ZPPR-15 Small Reactivity Worth Experiments

Nuclear Science and Engineering Division

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ABSTRACT

In addition to measuring the worth of sodium voiding and the worth of simulated control rods, the ZPPR staff measured the Doppler worth of four standard samples, the worth of axial expansion and the worth of radial bowing in ZPPR-15.

Doppler sample worths were measured in ZPPR-15A, ZPPR-15B and ZPPR-15D. The Doppler samples were natural UO_2 , depleted uranium metal, depleted U-10Zr alloy and 33% enriched UO_2 . These samples were placed in a sample capsule in the inner core of ZPPR-15 and heated to various temperatures between 300 K and 1100 K. The resulting changes in reactivity relative to the reference configuration were measured to determine the Doppler worths of the samples.

Special segmented drawers were constructed to measure the worth of axial expansion in ZPPR-15. The segments were connected to each other, and the back segment was connected to a spring-loaded cable. Pulling the cable introduced small gaps between drawer segments to simulate axial expansion, and releasing the cable eliminated those gaps. The worth of this simulated axial expansion was measured in ZPPR-15A, ZPPR-15B and ZPPR-15D.

The worth of radial bowing was measured in ZPPR-15, but the experimenters regarded the result as unsatisfactory. Radial bowing was measured by two methods in ZPPR-17A, so the ZPPR-17A bowing measurements were analyzed in place of the unpublished ZPPR-15 radial bowing measurement. The first ZPPR-17A measurement consisted of rearranging the plates in 96 core drawers at the core-radial blanket boundary to simulate outward motion of the fuel during bowing. The second ZPPR-17A measurement used a new bowing oscillator to move the core plates a small distance vertically in a special drawer.

The published uncertainties for the Doppler worth, axial expansion worth and radial bowing worth measurements are the statistical uncertainties in the measurements. In reality, the published uncertainty for each of these measurements is just one component of the total uncertainty. There are additional uncertainties specific to each measurement and a common uncertainty related to conversion from the natural measurement units, cents, to pcm for calculations. A full uncertainty analysis was performed for each measurement. The significant uncertainties were quantified, and a total uncertainty was determined for each measurement.

The ZPPR-15 and ZPPR-17A experimental records were used to create detailed as-built Monte Carlo models of the Doppler worth, axial expansion and radial bowing measurement configurations.

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1 Introduction

The ZPPR-15 Program included measurements of several parameters that are important for reactor safety purposes. Sodium void worth and the worths of simulated control rods were measured in all four phases of the ZPPR-15 Program although the ZPPR staff did not publish the control rod worth measurement in ZPPR-15C. The sodium void worth and control rod worth measurements are discussed in a separate report [1]. In addition to the sodium void worth and control rod worth, the experimenters measured the Doppler worth of small samples, the worth of axial expansion and the worth of radial bowing. This document addresses the Doppler worth, axial expansion and radial bowing measurements. The Zero Power Plutonium Reactor (ZPPR) facility is described in Ref. 2.

2 Doppler Sample Worth Measurements

Doppler reactivity worth measurements were performed in ZPPR-15A loading 43, ZPPR-15B loadings 139 and 140, and ZPPR-15D loading 207. As a matter of clarification, the Doppler reactivity worth measurements performed at ZPPR were measurements of the Doppler reactivity worth of small samples rather than measurements of the Doppler reactivity of the entire core.

The temperature feedback coefficient for the entire ZPPR-15 assembly was measured as part of the standard operational measurements for the assembly, but that measurement was separate from the Doppler reactivity worth measurements covered here. In addition to Doppler reactivity, the temperature feedback reactivity for any ZPPR assembly includes other reactivity feedback mechanisms such as thermal expansion of plates, drawers and matrix tubes.

It would be difficult, or impossible, to use the temperature coefficient measurement for the entire ZPPR-15 assembly for benchmarking purposes because the true temperature distribution in the assembly is unknown. The temperature used to determine the temperature coefficient for the assembly was an average of the readings of approximately 12 thermocouples placed at various locations in the assembly. That average temperature was a representative value for the assembly, but it was not necessarily the true temperature at any selected core location other than a thermocouple location. The locations of the thermocouples are not known, so the temperature distribution throughout the assembly cannot be determined from the measured temperatures. Even if the reactor temperature distribution were known, computing the effects of thermal expansion on the plates, drawers and matrix tubes would be difficult or impossible. Available information is not sufficient to construct an accurate model of the ZPPR-15 temperature coefficient measurement or to evaluate the associated uncertainties.

