$$

LOADS & MOMENTS DUE TO $P_1, P_2, \dots, P_6$

$$\Delta_{ST_1} = \frac{(6.785 P_1)}{(1.028 E) 6} \left[\frac{3(174)^2 - (174)^3}{240} - 2(240)(174) \right]$$

$$= \frac{6.785 P_1}{E} (-2373.881) = -16106.78 \frac{P_1}{E}$$

$$\Delta_{ST_2} = \left(\frac{-6.718 P_2}{E} \right) (-2373.881) = 15947.73 \frac{P_2}{E}$$

$$\Delta_{ST_2} = -\frac{P_2(11)(66)}{1432.80 E} \left[(480)(229) - (229)^2 - (66)^2 \right] = -26917.43 \frac{P_2}{E}$$

$$\Delta_{ST_3} = \left(\frac{22.332 P_3}{E} \right) (-2373.881) = -53013.51 \frac{P_3}{E}$$

$$\Delta_{ST_3} = \frac{(P_3)(47)(66)}{1432.80 E} \left[(480)(193) - (193)^2 - (66)^2 \right] = 110490.35 \frac{P_3}{E}$$

$$\Delta_{ST4} = \frac{(30.181 P_4)(-2373.881)}{E} = -\frac{71646.10 P_4}{E}$$

$$\Delta_{ST4} = \frac{P_4(107)(66)}{1432.80 E} \left[(480)(133) - (133)^2 - (66)^2 \right] = \frac{205999.64 P_4}{E}$$

$$\Delta_{ST5} = \frac{(-26.251 P_5)(-2373.881)}{E} = \frac{62316.75 P_5}{E}$$

$$\Delta_{ST5} = -\frac{P_5(143)(66)}{1432.80 E} \left[(480)(97) - (97)^2 - (66)^2 \right] = -\frac{216024.02 P_5}{E}$$

$$\Delta_{ST6} = \frac{(18.687 P_6)(-2373.881)}{E} = -\frac{44360.71 P_6}{E}$$

$$\Delta_{ST6} = \frac{P_6(61)(174)}{1432.80 E} \left[(480)(66) - (61)^2 - (66)^2 \right] = \frac{174848.02 P_6}{E}$$

SUMMING THE DEFL. $E = 26.8 \times 10^6$

$$\begin{aligned} \Delta_{ST} = & \left[-16106.78 P_1 + 15947.73 P_2 - 26917.43 P_2 - 53013.51 P_3 \right. \\ & + 110490.35 P_3 - 71646.10 P_4 + 205999.64 P_4 \\ & + 62316.75 P_5 - 216024.02 P_5 - 44360.71 P_6 \\ & \left. + 17484.02 P_6 \right] \frac{1}{26.8 \times 10^6} + 42.372 \theta'_{1C} - 27.134 \theta'_{1C} \end{aligned}$$

WHICH SIMPLIFIES TO: $\theta'_{1C} = 50.328 \times 10^{-6} \Delta T_{1C}$

$$\begin{aligned} \Delta_{ST} = & \left[-16106.78 P_1 - 10969.70 P_2 + 57476.04 P_3 + 134353.54 P_4 \right. \\ & \left. - 153707.27 P_5 - 26876.69 P_6 \right] \frac{1}{26.8} + (766.90)(\Delta T_{1C}) \times 10^{-6} \end{aligned}$$

E.6. THE FOUR-SUPPORT THERMAL BOW MODEL

INSULATION CAN LOADINGS

$$I_1 = .0491(4^4 - 3.625^4) = 4.091 \text{ in}^4$$

$$I_2 = .0491(2.875^4 - 2.633^4) = 0.995 \text{ in}^4$$

$$I_3 = .0491(3.122^4 - 2.633^4) = 2.309 \text{ in}^4$$

PRESSURE TUBE LOADINGS

17

$$\Delta_6 = 80(\text{ " }) = 91.680 \text{ e, '}$$

INSULATION CAN — INITIAL DEFLECTION
DUE TO A ΔT ACROSS THE TUBE
(NON-UNIFORM HEAT FLUX) IN THE
IN-CORE LOCATION

+A
▽

$$\Delta'_{ic_2} = 11(1.115 \theta'_{ic}) = 12.265 \theta'_{ic}$$

$$\Delta'_{ic_3} = 47(1.115 \theta'_{ic}) = 52.405 \theta'_{ic}$$

$$\Delta'_{ic_0} = 77(1.115 \theta'_{ic}) + \Delta''_{ic_0} = 85.855 \theta'_{ic} + \Delta''_{ic_0}$$

$$\Delta'_{ic_4} = 167(.885 \theta'_{ic}) = 147.695 \theta'_{ic}$$

$$\Delta'_{ic_5} = 31(.885 \theta'_{ic}) = 27.435 \theta'_{ic}$$

$$\Delta'_{ic_0} = 53(.115 \theta'_{ic}) + 24(.115 \theta'_{ic}) + \Delta''_{ic_0} = 61.855 \theta'_{ic} + \Delta''_{ic_0}$$

DETERMINING EQUIVALENT I TO BE USED IN MOMENT DISTRIBUTION SOLUTION

$$A_1 = \frac{1}{2}(52)(.311M) = 8.086 M$$

$$A_2 = 52(.689M) = 35.828 M$$

$$A_3 = \frac{1}{2}(115)(.168M) = 9.660 M$$

$$\underline{53.574 M}$$

$$\bar{x}_A = \frac{9.660 M (76.705) + 35.828 M (141) + 8.086 M (149.684)}{53.574 M} = 130.7"$$

$$F_A = \frac{53.574 M (167 - 130.7)}{167} = 11.645 M$$

$$F_B = 53.574 M - 11.645 M = 41.929 M$$

$$\phi_B = \frac{41.929 M}{EI_2} = \frac{ML}{3EI} \left(\text{constant } I \right)$$

$$\therefore \bar{I} = \frac{LI_2}{3(F_B)} = \frac{167(.995)}{125.787} = 1.321 m^4$$

EQUIVALENT

DETERMINING EQUIVALENT I TO BE USED IN MOMENT DISTRIBUTION SOLUTION

$$\Delta_1 = -\frac{PL^3}{3EI} - \frac{12PL^2}{2EI} + \frac{ML^2}{2EI} = -\frac{P(54)^3}{3(2309)E} - \frac{12(54)^2P}{2(2309)E} + \frac{(54)^2M}{2(2309)E}$$

22731.9 7517.3 631.44 M
6.927 4.618

$$\Delta_1 = -\frac{30309.2P}{E} + \frac{631.44M}{E}$$

$$\phi_1 = -\frac{PL^2}{2EI} - \frac{12PL}{EI} + \frac{ML}{EI} = -\frac{(54)^2P}{2(2309)E} - \frac{12(54)P}{2309E} + \frac{54M}{2309E}$$

631.44 280.64 23.387

$$\phi_1 = -\frac{912.08P}{E} + \frac{23.387M}{E}$$

$$\Delta_2 = -\frac{P(12)^3}{3(2309)E} + \frac{M(12)^2}{2(2309)E} + 12\left(\underbrace{-\frac{912.08P}{E} + \frac{23.387M}{E}}_{\phi_1}\right) - \underbrace{\frac{30309.2P}{E} + \frac{631.44M}{E}}_{\Delta_1}$$

374.19 31.182

$$\Delta_2 = -\frac{41,628.17P}{E} + \frac{943.266M}{E}$$

$$\phi_2 = -\frac{P(12)^2}{2(2309)E} + \frac{12M}{2309E} - \frac{912.08P}{E} + \frac{23.387M}{E}$$

-31.182 5.197

$$\phi_2 = -\frac{943.26P}{E} + \frac{28.584M}{E}$$

$$\text{For } \Delta_2 = 0$$

$$P = \frac{943.266 \text{ M}}{41628.17}$$

$$\phi_2 = -\frac{943.266}{E} \left(\frac{943.266 \text{ M}}{41628.17} \right) + \frac{28.584 \text{ M}}{E} = -\frac{21.374 \text{ M}}{E} + \frac{28.584 \text{ M}}{E}$$

$$\phi_2 = \frac{7.210 \text{ M}}{E}$$

Equivalent I for Uniform Section

$$\phi = \frac{7.210 \text{ M}}{E} = \frac{M L}{4 E I}$$

$$\frac{I}{E Q} = \frac{L}{4(7.21)} = \frac{66}{28.84} = 2.288$$

$I_{\text{EQUIVALENT}}$
 L
 $K = \frac{I}{L}$

1.321
 $167''$
 $.00791 \times \frac{3}{4} = .00593$

$.995$
 $174''$
 $.00571$

2.288
 $66''$
 $.03466 \times \frac{3}{4} = .02600$

$\frac{M_B L}{3EI} + \frac{M_C L}{6EI} = 1.115 \theta'_C$

$\frac{M_C L}{3EI} + \frac{M_B L}{6EI} = .885 \theta'_C$

$2M_B + M_C = 1.115 \theta'_C (6EI/L)$; $M_C = 1.115 \theta'_C (6EI/L) - 2M_B$

$M_B + 2M_C = .885 \theta'_C (6EI/L)$

$M_B + 2.23 \theta'_C (6EI/L) - 4M_B = .885 \theta'_C (6EI/L)$

$M_B = .448 (6EI/L) \theta'_C = .448 (6EI/174) \theta'_C = 15.448 (10^{-6}) EI \theta'_C$

