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SPECTRAL SHIFT CONTROL REACTOR
BASIC PHYSICS PROGRAM

EXPONENTIAL EXPERIMENTS AT ELEVATED
TEMPERATURES ON LATTICES MODERATED
BY D₂O-H₂O MIXTURES

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By
L. G. Barrett
H. J. Worsham
T. C. Engelder
Development Department

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ABSTRACT

Summarized here are the results of exponential experiments conducted at elevated temperatures on rod lattices of slightly-enriched UO_2 moderated by D_2O - H_2O mixtures. The fuel rods, 4%-enriched UO_2 swaged in stainless steel, were 0.476-inch OD by 0.016-inch wall. The non-moderator-to-moderator volume ratio was 1.006. The two moderator compositions studied were light water (0% D_2O) and a D_2O - H_2O mixture containing 81.5 mole % D_2O .

The experimental facility and techniques are described. Material buckling values derived from radial and axial flux measurements are summarized below.

<u>0% D_2O</u>		<u>81.5% D_2O</u>	
<u>Temperature, F</u>	<u>$B_m^2, \times 10^{-4} \text{ cm}^{-2}$</u>	<u>Temperature, F</u>	<u>$B_m^2, \times 10^{-4} \text{ cm}^{-2}$</u>
66	88.24 ± 0.87	70	3.81 ± 0.41
103	88.03 ± 0.96	105	3.18 ± 0.26
203	85.76 ± 1.37	150	1.86 ± 1.12
308	80.12 ± 0.66	200	1.12 ± 0.61
406	72.72 ± 0.65	297	-0.46 ± 0.89
		384	-2.02 ± 0.92

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1. INTRODUCTION

1.1. SSCR Basic Physics Program

The general objective of the SSCR Basic Physics Program is to study the nuclear properties of rod lattices moderated by D_2O - H_2O mixtures. In the first phase, the lattice non-moderator-to-moderator volume ratio was approximately 1.0, and the fuel was either 4%-enriched UO_2 clad in stainless steel, or 93%-enriched UO_2 - ThO_2 ($N_{Th}/N_{25} = 15$) pellets clad in aluminum. The D_2O concentration in the moderator ranged from 0 to approximately 90%.

The program consisted of critical experiments with both types of fuel, exponential experiments at room temperature with both types of fuel, exponential experiments at elevated temperatures with the 4%-enriched UO_2 fuel, neutron age measurements in ThO_2 - D_2O - H_2O lattices, and theoretical analysis.

The exponential experiments at elevated temperatures are reported here. The work performed on the other tasks is described in the referenced topical reports.¹⁻⁴ Additional program details are available in the series of SSCR Basic Physics Program Quarterly Technical Reports.⁵⁻⁹

1.2. Hot Exponential Experiments

The SSCR hot exponential experiments measured the material buckling (between 70 and 400 F) of 4%-enriched UO_2 fuel lattices moderated by D_2O - H_2O mixtures. The two moderator compositions studied were 0% D_2O and approximately 81% D_2O . The non-moderator-to-moderator volume ratio in each lattice was approximately 1.0. These experiments provide nuclear data at temperatures and pressures approaching those of an operating power reactor.

The hot exponential experiments with a light water moderator were performed in the spring of 1961. The experiment with heavy water in the moderator began in December, 1961 and was completed in January, 1962.

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2. DESCRIPTION FACILITY

The hot exponential experiments were performed in the Hot Exponential Facility of the Babcock and Wilcox Company. The exponential lattices were assembled in a pressure vessel equipped with heaters, pressurizer, and other auxiliary equipment required to raise the moderator temperature and pressure. The Lynchburg Pool Reactor (LPR) supplied neutrons to drive the exponential lattices. A general description of this facility is given in the following sections; additional details are available in the Hazards Evaluation for these experiments ¹⁰.

2.1. Lynchburg Pool Reactor

The LPR (Fig. 2-1, was used as the neutron source for these experiments. This facility is a light-water moderated swimming pool research reactor using MIR-type highly-enriched U-Al fuel elements. The reactor is cooled by natural circulation and can be operated intermittently at power levels up to 450 kw

LPR core configuration No. 6 was used for the light-water moderated exponential experiments and configuration No. 1 was used for the 81.5% D₂O cases. Both configurations used 16 fuel elements in a 4 x 4 array. However, configuration No. 6 differed slightly since one of the four control rod elements was replaced by a partially-loaded fuel element. The fuel elements were assembled on the LPR grid plate against the boral shutter.

2.2. Hot Exponential Facility

Figure 2-2 is a horizontal section through the LPR core and the autoclave (or pressure vessel) in which the exponential lattices were placed. The autoclave, a 3-foot ID by 9-foot-long unfired cylindrical pressure vessel, is fabricated of stainless-steel clad 1-inch-thick carbon steel, and is designed for a maximum pressure and temperature of approximately 800 psi and 530 F.

The vessel has a quick-opening door to facilitate loading changes and foil removal. The inside of the vessel is lined with a 1/8-inch-thick boron steel (≈ 1.25 wt % B) sheet to reduce the activation of the steel and to decrease the effect of neutron reflections from the walls. (See Section 3.2.)

The following structural elements are located between the LPR core and the pressure vessel: a 0.25-inch-thick removable boral shutter, a 1-inch-thick aluminum closure plate, 4 inches of lead shielding, concrete shielding blocks, a void space, a thin aluminum radiant heat reflector, and the 1-inch-thick pressure vessel wall. This arrangement was designed to minimize reactivity coupling between the LPR and the exponential assembly, to maximize the available thermal neutron flux, and to reduce fast neutron and gamma radiation levels in the surrounding area. The region between the pressure vessel and the permanent concrete shielding is filled with high purity sand which forms an inexpensive removable shield and thermal insulation.

Figure 2-3 shows the front of the pressure vessel with the door open. The LPR control rod drives are at the upper level. To the right, is the pressurization loop, the pressurizer, and other moderator system components.

2.3. Moderator System

Figure 2-4 shows the system for circulating, heating, and pressurizing the moderator. Shown here are several features added to the light water system to accommodate heavy water in the moderator.

The moderator is pumped through the primary loop by a 50-gpm canned-rotor circulating pump. The loop is pressurized by nitrogen gas directly contacting the moderator in a 10-inch diameter by 15-foot long pressurizer. The system pressure is always maintained at least 15 psi above saturation, and to prevent pump cavitation, it is never less than 40 psig. Heat is supplied by two tubular resistance heaters with capacities of 100 kw and 20 kw. The 20-kw heater is variable and can be used for automatic temperature control. All components of the 550-gallon primary loop are stainless steel.

After an experiment is completed or if an emergency occurs, the moderator is discharged through a 4-inch diameter carbon steel pipe to an 8-foot diameter by 7.5-foot-high painted carbon steel letdown

tank outside the building. Water or steam is ejected through six nozzles at the bottom of the tank. This tank was 2/3-filled with light water to condense steam during the light water experiments.

Some modifications to the light water system were required before the heavy water experiment could be undertaken. The following considerations influenced the design of these modifications.