2.1 Doppler Sample Worth Measurement Technique

Doppler worths of small samples were measured in the following way. The Doppler sample was loaded into the Doppler mechanism which consisted of a heating element surrounded by an outer capsule. The temperature of the sample was measured by a thermocouple inserted into a small cylindrical cavity in the center of the sample. The Doppler mechanism was placed in a tray that was placed in a matrix tube at the designated core location. The tray was long enough to extend through both halves of the matrix. The worth of the sample was measured by measuring the reactivity change as the Doppler mechanism and sample were oscillated into and out of the center of the core. To reduce the experimental uncertainty, the sample was oscillated

approximately eight times. The worth of the heating element, capsule and other components of the mechanism was measured by repeating the measurement without the Doppler sample present in the mechanism. The difference between the measured worths with and without the Doppler sample determines the worth of just the Doppler sample. Measurements were obtained at several temperatures between 300 K and 1100 K.

The Doppler worth of the sample is very small relative to the total worth of the sample plus the associated equipment. Thus, a direct measurement as described in the preceding paragraph would be a small difference between two much larger numbers and would have a relatively large experimental uncertainty. The experimental uncertainty was reduced by using a balance tray. A balance tray consisted of a small tray that was placed in the long Doppler tray at the opposite end from the Doppler samples. This small tray contained a carefully selected group of plates (depleted uranium, stainless steel, enriched uranium, plutonium, etc.) that approximately matched the mass, composition and worth of the Doppler sample and related equipment. As the Doppler sample was oscillated into and out of the core, the balance tray moved in the opposite direction. The difference in worth between the Doppler sample plus equipment and the balance tray was small, so the small Doppler worth showed up more clearly as the difference between two small worths.

Figure 2.1 shows a cross-sectional view of the Doppler sample, equipment and tray. Figure 2.2 shows another view of the Doppler sample and equipment. Figure 2.3 shows the two positions of the Doppler equipment during measurements.

Figure 2.1 Cross-Sectional View of Doppler Sample and Equipment

Figure 2.2 Doppler Sample.

Figure 2.3 Doppler Sample Measurement Positions

Four Doppler samples were measured in ZPPR-15 although the specific set of samples measured varied between phases A, B and D. Doppler sample N-3 was natural UO_2 , sample N-11 was depleted uranium metal, sample N-24 was depleted U-10Zr (depleted uranium metal alloyed with 10 wt.% Zr), and sample E-33-A was 33% enriched UO_2 . Each sample had a diameter of 25.4 mm (1 in). Samples N-3, N-24 and E-33-A were 305 mm (12 in) long while sample N-11 was 254 mm (10 in) long. Samples N-3 and N-11 were measured in ZPPR-15A, loading 43. Samples N-3, N-11 and N-24 were measured in ZPPR-15B loadings 139 and 140. All four samples were measured in ZPPR-15D loading 207. Table 2.1 shows the characteristics of the four samples.

Table 2.1 Specifications of Doppler Samples Measured in ZPPR-15a.

Sample	Length, ^b mm	²³⁸ U Mass, kg	Atom Densities, atoms/b-cm			
			²³⁸ U	²³⁵ U	O	Zr
Natural UO ₂ (N-3)	305	1.086	0.01827	0.00013	0.03680	
Depleted U Metal (N-11)	254	2.386	0.04736	0.00019		
Depleted U Metal, 10 w/o Zr (N-24)	305	2.375 ^c	0.03562	0.00009		0.01068
33% Enriched UO ₂ (E-33-A)	305	0.9896 ^d	0.01081	0.00548	0.03905	

- a) These are the sample specifications from the original ZPPR-15 report.
- b) The diameter for all samples is 25.4 mm.
- c) The 2.375 kg ²³⁸U mass for sample N-24 is inconsistent with the dimensions of the sample and the density of U-10Zr alloy. This is discussed in a later section.
- d) Total uranium mass.

2.2 Measured ZPPR-15 Doppler Sample Worths

Tables 2.2 – 2.10 give the measured Doppler reactivity worths in ZPPR-15A, ZPPR-15B and ZPPR-15D. The reference temperature in all cases was 300 K. For the depleted uranium metal sample, N-11, and the depleted U-10Zr sample, N-24, the tables show uncorrected and corrected values. The corrected values for samples N-11 and N-24 reflect corrections derived by the ZPPR staff for axial expansion of the metal samples for temperatures greater than 300 K. The calculated axial expansion correction is based upon a calculated first order axial worth profile for ²³⁸U. The uncertainty for each measured value includes ±5 K temperature uncertainty.