$M_C = 1.115 \theta'_C (6EI/L) - 2(.448 \theta'_C (6EI/L)) = .219 \theta'_C (6EI/L) = 7.552 (10^{-6}) EI \theta'_C$

-7863	15448	-7552	6193
	7585		1359
	680		-3792
-346	334		682
	341		-167
-174	167		30
	15		-83
-8	7		15
-839.1	8391 (10 ⁻⁶) EI θ'_C	-9508	9508 (10 ⁻⁶) EI θ'_C

I_2

$$\Delta = \frac{M_B}{6EI} (3x^2 - x^3 - 2lx)$$

$$\Delta'_{1c_2} = \frac{8391(10^6)}{6} \theta'_c \left[\frac{3(11)^2 - (11)^3 - 2(174)(11)}{174} \right] = -4.9 \theta'_c$$

$$\Delta'_{1c_3} = \frac{1398(10^6)}{6} \theta'_c \left[\frac{3(47)^2 - (47)^3 - 2(174)(47)}{174} \right] = -14.4 \theta'_c$$

$$\Delta'_{1c_4} = \frac{1398(10^6)}{6} \theta'_c \left[\frac{3(77)^2 - (77)^3 - 2(174)(77)}{174} \right] = -16.3 \theta'_c$$

$$\Delta'_{1c_5} = \frac{1398(10^6)}{6} \theta'_c \left[\frac{3(107)^2 - (107)^3 - 2(174)(107)}{174} \right] = -13.8 \theta'_c$$

$$\Delta'_{1c_6} = \frac{1398(10^6)}{6} \theta'_c \left[\frac{3(143)^2 - (143)^3 - 2(174)(143)}{174} \right] = -7.3 \theta'_c$$

$$\Delta'_{1c_7} = \frac{1585(10^6)}{6} \theta'_c \left[\frac{3(163)^2 - (163)^3 - 2(174)(163)}{174} \right] = -3.0 \theta'_c$$

$$\Delta'_{1c_8} = \frac{1585(10^6)}{6} \theta'_c \left[\frac{3(127)^2 - (127)^3 - 2(174)(127)}{174} \right] = -12.0 \theta'_c$$

$$\Delta'_{1c_9} = \frac{1585(10^6)}{6} \theta'_c \left[\frac{3(97)^2 - (97)^3 - 2(174)(97)}{174} \right] = -17.1 \theta'_c$$

$$\Delta'_{1c_{10}} = \frac{1585(10^6)}{6} \theta'_c \left[\frac{3(67)^2 - (67)^3 - 2(174)(67)}{174} \right] = -18.4 \theta'_c$$

$$\Delta'_{1c_{11}} = \frac{1585(10^6)}{6} \theta'_c \left[\frac{3(31)^2 - (31)^3 - 2(174)(31)}{174} \right] = -12.8 \theta'_c$$

DEFLECTIONS OF INSULATION CAN DUE TO
INITIAL BOW OF CAN FROM A GRADIENT (ΔT)
ACROSS CAN. (SUMMATION OF Δ 'S FROM PP 4 & 9)

$$+\Delta \quad \begin{array}{l} \text{from initial A (pp 4)} \\ \downarrow \end{array} \quad \begin{array}{l} \text{from Moment Distribution (pp 9)} \\ \downarrow \end{array}$$

$$\Delta'_{ic_2} = [12.265 - 4.9 - 3.0] \theta'_{ic} = 4.365 \theta'_{ic}$$

$$\Delta'_{ic_3} = [52.405 - 14.4 - 12.0] \theta'_{ic} = 26.005 \theta'_{ic}$$

$$\Delta'_{ic_0} = [61.855 + \Delta''_{ic_0} - 16.3 - 12.1] \theta'_{ic} = 28.455 \theta'_{ic} + \Delta''_{ic_0}$$

$$\Delta'_{ic_4} = [59.295 - 13.8 - 18.4] \theta'_{ic} = 27.095 \theta'_{ic}$$

$$\Delta'_{ic_5} = [27.435 - 7.3 - 12.8] \theta'_{ic} = 7.335 \theta'_{ic}$$

$$\text{see } \left\{ \begin{array}{l} \Delta'_{ic_1} = \frac{754.6 \text{ M}}{E} = \frac{754.6 (8391)(10^{-6})}{E} (.995) \theta'_{ic} = -6.300 \theta'_{ic} \\ \text{pp 15f26} \end{array} \right.$$

$$\Delta'_{ic_6} = \frac{63.9 \text{ M}}{E} = \frac{63.9 (9508)(10^{-6})}{E} (.995) \theta'_{ic} = -604 \theta'_{ic}$$

$$k = \frac{I}{L}$$

$$1.321 \text{ (Equivalent)}$$

$$167$$

$$00791 \times 3/4 = .00593$$

$$.995$$

$$174$$

$$00571$$

$$2.288 \text{ (Equivalent)}$$

$$66$$

$$03466 \times 3/4 = 0.2600$$

FEM

$M_1 = P_1 \frac{(142)(25)^2}{27889} = 3.182 P_1$

$M_2 = P_1 \frac{(142)^2(25)}{(167)^2} = -18.075 P_1$

$$M_1 = P_2 \frac{(11)(163)^2}{30276} = -9.654 P_2$$

$$M_2 = P_2 \frac{(11)^2(163)}{30276} = 0.654 P_2$$

$$M_1 = \frac{P_6(5)(6)^2}{(66)^2} = 4.271$$

$$M_2 = \frac{-P_0(5)(61)}{4356} = -0.350 P_0$$

$$V_A = \frac{265.7 P_1(16.7) + 54.6 P_1(34) + 464.8 P_1(38.5) + 240.5 P_1(90.3)}{167} = 274.9 P_1$$

$$V_B = 1025.6 P_1 - 274.9 P_1 = 750.7 P_1$$

$$\Delta_1 = \frac{750.7 P_1(25) - 265.7 P_1(8.3)}{EI_2} = \frac{16645 P_1}{E}$$

$$V_A = \frac{76.3 P_1(17.3) + 337.5 P_1(26) + 90.7 P_1(90.3)}{167} = 109.5 P_1$$

$$V_B = 504.5 P_1 - 109.5 P_1 = 395 P_1$$

$$\Delta_1 = - \left[\frac{395 P_1(25)}{EI_2} - \frac{18.014 P_1(25)(12.5)}{EI_2} - \frac{1}{2}(1.411 P_1)(25)(16.7) \right] = - \frac{7112 P_1}{E}$$

$$\Delta_{Total} = \frac{(16645 - 7112) P_1}{E} = \frac{9533 P_1}{E}$$

$$A_1 = \frac{1}{2} (52) (M - .689 M) = 8.086 M$$

$$A_2 = (52) (.689 M) = 35.828 M$$

$$A_3 = \frac{1}{2} (115) (.167 M) = 9.602 M$$

$$53.516 M$$

$$V_B = \frac{8.086 M (149.7) + 35.828 M (141) + 9.602 M (76.7)}{167} = 41.908 M$$

$$\Delta_1 = \frac{41.908 M (25) - \frac{1}{2} (.150 M) (25) (16.7) - .85 M (25) (12.5)}{EI_2} = \frac{754.6 M}{E}$$

$$\Delta_1 = \frac{754.6 (5.052 P_2)}{E} = \frac{3812 P_2}{E}$$

$$\Delta_1 = \frac{754.6 (13.449 P_3)}{E} = - \frac{10149 P_3}{E}$$

$$\Delta_1 = - \frac{754.6 (9.413 P_4)}{E} = - \frac{7103 P_4}{E}$$

$$\Delta_1 = \frac{754.6 (3.373 P_5)}{E} = \frac{2545 P_5}{E}$$

$$\Delta_1 = \frac{754.6 (.204 P_6)}{E} = \frac{154 P_6}{E}$$

$$+\Delta \quad \Delta = \frac{M}{6EI} (3x^2 - x^3 - 2(x))$$

$$\Delta_2 = \frac{5.052 P_2}{6E(995)} \left[\overset{363}{3(11)^2} - \overset{-8}{(11)^3} - \overset{-3828}{2(174)(11)} \right] = \frac{2939 P_2}{E}$$

$$\Delta_3 = \frac{-846 P_2}{E} \left[\overset{6627}{3(47)^2} - \overset{-597}{(47)^3} - \overset{-16356}{2(174)(47)} \right] = \frac{8738 P_2}{E}$$

$$\Delta_6 = \frac{-846 P_2}{E} \left[\overset{17787}{3(77)^2} - \overset{-2624}{(77)^3} - \overset{-26796}{2(174)(77)} \right] = \frac{9844 P_2}{E}$$

$$\Delta_4 = \frac{-846 P_2}{E} \left[\overset{34347}{3(107)^2} - \overset{-7040}{(107)^3} - \overset{-37236}{2(174)(107)} \right] = \frac{8402 P_2}{E}$$

$$\Delta_5 = \frac{-846 P_2}{E} \left[\overset{61347}{3(143)^2} - \overset{-16806}{(143)^3} - \overset{-49764}{2(174)(143)} \right] = \frac{4420 P_2}{E}$$

