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Westinghouse Astronuclear Laboratory

FULL CORE AXIAL INTERELEMENT
IMPEDANCE TEST

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39

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FULL CORE AXIAL INTERELEMENT
 IMPEDANCE TEST

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Submitted By:

ENGINEERING MECHANICS DEPARTMENT
 Westinghouse Electric Corporation
 Astronuclear Laboratory
 P. O. Box 10864
 Pittsburgh, Pennsylvania - 15236

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by H. F. C. TIC, date SEP 12 1973

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PREPARED BY:

R. D. Burack
 R. D. Burack

Reactor Assembly & Dynamics Experiments

SPECIAL REVIEW FINAL DETERMINATION	Reviewer	Class.	Date
	KAW	U	4-17-82
Class:	U		

APPROVED BY:

W. J. Rowan
 W. J. Rowan, Manager
 Engineering Mechanics

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TABLE OF CONTENTS

	Page
1.0 SUMMARY	1
2.0 INTRODUCTION	3
3.0 TEST SETUP	
3.1 Full Core Flow Test	5
3.2 Porosity and Leak Test	7
4.0 INSTRUMENTATION	8
5.0 TEST RESULTS	
5.1 Porosity	10
5.2 Core Geometry	11
5.3 Flow Tests	12

LIST OF FIGURES

3.1a Schematic of Test Fixture for Core Effective Gap Test	15
3.1b Cluster Locations in Core	16
3.2 Element Cap Cemented in Place	17
3.3 Core Support Base	18
3.4 Bundling Bands	19
3.5 Core Assembly	20
3.6 Core Assembly with Rubber Peripheral Seal	21
3.7 Complete Test Setup.	22
3.8 Schematic of Porosity and Leak Check Fixture	23
4.1 Instrumented Fuel Element (Pressure Probes)	24
4.2 Pressure Probe Hookup to Scanivalve	25
4.3 Schematic of Diaphragm Pressure Transducer Mounting.	26
5.1 Typical Chamber Pressure Vs. Time	27
5.2 Element Porosity Leak Rate	28

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WANL-TME-1219

LIST OF FIGURES

(Continued)

	Page
5.3 Core Diameter Vs. Bundling Pressure	29
5.4 Interelement Flow Vs. $P\Delta P$	30
5.5 Flow Vs. Core Diameter Change Nitrogen Gas	31
5.6 Interelement Pressure Distribution Helium Gas	32
5.7 Interelement Pressure Distribution Nitrogen Gas	33
5.8 Interelement Pressure Distribution Helium Gas	34
5.9 Interelement Pressure Distribution Nitrogen Gas	35
5.10 Radial Pressure Distribution Clusters Helium Gas.	36

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1.0 SUMMARY

This report presents the results of the EML-60 Core Effective Gap Tests that have been obtained to date. The objective of the test was to determine the effective axial core gap impedance and the effect of increased lateral bundling pressures on this impedance. In order to attain this goal it was also necessary to determine fuel element porosity and core dimensional properties. Experimental measurements of 1) core diameter vs. bundling pressure, 2) fuel element porosity, and 3) interelement axial flow rate and pressure distribution with both helium and nitrogen gas are presented. These results are now being used to verify and improve empirical and theoretical impedance relationships.

Porosity measurements were made on 100 elements randomly selected from the core. The core diameter vs. bundling characteristics were measured and a calculated gap determined.

A total of forty-one interelement pressure probes, reading at four axial levels, were monitored during the flow test series. A uniform lateral bundling pressure was varied from 3 to 10 psi. The measured variables were interelement pressures, flow rate, bundling pressure and core diameter. Input pressures to 100 psig and differential pressures to 35 psi were applied to the core using both helium and nitrogen gas.

It was found that the porosity leakage rate varied considerably between elements. The measured leakage varied from 1.4×10^{-6} to 1.4×10^{-7} lb/sec/in. with helium gas at 100 psig external pressure.

A 10 mil decrease in core diameter was measured as a result of increasing the bundling pressure from 2 to 10 psi in agreement with partial core data. The calculated average interelement gap is 1.3 mils for this core. The calculated gap is obtained from the sum of known element dimensions across a core diameter. A 10 mil decrease in core diameter, therefore, represents a 15% decrease in the calculated gap size.

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The maximum helium flow rate was 0.13 lb/sec at a pressure differential of 100 to 65 psig. This flow rate is within the range expected.