Table 2.2 Measured Doppler Worths in ZPPR-15A – Sample N-3 – Natural UO₂

Temperature, K	Worth, ϕ /kg ²³⁸ U	
	ρ	σ
543	-0.0350	0.0013
685	-0.0491	0.0017
800	-0.0570	0.0012
954	-0.0690	0.0013
1100	-0.0784	0.0012
Sample worth	-1.574	0.002

Table 2.3 Measured Doppler Worths in ZPPR-15A – Sample N-11 – Depleted U Metal

Temperature, K	Uncorrected Worth, $\phi/\text{kg } ^{238}\text{U}$		Corrected Worth, $\phi/\text{kg } ^{238}\text{U}$	
	ρ	σ	ρ	σ
503	-0.0255	0.0008	-0.0253	0.0008
640	-0.0377	0.0008	-0.0374	0.0008
784	-0.0487	0.0008	-0.0483	0.0008
892	-0.0563	0.0008	-0.0558	0.0008
1023	-0.0632	0.0008	-0.0624	0.0008
Sample worth	-1.169	0.0014		

Table 2.4 Measured Doppler Worths in ZPPR-15B – Sample N-3 – Natural UO₂

Temperature, K	Worth, $\phi/\text{kg } ^{238}\text{U}$	
	ρ	σ
490	-0.0262	0.0009
642	-0.0412	0.0009
777	-0.0526	0.0008
914	-0.0610	0.0008
1013	-0.0712	0.0007
Sample worth	-1.945	0.005

Table 2.5 Measured Doppler Worths in ZPPR-15B – Sample N-11 – Depleted U Metal

Temperature, K	Uncorrected Worth, $\phi/\text{kg } ^{238}\text{U}$		Corrected Worth, $\phi/\text{kg } ^{238}\text{U}$	
	ρ	σ	ρ	σ
490	-0.0280	0.0007	-0.0278	0.0007
659	-0.0442	0.0007	-0.0439	0.0007
802	-0.0551	0.0006	-0.0547	0.0006
913	-0.0615	0.0006	-0.0609	0.0006
1016	-0.0673	0.0005	-0.0665	0.0005
Sample worth	-1.227	0.001 ^a		

- a) The report lists 0.0001 but that value must be a typographical error because it is inconsistent with any of the other uncertainty values. An uncertainty of 0.001 is consistent with the other uncertainty values.

Table 2.6 Measured Doppler Worths in ZPPR-15B – Sample N-24 – Depleted U-Zr Metal

Temperature, K	Uncorrected Worth, $\phi/\text{kg } ^{238}\text{U}$		Corrected Worth, $\phi/\text{kg } ^{238}\text{U}$	
	ρ	σ	ρ	σ
505	-0.0268	0.0005	-0.0266	0.0005
655	-0.0406	0.0005	-0.0402	0.0005
806	-0.0509	0.0005	-0.0503	0.0005
904	-0.0556	0.0005	-0.0550	0.0005
1047	-0.0648	0.0004	-0.0637	0.0005
Sample worth	-1.310	0.001		

Table 2.7 Measured Doppler Worths in ZPPR-15D – Sample N-3 – Natural UO_2

Temperature, K	Worth, $\phi/\text{kg } ^{238}\text{U}$	
	ρ	σ
531	-0.0145	0.0006
651	-0.0195	0.0006
790	-0.0246	0.0006
936	-0.0300	0.0006
1081	-0.0329	0.0005
Sample worth	-0.641	0.002

Table 2.8 Measured Doppler Worths in ZPPR-15D – Sample N-11 – Depleted U Metal

Temperature, K	Uncorrected Worth, $\phi/\text{kg } ^{238}\text{U}$		Corrected Worth, $\phi/\text{kg } ^{238}\text{U}$	
	ρ	σ	ρ	σ
503	-0.0131	0.0003	-0.0130	0.0003
650	-0.0204	0.0003	-0.0203	0.0003
797	-0.0255	0.0003	-0.0253	0.0003
896	-0.0284	0.0003	-0.0281	0.0003
1011	-0.0314	0.0003	-0.0310	0.0003
Sample worth	-0.584	0.001		

Table 2.9 Measured Doppler Worths in ZPPR-15D – Sample N-24 – Depleted U-Zr Metal

Temperature, K	Uncorrected Worth, $\phi/\text{kg } ^{238}\text{U}$		Corrected Worth, $\phi/\text{kg } ^{238}\text{U}$	
	ρ	σ	ρ	σ
532	-0.0147	0.0003	-0.0146	0.0003
656	-0.0201	0.0003	-0.0199	0.0003
809	-0.0257	0.0003	-0.0254	0.0003
904	-0.0288	0.0003	-0.0285	0.0003
1032	-0.0323	0.0002	-0.0318	0.0003
Sample worth	-0.618	0.001		