1. If light water should accidentally be introduced into the system, the large exponential lattice could become supercritical.

2. Because of its value, the moderator should not be discharged into the atmosphere after an experiment is completed or if an emergency dump occurs.

Based on these considerations, the following modifications were made:

1. All light water lines were disconnected and sealed. A reciprocating pump was included to provide fresh water makeup to the primary loop.

2. An existing $4 \times 4 \times 5$ -foot closed steel tank was used to store the moderator under controlled conditions. The moderator was transferred by a 50-gpm mobile pump from the storage tank to the primary loop at the beginning of each experiment. After the day's experiments, it was transferred back to the storage tank by system pressure or by pumping.

3. Previously, the light water moderator was discharged to the letdown tank after an experiment was completed. To avoid these losses, a letdown cooler was provided to cool and condense the moderator, and it was returned to the storage tank after each experiment. This heat exchanger had a capacity of about 20 gpm (400 to 150 F) and was cooled by light water.

4. Provision was made to dump the moderator quickly to the letdown tank in the event of a serious emergency. To prevent a heavy water loss, the letdown tank was provided with a cover and a vent valve (2 oz/in.²) and was filled with about a 750-gallon borated D₂O-H₂O mixture (~ 60% D₂O), available from another set of experiments. This material in place of light water would prevent excessive moderator dilution.

5. The primary pump, normally cooled by light water, was cooled by a small volume 90% D₂O-H₂O mixture. This mixture was cooled by a small air-cooled truck radiator to prevent light water injection into the primary loop if a leak in the pump cooling developed.

6. The small heat exchanger for the sample line and bleeder was also cooled by the 90% D₂O-H₂O mixture. As the system was heated, excess moderator was removed from the primary loop through the bleeder.

All components containing heavy water were assembled in a galvanized steel-lined retention basin (Fig. 2-5). The 55-gallon drum was used as a reservoir for the small auxiliary loop that cooled the pump and the heat exchanger for the sample line and bleeder.

The moderator mixtures were prepared in a mix tank in another part of the building and were pumped to the storage tank. To detect gross changes, the D₂O concentration was checked daily with a calibrated hydrometer. A 12-channel leak detector, with stations located strategically throughout the system, monitored heavy water losses. Details of these aspects of the heavy water system are given in Reference 2.

Figure 2-1. LPR and Hot Exponential Facility — Schematic Diagram

Figure 2-2. LPR and Hot Exponential Facility — Horizontal Section

NOTE:
 AUTOCLAVE INTERNALS SHOWN
 IN SECTIONAL ELEVATION, ALL
 OTHER EQUIPMENT SHOWN IN
 SECTIONAL PLAN.

Figure 2-3. Hot Exponential Facility

Figure 2-4. Moderator Flow System

Figure 2-5. Pressure Vessel and Auxiliary Equipment

3. DESCRIPTION OF LATTICES

3.1. Fuel Rods

The fuel rods in both experiments were 4%-enriched UO_2 swaged in stainless-steel tubes. Their physical properties are summarized in Table 3-1. The clad thickness of a random 9% rod sampling measured by an electrical conductivity device varied slightly in the axial direction. The value listed in Table 3-1 is a cosine square weighted average between 10 and 170 cm. Additional details concerning the axial variation in wall thickness and a list of impurities are given in Reference 2.

The end caps, each approximately 2.35 inches long, consisted of inverted stainless-steel thimbles filled either with aluminum or stainless-steel plugs. Approximately 20% were stainless steel, but no distinction was made in the experiments since the reactivity differences were negligible.

Table 3-1. Physical Properties of Fuel Rods

<u>Parameter</u>	<u>Value</u>
OD, in.	0.4755 ± 0.0015
Wall thickness, in.	$0.0160 \pm 0.0005^*$
Wall material	Type-304 stainless steel
Fuel diameter, in.	0.444 ± 0.002
Active fuel length, in.	66.7 ± 0.3
Total length, in.	71.5
Weight of fuel, gm UO_2 /rod	1600 ± 2
Weight of uranium, gm/rod	1408 ± 2
Weight of U^{235} , gm/rod	56.61 ± 0.10
Enrichment, wt 25/wt U, %	4.020 ± 0.005
Fuel density, gm/cm ³	9.46 ± 0.10

* $\text{Cos}^2 z$ weighted average

3.2. Exponential Lattices

3.2.1. Design Considerations

The fuel rods were arranged on a uniform square pitch and supported horizontally in the pressure vessel by a series of grid plates and support structures. The number, spacing, thickness, and material of the grid plates were based on a design requirement of supporting the fuel rods rigidly without introducing excessive perturbing material in the region where the relaxation length measurements were to be made.

The lattice diameter compromised between maximizing the radial asymptotic region extent, which implied a large diameter and small moderator-reflector thickness, and the operating license requirement which limited the effective multiplication factor to 0.95. Since in the light water experiment, the lattice radius was about 6.5 inches, the reflector thickness was essentially infinite. Experience with similar assemblies supported calculations showing that a sufficiently large radial asymptotic region would exist with this geometry.

In the heavy-water moderated experiments, the D_2O concentration was selected to match an earlier room temperature exponential experiment³ so that the results from the two different facilities could be compared. Calculations showed that at this concentration ($\sim 81\% D_2O$), the lattice diameter would have to be increased significantly to reduce the reflector thickness and to create a sufficiently large radial asymptotic region for good radial buckling measurements.

3.2.2. Conduits for Activation Wires

Radial and axial flux measurements were made by activating gold and dysprosium wires in thin-walled stainless-steel conduits. The conduits were an integral part of the lattice and extended through the pressure vessel wall to enable wires to be inserted and removed during an experiment.

Since the asymptotic region in each lattice could not be predetermined, radial conduits were located at several axial positions, and axial conduits were located at several radial positions. The radial conduits were 0.120 inches OD by 0.010 inches wall, and the axial conduits were 0.187 inches OD by 0.031 inches wall. The wires were driven through the conduits by Teleflex cables.

3.2.3. Lattice at 0% D₂O

Since in the light-water moderated experiments the lattice diameter was comparatively small, an existing support structure was used. The grid plates were mounted on a rigid stainless-steel support frame. After the fuel rods were loaded, the entire assembly was rolled into the pressure vessel where it rested on angle brackets welded to the inside of the pressure vessel.

The fuel rods were supported by five grid plates. The two end grid plates were 0.25-inch-thick stainless steel, and the three intermediate grid plates were 1/16-inch aluminum. Figure 3-1 shows the location of the grid plates, the peripheral fuel rods, and conduits in this lattice. The conduits were carefully aligned and held under tension by heavy steel side plates (Fig. 3-2). Figures 3-3 and 3-4 show the fully assembled lattice, with details of the support frame, grid plates, and conduits.

3.2.4. Lattice at 81.5% D₂O

The support frame for the light-water moderated experiments cannot accommodate lattices larger than 17 inches in diameter. With this limitation, the radial asymptotic region at high D₂O concentrations would be too small because of the influence of the resulting 9.5-inch-thick moderator-reflector and the 1-inch-thick steel pressure vessel wall. Calculations showed that the lattice would have to occupy the entire cross-sectional area of the 36-inch ID pressure vessel to achieve a sufficiently large radial asymptotic region for useful radial buckling measurements.