////

$$\Delta_2 = \frac{-2.504 P_2}{6E(995)} \left[\overset{79707}{3(163)^2} - \overset{-24889}{(163)^3} - \overset{-56724}{2(174)(163)} \right] = \frac{798 P_2}{E}$$

$$\Delta_3 = \frac{-419 P_2}{E} \left[\overset{48387}{3(127)^2} - \overset{-11772}{(127)^3} - \overset{-44196}{2(174)(127)} \right] = \frac{3178 P_2}{E}$$

$$\Delta_2 = \frac{-419 P_2}{E} \left[\overset{28227}{3(97)^2} - \overset{-5244}{(97)^3} - \overset{-33756}{2(174)(97)} \right] = \frac{4515 P_2}{E}$$

$$\Delta_4 = \frac{-419 P_2}{E} \left[\overset{13467}{3(67)^2} - \overset{-1728}{(67)^3} - \overset{-23316}{2(174)(67)} \right] = \frac{4853 P_2}{E}$$

$$\Delta_5 = \frac{-419 P_2}{E} \left[\overset{2883}{3(31)^2} - \overset{-171}{(31)^3} - \overset{-10788}{2(174)(31)} \right] = \frac{3384 P_2}{E}$$

$$(A \text{ to } B) \quad \Delta = \frac{P_2 b x}{6EI} [2l(1-x) - b^2 - (1-x)^2]$$

$$(B \text{ to } C) \quad \Delta = \frac{P_2 a(1-x)}{6EI} [2lb - b^2 - (1-x)^2]$$

$$\Delta_2 = \frac{P_2 (163)(11)}{6EI (174)} \left[\overset{56724}{2(174)(174-11)} - \overset{-26569}{(163)^2} - \overset{-26569}{(174-11)^2} \right] = -\frac{6188 P_2}{E}$$

$$\Delta_3 = -\frac{P_2 (11)(174-47)}{6EI (174)} [2(174)(163) - (163)^2 - (174-47)^2] = -\frac{18862 P_2}{E}$$

$$\Delta_0 = -\frac{P_2 (11)(174-77)}{1044EI} [56724 - 26569 - (174-77)^2] = -\frac{21309 P_2}{E}$$

$$\Delta_4 = -\frac{P_2 (11)(174-107)}{1044EI} [2(174)(163) - (163)^2 - (174-107)^2] = -\frac{18210 P_2}{E}$$

$$\Delta_5 = -\frac{P_2 (11)(174-143)}{1044EI} [56724 - 26569 - (174-143)^2] = -\frac{9584 P_2}{E}$$

TOTALS

$$\Delta_2 = \left(-6188 + 2939 + 798 \right) \frac{P_2}{E} = -\frac{2451 P_2}{E}$$

$$\Delta_3 = \left(-18862 + 8738 + 3178 \right) \frac{P_2}{E} = -\frac{6946 P_2}{E}$$

$$\Delta_0 = \left(-21309 + 9844 + 4515 \right) \frac{P_2}{E} = -\frac{6950 P_2}{E}$$

$$\Delta_4 = \left(-18210 + 8402 + 4853 \right) \frac{P_2}{E} = -\frac{4955 P_2}{E}$$

$$\Delta_5 = \left(-9584 + 4420 + 3384 \right) \frac{P_2}{E} = -\frac{1780 P_2}{E}$$

$$\Delta_2 = \frac{13.459 P_3}{6EI} (-3473) = \frac{7827 P_3}{EI}$$

$x=11$

$$\Delta_3 = \frac{2.254 P_3}{EI} (-10326) = \frac{23274 P_3}{EI}$$

$x=47$

$$\Delta_0 = \frac{2.254 P_3}{EI} (-11633) = \frac{-26,216 P_3}{EI}$$

$x=77$

$$\Delta_4 = \frac{2.254 P_3}{EI} (-9929) = \frac{-22376 P_3}{EI}$$

$x=107$

$$\Delta_5 = \frac{2.254 P_3}{EI} (-5223) = \frac{-11771 P_3}{EI}$$

$x=143$

~~****~~

$$\Delta_1 = \frac{12.803 P_3}{6EI} (-1906) = \frac{-4087 P_3}{EI}$$

$x=163$

$$\Delta_3 = \frac{2.144 P_3}{EI} (-7581) = \frac{-16259 P_3}{EI}$$

$x=127$

$$\Delta_0 = \frac{2.144 P_3}{EI} (-10773) = \frac{-23103 P_3}{EI}$$

$x=97$

$$\Delta_4 = \frac{2.144 P_3}{EI} (-11577) = \frac{-24828 P_3}{EI}$$

$x=67$

$$\Delta_5 = \frac{2.144 P_3}{EI} (-8076) = \frac{-17320 P_3}{EI}$$

$x=31$

$$\Delta_2 = \frac{P_3(127)(11)}{1044EI} [2(174)(174-11) - (127)^2 - (174-11)^2] = \frac{18862 P_3}{E}$$

$$\Delta_3 = \frac{P_3(127)(47)}{1044EI} [2(174)(174-47) - 16129 - (174-47)^2] = \frac{68596 P_3}{E}$$

$$\Delta_6 = \frac{P_3(47)(174-77)}{1044EI} [4496 - 16129 - (174-77)^2] = \frac{81884 P_3}{E}$$

$$\Delta_4 = \frac{P_3(47)(174-107)}{1044EI} [2(174)(127) - 16129 - (174-107)^2] = \frac{71474 P_3}{E}$$

$$\Delta_5 = \frac{P_3(107)(174-143)}{1044EI} [2(174)(127) - 16129 - (174-143)^2] = \frac{38018 P_3}{E}$$

TOTALS

$$\Delta_2 = (18862 - 7827 - 4087) \frac{P_3}{E} = \frac{6948 P_3}{E}$$

$$\Delta_3 = (68596 - 23274 - 16259) \frac{P_3}{E} = \frac{29063 P_3}{E}$$

$$\Delta_6 = (81884 - 26216 - 23103) \frac{P_3}{E} = \frac{32565 P_3}{E}$$

$$\Delta_4 = (71474 - 22376 - 24828) \frac{P_3}{E} = \frac{24270 P_3}{E}$$

$$\Delta_5 = (38018 - 11771 - 17320) \frac{P_3}{E} = \frac{8927 P_3}{E}$$

$$\Delta_2 = \frac{9.413 P_4}{6EI} (-3473) = -\frac{5477 P_4}{E}$$

$x=11$

$$\Delta_3 = \frac{1.577 P_4}{E} (-10326) = -\frac{16284 P_4}{E}$$

$x=47$

$$\Delta_0 = \frac{1.577 P_4}{E} (-11633) = -\frac{18345 P_4}{E}$$

$x=77$

$$\Delta_4 = \frac{1.577 P_4}{E} (-9929) = -\frac{15658 P_4}{E}$$

$x=107$

$$\Delta_5 = \frac{1.577 P_4}{E} (-5223) = -\frac{8237 P_4}{E}$$

$x=143$

~~###~~

$$\Delta_2 = \frac{24.429 P_4}{6EI} (-1906) = -\frac{7799 P_4}{E}$$

$x=163$

$$\Delta_3 = \frac{4.092 P_4}{E} (-7581) = -\frac{31021 P_4}{E}$$

$x=127$

$$\Delta_0 = \frac{4.092 P_4}{E} (-10773) = -\frac{44083 P_4}{E}$$

$x=97$

$$\Delta_4 = \frac{4.092 P_4}{E} (-11577) = -\frac{47373 P_4}{E}$$

$x=67$

$$\Delta_5 = \frac{4.092 P_4}{E} (-8076) = -\frac{33047 P_4}{E}$$

$x=31$

$$\Delta_2 = \frac{P_4(67)(11)}{1044EI} \left[2(174)(174-11) - (67)^2 - (174-11)^2 \right] = \frac{18210}{E} P_4$$

$$\Delta_3 = \frac{P_4(67)(47)}{1044EI} \left[2(174)(174-47) - 4489 - (174-47)^2 \right] = \frac{71474}{E} P_4$$

$$\Delta_0 = \frac{P_4(67)(77)}{1044EI} \left[2(174)(174-77) - 4489 - (174-77)^2 \right] = \frac{98621}{E} P_4$$

$$\Delta_4 = \frac{P_4(67)(107)}{1044EI} \left[2(174)(174-107) - 4489 - (174-107)^2 \right] = \frac{98949}{E} P_4$$

$$\Delta_5 = \frac{P_4(107)(174-143)}{1044EI} \left[2(174)(67) - 4489 - (174-143)^2 \right] = \frac{57048}{E} P_4$$