The nitrogen mass flow was 12 times that of helium. The density ratio between the two gasses is 7 to 1. This greater flow can be attributed in part to the smaller viscosity of nitrogen, flow being inversely proportional to viscosity.

The interelement pressure axial gradients are not linear, dropping off more rapidly at the dome end. This can be attributed to porosity and gas compressibility effects.

An 8% decrease in calculated gap size results in a 5% decrease in total flow rate.

The flow rate measured in a simulated core band test (top band 15 psi, 3 psi uniform on the remaining) was the same as at a uniform bundling pressure of 10 psi.

The accuracy of gas sampling pressure probe type instrumentation was demonstrated using a flush mounted diaphragm system.

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2.0 INTRODUCTION

One of the main design considerations in the current NERVA reactor program is the problem of fuel element surface corrosion. It is believed that this corrosion results from interelement gap flow, pressure distribution and element porosity characteristics. It is necessary to understand and be able to calculate this flow. Computer codes have been developed by WANL for this purpose and are constantly being upgraded. As new design concepts evolve, the interelement flow must be reevaluated.

There are two types of interelement flow, axial and radial, each of which contributes to the total gap leakage. The effects of porosity and gap size as functions of temperature and bundling pressure are significant. By separating out and measuring only pure axial core flow at known core dimensional conditions an effective channel flow impedance can be determined. Up to this point, only empirical and theoretical methods were used in calculating gap impedance. The tests described have now provided experimental results for direct comparison. As theoretical techniques are confirmed by direct experimental comparison, they can be applied with increased confidence to other conditions affecting flow, such as core temperature.

The test program described here, EML-60, was initiated to determine interelement flow impedance as a function of external bundling pressures. The test specimen consists of a full core composed of unfueled elements supported within a test fixture so that only pure axial channel flow exists. Simple modifications can convert this setup to a pure radial flow test; giving impedance information on the other major leakage path. The test core is readily accessible so that future design concepts, such as extruded to size element, core wrappers and peripheral redesigns, can be incorporated and evaluated.

In order to effectively measure the parameters involved, testing was performed in three steps:

1. Determination of element porosity leakage rates.

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2. Determination of core diameter and calculated gap size as a function of bundling pressure.
3. Determination of interelement flow rates and pressure profiles.

The results from each of these tests are presented in this report. Two gases, helium and nitrogen, were utilized to determine the effect of gas properties. Analysis of the test data is presently being performed.

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3.0 TEST SETUP

3.1 Full Core Flow Test

The test specimen consists of a full core composed of unfueled elements and filler strips mounted within a pressure vessel. A schematic of the test assembly is shown in Figure 3.1. Support blocks and tie rods are not used. Axial core support is provided by a base which does not inhibit flow. The core is bundled by six hydraulically loaded bands which can apply either a uniform or varying bundling pressure along the core length. Fuel element holes are plugged so that only interelement axial flow is present. Interelement pressure profiles are measured with pressure probes.

The core is composed of 13 and 19 hole unfueled Y12 elements, all of which have been inspected and found to be within NERVA fuel element tolerance. Each element is individually capped at the dome end with an aluminum hex as shown in Figure 3.2. The hex is cemented in place using RTV891 adhesive. One hundred percent of the caps were checked at 100 psi for leakage. The fixture used for this check is described in Section 3.2. Aluminum filler strips complete the core periphery. These filler strips were originally used as gage blocks in assembling the ND 20102 and NRX-A1 reactors and are the exact dimensional envelope of the graphite filler strips.

The core is supported by a base which does not inhibit flow. It is composed of 289 star shaped aluminum extrusions cemented to a base plate as shown in Figure 3.3. Each extrusion supports seven elements.

Six, four-inch steel bands apply a lateral bundling pressure to the core. The pressure applied by each band is controlled individually using two hydraulic cylinders. A photograph of the bands is shown in Figure 3.4. Teflon tape, placed

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between the band and filler strips, minimizes friction and therefore assures a uniform bundling pressure. The band ends are welded to cylinders and the hydraulic force applied through these cylinders. This arrangement produces a tangential force at the band ends and consequently produces a nearly uniform circumferential bundling pressure.

Each band has a maximum pressure bundling capacity of 35 psi, due to stress limitations, representing a maximum equivalent uniform core bundling pressure of 16 psi. Each band can be controlled individually to produce a non-uniform bundling pressure, as desired.