Table 2.10 Measured Doppler Worths in ZPPR-15D – Sample E-33-A – Enriched UO_2

Temperature, K	Worth, $\phi/\text{kg } ^{238}\text{U}$	
	ρ	σ
500	-0.0080	0.0008
649	-0.0130	0.0008
786	-0.0172	0.0007
940	-0.0194	0.0007
1083	-0.0235	0.0006
Sample worth	2.393	0.001

2.3 Uncertainty Evaluation for the ZPPR-15 Doppler Worth Measurements

The uncertainties listed in Tables 2.2 – 2.10 are the uncertainties that are directly associated with the Doppler reactivity worth measurement. They include counting statistics, detector calibration and a ± 5 K uncertainty in the measured temperature of the Doppler sample.

All uncertainties related to the overall reactor configuration, i.e., uncertainties for the reference critical configuration [2], are completely correlated between the cold Doppler sample and the hot Doppler sample as a consequence of the Doppler sample worth measurement technique. Those uncertainties drop out of the uncertainty analysis of the Doppler measurements. Likewise, uncertainty related to reproducibility is eliminated except possibly for small uncertainties in the precise positioning of the Doppler sample and balance tray when they are oscillated into the center of the core. The axial flux profile at the center of the core, i.e., the interface between half 1 and half 2, is relatively flat. Any uncertainties in the axial positioning of the Doppler sample and balance tray are negligible compared to the uncertainties discussed below.

There are three uncertainties related to the Doppler sample and one uncertainty related to conversion of units that remain to be considered.

First, the actual mass of the sample is uncertain. All ICSBEP and IRPhEP benchmarks of ZPR and ZPPR assemblies have assigned an uncertainty of 0.15% to the mass of any plate, drawer or other component with the exception of the matrix tubes for which the mass uncertainty is significantly larger [3,4]. This 0.15% uncertainty arises from lack of knowledge concerning the specific procedure and equipment used for weight measurements plus an assumed uncertainty in the weight calibration standards. There is no reason to believe that the Doppler sample weights were known more accurately than those of other items used in ZPPR experiments, so the 0.15% weight uncertainty is assumed to apply to the Doppler samples.

The uncertainty in the weight of the sample does not affect the measured total worth of the sample, but it does introduce a 0.15% uncertainty in the worth per unit mass of ^{238}U since the sample mass has a 0.15% uncertainty and the measured Doppler sample worths were reported with respect to the masses of the samples. Reporting the measured worths in cents rather than cents per kilogram would not eliminate this uncertainty because the 0.15% mass uncertainty is associated with the sample itself and carries over into any calculation of the worth of the sample.

Second, the composition of the Doppler samples is uncertain. Specifically, there is an uncertainty in the weight fraction of ^{235}U in the depleted uranium and in the enriched uranium in sample E-33-A. The manufacturing specification for the depleted U_3O_8 plates used in ZPPR required a two-sigma uncertainty of 10% in the ^{235}U content of the depleted uranium. Although no similar manufacturing specification has been located for the depleted uranium metal plates or for the Doppler samples, it seems likely that the ^{235}U content specification would have been similar or possibly much tighter for the Doppler samples because similar considerations would apply with respect to the effects of uncertainties.

The uncertainty in the ^{235}U content of the Doppler samples is not important compared to the other uncertainties for the Doppler worth measurements. Consider a depleted uranium sample containing a nominal 0.2 wt.% ^{235}U with a one-sigma uncertainty of 5% in the ^{235}U content. At the one-sigma level, the ^{235}U range would be 0.19 wt.% – 0.21 wt.%, and the corresponding ^{238}U range would be 99.81 wt.% – 99.79 wt.%. This uncertainty is much smaller than the 0.15% uncertainty in the weight of the sample, so the effect of uncertainty in the ^{235}U content of the depleted uranium Doppler samples is considered to be negligible. The effect of uncertainty in the composition of the enriched uranium sample, E-33-A, is considered negligible for similar reasons.

There could also be a small uncertainty in the exact stoichiometry of the UO_2 samples. The effects of uncertainty in the UO_2 sample stoichiometry are negligible compared to the uncertainty in reactivity conversion discussed below and will not be considered further.