TOTALS

$$\Delta_1 = (18210 - 5477 - 7799) \frac{P_4}{E} = \frac{4934}{E} P_4$$

$$\Delta_3 = (71474 - 16284 - 31021) \frac{P_4}{E} = \frac{24169}{E} P_4$$

$$\Delta_0 = (98621 - 18345 - 44083) \frac{P_4}{E} = \frac{36193}{E} P_4$$

$$\Delta_4 = (98949 - 15658 - 47373) \frac{P_4}{E} = \frac{35918}{E} P_4$$

$$\Delta_5 = (57048 - 8237 - 33047) \frac{P_4}{E} = \frac{15764}{E} P_4$$

$$\Delta_2 = - \frac{3.373 P_5}{6EI} (-3473) = \frac{1962 P_5}{E}$$

$x = 11$

$$\Delta_3 = - \frac{.565 P_5}{E} (-10326) = \frac{5834 P_5}{E}$$

$x = 47$

$$\Delta_4 = - \frac{.565 P_5}{E} (-10652) = \frac{6018 P_5}{E}$$

$x = 77$

$$\Delta_5 = - \frac{.565 P_5}{E} (-9929) = \frac{5610 P_5}{E}$$

$x = 107$

$$\Delta_6 = - \frac{.565 P_5}{E} (-5223) = \frac{2951 P_5}{E}$$

$x = 143$

~~1111~~

$$\Delta_2 = - \frac{18.274 P_5}{6EI} (-1906) = \frac{5834 P_5}{E}$$

$x = 163$

$$\Delta_3 = - \frac{3.016 P_5}{E} (-7581) = \frac{23205 P_5}{E}$$

$x = 127$

$$\Delta_4 = \quad " \quad (-10773) = \frac{32976 P_5}{E}$$

$x = 97$

$$\Delta_5 = \quad " \quad (-11577) = \frac{35437 P_5}{E}$$

$x = 67$

$$\Delta_6 = \quad " \quad (-8076) = \frac{24721 P_5}{E}$$

$x = 31$

$$\begin{aligned}
 \Delta_2 &= (-9911 + 1962 + 5834) \text{ P\$} = -2115 \text{ P\$} \\
 \Delta_3 &= (-38018 + 5834 + 23205) \text{ P\$} = -8979 \text{ P\$} \\
 \Delta_6 &= (-53737 + 6018 + 32976) \text{ P\$} = -14743 \text{ P\$} \\
 \Delta_4 &= (-57048 + 5610 + 35437) \text{ P\$} = -16001 \text{ P\$} \\
 \Delta_5 &= (-37834 + 2951 + 24721) \text{ P\$} = -10162 \text{ P\$}
 \end{aligned}$$

TOTALS

$$\begin{aligned}
 \Delta_2 &= - \text{P\$} (31)(11) \left[2(174)(174-11) - (31)^2 - (174-11)^2 \right] = -9911 \text{ P\$} \\
 \Delta_3 &= - \text{P\$} (31)(47) \left[2(174)(174-47) - 961 - (174-47)^2 \right] = -38018 \text{ P\$} \\
 \Delta_6 &= - \text{P\$} (31)(77) \left[2(174)(174-77) - 961 - (174-77)^2 \right] = -53737 \text{ P\$} \\
 \Delta_4 &= - \text{P\$} (31)(107) \left[2(174)(174-107) - 961 - (174-107)^2 \right] = -57048 \text{ P\$} \\
 \Delta_5 &= - \text{P\$} (31)(143) \left[2(174)(174-143) - 961 - (174-143)^2 \right] = -37834 \text{ P\$}
 \end{aligned}$$

$$V_A = 11.6 P_6(62.7) + 1.8 P_6(58.7) + 28.6 P_6(52.5) + 47.6 P_6(36) = 63.5 P_6$$

$$V_B = 89.6 P_6 - 63.5 P_6 = 26.1 P_6$$

$$\Delta_1 = \frac{63.5 P_6(5)}{EI_1} - \frac{11.6 P_6(3.3)}{EI_1} = \frac{281 P_6}{E}$$

$$V_A = .8 P_6(62) + 7.1 P_6(60) + 6.8 P_6(36) = 10.9 P_6$$

$$V_B = 14.7 P_6 - 10.9 P_6 = 3.8 P_6$$

$$\Delta_6 = - \left[\frac{5(10.9 P_6)}{EI_2} - \frac{1}{2} \left(\frac{5(.055 P_6)(3.3)}{EI_2} - \frac{5(.665 P_6)(2.5)}{EI_2} \right) \right] = - \frac{46 P_6}{E}$$

$$\Delta_{Total} = \frac{(281 - 46) P_6}{E} = \frac{235 P_6}{E}$$

$$V_A = \frac{573.5 P_1(133.5) - 105.8 P_1(17.4)}{174} = 429.4 P_1$$

$$V_B = 573.5 P_1 - 105.8 P_1 - 429.4 P_1 = 38.3 P_1$$

$$\Delta_2 = - \left[429.4 P_1(11) - \frac{1}{2} \left(\frac{34.2}{EI} \right) (11)(7.3) - \frac{518.7}{EI} (11)(5.5) \right] = - \frac{4191 P_1}{EI}$$

$$\Delta_3 = - \left[429.4 P_1(47) - \frac{1}{2} \left(\frac{2677.4}{EI} \right) (47)(31.3) - \frac{6389.5}{EI} (47)(23.5) \right] = - \frac{11171 P_1}{EI}$$

$$\Delta_0 = - \left[429.4 P_1(77) - \frac{1}{2} \left(\frac{11794.2}{EI} \right) (77)(51.4) - \frac{10272.0}{EI} (77)(38.5) \right] = - \frac{11053 P_1}{EI}$$

$$\Delta_4 = - \left[429.4 P_1(107) - \frac{1}{2} \left(\frac{31667}{EI} \right) (107)(71.4) - \frac{6497}{EI} (107)(53.5) \right] = - \frac{7821 P_1}{EI}$$

$$\Delta_5 = - \left[38.3 P_1(31) + \frac{1}{2} \left(\frac{1187}{EI} \right) (31)(20.7) + \frac{791}{EI} (31)(15.5) \right] = - \frac{2762 P_1}{EI}$$

$$A = \frac{1}{2}(M)(3) = 33M$$

$$V_A = \frac{2}{3} 33M = 22M$$

$$V_B = 11M$$

CHECK

$$\Delta = 33(22M) - \frac{1}{2}(33)(54)\left(\frac{2}{3}\right)(33)$$

$$= 33(22M) - 33(54)(18.5)$$

$$= 272$$

$$\Delta_{CL} = \frac{272}{EI}$$

$$\Delta = \frac{M}{6EI} \left[3(33)^2 - \frac{(33)^3}{66} - 2(66)(33) \right]$$

$$= \frac{272.25}{EI}$$

$$A_1 = \frac{1}{2}(12)(1.82M) = 1.092M$$

$$A_2 = (12)(0.818M) = 9.816M$$

$$A_3 = \frac{1}{2}(54)(0.353M) = 9.531M$$

$$A_T = 20.439M$$

$$V_A = \frac{1.092M(66) + 9.816M(60) + 9.531M(36)}{66} = 15.15M$$

$$V_B = 20.439M - 15.15M = 5.289M$$

$$\Delta_C = \frac{5(15.15M) - \frac{1}{2}(5)(0.076M)(3.3) - 5(9.24M)(2.5)}{EI} = \frac{63.9M}{EI}$$

$$\Delta_C = \frac{63.9}{EI} (2.504 P_2) = \frac{160 P_2}{EI}$$

$$\Delta_C = \frac{63.9}{EI} (4.047 P_1) = \frac{259 P_1}{EI}$$

$$\Delta_C = \frac{-63.9}{EI} (12.803 P_3) = \frac{-818 P_3}{EI}$$

$$\Delta_C = \frac{-63.9}{EI} (24.429 P_4) = \frac{-1561 P_4}{EI}$$

$$\Delta_C = \frac{63.9}{EI} (18.274 P_5) = \frac{1168 P_5}{EI}$$

.034

$$\Delta_2 = \frac{-.204 P_6 (-3473)}{6EI} = \frac{118 P_6}{E}$$

$x=11$

$$\Delta_3 = \frac{-.034 P_6 (-10326)}{E} = \frac{351 P_6}{E}$$

$x=47$

$$\Delta_0 = \frac{'' (-11633)}{E} = \frac{396 P_6}{E}$$

$x=77$

$$\Delta_4 = \frac{'' (-9929)}{E} = \frac{338 P_6}{E}$$

$x=107$

$$\Delta_5 = \frac{'' (-5223)}{E} = \frac{178 P_6}{E}$$

$x=143$

$$\Delta_2 = \frac{.720 P_6 (-1966)}{6EI} = \frac{-230 P_6}{E}$$

$x=163$

$$\Delta_3 = \frac{.1206 P_6 (-7581)}{E} = \frac{-914 P_6}{E}$$

$x=127$

$$\Delta_0 = \frac{'' (-10773)}{E} = \frac{-1299 P_6}{E}$$

$x=97$

$$\Delta_4 = \frac{'' (-11577)}{E} = \frac{-1396 P_6}{E}$$

$x=67$

$$\Delta_5 = \frac{'' (-8076)}{E} = \frac{-974 P_6}{E}$$

$x=31$

TOTALS

$$\Delta_2 = \frac{(-230 + 118) P_6}{E} = \frac{-112 P_6}{E}$$

$$\Delta_3 = \frac{(-914 + 351) P_6}{E} = \frac{-563 P_6}{E}$$

$$\Delta_0 = \frac{(-1299 + 396) P_6}{E} = \frac{-903 P_6}{E}$$

$$\Delta_4 = \frac{(-1396 + 338) P_6}{E} = \frac{-1058 P_6}{E}$$

$$\Delta_5 = \frac{(-974 + 178) P_6}{E} = \frac{-796 P_6}{E}$$

E-131

$$\Delta_1 = - \left[\frac{8449 P_1 (284) - 13447 P_1 (94.6)}{EI_2} \right] = - \frac{1.0967(10^6) P_1}{E}$$