Six steel rings, one-inch thick and bolted together, provide lateral core support. A photograph showing the core mounted within the rings is shown in Figure 3.5. Six chambers are formed by these rings on the core periphery. Each chamber is sealed and assumes the axial interelement pressure at the core periphery. The pressure gradient across the filler strips, therefore, approaches zero, giving a pure axial flow condition. The lower portion of each chamber is sealed so that it assumes the middle end interelement pressure. A seal is used between the rings and core to eliminate flow from chamber to chamber on the core side.

A rubber bladder is placed over the ring assembly (Figure 3.6) and banded in place to provide a peripheral chamber seal. As the chambers become pressurized, the bladder expands against the pressure vessel wall.

A photograph showing the complete assembly and piping system is shown in Figure 3.7. The pressure vessel is ASME coded to 150 psi. All instrumentation leads are brought out the dome end through Conax fittings.

A one-half inch air-operated control valve is manually controlled to regulate the input or head pressure. A two-inch self-contained back pressure regulator is used to control the exit plenum pressure. The input flow rate is measured using a three-inch orifice plate meter.

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3.2 Porosity and Leak Check Test

A schematic of the fixture used for porosity and leak check investigations is shown in Figure 3.8.

In order to perform a cap leak check, the element is placed within a chamber pressurized to 100 psig with helium gas. A pressurized rubber bladder with a hex shaped hole prevents any leakage around the edge of the element. Any gas leakage through the cap can be determined from the pressure change in the chamber using the relationship $W = PV/RT$, so that the gas weight loss for isothermal flow becomes:

$$(W_2 - W_1) = \frac{V\Delta P}{RT}$$

where:

Chamber Volume - V	=	0.085 ft ³
Gas Constant - R _{He}	=	1544/M = 386
Temperature - T	=	530°R

An acceptance leakage rate of 4×10^{-6} lb/sec was established. This limit represents a total core cap leakage of 0.008 lb/sec which is small in comparison to the interelement flow rate. In practice, it was determined that the cap either leaked badly or not at all.

Tests to determine element porosity were performed by placing the entire element within the chamber and pressurizing the chamber to 100 psig. Chamber pressure readings were taken every 15 seconds. The resulting curve of pressure change vs. time was used to calculate the porosity flow rate, again using the relationship

$$\frac{dW}{dt} = \frac{V}{RT} \frac{dP}{dt}$$

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4.0 INSTRUMENTATION

The test assembly transducers are placed so as to measure:

1. Gas flow rate.
2. Interelement pressure distribution.
3. Core diameter.
4. Entrance, exit and chamber pressures.
5. Lateral mechanical bundling pressures.

A three-inch orifice meter with flange taps is used to measure input flow. Two orifice plates are used to efficiently measure the expected flow range. Pressure readings, from a 2.5 psi differential pressure transducer across the orifice plate, are converted directly to mass flow rate.

Interelement pressures are measured using pressure probes as shown in Figure 4.1. These probes are the type used in the ND 207 and NRX-A1 reactors. Forty-one probes are located at four axial core elevations, four radii and three azimuthal positions as defined in Figure 3.1. A "Scanivalve" is used to record these pressures.

The Scanivalve (Figure 4.2) is a device which sequentially scans a maximum of forty-eight pressure taps using a single pressure transducer. The scanning rate used for this test was 10 measurements/sec. This method is particularly effective for recording multiple pressures, as all readings are taken from a single transducer, thus establishing a single reference. The elimination of forty-seven pressure transducers from the data system also represents a considerable cost savings.

Pressure tap probes of this type are used to measure the pressure in the inter-element gaps of approximately 0.001 inch magnitude. Some concern has been shown about the effect on this measurement of the large plenum created by the probe itself. Nine flush mounted diaphragm type pressure transducers were placed randomly within the core to resolve this question. Their mounting configuration is shown in Figure 4.3.

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Three half-inch bands, spring loaded with 1/4 inch linear pots, are located at the top, center and bottom of the core as shown in Figure 3.5. These bands measure core circumferential change which is then converted to diameter change.

The entrance, exit, and chamber pressures are measured with pressure taps connected to the scanivalve. As an additional instrumentation check, two 150 psig strain gage pressure transducers are located in the entrance and exit chambers.