In previous ICSBEP and IRPhEP benchmarks of ZPPR critical configurations [3,4], the estimated uncertainty in the thermocouple calibration was 0.5 °C or 0.5 K, and that uncertainty would also apply to calibration of the thermocouple used to measure the temperature of the Doppler sample or the temperature of the Doppler mechanism when no sample was present. However, the same thermocouple was used for all Doppler sample measurements, so the effect of uncertainty in the thermocouple calibration is correlated among all Doppler measurements. In addition, the uncertainties listed in Tables 2.2 – 2.10 include a 5 K sample temperature uncertainty specified by the experimenters. Adding a 5 K uncertainty and a 0.5 K uncertainty in quadrature only increases the total temperature uncertainty to 5.02 K. Consequently, the effect of the uncertainty in thermocouple calibration is considered negligible.

In practice, the uncertainties in the mass of the Doppler sample, the ^{235}U content of the samples, the UO_2 sample stoichiometry and the thermocouple calibration are not important compared to the uncertainty in β_{eff} . Doppler reactivities were reported in the natural measurement units, cents, and those are the units listed in Tables 2.2 – 2.10. However, Doppler reactivities are calculated in units of $\Delta k/k_{1k2}$ or pcm. Conversion from the measurements units to the calculation units requires β_{eff} . The uncertainty that is typically assigned to β_{eff} in ICSBEP and IRPhEP benchmarks is around 5%. The 5% value is assumed not only in ZPR/ZPPR benchmarks but also in most other benchmarks in the ICSBEP and IRPhEP Handbooks [3,4]. The 5% uncertainty is consistent with the assigned uncertainty for the limited number of published β_{eff} measurements in ZPR/ZPPR assemblies and with calculations of those measured values. The ZPPR experimenters typically used calculated β_{eff} values when reporting the measurement results. Table 2.11 lists the values of β_{eff} calculated and used by the ZPPR staff for ZPPR-15A, ZPPR-15B and ZPPR-15D.

The uncertainty in β_{eff} and the corresponding uncertainty in the Doppler reactivity worth when the measured worth is converted from cents to pcm is 5%. The uncertainty in the mass of a Doppler sample is 0.15%. The 0.5 K uncertainty in thermocouple calibration is equivalent to less than 0.5% uncertainty over the measurement temperature range. The uncertainty in the composition of a sample is less than 0.1%. If all of these uncertainties are added in quadrature, the resulting total uncertainty in the measured Doppler worths is 5.03%.

Table 2.11 β_{eff} for ZPPR-15 Phases A, B and D.

Phase	β_{eff}
ZPPR-15A	0.003357
ZPPR-15B	0.003361
ZPPR-15D	0.006564

2.4 ZPPR-15 Doppler Sample Worths and Associated Uncertainties

Table 2.12 and 2.13 show the measured Doppler sample worths and associated uncertainties in units of pcm for ZPPR-15A. The measured worth in column 7 of Tables 2.12 and 2.13 is the product of column 2 and the ^{238}U mass of the sample.

Table 2.12 ZPPR-15A Doppler Sample Worth – N-3 – Natural UO_2

Temperature, K ^a	ρ_{meas} , pcm/kg ^b	σ_{meas} , pcm/kg	$\sigma_{\beta\text{-eff}}$, pcm/kg	σ_{total} , pcm/kg	σ_{total} , %	ρ_{meas} , pcm
543	-0.1175	0.0044	0.0059	0.0073	6.23	-0.1276
685	-0.1648	0.0057	0.0082	0.0100	6.08	-0.1790
800	-0.1913	0.0040	0.0096	0.0104	5.43	-0.2078
954	-0.2316	0.0044	0.0116	0.0124	5.34	-0.2516
1100	-0.2632	0.0040	0.0132	0.0138	5.23	-0.2858
Sample worth	-5.2839	0.0067	0.2642	0.2643	5.00	-5.7383

- Temperature is in kelvins. The reference temperature is 300 K.
- Measured worth in column 2 and uncertainties in columns 3 – 5 are in pcm/kg ^{238}U . The published ^{238}U mass for N-3 is 1.086 kg. The measured worth in column 7 is the total worth.

Table 2.13 ZPPR-15A Doppler Sample Worth - N-11 - Depleted U Metal

Temperature, K ^a	ρ_{meas} , pcm/kg ^b	σ_{meas} , pcm/kg	$\sigma_{\beta\text{-eff}}$, pcm/kg	σ_{total} , pcm/kg	σ_{total} , %	ρ_{meas} , pcm
503	-0.0849	0.0027	0.0042	0.0050	5.92	-0.2026
640	-0.1256	0.0027	0.0063	0.0068	5.44	-0.2996
784	-0.1621	0.0027	0.0081	0.0085	5.27	-0.3869
892	-0.1873	0.0027	0.0094	0.0097	5.20	-0.4469
1023	-0.2095	0.0027	0.0105	0.0108	5.16	-0.4998
Sample worth	-3.9243	0.0047	0.1962	0.1963	5.00	-9.3635

- a) Temperature is in kelvins. The reference temperature is 300 K.
- b) Measured worth in column 2 and uncertainties in columns 3 – 5 are in pcm/kg ²³⁸U. The published ²³⁸U mass for N-11 is 2.386 kg. The measured worth in column 7 is the total worth.