In practice, it was impossible to meet this objective completely. However, by omitting the requirement that the fuel rods be pre-loaded into the lattice before it is placed in the pressure vessel, the bulky support frame could be eliminated. In this design (Fig. 3-5), much larger grid plates could be used. They were spaced and aligned by 12 aluminum tie rods so that the entire unit could be lifted into the pressure vessel before the fuel rods were loaded. With this design, a 33-inch diameter lattice could be assembled, leaving a 1.5-inch-thick moderator-reflector annulus.

Figure 3-6 shows the location of the grid plates and conduits. Since the weight of fuel rods was much greater than in the light-water experiments, the grid plates were thicker. The load was supported by 1/4-inch-thick aluminum grid plates at the ends of the fuel rods and a 1/8-inch-thick stainless-steel grid plate at the center. Two 1/16-inch aluminum grid plates carried no load, but they maintained the proper lattice pitch. The load-bearing grid plates rested on existing angle brackets welded inside the pressure vessel.

The conduits were aligned carefully and were brazed to 1/16-inch-thick stainless-steel side plates which were bolted to the grid plates. The side plates on one side were stiffened by bolting 1/4-inch-thick aluminum plates to them. The limited space in the radial direction, imposed by maximizing the lattice diameter, made it difficult to mount the conduits under tension. This design may have allowed the conduits to deflect slightly during the measurements at elevated temperatures.

Figure 3-7 shows the fully-assembled lattice in the pressure vessel and the conduits, the support angle brackets, the boron liner, and details of the pressure vessel closure.

3.2.5. Summary of Lattice Parameters

The lattice parameters are summarized in Table 3-2. The D_2O concentration in the 81.5% D_2O experiments was determined by precise measurements of the moderator density. (See Reference 2.) The value listed in Table 3-2 is the average of measurements at the beginning and completion of the experiments (81.55 ± 0.02 and 81.45 ± 0.02 mole % D_2O). Since the absolute analytical accuracy is about ± 0.05 mole %, a slight degradation may have occurred.

The effective core radius was computed from the relation

$$\pi R^2 = (\text{no. of rods}) (\text{pitch})^2.$$

For the 81.5% experiments, the lattice was not perfectly cylindrical because eight rods were removed from the lower corners to provide space for the supporting angle brackets (Fig. 3-6). The reflector thickness was obtained by subtracting the effective radius from the inner radius of the pressure vessel (~ 44.61 cm). It was essentially infinite in the light-water experiments, but it was finite at 81.5% D_2O . For 81.5% D_2O , additional reflection occurred from the 0.32-cm-thick boron-steel liner, the 2.54-cm-thick steel pressure vessel, and an approximate 20-cm sand thickness.

Table 3-2. Summary of Lattice Parameters

<u>Parameter</u>	<u>0% D₂O</u>	<u>81.5% D₂O</u>
D ₂ O Concentration, mole %	0.00	81.5 ± 0.1
Number of fuel rods	368	2284
Effective core radius, cm	16.36	40.82*
Reflector thickness, cm	~ 28.25	~ 3.79
Rod diameter, in.	0.4755 ± 0.0015	0.4755 ± 0.0015
Lattice pitch, in.	0.595 ± 0.002	0.595 ± 0.002
Non-moderator-to-moderator volume ratio	1.006	1.006

*Based on 2292 rods for the equivalent cylindrical lattice.

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Figure 3-1. Location of Grid Plates and Conduits
(0% D₂O)

Figure 3-2. Partially Loaded Lattice
(0% D₂O)

Figure 3-3. Side View of Lattice
(0% D₂O)

Figure 3-4. End View of Lattice
(0% D₂O)

Figure 3-5. Partially Loaded Lattice
(81.5% D₂O)

Figure 3-6. Location of Grid Plates and Conduits
(81.5% D₂O)

Figure 3-7. Fully Loaded Lattice
(81.5% D₂O)

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4. EXPERIMENTAL PROCEDURES

4.1. Initial Loading

In the 0% D₂O experiment, the fuel rods were loaded in the support frame and were inserted in the pressure vessel. A 3.5-curie Po-Be neutron source and two water-proofed BF₃ counters were placed inside the pressure vessel around the lattice. Count rates were measured as the water level in the pressure vessel was raised. The reciprocal multiplication data indicated that k_{eff} was in the range of 0.90 to 0.95 under the condition of full moderator height. During these experiments, the LPR was fully assembled since earlier work showed that the reactivity coupling between the LPR and a similar exponential assembly was less than a few cents.

The loading procedure for the 81.5% D₂O experiment was similar, except an additional BF₃ counter was located outside and below the pressure vessel, and the neutron source (5-curie Pu-Be) was outside the pressure vessel. Count rates were measured as the fuel rods were inserted in the grid plates. The first batch of moderator, approximately 90% D₂O, was added and multiplication data were taken as a function of moderator level. The D₂O concentration was then reduced and the experiment was repeated. Multiplication measurements were made at small increments of D₂O concentration until the desired concentration (81.5% D₂O) was achieved. For this case, the multiplication was still too low to derive an accurate value of k_{eff} , but the calculated k_{eff} was in the range of 0.8 to 0.9. The LPR core was assembled and no significant change in critical rod position was observed indicating that reactivity coupling was essentially negligible.

4.2. Operating Procedures

When the final configuration and moderator composition were reached, the neutron source was removed and the internal detectors were moved to a position outside and below the pressure vessel. In the

0% D₂O case only, phosphoric acid ($\sim 9 \times 10^{-5}$ gm/cm³) was added to the moderator to inhibit aluminum corrosion.

The primary loop pressure was set at 40 psig to prevent pump cavitation, and the moderator was circulated through the system. The activation wires were inserted, the LPR was raised to operating power, and the wires were activated.

As the temperature was raised incrementally, a quick estimate of the material buckling was made to ensure that a strong positive temperature coefficient was absent. At 0% D₂O, a Dy-Al wire was activated to obtain an estimate of the relaxation length. At 81.5% D₂O, count rates were taken on the external detectors by using the neutron source or the LPR at a constant low power as the temperature was raised in small increments. Once it was established that the buckling was not increasing strongly with temperature, the temperature was raised to the proper value and the wires were activated.

The pressure was kept at least 15 psi above saturation during the 0% D₂O experiments, and 30 psi during the 81.5% D₂O experiments. The moderator was circulated for at least 20 minutes to assure temperature uniformity. The effective moderator temperature was assumed to be the average of the inlet and outlet temperatures; the temperature difference was never greater than 4 F. The temperatures were measured with calibrated iron-constantan thermocouples, and were monitored on a multi-point recorder.