Two strain gages, located 120° apart on each bundling band, measure band strain. This strain is converted to bundling pressure using the relationship:

$$P_B = \frac{2T}{DW}$$

where: T = Tension in band from strain gage readings.
D = Core diameter - 35.6"
W = Band width - 4"

An additional backup on bundling band pressure is provided by the calibrated hydraulic pressure supplied to the hydraulic cylinders.

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5.0 TEST RESULTS

5.1 Porosity

One hundred elements randomly selected from the core were tested for porosity leak rate. An external pressure of 100 psig was applied to each element using helium gas and the test chamber sealed. The bore hole pressure remains at ambient conditions. It was found that the porosity leakage flow rate varied considerably between elements.

The leakage rate as represented by the chamber pressure change is shown in Figure 5.1. The six curves shown are typical of those for all elements and cover the measured leakage range. Each of the elements tested are classified as being represented by one of these typical curves. The percentage of elements having the porosity shown by each curve is tabulated below:

First 21 Elements Sampled		Second 50 Elements Sampled	
Curve No.	% of Total	Curve No.	% of Total
1	38	1	34
2	5	2	10
3	14	3	18
4	10	4	12
5	20	5	12
6	5	6	12
Below	5	Below	2

The remaining elements sampled contained one central hole and exhibited negligible leakage. Approximately 400 elements in the core contain only one central hole or are solid.

A plot of the porosity flow per unit length for each of the six ranges is given in Figure 5.2. A total flow rate due to porosity of 0.04 lb/sec is obtained if these porosity values are extrapolated to an entire core for this pressure drop. This value is conservative as it represents full pressure over the entire element length.

The porosity mass leakage rate for nitrogen is 6.5 times that of helium as determined from comparison tests on the same elements.

Several element characteristics were noted during the check. Most of the porosity leakage occurred through the peripheral flow holes, which was expected. Because of this, negligible difference was found between 19 and 13 hole elements. This flow could be detected visually using "Leak-Tec", a liquid which bubbles when exposed to gas flow. One element with an apparently high porosity leakage rate was found to contain several small pinholes.

5.2 Core Geometry

Diameter measurements were taken on the assembled core at three axial locations; top, middle and bottom. The average core diameter as assembled with no bundling pressure is approximately 35.610 inches. The average interelement gap at 3 psi bundling pressure calculated from known across flats element dimensions was found to be 1.3 mils.

A curve of core diameter vs. bundling pressure is given in Figure 5.3. The sharp decrease in diameter as the bundling pressure is increased from 0 to 2 psi is caused by initial core packing. A 15 mil difference in diameter can be seen along the core length. An approximate diameter decrease of 10 mils results from increasing the bundling pressure from 2 to 10 psi. This is in very close agreement with previous diameter vs. bundling pressure measurements taken on a partial length 9 inch core. Since the 9 inch core length results agree with full length results, it appears that element bow and twist do not significantly affect core packing in this bundling pressure range.

In order to obtain an approximate magnitude of the average core gap size the across flats element dimensions were summed across three core diameters. This sum was then subtracted from the total core diameter. The difference divided by the number of element interfaces across the core provides an estimate of the average interelement gap.

The average gap size for the top of the core at a bundling pressure of 3 psi on this basis was calculated to be 1.3 mils. Forty-eight interfaces, including that between a filler strip and its adjacent element, exist across the core diameter location chosen. An increase in bundling pressure from 2 to 10 psi therefore causes a gap decrease of 10/48 or 0.21 mils. This represents an average core gap decrease of about 15%. The diameter change and consequently the gap size levels off at this pressure.

5.3 Flow Tests

Pressure differentials* of 25-0, 25-10, 50-25 and 100-65 psig were applied across the core using helium gas. Pressure drops of 50-25 and 100-65 psig were also applied using nitrogen gas. The mechanical lateral bundling pressure was varied during each test from 3 to 10 psi. A single test at a pressure drop of 100-65 psig was performed using nitrogen gas in which a uniform bundling pressure of 3 psi was applied to the core while the top band bundling pressure was held at 15 psi. This pressure was set to simulate the effect of a core band and determine its effect on the flow rate.

A plot of mass flow rate vs. applied pressure for both helium and nitrogen gas is shown in Figure 5.4. The helium flow varied from 0.03 to 0.13 lb sec which is within the range expected for the pressure ratios applied.