Table 2.14 – 2.16 show the measured Doppler sample worths and associated uncertainties in units of pcm for ZPPR-15B. The measured worth in column 7 of Tables 2.14 – 2.16 is the product of column 2 and the ²³⁸U mass of the sample.

Table 2.14 ZPPR-15B Doppler Sample Worth - N-3 - Natural UO2

Temperature, K ^a	ρ_{meas} , pcm/kg ^b	σ_{meas} , pcm/kg	$\sigma_{\beta\text{-eff}}$, pcm/kg	σ_{total} , pcm/kg	σ_{total} , %	ρ_{meas} , pcm
490	-0.0881	0.0030	0.0044	0.0053	6.07	-0.0956
642	-0.1385	0.0030	0.0069	0.0076	5.46	-0.1504
777	-0.1768	0.0027	0.0088	0.0092	5.23	-0.1920
914	-0.2050	0.0027	0.0103	0.0106	5.17	-0.2227
1013	-0.2393	0.0024	0.0120	0.0122	5.10	-0.2599
Sample worth	-6.5371	0.0168	0.3269	0.3273	5.01	-7.0993

- a) Temperature is in kelvins. The reference temperature is 300 K.
- b) Measured worth in column 2 and uncertainties in columns 3 – 5 are in pcm/kg ²³⁸U. The published ²³⁸U mass for N-3 is 1.086 kg. The measured worth in column 7 is total worth.

Table 2.15 ZPPR-15B Doppler Sample Worth – N-11 – Depleted U Metal

Temperature, K ^a	ρ_{meas} , pcm/kg ^b	σ_{meas} , pcm/kg	$\sigma_{\beta\text{-eff}}$, pcm/kg	σ_{total} , pcm/kg	σ_{total} , %	ρ_{meas} , pcm
490	-0.0934	0.0024	0.0047	0.0052	5.60	-0.2229
659	-0.1475	0.0024	0.0074	0.0077	5.25	-0.3520
802	-0.1838	0.0020	0.0092	0.0094	5.12	-0.4387
913	-0.2047	0.0020	0.0102	0.0104	5.10	-0.4884
1016	-0.2235	0.0017	0.0112	0.0113	5.06	-0.5333
Sample worth	-4.1239	0.0034	0.2062	0.2062	5.00	-9.8397

- a) Reference temperature is 300 K. The experimenters regarded the 300 K value as suspect.
- b) Measured worth in column 2 and uncertainties in columns 3 – 5 are in pcm/kg ²³⁸U. The published ²³⁸U mass for N-11 is 2.386 kg. The measured worth in column 7 is total worth.

Table 2.16 ZPPR-15B Doppler Sample Worth – N-24 – Depleted U-Zr Metal

Temperature, K ^a	ρ_{meas} , pcm/kg ^b	σ_{meas} , pcm/kg	$\sigma_{\beta\text{-eff}}$, pcm/kg	σ_{total} , pcm/kg	σ_{total} , %	ρ_{meas} , pcm
505	-0.0894	0.0017	0.0045	0.0048	5.34	-0.1917
655	-0.1351	0.0017	0.0068	0.0070	5.15	-0.2897
806	-0.1691	0.0017	0.0085	0.0086	5.10	-0.3625
904	-0.1849	0.0017	0.0092	0.0094	5.08	-0.3963
1047	-0.2141	0.0017	0.0107	0.0108	5.06	-0.4590
Sample worth	-4.4029	0.0034	0.2201	0.2202	5.00	-9.4398

- a) Temperature is in kelvins. The reference temperature is 300 K.
- b) Measured worth in column 2 and uncertainties in columns 3 – 5 are in pcm/kg ²³⁸U. The published ²³⁸U mass for sample N-24 is 2.375 kg. This mass is inconsistent with the sample dimensions and the density of U-10Zr alloy. A ²³⁸U mass of 2.144 kg is consistent with the published sample dimensions and the density of U-10Zr alloy. The measured worth in column 7 is total worth.