The operating procedures for the 81.5% D₂O experiments were generally the same, although extra steps were required because of the heavy water. Before the fuel rods were loaded, the system was checked out with light water over the entire temperature range to assure the satisfactory operation of all components, and minor leaks were repaired. During actual operations at 200 F and below, the letdown tank was empty because the moderator could be safely dumped to the storage tank. Before the runs at 300 F and above, the letdown tank was filled with about 750 gallons of a borated D₂O-H₂O mixture to condense the moderator in case of an emergency dump.

4.3. Activation and Counting

In the 0% D₂O experiments, 0.020-inch diameter gold wire was the detector for radial and axial flux measurements. For bare measurements,

the wires were inserted in 0.090-inch OD Teflon sleeves; for cadmium-covered measurements, they were inserted in 0.075-inch OD by 0.020-inch wall cadmium sleeves. Cadmium-covered runs were made at each temperature. Also, one bare run at room temperature was made to compare thermal and epithermal bucklings.

At 81.5% D₂O, bare gold wires (Teflon sleeve) were activated at each temperature. Several additional runs at room temperature were made with Teflon-covered 0.020-inch diameter wires of dysprosium-aluminum alloy (~7 wt % Dy) to compare thermal and epithermal effects.

The wires were activated from 40 to 75 minutes with the LPR operating at 200 kw for the 0% D₂O experiments, and from 60 to 90 minutes at 100 kw for the 81.5% D₂O experiments. The wires were then counted on a linear and a wheel wire scanner. The wires were usually counted two to three times on each scanner to improve statistical accuracy of the data. The wires were counted at intervals of one lattice pitch (0.595 inches) in the 81.5% D₂O experiments. At 0% D₂O, the intervals were 0.322 or 0.644 inches on the wheel scanner and 0.595 (radial) and 0.595 inches or 1.190 inches (axial) on the linear scanner.

The linear wire scanner (Fig. 4-1) uses two detectors in a master-slave counting system. Wires are attached under moderate tension to the movable aluminum bed advanced by a friction drive under the main detector. The forward motion is controlled by a series of mechanical stops. The second detector continuously counts a short length of activated wire. The counting time intervals for both detectors are determined by the time necessary for the second detector to accumulate a preset count. As the wire decays, the time necessary to accumulate this preset count increases; therefore, all data are corrected automatically for decay. After completing the preset count, the bed automatically advances and allows another section of the wire to be counted. The output of the linear wire scanner is automatically printed on paper tape or punched into IBM cards.

Usually, the wires were beta counted by a photomultiplier tube with a 1-mm thick anthracene scintillation crystal. In the experiments at 81.5% D₂O at elevated temperatures (after Run 70-12), this counting head was replaced by a photomultiplier tube with an integral 2-inch-thick NaI crystal for gamma counting. The counters were located in a thick lead shield with a 0.5-inch diameter aperture and collimator.

The wheel wire scanner (Fig. 4-2) consists of an end-window gas-flow proportional counter in a shielded housing. The wires are mounted on a 27-inch diameter wheel or scanning drum which automatically rotates a preset distance (one or two lattice pitches) after each count. The beta counter is collimated by a 1/4-inch-thick lucite cover plate with a 7/8-inch diameter aperture. The output is transmitted to a printer which records the total counts and the elapsed time on paper tape.

On the wheel scanner, count rates varied typically between 15,000 and 50,000 cpm in the axial range used to obtain the relaxation length. One minute counts were taken. On the linear scanner, the total counts accumulated were typically 5,000 and 35,000 at the same two positions. Background counts were usually several hundred.

4.4. Data Reduction

The material buckling, B_m^2 , was obtained from measurements of the radial buckling, B_r^2 , and the axial buckling (inverse relaxation length), γ^2 , by the equation

$$B_m^2 = B_r^2 - \gamma^2.$$

Radial bucklings were derived from least-square fits to the radial flux distribution

$$\phi(r) = A J_0 [B_r (r-r_0)],$$

and axial bucklings were derived from least-square fits to the axial flux distribution of the form $\exp(-\gamma z)$. The usual sinh fit,

$$\phi(z) = A e^{-\gamma z} [1 - e^{-2\gamma(H-z)}],$$

was not necessary because data in the region where the end correction is important were not needed. This conclusion was confirmed in the light water experiments (Fig. 5-5) where data were fit to a larger axial position than in the 81.5% D₂O experiments.

Several steps were taken to assure that the flux distributions were asymptotic in the lattice region where the bucklings were derived. Radial flux measurements were made at different axial distances, and axial flux measurements were made at different radial distances. In the 0% D₂O experiments, bare and cadmium-covered gold traverses were compared to separate thermal and epithermal effects. In the highly-epithermal

81.5% D₂O lattice, bare gold, responsive primarily to epithermal neutrons, and bare Dy-Al alloy, responsive primarily to thermal neutrons, were compared.

Since background flux measurements could not be made, the total flux distribution was fit in all cases. Since the background flux would also distort the fundamental mode distribution, the procedures used to show that the flux distribution is asymptotic in the region of the buckling fits should prove equally well the absence of significant background in that region.

Figure 4-1. Linear Wire Scanner

Figure 4-2. Wheel Wire Scanner

5. EXPERIMENTS AT 0% D₂O

5.1. Radial Buckling

The radial buckling, B_r , was derived from least-square fits to the radial flux distribution in the asymptotic region. Figure 5-1 is a typical radial flux measurement (E-4 position, 66 F) obtained from bare and cadmium-covered gold wires. Similar flux shapes were observed at other E positions and at elevated temperatures, but no bare gold data were taken above room temperature.

The following criteria were adopted to define the extent of the radial asymptotic region:

1. a gold cadmium ratio independent of r
2. identical bare and cadmium-covered B_r
3. B_r independent of r .

These criteria were investigated at room temperature where both bare and cadmium-covered data were available. Figure 5-1 shows a constant gold-cadmium ratio to a radius of about 12 cm. However, plots of the apparent radial-buckling versus radius of fit show a constant buckling for cadmium-covered data to radii of at least 15 cm (1 cm less than core radius). The bucklings derived from the bare gold flux traverses, however, were constant only to a radius of about 12 cm. The bucklings derived from the bare and cadmium-covered data were the same within the statistical accuracy of the data. (See Table 5-1.)

Calculations¹¹ show that the flux can be fit to as much as a 15-cm radius without deviating from the asymptotic value of B_r^2 by more than 0.5%. This confirms the validity of the experimental criteria for the asymptotic region. Therefore, at room temperature, the correct buckling was obtained by fitting the cadmium-covered data to a radius of about 15 cm and the bare data to a radius of about 11 cm. Figure 5-2 shows typical examples of the variation of apparent radial buckling with the radius of fit.

Since only cadmium-covered data were obtained at elevated temperatures, the radial asymptotic region was selected on the basis of B_r independent of r since this region, at room temperature, was shown to be as restrictive as the other criteria. On this basis, the cadmium covered data at elevated temperatures also could be fit to a radius of about 15 cm.

Table 5-1 summarizes the results of the radial buckling measurements at four axial distances from the source end of the lattice. The code E1 through E4 refers to the four axial positions of the radial traverses (Fig. 3-1). Generally, the wires were counted on both the linear (L) and wheel (W) wire scanners. With one exception (Run 66-4, E1), the results agree approximately within their combined standard deviations.