$$A = \frac{1}{2} (248) (82.7 P_1) = 10,255 P_1$$

$$\Delta_2 = - \left[\frac{8449 P_1 (248) - 10255 P_1 (82.6)}{EI_2} \right] = - \frac{1.2143(10^6) P_1}{E}$$

$$A = \frac{1}{2} (212) (70.7 P_1) = \frac{7494 P_1}{E}$$

$$\Delta_3 = - \left[\frac{8449 P_1 (212) - 7494 P_1 (70.6)}{EI_2} \right] = - \frac{1.2277(10^6) P_1}{E}$$

$$A = \frac{1}{2} (182) (60.6 P_1) = 5515 P_1$$

$$\Delta_0 = - \left[\frac{8449 P_1 (182) - 5515 P_1 (60.6)}{EI_2} \right] = - \frac{1.1707(10^6) P_1}{E}$$

$$A = \frac{1}{2} (152) (50.6 P_1) = 3846 P_1$$

$$\Delta_4 = - \left[\frac{8449 P_1 (152) - 3846 P_1 (50.6)}{EI_2} \right] = - \frac{1.0609 P_1}{E}$$

$$A = \frac{1}{2}(116)(38.6 P_1) = 2239 P_1$$

$$\Delta_5 = - \left[\frac{8449 P_1 (116) - 2239 P_1 (38.6)}{EI} \right] = - \frac{.869 (10^6) P_1}{E}$$

$$A = \frac{1}{2}(26.6 P_1)(80) = 1064 P_1$$

$$\Delta_6 = - \left[\frac{8449 P_1 (80) - 1064 P_1 (26.6)}{EI} \right] = - \frac{.630 (10^6) P_1}{E}$$

$$P_2 \frac{(178)(248)}{426} = 103.6 P_2$$

$$\begin{aligned} A_1 &= \frac{1}{2} (103.6 P_2) (248) = 12846 P_2 \\ A_2 &= \frac{1}{2} (39.6 P_2) (68) = 1346 P_2 \\ A_3 &= 64.0 P_2 (68) = 4352 P_2 \\ A_4 &= \frac{1}{2} (16.4 P_2) (110) = 902 P_2 \end{aligned}$$

$$A_T = 19446 P_2$$

$$\bar{X}_B = \frac{12846 P_2 (165.4) + 1346 P_2 (270.6) + 4352 P_2 (282) + 902 P_2 (352.6)}{19446 P_2}$$

$$\bar{X}_B = 207.5$$

$$V_A = \frac{19446 P_2 (207.5)}{426} = 9472 P_2$$

$$V_B = 19446 P_2 - 9472 P_2 = 9974 P_2$$

$$A_1 = \frac{1}{2}(18.6 P_2)(32) = 298 P_2$$

$$A_2 = 64 P_2(32) = 2048 P_2$$

$$A_3 = \frac{1}{2}(16.4 P_2)(110) = 902 P_2$$

$$\Delta_1 = \frac{9472 P_2(142) - 298 P_2(10.7) - 2048 P_2(16) - 902 P_2(68.6)}{E I_2} = \frac{1.232(10^6) P_2}{E}$$

$$A = 12846 P_2$$

$$\Delta_2 = \frac{9974 P_2(248) - 12846 P_2(82.6)}{E I_2} = \frac{1.374(10^6) P_2}{E}$$

$$A = \frac{1}{2}(212)(88.6 P_2) = 9392 P_2$$

$$\Delta_3 = \frac{9974 P_2(212) - 70.6(9392 P_2)}{E I_2} = \frac{1.4119(10^6) P_2}{E}$$

$$A = \frac{1}{2}(182)(76.1 P_2) = 6925 P_2$$

$$\Delta_0 = \frac{9974 P_2(182) - 6925 P_2(60.6)}{E I} = \frac{1.3576(10^6) P_2}{E}$$

$$A = \frac{1}{2}(152)(63.5 P_2) = 4826 P_2$$

$$\Delta_4 = \frac{9974 P_2(152) - 4826 P_2(50.6)}{E I} = \frac{1.2372(10^6) P_2}{E}$$

$$A = \frac{1}{2}(116)(48.5 P_2) = 2813 P_2$$

$$\Delta_5 = \frac{9974 P_2 (116)}{EI} - \frac{2813 P_2 (38.6)}{EI} = \frac{1.0198(10^6)}{EI} P_2$$

$$A = \frac{1}{2}(80)(33.4 P_2) = 1338 P_2$$

$$\Delta_6 = \frac{9974 P_2 (80)}{EI} - \frac{1338 P_2 (26.6)}{EI} = \frac{.7416(10^6)}{EI} P_2$$

$$P_{3ab} = P_3 \left(\frac{214}{426} \right) (212) = 106.5 P_3$$

$$A_1 = \frac{1}{2} (106.5 P_3) (212) = 11289 P_3$$

$$A_2 = \frac{1}{2} (51.8 P_3) (104) = 2694 P_3$$

$$A_3 = 54.7 P_3 (104) = 5689 P_3$$

$$A_4 = \frac{1}{2} (14.0 P_3) (110) = 770 P_3$$

$$A_T = 20442 P_3$$

$$\bar{x}_B = \frac{11289 P_3 (141.4) + 2694 P_3 (246.6) + 5689 P_3 (264) + 770 P_3 (352.6)}{20442 P_3}$$

$$\bar{x}_B = 197.3 "$$

$$V_A = \frac{197.3 (20442 P_3)}{426} = 9468 P_3$$

$$V_B = 20442 P_3 - 9468 P_3 = 10,974 P_3$$

$$\begin{aligned} A_1 &= \frac{1}{2} (14 P_3) (32) = 256 P_3 \\ A_2 &= 54.7 P_3 (32) = 1750 P_3 \\ A_3 &= \frac{1}{2} (14 P_3) (110) = 770 P_3 \end{aligned}$$

$$\Delta_1 = - \frac{[9468 P_3 (142) - 256 P_3 (10.7) - 1750 P_3 (16) - 770 P_3 (68.6)]}{EI} = - \frac{1.224 (10^6) P_3}{EI}$$

$$\begin{aligned} A_1 &= \frac{1}{2} (33.9 P_3) (68) = 1153 P_3 \\ A_2 &= 54.7 P_3 (68) = 3720 P_3 \\ A_3 &= \frac{1}{2} (14 P_3) (110) = 770 P_3 \end{aligned}$$

$$\Delta_2 = - \frac{[9468 P_3 (178) - 1153 P_3 (22.6) - 3720 P_3 (34) - 770 P_3 (104.6)]}{EI} = - \frac{1.4127 (10^6) P_3}{EI}$$

$$A = \frac{1}{2} (106.5 P_3) (212) = 11289 P_3$$

$$\Delta_3 = - \frac{[10974 P_3 (212) - 11289 P_3 (70.6)]}{EI} = - \frac{1.4878 (10^6) P_3}{EI}$$

$$A = \frac{1}{2} (182) (91.4 P_3) = 8317 P_3$$

$$\Delta_4 = - \frac{[10974 P_3 (182) - 8317 P_3 (60.6)]}{EI} = - \frac{1.4524 (10^6) P_3}{EI}$$

$$A = \frac{1}{2} (152) (76.3 P_3) = 5799 P_3$$

$$\Delta_5 = - \frac{[10974 P_3 (152) - 5799 P_3 (50.6)]}{EI} = - \frac{1.3374 (10^6) P_3}{EI}$$

$$A = \frac{1}{2}(116)(58.2 P_3) = 3376 P_3$$

$$\Delta_5 = - \left[\frac{10974 P_3 (116)}{EI} - \frac{3376 P_3 (38.6)}{EI} \right] = - \frac{1.1115 (10^6)}{EI} P_3$$

$$A = \frac{1}{2}(80)(40.2 P_3) = 1608 P_3$$

$$\Delta_6 = - \left[\frac{10974 P_3 (80)}{EI} - \frac{1608 P_3 (26.6)}{EI} \right] = - \frac{8124 (10^6)}{EI} P_3$$

$$A_1 = \frac{1}{2} (97.8 P_4) (152) = 7433 P_4$$

$$A_2 = \frac{1}{2} (58.5 P_4) (164) = 4797 P_4$$

$$A_3 = 39.3 P_4 (164) = 6445 P_4$$

$$A_4 = \frac{1}{2} (10.1 P_4) (110) = 556 P_4$$

$$A_T = 19231 P_4$$

$$\bar{X}_B = \frac{7433 P_4 (101.4) + 4797 P_4 (206.6) + 6445 P_4 (234) + 556 P_4 (352.6)}{19231 P_4}$$