Table 2.17 – 2.20 show the measured Doppler sample worths and associated uncertainties in units of pcm for ZPPR-15D. Note that the E-33-A sample was reported with respect to the total uranium mass rather than just the ²³⁸U mass. The measured worth in column 7 of Tables 2.17 – 2.19 is the product of column 2 and the ²³⁸U mass of the sample. The measured worth in column 7 of Table 2.20 is the product of column 2 and the total uranium mass of the sample.

Table 2.17 ZPPR-15D Doppler Sample Worth – N-3 – Natural UO₂

Temperature, K ^a	ρ_{meas} , pcm/kg ^b	σ_{meas} , pcm/kg	$\sigma_{\beta\text{-eff}}$, pcm/kg	σ_{total} , pcm/kg	σ_{total} , %	ρ_{meas} , pcm
531	-0.0952	0.0039	0.0048	0.0062	6.49	-0.1034
651	-0.1280	0.0039	0.0064	0.0075	5.87	-0.1390
790	-0.1615	0.0039	0.0081	0.0090	5.56	-0.1754
936	-0.1969	0.0039	0.0098	0.0106	5.39	-0.2139
1081	-0.2160	0.0033	0.0108	0.0113	5.23	-0.2345
Sample worth	-4.2075	0.0131	0.2104	0.2108	5.01	-4.5694

- a) Temperature is in kelvins. The reference temperature is 300 K.
b) Measured worth in column 2 and uncertainties in columns 3 – 5 are in pcm/kg ²³⁸U. The ²³⁸U mass for N-3 is 1.086 kg.

Table 2.18 ZPPR-15D Doppler Sample Worth – N-11 – Depleted U Metal

Temperature, K ^a	ρ_{meas} , pcm/kg ^b	σ_{meas} , pcm/kg	$\sigma_{\beta\text{-eff}}$, pcm/kg	σ_{total} , pcm/kg	σ_{total} , %	ρ_{meas} , pcm
503	-0.0853	0.0020	0.0043	0.0047	5.51	-0.2036
650	-0.1332	0.0020	0.0067	0.0069	5.21	-0.3179
797	-0.1661	0.0020	0.0083	0.0085	5.14	-0.3962
896	-0.1844	0.0020	0.0092	0.0094	5.11	-0.4401
1011	-0.2035	0.0020	0.0102	0.0104	5.09	-0.4855
Sample worth	-3.8334	0.0066	0.1917	0.1918	5.00	-9.1464

- a) Temperature is in kelvins. The reference temperature is 300 K.
b) Measured worth in column 2 and uncertainties in columns 3 – 5 are in pcm/kg ²³⁸U. The ²³⁸U mass for N-11 is 2.386 kg.

Table 2.19 ZPPR-15D Doppler Sample Worth – N-24 – Depleted U-Zr Metal.

Temperature, K ^a	ρ_{meas} , pcm/kg ^b	σ_{meas} , pcm/kg	$\sigma_{\beta\text{-eff}}$, pcm/kg	σ_{total} , pcm/kg	σ_{total} , %	ρ_{meas} , pcm
532	-0.0958	0.0020	0.0048	0.0052	5.41	-0.2055
656	-0.1306	0.0020	0.0065	0.0068	5.22	-0.2801
809	-0.1667	0.0020	0.0083	0.0086	5.14	-0.3575
904	-0.1871	0.0020	0.0094	0.0096	5.11	-0.4011
1032	-0.2087	0.0020	0.0104	0.0106	5.09	-0.4475
Sample worth	-4.0566	0.0066	0.2028	0.2029	5.00	-8.6972

- a) Temperature is in kelvins. The reference temperature is 300 K.

- b) Measured worth in column 2 and uncertainties in columns 3 – 5 are in pcm/kg ^{238}U . The published ^{238}U mass for sample N-24 is 2.375 kg. This mass is inconsistent with the sample dimensions and the density of U-10Zr alloy. A ^{238}U mass of 2.144 kg is consistent with the published sample dimensions and the density of U-10Zr alloy.

Table 2.20 ZPPR-15D Doppler Sample Worth – E-33-A – Enriched UO₂

Temperature, K ^a	ρ_{meas} , pcm/kg ^b	σ_{meas} , pcm/kg	$\sigma_{\beta\text{-eff}}$, pcm/kg	σ_{total} , pcm/kg	σ_{total} , %	ρ_{meas} , pcm
500	-0.0525	0.0053	0.0026	0.0059	11.18	-0.0520
649	-0.0853	0.0053	0.0043	0.0068	7.93	-0.0844
786	-0.1129	0.0046	0.0056	0.0073	6.45	-0.1117
940	-0.1273	0.0046	0.0064	0.0079	6.17	-0.1260
1083	-0.1543	0.0039	0.0077	0.0087	5.61	-0.1526
Sample worth	15.7077	0.0066	-0.7854	0.7854	-5.00	15.5443

- a) Temperature is in kelvins. The reference temperature is 300 K.
b) Measured worth in column 2 and uncertainties in columns 3 – 5 are in pcm/kg U. The total U mass for E-33-A is 0.9896 kg.