Table 5-1 shows the average value at each position and temperature where the uncertainty is the largest internal or external standard deviation. These numbers are weighted averages of the linear and wheel scanner results, except in the case of Run 66-4 (E1) where the two results differ by more than five times the combined standard deviation.

By comparing the E1 through E4 values at each temperature, it is apparent that the radial buckling at the E1 position is consistently smaller than the others (particularly at high temperatures). This is consistent with the hypothesis that the axial position of the E1 traverse is not in the axial asymptotic region. (See Section 5.2.) Since the E2 through E4 values are statistically independent and are within the axial asymptotic region (Section 5.2), the best value of the radial buckling at each temperature is the weighted average of these three values. The uncertainties are the largest internal and external standard deviations.

Except in Run 66-3, all measurements were made with cadmium-covered gold wires. The results of Run 66-3, obtained from bare gold wires, allow a thermal and epithermal buckling comparison. Table 5-1 shows that the two bucklings differ by only slightly more than their combined standard deviations. The agreement is even closer if the E3 value in Run 66-3 is eliminated. This value is based on only one wire count, and appears to be too low. Therefore, it is concluded that the thermal and epithermal bucklings are the same.

Table 5-1. Summary of Radial Bucklings
(0% D₂O)

Run no.	66-2	66-3	66-4	66-7	66-8	66-9
Temperature, F	66	66	103	203	308	406
Wire and counter	$B_r \pm \sigma$ ($\times 10^{-4} \text{ cm}^{-1}$)	$B_r \pm \sigma$ ($\times 10^{-4} \text{ cm}^{-1}$)	$B_r \pm \sigma$ ($\times 10^{-4} \text{ cm}^{-1}$)	$B_r \pm \sigma$ ($\times 10^{-4} \text{ cm}^{-1}$)	$B_r \pm \sigma$ ($\times 10^{-4} \text{ cm}^{-1}$)	$B_r \pm \sigma$ ($\times 10^{-4} \text{ cm}^{-1}$)
E1L	---	985.1 $\pm$ 9.1	933.3 $\pm$ 10.5	995.6 $\pm$ 6.3	974.8 $\pm$ 4.6	959.3 $\pm$ 7.5
E1W	1006.3 $\pm$ 4.8	---	1005.3 $\pm$ 3.1	992.9 $\pm$ 3.7	969.4 $\pm$ 3.1	944.7 $\pm$ 4.3
E2L	1011.4 $\pm$ 4.5	1008.1 $\pm$ 19.5	1019.5 $\pm$ 10.4	1010.2 $\pm$ 5.6	979.8 $\pm$ 17.4	956.4 $\pm$ 7.5
E2W	1019.0 $\pm$ 8.4	1004.9 $\pm$ 8.5	---	---	993.4 $\pm$ 3.9	971.4 $\pm$ 5.4
E3L	1022.9 $\pm$ 13.6	979.3 $\pm$ 12.8	1011.7 $\pm$ 10.9	1014.0 $\pm$ 6.2	1009.5 $\pm$ 24.8	999.7 $\pm$ 20.6
E3W	1005.7 $\pm$ 12.4	---	1010.3 $\pm$ 6.8	1017.5 $\pm$ 6.2	978.0 $\pm$ 6.3	976.8 $\pm$ 8.2
E4L	1023.0 $\pm$ 11.8	990.6 $\pm$ 12.4	971.5 $\pm$ 33.4	996.5 $\pm$ 9.6	977.2 $\pm$ 11.2	972.1 $\pm$ 11.6
E4W	1026.8 $\pm$ 14.5	1018.6 $\pm$ 17.6	1018.3 $\pm$ 8.5	989.8 $\pm$ 7.8	999.1 $\pm$ 7.3	970.5 $\pm$ 6.2
<u>Average Values</u>						
E1	1006.3 $\pm$ 4.8	985.1 $\pm$ 9.1	969.3 $\pm$ 35.9	993.5 $\pm$ 3.2	971.1 $\pm$ 2.6	948.3 $\pm$ 6.3
E2	1012.6 $\pm$ 4.0	1005.5 $\pm$ 7.7	1019.0 $\pm$ 10.4	1010.2 $\pm$ 5.6	992.8 $\pm$ 3.9	969.3 $\pm$ 5.0
E3	1013.5 $\pm$ 9.2	979.3 $\pm$ 12.8	1010.7 $\pm$ 5.8	1015.8 $\pm$ 4.4	980.1 $\pm$ 7.5	979.7 $\pm$ 7.5
E4	1024.6 $\pm$ 9.0	999.9 $\pm$ 16.0	1015.5 $\pm$ 11.0	992.3 $\pm$ 6.0	992.5 $\pm$ 10.0	970.8 $\pm$ 5.5
Best value*	1014 $\pm$ 3.5	998.8 $\pm$ 7.6	1013 $\pm$ 4.7	1008 $\pm$ 6.8	990.4 $\pm$ 3.3	971.8 $\pm$ 3.3

* Excluding E1 values

Figure 5-3 shows the best values of the radial buckling plotted against the temperature. Also shown is the variation with temperature of the radial reflector savings, λ_r , derived from the relation

$$B_r = \frac{2.405}{R_c + \lambda_r},$$

where R_c is the core radius (16.36 cm). In contrast with the 81.5% D_2O experiments, the light water reflector was essentially infinite in this geometry.

5.2. Axial Buckling

The axial buckling, or inverse relaxation length, γ , was derived from least-square fits of the axial flux distribution in the asymptotic region to the function $e^{-\gamma z}$. The usual sinh fit was not necessary because the fuel rods were long enough to provide accurate data without having to use the region where the end correction is important. (See Fig. 5-5.)

Figure 5-4 is a typical axial flux measurement (A1 position, 66 F) obtained from bare and cadmium-covered gold wires. Similar data were obtained in the B5 and C7 positions and at elevated temperatures, although no bare gold traverses were made above room temperature.

As in the radial buckling measurements, three criteria defined the extent of the axial asymptotic region. However, the constant gold-cadmium ratio was less useful here. Figure 5-4 shows that the gold-cadmium ratio is approximately constant above $z = 10$ cm. The apparent increase in the cadmium ratio with axial distance is caused by the slightly larger value of γ for the cadmium-covered traverse. This can be attributed to a reduction in B_m^2 by the cadmium poison, rather than a real difference between the relaxation length of thermal and epithermal neutrons.

Figure 5-5 shows a more precise determination of the extent of the axial asymptotic region. In one case, the initial point of the axial flux distribution, z_1 , was fixed at 53.2 cm, and axial bucklings were calculated as the final point of the flux distribution, z_2 , varied between 105 and 135 cm. Since no significant change in buckling was observed, the slope of the axial flux distribution is constant in this region. In the other case, the final point was fixed, and the initial point varied between 30 and 55 cm. These data show that the axial asymptotic region begins at

an axial position of about 45 cm and extends to at least 135 cm.