$$\bar{X}_B = 179.3"$$

$$V_A = \frac{179.3 (19231 P_4)}{426} = 8094 P_4$$

$$V_B = 19231 P_4 - 8094 P_4 = 11,137 P_4$$

$$A_1 = \frac{1}{2} (32) (11.4 P_4) = 182 P_4$$

$$A_2 = 32 (39.3 P_4) = 1258 P_4$$

$$A_3 = \frac{1}{2} (110) (10.1 P_4) = 556 P_4$$

$$\Delta_1 = - \left[\frac{8094 P_4 (142) - 182 P_4 (10.7) - 1258 P_4 (16) - 556 P_4 (68.6)}{EI_2} \right] = - \frac{1.059 (10^6) P_4}{E}$$

$$A_1 = \frac{1}{2} (68) (24.2 P_4) = 823 P_4$$

$$A_2 = 68 (39.3 P_4) = 2672 P_4$$

$$A_3 = \frac{1}{2} (110) (10.1 P_4) = 556 P_4$$

$$\Delta_2 = - \left[\frac{8094 P_4 (178) - 823 P_4 (22.6) - 2672 P_4 (34) - 556 P_4 (104.6)}{EI_2} \right] = - \frac{1.2384 (10^6) P_4}{E}$$

$$A_1 = \frac{1}{2} (104) (37.1 P_4) = 1929 P_4$$

$$A_2 = 104 (39.3 P_4) = 4087 P_4$$

$$A_3 = \frac{1}{2} (110) (10.1 P_4) = 556 P_4$$

$$\Delta_3 = - \left[\frac{8094 P_4 (214) - 1929 P_4 (34.6) - 4087 P_4 (52) - 556 P_4 (140.6)}{EI_2} \right] = - \frac{1.337 (10^6) P_4}{E}$$

$$A_1 = \frac{1}{2} (134) (47.8 P_4) = 3203 P_4$$

$$A_2 = 134 (39.3 P_4) = 5266 P_4$$

$$A_3 = \frac{1}{2} (110) (10.1 P_4) = 556 P_4$$

$$\Delta_4 = - \left[\frac{8094 P_4 (244) - 3203 P_4 (44.6) - 5266 P_4 (67) - 556 P_4 (170.6)}{EI_2} \right] = - \frac{1.3487 (10^6) P_4}{E}$$

$$A = 7433 P_4$$

$$\Delta_5 = - \left[\frac{11,137 P_4 (152) - 7433 P_4 (50.6)}{EI_2} \right] = - \frac{1.2808 (10^6) P_4}{E}$$

$$A = \frac{1}{2} (116) (74.6 P_4) = 4327 P_4$$

$$\Delta_5 = - \left[\frac{11137 P_4 (116)}{EI_2} - \frac{4327 P_4 (38.6)}{E} \right] = - \frac{1.0942 (10^6)}{E} P_4$$

$$A = \frac{1}{2} (80) (51.5 P_4) = 2060 P_4$$

$$\Delta_6 = - \left[\frac{11137 P_4 (80)}{EI_2} - \frac{2060 P_4 (26.6)}{E} \right] = - \frac{.8134 (10^6)}{E} P_4$$

$$\begin{aligned}
 A_1 &= \frac{1}{2} (84.4 P_5) (116) = 4895 P_5 \\
 A_2 &= \frac{1}{2} (54.5 P_5) (200) = 5450 P_5 \\
 A_3 &= \frac{1}{2} (29.9 P_5) (200) = 5980 P_5 \\
 A_4 &= \frac{1}{2} (7.7 P_5) (110) = 424 P_5
 \end{aligned}$$

$$A_T = 16,749 P_5$$

$$\bar{x}_B = \frac{4895 P_5 (77.4) + 5450 P_5 (182.6) + 5980 P_5 (216) + 424 P_5 (352.6)}{16749 P_5}$$

$$\bar{x}_B = 168.1''$$

$$V_A = \frac{168.1 (16749 P_5)}{426} = 6609 P_5$$

$$V_B = 16749 P_5 - 6609 P_5 = 10140 P_5$$

$$A_1 = \frac{1}{2}(32)(8.7 P_s) = 139 P_s$$

$$A_2 = 32(29.9 P_s) = 957 P_s$$

$$A_3 = \frac{1}{2}(110)(7.7 P_s) = 424 P_s$$

$$\Delta_1 = \frac{6609 P_s(142) - 139 P_s(10.7) - 957 P_s(16) - 424 P_s(68.6)}{EI_2} = \frac{8683(10^6) P_s}{EI}$$

$$A_1 = \frac{1}{2}(68)(18.5 P_s) = 629 P_s$$

$$A_2 = 68(29.9 P_s) = 2033 P_s$$

$$A_3 = \frac{1}{2}(110)(7.7 P_s) = 424 P_s$$

$$\Delta_2 = \frac{6609 P_s(178) - 629 P_s(22.6) - 2033 P_s(34) - 424 P_s(104.6)}{EI_2} = \frac{1.0202(10^6) P_s}{EI}$$

$$A_1 = \frac{1}{2}(104)(28.3 P_s) = 1472 P_s$$

$$A_2 = 104(29.9 P_s) = 3110 P_s$$

$$A_3 = \frac{1}{2}(110)(7.7 P_s) = 424 P_s$$

$$\Delta_3 = \frac{6609 P_s(214) - 1472 P_s(34.6) - 3110 P_s(52) - 424 P_s(140.6)}{EI_2} = \frac{1.1110(10^6) P_s}{EI}$$

$$A_1 = \frac{1}{2}(134)(36.5 P_s) = 2446 P_s$$

$$A_2 = 134(29.9 P_s) = 4007 P_s$$

$$A_3 = \frac{1}{2}(110)(7.7 P_s) = 424 P_s$$

$$\Delta_4 = \frac{6609 P_s(244) - 2446 P_s(44.6) - 4007 P_s(67) - 424 P_s(170.6)}{EI_2} = \frac{1.1310(10^6) P_s}{EI}$$

$$A_1 = \frac{1}{2}(164)(44.6 P_s) = 3657 P_s$$

$$A_2 = 164(29.9 P_s) = 4904 P_s$$

$$A_3 = \frac{1}{2}(110)(7.7 P_s) = 424 P_s$$

$$\Delta_5 = \frac{6609 P_s(274) - 3657 P_s(54.6) - 4904 P_s(82) - 424 P_s(200.6)}{EI_2} = \frac{1.0934(10^6) P_s}{EI}$$

$$A = 4895 P_5$$

$$\Delta_5 = \frac{10140 P_5 (116) - 4895 P_5 (38.6)}{EI_2} = .9604 (10^6) P_5$$

$$A = \frac{1}{2} (80) (58.2 P_5) = 2328 P_5$$

$$\Delta_6 = \frac{10140 P_5 (80) - 2328 P_5 (26.6)}{EI_2} = .7289 (10^6) P_5$$

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$$A_1 = \frac{1}{2} (65.0 P_6) (80) = 2600 P_6$$

$$A_2 = \frac{1}{2} (44.3 P_6) (236) = 5227 P_6$$

$$A_3 = 20.7 P_6 (236) = 4885 P_6$$

$$A_4 = \frac{1}{2} (5.3 P_6) (110) = 292 P_6$$

$$A_T = 13004 P_6$$

$$\bar{x}_B = \frac{2600 P_6 (26.6) + 5227 P_6 (158.6) + 4885 P_6 (198) + 292 P_6 (352.6)}{13004 P_6}$$

$$\bar{x}_B = 151.4''$$

$$V_A = \frac{13004 P_6 (151.4)}{426} = 4622 P_6$$

$$V_B = 13004 P_6 - 4622 P_6 = 8382 P_6$$

NOTE : BEAM DIAGRAM SHOULD
BE INVERTED

$$A_1 = \frac{1}{2} (6 P_6) (32) = 96 P_6$$

$$A_2 = 20.7 P_6 (32) = 662 P_6$$

$$A_3 = \frac{1}{2} (5.3 P_6) (110) = 292 P_6$$

$$\Delta_1 = - \left[4622 P_6 (142) + 96 P_6 (10.7) - 662 P_6 (16) - 292 P_6 (68.6) \right] = - \frac{6026 (10^6) P_6}{EI_2}$$

$$A_1 = \frac{1}{2} (12.8 P_6) (68) = 435 P_6$$

$$A_2 = 20.7 P_6 (68) = 1408 P_6$$

$$A_3 = \frac{1}{2} (5.3 P_6) (110) = 292 P_6$$

$$\Delta_2 = - \left[4622 P_6 (178) - 435 P_6 (22.6) - 1408 P_6 (34) - 292 P_6 (104.6) \right] = - \frac{7149 (10^6) P_6}{EI_2}$$

$$A_1 = \frac{1}{2} (19.5 P_6) (104) = 1014 P_6$$

$$A_2 = 20.7 P_6 (104) = 2153 P_6$$

$$A_3 = \frac{1}{2} (5.3 P_6) (110) = 292 P_6$$

$$\Delta_3 = - \left[4622 P_6 (214) - 1014 P_6 (34.6) - 2153 P_6 (52) - 292 P_6 (140.6) \right] = - \frac{7792 (10^6) P_6}{EI_2}$$

$$A_1 = \frac{1}{2} (25.2 P_6) (134) = 1688 P_6$$

$$A_2 = 20.7 P_6 (134) = 2774 P_6$$

$$A_3 = \frac{1}{2} (5.3 P_6) (110) = 292 P_6$$

$$\Delta_4 = - \left[4622 P_6 (244) - 1688 P_6 (44.6) - 2774 P_6 (67) - 292 P_6 (170.6) \right] = - \frac{7946 (10^6) P_6}{EI_2}$$