The nitrogen mass flow rate is twelve times higher than for helium at equal applied pressure conditions. The density ratio between nitrogen and helium is seven to one meaning that a greater volumetric nitrogen flow exists. This seems reasonable as the viscosity of nitrogen is less than that of helium and flow is inversely proportional to viscosity. This is illustrated by the following relationship for incompressible laminar flow.

* The terminology 25-10 means inlet pressure is 25 psi and outlet pressure is 10 psi.

$$\dot{m} \propto \frac{e t^n \Delta P}{\mu l}$$

l	=	channel length
ΔP	=	pressure drop
t	=	gap thickness
ρ	=	gas density
μ	=	gas viscosity
$\dot{m}$	=	mass flow rate

Only a small change in total flow was measured as a result of varying the bundling pressure. A typical plot of total flow vs. bundling pressure for nitrogen gas is given in Figure 5.5. A change in calculated gap size of 8% caused a change in total flow of 5%. The actual channel flow change is a function of the porosity flow as well which much be calculated from the interelement pressure profiles.

Graphs of interelement pressure profiles are shown in Figure 5.6 through 5.9 at maximum bundling pressure. The axial pressure profile is not linear, dropping off more rapidly at the dome end, most likely slowing the effect of porosity flow and gas compressibility. The pressure profiles did not change with bundling pressure indicating that the porosity flow rate remained nearly constant. A slight difference in the interelement pressure profile exists between the gases at equal pressure drop conditions.

The pressure was nearly uniform across the core at each axial station, indicating either good radial communication or pure axial channel flow. Some typical radial pressure profiles at three azimuthal positions are shown in Figure 5.10.

No significant change in flow was found between the simulated core band and uniform bundling test runs both at pressure drops of 90-63 psi. A flow

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rate of 1.44 lb/sec of nitrogen was measured during a simulated band run. The same flow was measured at a uniform bundling pressure of 10 psi.

Diaphragm type pressure transducers were installed and monitored to determine the accuracy of probe type interelement pressure measurements. Both the probe and diaphragm type transducers gave the same readings for interelement pressure. Some typical readings from these transducers and the corresponding pressure probe measurements are tabulated below:

Cluster	Location (in.)	Reading (psi)	Reading (psi)	Type of Diaphragm
B3	7	38	36	Disc
A2	20.75	31	31.8	Micro Sys.
A3	20.75	31	31	Disc
B1	35	30	33	Disc
C3	43.75	26.5	25	Micro Sys.

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CORE EFFECTIVE GAP TEST

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FIGURE 3.1

Schematic of Test Fixture for Core Effective Gap Test

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FIGURE 3.1B

Cluster Locations in Core. Four Interelement Probes Randomly
Placed in Each Cluster at Levels of 7.0", 21.0", 35.0" and 44.0"

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FIGURE 3.2

Element Cap Cemented in Place

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FIGURE 3.3

Core Support Base

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FIGURE 3.4
Bundling Bands

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FIGURE 3.5

Core Assembly

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FIGURE 3.6

Core Assembly with Rubber Peripheral Seal

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FIGURE 3.7

Complete Core Setup

ELEMENT POROSITY CHECK

CAP LEAK CHECK

FIGURE 3.8

Schematic of Porosity and Leak Check Fixture

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INSTRUMENTED FUEL ELEMENT
(PRESSURE PROBES)

FIGURE 4.1

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FIGURE 4.2

Pressure Probe Hookup to Scanivalve

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Schematic of Diaphragm Pressure Transducer Mounting

FIGURE 4.3

FIGURE 5.1

Typical Chamber Pressure vs. Time
for Porosity Measurement

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605862A

FIGURE 5.2

Element Porosity Leak Rate

FIGURE 5.3

Core Diameter vs. Bundling Pressure

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FIGURE 5.4
Interelement Flow vs. $P \Delta P$

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FIGURE 5.5

Flow vs. Core Diameter Change Nitrogen Gas

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FIGURE 5.6

Nitrogen Pressure Distribution Helium Gas

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FIGURE 5.7

Interelement Pressure Distribution Nitrogen Gas

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FIGURE 5.8

Interelement Pressure Distribution Helium Gas

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FIGURE 5.9

Interelement Pressure Distribution Nitrogen Gas

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FIGURE 5.10

Radial Pressure Distribution Clusters
Helium Gas Pressure Drop 94-58 psig