Table 5-2 shows the results of least-square fits to the axial flux distribution (generally in the range 45 to 135 cm). Usually, each wire was counted on both the linear (L) and wheel (W) wire scanners, although in a few cases (omitted from Table 5-2), the wire had decayed substantially before the second count could be made and the statistical accuracy of the buckling fit was very poor. However, graphical examination of these data showed that the axial bucklings were in reasonably good agreement with the other measured values.

The two counts are combined at the bottom of Table 5-2 by using a weighted average unless they differ by more than two combined standard deviations. Since the average values show no systematic dependence on radial position, all measurements are within the radial asymptotic region. The best value of the axial buckling at each temperature is the weighted average of the three measurements except in Run 66-2, where they differ by more than twice the combined standard deviation. The uncertainties are always the largest internal and external standard deviations. Figure 5-6 shows the best values of the axial buckling plotted against the temperature.

The axial bucklings derived from the bare and cadmium-covered traverses can be compared at room temperature. The statistically significant difference can be attributed to a decrease in B_m^2 due to the poison of the cadmium sleeves around the gold wires (approximately 50 cents in reactivity).

Table 5-2. Summary of Axial Bucklings
(0% D₂O)

Run No.	66-2	66-3	66-4	66-7	66-8	66-9
Temperature, F	66	66	103	203	308	406
Wire and Counter	$\gamma \pm \sigma$ ($\times 10^{-4} \text{ cm}^{-1}$)	$\gamma \pm \sigma$ ($\times 10^{-4} \text{ cm}^{-1}$)	$\gamma \pm \sigma$ ($\times 10^{-4} \text{ cm}^{-1}$)	$\gamma \pm \sigma$ ($\times 10^{-4} \text{ cm}^{-1}$)	$\gamma \pm \sigma$ ($\times 10^{-4} \text{ cm}^{-1}$)	$\gamma \pm \sigma$ ($\times 10^{-4} \text{ cm}^{-1}$)
A1L	384.5 $\pm$ 2.3	355.1 $\pm$ 1.1	378.2 $\pm$ 1.9	- - -	456.0 $\pm$ 3.7	465.4 $\pm$ 2.6
A1W	383.1 $\pm$ 1.4	361.6 $\pm$ 0.9	382.9 $\pm$ 1.6	398.4 $\pm$ 1.1	433.1 $\pm$ 1.8	469.0 $\pm$ 1.2
B3L	376.1 $\pm$ 1.8	371.2 $\pm$ 1.4	387.4 $\pm$ 4.3	- - -	434.0 $\pm$ 2.4	- - -
B3W	371.3 $\pm$ 1.3	367.1 $\pm$ 1.9	380.3 $\pm$ 1.4	397.3 $\pm$ 1.8	418.8 $\pm$ 1.6	464.9 $\pm$ 1.0
C5L	390.4 $\pm$ 1.6	- - -	389.2 $\pm$ 3.0	416.1 $\pm$ 3.1	424.1 $\pm$ 2.4	- - -
C5W	389.2 $\pm$ 0.8	361.8 $\pm$ 1.1	382.7 $\pm$ 1.6	390.1 $\pm$ 1.4	423.5 $\pm$ 1.6	464.6 $\pm$ 1.5
<u>Average Values</u>						
A 1	383.4 $\pm$ 1.2	358.4 $\pm$ 4.6	381.0 $\pm$ 2.3	398.4 $\pm$ 1.1	444.6 $\pm$ 16.2	468.4 $\pm$ 1.1
B 3	372.9 $\pm$ 2.3	369.8 $\pm$ 2.1	381.0 $\pm$ 2.1	397.3 $\pm$ 1.8	426.4 $\pm$ 10.8	464.9 $\pm$ 1.0
C 5	389.4 $\pm$ 0.7	361.8 $\pm$ 1.1	384.2 $\pm$ 2.3	403.1 $\pm$ 18.4	423.7 $\pm$ 1.3	464.6 $\pm$ 1.5
Best Value	381.9 $\pm$ 6.7	363.3 $\pm$ 2.4	382.0 $\pm$ 1.3	398.1 $\pm$ 1.0	423.9 $\pm$ 1.3	466.1 $\pm$ 1.1

5.3. Material Buckling

The best values of the radial and axial bucklings, Table 5-3, give the material buckling as a function of temperature. (See Fig. 5-7.)

The uncertainties in the measured parameters are statistical. To minimize systematic errors, the grid plates were accurately machined, and the fuel rods were carefully aligned. The wire conduits were precisely centered in the moderator gap and were rigidly positioned under tension to prevent motion during the temperature runs. The characteristics of the counters in the wire scanners were measured and the indexing system was checked periodically during the experiments. Small corrections were made when necessary. The agreement between the two wire counting systems is a good test of the validity of the activation measurements.

The presence of residual boric acid from earlier experiments in the moderator was ruled out by a boron measurement which showed that, at the limit of detection, boron would affect the material buckling by only 0.02%. At a high temperature, approximately 3 volume % (STP) nitrogen was absorbed in the water. Since this would decrease the water density (at 406 F and 275 psig) by the equivalent of a 2 F temperature change, no correction was made.

Systematic errors, due to the inclusion of non-asymptotic fluxes in the buckling fits, do not appear to be significant. Spatial background measurements could not be made, but this source of error would also produce a spatial non-asymptotic situation. However, this source of error must be small because both the radial and axial flux distributions were indistinguishable from fundamental mode distributions within the accuracy of the measurement over a larger range than was used to derive the radial and axial bucklings.

The best check for systematic error is to compare the material buckling at room temperature with the buckling of the same lattice as measured in a critical experiment. The critical buckling of the identical lattice (Core I) was measured² at $(88.0 \pm 0.4) \times 10^{-4} \text{ cm}^{-2}$ (in very good agreement with these results). The comparison also shows that anisotropy effects must be small. No independent check at elevated temperature can be made. Data from critical experiments on a similar lattice suggest a

small positive temperature coefficient below 150 F. The present work is consistent with that observation if the uncertainties are considered. At high temperatures, a systematic error will be introduced into these measurements if the asymptotic region shifts significantly outside the range used to obtain radial and axial bucklings. However, this shift was not observed.