$$A_1 = \frac{1}{2} (30.8 P_6) (164) = 2526 P_6$$

$$A_2 = 20.7 P_6 (164) = 3395 P_6$$

$$A_3 = \frac{1}{2} (5.3 P_6) (110) = 292 P_6$$

$$\Delta_5 = - \left[4622 (274) - 2526 P_6 (54.6) - 3395 P_6 (82) - 292 P_6 (200.6) \right] = - \frac{7700 (10^6) P_6}{EI_2}$$

$$A_1 = \frac{1}{2} (37.6 P_6) (200) = 3760 P_6$$

$$A_2 = 20.7 P_6 (200) = 4140 P_6$$

$$A_3 = \frac{1}{2} (5.3 P_6) (110) = 292 P_6$$

$$\Delta_5 = - \left[\frac{4622 P_6 (310)}{EI_1} - \frac{3760 P_6 (66.7)}{EI_1} - \frac{4140 P_6 (100)}{EI_1} - \frac{292 P_6 (236.6)}{EI_1} \right] = - \frac{6799 (10^6) P_6}{EI_1}$$

$$A = 2600 P_6$$

$$\Delta_6 = - \left[\frac{8382 P_6 (80)}{EI_1} - \frac{2600 P_6 (26.6)}{EI_1} \right] = - \frac{5850 (10^6) P_6}{EI_1}$$

CONTINUITY EQUATIONS

INSULATION
CAN

PRESSURE
TUBE

$$\begin{array}{rcl} \Delta_1 + \Delta_1' & = & \Delta_1 + \Delta_1' \\ \Delta_2 + \Delta_2' & = & \Delta_2 + \Delta_2' \\ \Delta_3 + \Delta_3' & = & \Delta_3 + \Delta_3' \\ \Delta_4 + \Delta_4' & = & \Delta_4 + \Delta_4' \\ \Delta_5 + \Delta_5' & = & \Delta_5 + \Delta_5' \\ \Delta_6 + \Delta_6' & = & \Delta_6 + \Delta_6' \end{array}$$

$$\begin{aligned}
& \frac{9533}{\epsilon} P_1 + \frac{3812}{\epsilon} P_2 - \frac{10149}{\epsilon} P_3 - \frac{7103}{\epsilon} P_4 + \frac{2545}{\epsilon} P_5 + \frac{154}{\epsilon} P_6 - 6.300 \theta'_{1c} \\
& - \frac{4192}{\epsilon} P_1 - \frac{2451}{\epsilon} P_2 + 6948 + 4934 - 2115 - 112 + 4.365 \theta'_{1c} \\
& - 11171 - 6946 P_2 + 29063 + 24169 - 8978 - 563 + 16.005 \theta'_{1c} \\
& - 7821 - 4955 + 24270 + 35918 - 16001 - 1058 + 27.095 \theta'_{1c} \\
& - 2762 - 1780 + 8927 + 15764 - 10162 - 796 + 7.335 \theta'_{1c} \\
& 259 + 160 - 818 - 1561 + 1168 + 235 P_6 - .604 \theta'_{1c}
\end{aligned}$$

$\checkmark \quad \checkmark \quad \checkmark \quad \checkmark \quad \checkmark \quad \checkmark$

$$\begin{aligned}
& = -\frac{1,096,700}{\epsilon} P_1 + \frac{1,213,200}{\epsilon} P_2 - \frac{12,266,000}{\epsilon} P_3 - \frac{10,595,500}{\epsilon} P_4 + \frac{868,300}{\epsilon} P_5 - \frac{607,600}{\epsilon} P_6 \\
& = -\frac{121,1300}{\epsilon} P_1 + \frac{139,4200}{\epsilon} P_2 - \frac{14,12700}{\epsilon} P_3 - \frac{12,38400}{\epsilon} P_4 + 1020200 - 714500 \\
& = -1227700 + \frac{14,11900}{\epsilon} P_2 - 1487800 - 1337200 + 1111000 - 779200 \\
& = -1060000 + 1237200 - 1337200 - 1280800 + 1093400 - 770000 \\
& = -869300 + 1019800 - 1111500 - 1094200 + 960400 - 679900 \\
& = -630000 + 741600 - 812400 - 813400 + 728900 - 585000
\end{aligned}$$

Continuity Equations

Insulation Can (constants rounded off to nearest 100)							Pressure Tube						
$\Delta_1 + \Delta_1'$							$\Delta_1 \Delta_1'$						
$\Delta_2 + \Delta_2'$							$\Delta_2 \Delta_2'$						
$\Delta_3 + \Delta_3'$							$\Delta_3 \Delta_3'$						
$\Delta_4 + \Delta_4'$							$\Delta_4 \Delta_4'$						
$\Delta_5 + \Delta_5'$							$\Delta_5 \Delta_5'$						
$\Delta_6 + \Delta_6'$							$\Delta_6 \Delta_6'$						
P_1	P_2	P_3	P_4	P_5	P_6		P_1	P_2	P_3	P_4	P_5	P_6	
9,500	3,800	10,200	7,100	2,500	200	$- 6.300 E8 \frac{E}{IC}$	$- 1,096,700$	$1,213,200$	$- 1,226,600$	$- 1,059,500$	$868,300$	$- 607,600$	$121.2688 \frac{E}{PT}$
- 4,200	- 2,500	6,900	4,900	- 2,100	- 100	$4.365 E8 \frac{E}{IC}$	$- 1,214,300$	$1,374,000$	$- 1,412,700$	$- 1,238,400$	$1,020,200$	$- 714,500$	$152.0128 \frac{E}{PT}$
- 11,200	- 6,900	29,100	24,200	- 9,000	- 600	$26.005 E8 \frac{E}{IC}$	$- 1,227,700$	$1,411,900$	$- 1,487,800$	$- 1,337,200$	$1,111,000$	$- 779,200$	$182.7568 \frac{E}{PT}$
- 7,800	- 5,000	24,300	35,900	- 16,000	- 1,100	$27.095 E8 \frac{E}{IC}$	$- 1,060,000$	$1,237,200$	$- 1,337,200$	$- 1,280,800$	$1,093,400$	$- 770,000$	$174.1928 \frac{E}{PT}$
- 2,800	- 1,800	8,900	15,800	- 10,200	- 800	$7.335 E8 \frac{E}{IC}$	$- 869,300$	$1,019,800$	$- 1,111,500$	$- 1,094,200$	$960,400$	$- 679,900$	$132.9368 \frac{E}{PT}$
300	200	800	1,600	1,200	200	$- 0.604 E8 \frac{E}{IC}$	$- 630,000$	$741,600$	$- 812,400$	$- 813,400$	$728,900$	$- 585,000$	$91.6808 \frac{E}{PT}$
1,105,200	- 1,209,400	1,216,400	1,052,400	- 865,800	607,800	$= E_{PT} 121.2688 \frac{E}{PT} + 6.3008 \frac{E}{IC}$							
1,210,100	- 1,376,500	1,419,600	1,243,300	- 1,022,300	714,400	$= E_{PT} 152.0128 \frac{E}{PT} - 4.3658 \frac{E}{IC}$							
1,216,500	- 1,418,800	1,516,900	1,361,400	- 1,120,000	778,600	$= E_{PT} 182.7568 \frac{E}{PT} - 26.0058 \frac{E}{IC}$							
1,052,200	- 1,242,200	1,361,500	1,316,700	- 1,109,400	768,900	$= E_{PT} 174.1928 \frac{E}{PT} - 27.0958 \frac{E}{IC}$							
866,500	- 1,021,600	1,120,400	1,110,000	- 970,600	679,100	$= E_{PT} 132.9368 \frac{E}{PT} - 7.3358 \frac{E}{IC}$							
630,300	- 741,400	811,600	811,600	- 727,700	585,200	$= E_{PT} 91.6808 \frac{E}{PT} + 0.6048 \frac{E}{IC}$							
Let insulation can temperature = 300 F avg; $E_{IC} = 26.8 \times 10^6$							Pressure tube temperature = 800 F; $E = 24.2 \times 10^6$						
1.1052	- 1.2094	1.2164	1.0524	- 0.8658	0.6078	$= 2,934.6868 \frac{E}{PT} + 168.8408 \frac{E}{IC} = K_1$							
1.2101	- 1.3765	1.4196	1.2433	- 1.0223	0.7144	$= 3,678.6908 \frac{E}{PT} - 116.9828 \frac{E}{IC} = K_2$							
1.2165	- 1.4188	1.5169	1.3614	- 1.1200	0.7786	$= 4,422.6958 \frac{E}{PT} - 696.9348 \frac{E}{IC} = K_3$							
1.0522	- 1.2422	1.3615	1.3167	- 1.1094	0.7689	$= 4,215.4468 \frac{E}{PT} - 726.1468 \frac{E}{IC} = K_4$							
0.8665	- 1.0216	1.1204	1.1100	- 0.9706	0.6791	$= 3,217.0518 \frac{E}{PT} - 196.5788 \frac{E}{IC} = K_5$							
0.6303	- 0.7414	0.8116	0.8116	- 0.7277	0.5852	$= 2,218.6568 \frac{E}{PT} + 16.1878 \frac{E}{IC} = K_6$							