Table 5-3. Material Buckling Vs Temperature
(0% D₂O)

Run No.	66-2	66-3	66-4	66-7	66-8	66-9
Temperature, F	66	66	103	203	308	406
Pressure, psig	40	40	40	40	75-100	275-300
Detector	<u>Cd-covered</u>	<u>Bare</u>	<u>Cd-covered</u>	<u>Cd-covered</u>	<u>Cd-covered</u>	<u>Cd-covered</u>
$B_r^2, \times 10^{-4} \text{ cm}^{-2}$	102.82 ± 0.71	99.76 ± 1.52	102.62 ± 0.95	101.61 ± 1.37	98.09 ± 0.65	94.44 ± 0.64
$\gamma^2, \times 10^{-4} \text{ cm}^{-2}$	14.58 ± 0.51	13.20 ± 0.17	14.59 ± 0.10	15.85 ± 0.08	17.97 ± 0.11	21.72 ± 0.10
$B_m^2, \times 10^{-4} \text{ cm}^{-1}$	88.24 ± 0.87	86.56 ± 1.53	88.03 ± 0.96	85.76 ± 1.37	80.12 ± 0.66	72.72 ± 0.65
$\lambda_r, \text{ cm}$	7.36 ± 0.08	7.70 ± 0.18	7.38 ± 0.11	7.50 ± 0.16	7.92 ± 0.08	8.39 ± 0.08

Figure 5-1. Typical Radial Flux Distribution
(0% D₂O)

Figure 5-2. Radial Buckling Vs Radius of Fit
(0% D₂O)

Figure 5-3. Radial Buckling and Reflector Savings Vs Temperature
(0% D₂O)

Figure 5-5. Axial Buckling Vs Region Fit
(0% D₂O)

Figure 5-6. Axial Buckling Vs Temperature
(0% D₂O)

Figure 5-7. Material Buckling Vs Temperature
(0% D₂O)

6. EXPERIMENTS AT 81.5% D₂O

6.1. Radial Buckling

The radial buckling was obtained from least-square fits of the radial flux distribution in the asymptotic region. Figure 6-1 shows typical traverses at room temperature in the E4 position from gold and Dy-Al alloy wires. Similar curves were obtained in the other E-positions and at elevated temperatures. Generally, the statistical accuracy of the dysprosium traverses was not as good as for the gold because of dysprosium content variations. The ratio plot of dysprosium to gold activity indicates the extent of the asymptotic region, since dysprosium is responsive primarily to thermal neutrons, and gold is responsive primarily to epithermal neutrons in the highly epithermal spectrum of this lattice.

Comparisons of the gold and dysprosium flux distributions and bucklings were not very useful in these experiments because of the poor statistical accuracy of the dysprosium data. Therefore, more reliance was placed on constant buckling with radius of fit (Section 5.1). Data of this type are shown in Figure 6-2, where the bucklings are averages of fits to the linear and wheel wire scanner data.

Neglecting the disagreement between E3 and E4 absolute values at high temperatures, the data indicate that the radial asymptotic region extends to a radius of at least 18 lattice pitches (~27 cm). This agrees with theoretical calculations¹¹ showing that the apparent buckling deviates from the asymptotic buckling by less than 0.5% at a radius of fit equal to 20 lattice pitches at room temperature (18 lattice pitches at 400 F). The results are also consistent with the data of Figure 6-1 which show a constant Dy/Au flux ratio to a radius of about 18 lattice pitches.

Table 6-1 summarizes the radial bucklings at axial positions E3 and E4. The E1 and E2 positions were not used because they may not have been in the axial asymptotic region. (See Section 6.2) The values

are averages of fits to radii of 15 and 18 lattice pitches, and have a statistical uncertainty based on the residuals of the least-square buckling fits and the difference between the 15 and 18 pitch fits between 1 and 1.5%. The average value of the radial buckling at each temperature and wire position is listed in Table 6-1, where the uncertainty is the largest internal and external standard deviation.

The results, (Fig. 6-3) indicate a discrepancy between the radial bucklings at the E3 and E4 positions at temperatures of 150 F and above. While the error bars overlap in two cases, the difference appears to be too consistent with temperature to be explained by statistical inaccuracies in the measurements. However, this possibility cannot be eliminated entirely.

Several other explanations were investigated. The possibility that the E3 or E4 measurements were made in a non-asymptotic region does not appear to be reasonable for the following reasons:

1. The axial positions of the E3 and E4 radial traverses are both in the axial asymptotic region. (See Section 6.2.)
2. Since E3 and E4 are far enough from the neutron source, energy transients and spatial harmonics should be negligible.
3. Plots of B_r versus radius of fit (Fig. 6-2) show no tendency to converge as the radius of the fit decreases.
4. The size of the asymptotic region should change smoothly with temperature and not abruptly between 105 and 150 F.

Table 6-1. Summary of Radial Bucklings
(81.5% D₂O)

Radial Buckling, $B_r \times 10^{-4} \text{ cm}^{-1}$										
Run no.	Temperature, F	Wire position	Linear Scanner			Wheel Scanner			Average value	Best value
			Scan no. 1	Scan no. 2	Scan no. 3	Scan no. 1	Scan no. 2	Scan no. 3		
70-11	73	E3	429	430	---	---	---	---	416 $\pm$ 11 415 $\pm$ 4	415.1 $\pm$ 3.8
		E4	---	---	---	414	---			
70-12	73	E3	---	407	411	411	405	---	413 $\pm$ 4 408 $\pm$ 4	410.5 $\pm$ 2.8
		E4	---	419	412	---	---	---		
70-14	105	E3	411	415	---	412	---	---	392 $\pm$ 4 412 $\pm$ 6	402 $\pm$ 14
		E4	---	408	---	407	---	---		
70-16	150	E3	391	---	---	391	395	---	396 $\pm$ 9 406 $\pm$ 4	401 $\pm$ 7
		E4	407	---	---	416	---	---		
70-15	200	E3	391	390	---	386	---	---	387 $\pm$ 12 403 $\pm$ 5	395 $\pm$ 11
		E4	405	405	---	411	---	---		
70-17	201	E3	405	408	---	---	---	---	380 $\pm$ 5 396 $\pm$ 4	388 $\pm$ 11
		E4	---	403	---	---	---	---		
70-18	297	E3	386	391	---	405	377	377	387 $\pm$ 12 403 $\pm$ 5	395 $\pm$ 11
		E4	402	397	---	407	407	---		
70-19	384	E3	384	383	---	374	377	---	380 $\pm$ 5 396 $\pm$ 4	388 $\pm$ 11
		E4	394	397	---	---	---	---		

Radial background, which cannot be corrected experimentally, is another potential source of error. However, this does not appear to be significant for the following reasons:

1. Normally, radial background is most serious at distances far from the neutron source since the background flux falls off less rapidly than the flux in the exponential lattice. This background would make the E4 buckling smaller than the E3 buckling (the opposite of what was observed).

2. If radial background were significant, plots of the radial buckling with radius of fit would show an increase in apparent buckling as the radius of the fit decreased. No such behavior is shown in Figure 6-2.

3. The relaxation lengths in the B3 and C5 radial positions are identical. (See Section 6.2.) They would not be if the background were different at the axial positions of the E3 and E4 radial traverses.

4. Background errors should be a smoothly varying function of temperature and should not increase abruptly above 105 F.

The most plausible explanation of the difference between the E3 and E4 bucklings appears to be movement of the wire conduits as the temperature of the system was raised. When the lattice was disassembled, it was observed that the center of the conduits could easily be displaced 1 cm or more parallel to the fuel rods. It was also observed that this distortion could be retained when the driving force was removed by friction against the fuel rods.

Conduit movement could have occurred when the lattice was heated due to the relatively large difference in expansion coefficient between aluminum and stainless steel, the two components of the system. It is impossible to evaluate the mechanism quantitatively because of the complex assembly structure (steel and aluminum grid plates, steel and aluminum side plates, steel conduits, and aluminum tie rods) and because of the unpredictability of the friction between the conduits and fuel rods.

A 1-cm movement of the center of the conduits would change B_r about $10 \times 10^{-4} \text{ cm}^{-1}$, and would easily explain the discrepancy between the E3 and E4 bucklings at elevated temperature. If this hypothesis is

correct, the measurement at 150 F should be examined since it is the only case preceded by operations at a higher temperature.

The best value of the radial buckling in Table 6-1 is the weighted average of the E3 and E4 measurements at 70 and 105 F, since the differences here are clearly statistical. At the other temperatures, it is the unweighted average since the differences may be systematic. This type of averaging increases the numerical value of the standard deviation so that it overlaps the E3 and E4 measurements.

6.2. Axial Buckling

The axial buckling was derived from least-square fits of the axial flux distribution in the asymptotic region. Figure 6-4 shows typical axial flux traverses at room temperature in the C7 position obtained from gold and Dy-Al alloy wires. Similar flux shapes were observed in the other positions (A1, B5) and at elevated temperature, but the statistical accuracy of the data above room temperature was considerably better than is shown.

The axial asymptotic region, based on a constant Dy/Au ratio, definitely includes the axial positions of the E3 and E4 radial traverses. This point was confirmed by least-square fitting the axial flux in the 57-113-cm, 57-106-cm, and 65-106-cm ranges. The values of γ agreed in all cases within the statistical accuracy of the fit. There is some evidence, from Figure 6-4 and from least-square fits covering a larger range, that γ is slightly smaller around the E2 position. Therefore, the radial bucklings derived from the E2 traverses were rejected. The E1 position is definitely outside the axial asymptotic range and was not used.

Table 6-2 summarizes the axial bucklings obtained from the B5 and C7 positions. Each entry is the weighted average of three fits in the 57-113, 57-106, and 65-106-cm ranges, and except at room temperature, the entry is the average of two scans by each wire scanner. Since with very few exceptions the axial bucklings at each temperature agree within one or two combined standard deviations, the final column in Table 6-2 is the weighted average of all measurements made by using the largest internal and external standard deviation. (See Fig. 6-3.)

The axial conduit in the A1 position was removed after the first few runs because it may have perturbed the radial flux measurements.

The average ratio of the axial buckling in the B5 position to that in the C7 position is 1.004. Therefore, significant axial variations of the radial background cannot be present near the core centerline.

6.3. Material Buckling

In Table 6-3, the best values of the radial and axial bucklings are combined to give the material buckling as a function of temperature. Since the room temperature measurements were made at several slightly different temperatures, an effective temperature of about 70 F is used. This is a reasonable choice because the radial buckling is less sensitive to temperature changes than the axial buckling. Figure 6-5 shows the results.

The material buckling at room temperature, derived from critical ² and other exponential ³ experiments, is shown for comparison. This value, when corrected slightly for temperature and D₂O concentration, is approximately $(4.2 \pm 0.3) \times 10^{-4} \text{ cm}^{-2}$. Its fair agreement with the hot exponential experiment value shows that significant systematic errors cannot be present at 70 and 105 F. The slight disagreement at room temperature is in the wrong direction to be explained by anisotropy.

At temperatures above 105 F, the uncertainty in the material buckling is due almost entirely to the difference between the E3 and E4 values of the radial buckling. As suggested previously, the buckling at 105 F may be discounted. At 200 F, the E3 and E4 radial bucklings are in fairly good agreement, so the material buckling should be reasonably free from gross systematic error. The error bars for the material bucklings at 297 and 384 F are believed to be large enough to cover systematic errors due to wire conduit movement. They are conservative if the difference between the E3 and E4 radial bucklings is statistical.

Table 6-2. Summary of Axial Bucklings
(81.5% D₂O)

Run no.	Temperature, F	Wire position	Axial Buckling γ , $\times 10^{-4}$ cm ⁻¹		
			Linear scanner	Wheel scanner	Weighted average
70-6	68	B5	368.2 $\pm$ 1.0	----	366.4 $\pm$ 3.6
		C7	366.7 $\pm$ 1.3	366.0 $\pm$ 2.5	
70-9	70	B5	371.4 $\pm$ 3.6	----	369.7 $\pm$ 1.6
		C7	360.3 $\pm$ 2.8	365.5 $\pm$ 2.2	
70-14	105	B5	369.3 $\pm$ 0.6	371.8 $\pm$ 0.6	369.7 $\pm$ 1.6
		C7	369.8 $\pm$ 0.6	367.8 $\pm$ 0.7	
70-16	150	B5	378.2 $\pm$ 0.6	378.3 $\pm$ 0.9	378.1 $\pm$ 1.1
		C7	376.6 $\pm$ 0.8	379.3 $\pm$ 0.9	
70-15	200	B5	387.3 $\pm$ 0.7	385.0 $\pm$ 0.9	386.8 $\pm$ 3.2
		C7	385.5 $\pm$ 0.8	393.2 $\pm$ 0.6	
70-17	201	B5	387.0 $\pm$ 0.7	384.0 $\pm$ 0.7	400.8 $\pm$ 2.3
		C7	388.9 $\pm$ 0.6	383.4 $\pm$ 0.5	
70-18	297	B5	400.6 $\pm$ 0.7	398.3 $\pm$ 0.6	413.2 $\pm$ 3.8
		C7	403.8 $\pm$ 0.7	400.3 $\pm$ 0.6	
70-19	384	B5	413.5 $\pm$ 0.7	410.7 $\pm$ 0.5	413.2 $\pm$ 3.8
		C7	418.5 $\pm$ 0.7	410.0 $\pm$ 0.6	

Table 6-3. Material Buckling Vs Temperature
(81.5% D₂O)

Temperature, F	Pressure, psig	Radial buckling, B_r^2 $\times 10^{-4} \text{ cm}^{-2}$	Axial buckling, γ^2 $\times 10^{-4} \text{ cm}^{-2}$	Material buckling, B_m^2 $\times 10^{-4} \text{ cm}^{-2}$
70	50	17.23 ± 0.32	13.42 ± 0.26	3.81 ± 0.41
105	50	16.85 ± 0.23	13.67 ± 0.12	3.18 ± 0.26
150	50	16.16 ± 1.12	14.30 ± 0.08	1.86 ± 1.12
200	50	16.08 ± 0.56	14.96 ± 0.25	1.12 ± 0.61
297	100	15.60 ± 0.87	16.06 ± 0.18	-0.46 ± 0.89
384	230	15.05 ± 0.85	17.07 ± 0.31	-2.02 ± 0.92

Figure 6-1. Typical Radial Flux Distribution
(81.5% D₂O)

Figure 6-2. Radial Buckling Vs Radius of Fit
(81.5% D₂O)

Figure 6-3. Radial and Axial Buckling Vs Temperature
(81.5% D₂O)

Figure 6-4. Typical Axial Flux Distribution
(81.5% D₂O)

Figure 6-5. Material Buckling Vs Temperature
(81.5% D₂O)

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