Assuming the gradient along the in-core length varies as a sine function and the ΔT across tube wall is linear,

$$\Theta'_{ic} = \frac{\alpha L}{D\pi} \Delta T_{ic} \quad \text{where } \alpha @ 300^\circ\text{F} = 9.47(10^{-6})$$

$$L = 48$$

$$D = 2.875$$

$$\Theta'_{ic} = \frac{9.47(10^{-6})(48)}{2.875\pi} \Delta T_{ic} = 50.328(10^{-6}) \Delta T_{ic}$$

$$\Theta'_{PT} = \frac{10.05(10^{-6})(48)}{2.535\pi} \Delta T_{PT} = 60.572(10^{-6}) \Delta T_{PT}$$

$$K_1 = 2934.686 \Theta'_{PT} + 168.840 \Theta'_{ic}$$

$$= 2934.686 (60.572(10^{-6}) \Delta T_{PT}) + 168.84 (50.328(10^{-6}) \Delta T_{ic})$$

$$= .17776 \Delta T_{PT} + .00850 \Delta T_{ic}$$

$$K_2 = 3678.690 (60.572(10^{-6}) \Delta T_{PT}) - 116.982 (50.328(10^{-6}) \Delta T_{ic})$$

$$= .22282 \Delta T_{PT} - .00589 \Delta T_{ic}$$

$$K_3 = 4422.695 (60.572(10^{-6}) \Delta T_{PT}) - 696.934 (50.328(10^{-6}) \Delta T_{ic})$$

$$= .26789 \Delta T_{PT} - .03508 \Delta T_{ic}$$

$$K_4 = 4215.446 (60.572(10^{-6}) \Delta T_{PT}) - 726.146 (50.328(10^{-6}) \Delta T_{ic})$$

$$= .25534 \Delta T_{PT} - .03654 \Delta T_{ic}$$

$$K_5 = 3217.015 (60.572(10^{-6}) \Delta T_{PT}) - 196.578 (50.328(10^{-6}) \Delta T_{ic})$$

$$= .19486 \Delta T_{PT} - .00989 \Delta T_{ic}$$

$$K_6 = 2218.656 (60.572(10^{-6}) \Delta T_{PT}) + 16.187 (50.328(10^{-6}) \Delta T_{ic})$$

$$= .13439 \Delta T_{PT} + .00081 \Delta T_{ic}$$

$$\Delta T_{PT} = 100^\circ F$$

$$\Delta T_{IC} = 100^\circ F$$

$$\frac{\Delta T_{PT}}{\Delta T_{IC}} = \frac{100}{100} = 1$$

$$K_1 = 18.626$$

$$K_2 = 21.693$$

$$K_3 = 23.281$$

$$K_4 = 21.880$$

$$K_5 = 18.497$$

$$K_6 = 13.520$$

$$\Delta T_{PT} = 100$$

$$\Delta T_{IC} = 50$$

$$\frac{\Delta T_{PT}}{\Delta T_{IC}} = \frac{100}{50} = 2$$

$$K_1 = 18.201$$

$$K_2 = 21.988$$

$$K_3 = 25.035$$

$$K_4 = 23.707$$

$$K_5 = 18.992$$

$$K_6 = 13.480$$

$$\Delta T_{PT} = 100$$

$$\Delta T_{IC} = 33.333$$

$$\frac{\Delta T_{PT}}{\Delta T_{IC}} = \frac{100}{33.333} = 3$$

$$K_1 = 18.059$$

$$K_2 = 22.086$$

$$K_3 = 25.620$$

$$K_4 = 24.316$$

$$K_5 = 19.156$$

$$K_6 = 13.466$$

$P_1, P_2, P_3, P_4, P_5, P_6$

$$\Delta T_{PT} = 100$$

$$\Delta T_{IC} = 25$$

$$\frac{\Delta T_{PT}}{\Delta T_{IC}} = \frac{100}{25} = 4$$

$$K_1 = 17.988$$

$$K_2 = 22.135$$

$$K_3 = 25.912$$

$$K_4 = 24.620$$

$$K_5 = 19.239$$

$$K_6 = 13.459$$

Total Deflection at Core Mid-Height

$$\Delta_{ic_0} + \Delta'_{ic_0} = -\frac{11053}{E} P_1 - \frac{6950}{E} P_2 + \frac{32565}{E} P_3 + \frac{36193}{E} P_4 - \frac{14743}{E} P_5 - \frac{903}{E} P_6$$

$$+ 28.455 \theta'_{ic} + \Delta''_{ic_0}$$

$$\Delta_{PT_0} + \Delta''_{PT_0} = -\frac{1.1707(10^6)}{E} P_1 + \frac{1.3576(10^6)}{E} P_2 - \frac{1.4526(10^6)}{E} P_3 - \frac{1.3467(10^6)}{E} P_4 + \frac{1.1310(10^6)}{E} P_5 - \frac{7946(10^6)}{E} P_6$$

$$+ 187.756 \theta'_{PT_0} + \Delta''_{PT_0}$$

with $E_{ic} = 26.8(10^6)$

$E_{PT} = 24.2(10^6)$

$\theta'_{ic} = 50.328(10^{-6}) \Delta T_{ic}$

$\theta'_{PT} = 60.572(10^{-6}) \Delta T_{PT}$

$$\Delta''_{ic_0} = \frac{\alpha L^2}{\pi^2 D} \Delta T_{ic} = \frac{9.47(10^{-6})(48)^2}{2.875 \pi^2} \Delta T_{ic} = 768.947(10^{-6}) \Delta T_{ic}$$

$$\Delta''_{PT_0} = \frac{10.05(10^{-6})(48)^2}{2.535 \pi^2} \Delta T_{PT} = 925.468(10^{-6}) \Delta T_{PT}$$

$$\Delta_{ic} = \left[-412.387 P_1 - 259.304 P_2 + 1215 P_3 + 1350.361 P_4 - 550.061 P_5 - 33.691 P_6 \right] 10^{-6}$$

Total $+ 1432.083(10^{-6}) \Delta T_{ic} + 768.947(10^{-6}) \Delta T_{ic}$

$2201(10^{-6}) \Delta T_{ic}$

$$\Delta_{PT} = \left[-48373 P_1 + 56096 P_2 - 60021 P_3 - 55646 P_4 + 46733 P_5 - 32833 P_6 \right] 10^{-6}$$

Total $+ 11372.756(10^{-6}) \Delta T_{PT} + 925.468(10^{-6}) \Delta T_{PT}$

$12298(10^{-6}) \Delta T_{PT}$

E.7. STRESS CALCULATION RESULTS FOR OTHER CONFIGURATIONS INVESTIGATED

In addition to the recommended permanent modifications, several modifications were investigated from a stress and/or thermal bow standpoint.

E.7.1. Inner/Outer Loop Positions

A. A 12-inch-long "stove pipe" was installed on the upper ID of the safety rod. The stresses on the stove pipe and on the safety rod strongback due to this modification were negligible.

B. A 40-inch-long sleeve was attached just below the splines on the NR loop insulation jacket. The stresses on the sleeve were 5230 psi hoop, 26,000 psi thermal stress at the lower end in the core region, and 13,600 psi stress due to differential growths of the sleeve and the insulation jacket.

C. A combination of A and B above. The stresses were the same as above. The thermal bow of the NR loop was calculated at 0.152 inch, which, at approximately 3 inches withdrawal of the safety rod, would leave only 0.015-inch gap between the sleeve and the stove pipe after the safety rod tilted at the articulated joint to give a 0.025-inch motion at the top of the safety rod.

D. A 37-inch-long sleeve was attached on the insulation jacket just below the splines. The stresses were essentially the same as those for B, except that the thermal stress was much lower.

E. A 10-inch-long stove pipe was mounted on the upper ID of the safety rod. The stresses were negligible.

E.7.2. Center Loop Position

A. A 20-inch-long sleeve was attached just below one spline on the insulation jacket. The stresses were essentially the same as for E.7.1.B except that the thermal stress was negligible.

B. Several 7/8-inch-long collars were attached to the splines on the insulation jacket. The major variation in the collars was the flow area. The stresses on the collars were 12,300 psi tensile stress in the minimum cross section, 100 psi bearing stress at the contact surface with the splines, and 24,200 psi shear stress on the down pins.

APPENDIX F
Drawings Showing Modifications to the Internals

CONTENTS

<u>Drawing No.</u>	<u>Title</u>
INC 035761	ATR Safety Rod Guide Tube Internal Sleeve
INC 035763	ATR Safety Rod Modified Flux Trap Filler and Modified Hafnium Stop
INC 035770	ATR Safety Rod Extension Sleeve Internal Flow Restrictor
INC 035777	ATR Dummy Flux Trap Filler Internal Flow Restrictor
INC 035800	ATR Dummy Flux Trap Filler Internal Sleeve
INC 035819	ATR Center Loop In-Pile Tube Flow Restrictor
B&W ATR-1075-MTR-670-M1111	ATR Insulating Jacket Subassembly and Details
B&W SK-RWR-8-24-67-5072-1	ATR Pressure Tube Locator Ties - Details
B&W SK-RWR-8-24-67-5072-2	ATR Pressure Tube Locator Ties

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