2.5 ZPPR- 15 As-Built Monte Carlo Models for Doppler Measurements

As-built MCNP models were created for all Doppler worth measurements in ZPPR-15A, ZPPR-15B and ZPPR-15D. The only difference between ZPPR-15B loadings 139 and 140 was the replacement of two normal drawers in loading 139 by some experimental apparatus in loading 140 at locations far from the Doppler device. These differences would not have impacted the Doppler measurements, so no separate as-built model was constructed for loading 140.

Core layouts, i.e., core interface matrix maps, for half 1 and half 2 of ZPPR-15 loadings 43, 139 and 207 are shown in Figures 2.5 – 2.10. The matrix map specifies the position of each drawer master, i.e., unique drawer type, in the matrix tubes in each half of the machine (see Ref. 2). Figure 2.4 shows the color code for the drawer masters in Figures 2.5 – 2.10. In Figures 2.5 – 2.10, the numbers in the top row are the column numbers in the ZPPR matrix, and the numbers in the first column are the row numbers in the matrix. The numbers in the cells are abbreviations of the drawer master identifiers for the drawers that occupied those cells. A full ZPPR-15 identifier is 15-0-xxx where xxx is the unique three digit identifier for a specific drawer loading pattern or configuration. For example, the full identifier for drawer master 101 in various cells in Figure 2.5 is 15-0-101. Only the unique three digit identifier for the drawer master is shown in the figures because inclusion of the full identifier would make the numbers too small to read.

	100 - 199 SCF Pu drawer
	200 - 299 DCF Pu drawer
	400 - 499 Radial reflector
	500 - 599 Radial blanket
	700 - 799 Detector drawer
	800 - 899 PSR control rod drawer
	900 - 999 HEU drawer
	Doppler measurement device

Figure 2.4 Drawer Master Color Code for Figures 2.5 – 2.10

SCF refers to a drawer with a single column of fuel, and DCF refers to a drawer with two columns of fuel. PSR refers to a drawer with a poison safety or shim rod, i.e., a narrow drawer with an adjacent control rod. For ZPPR-15A L043, the Doppler measurement apparatus was located in row 63, column 46 in both halves (163-46 and 263-46). For ZPPR-15B L139 and ZPPR-15D L207, the Doppler measurement apparatus was located in row 63, column 51 in both halves (163-51 and 263-51). Ref. 2 discusses the numbering convention for the rows and columns in the ZPPR matrix.

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Figure 2.5 ZPPR-15A – Loading 43 – Half 1 – Doppler Measurement

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Figure 2.6 ZPPR-15A - Loading 43 - Half 2 - Doppler Measurement.

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Figure 2.7 ZPPR-15B – Loading 139 – Half 1 – Doppler Measurement.

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Figure 2.8 ZPPR-15B – Loading 139 – Half 2 – Doppler Measurement

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Figure 2.9 ZPPR-15D – Loading 207 – Half 1 – Doppler Measurement

Figure 2.10 ZPPR-15D – Loading 207 – Half 2 – Doppler Measurement

Tables 2.12 – 2.20 show that the measured Doppler worths are in the 0.05 – 0.2 pcm. Given the fact that one billion (10^9) histories gives ~ 2 pcm as the statistical uncertainty for the MCNP calculation of k_{eff} any of the ZPPR-15 reference critical configurations, it does not seem feasible to directly compute the Doppler worth with MCNP. Deterministic models were created for the ZPPR-15 Doppler experiments. The results from the deterministic calculations with MC2-3/DIF3D were excellent for ZPPR-15A and ZPPR-15B and were good for ZPPR-15D [5].

3 Axial Expansion Worth Measurements

Axial expansion worth experiments were performed in ZPPR-15A loading 61 (ZPPR-15A L061), ZPPR-15B loading 117 (ZPPR-15B L117) and ZPPR-15D loading 206 (ZPPR-15D L206). A segmented drawer was constructed for each measurement. The back of the segmented

drawer was connected to a spring-loaded cable that could be pulled away from the axial core centerline to introduce gaps between drawer segments. Releasing the cable eliminated the gaps between drawer segments such that the segmented drawer was essentially identical to any other core drawer when the cable was released. The small gaps introduced between drawer segments simulated core axial expansion as closely as possible given the constraint that the core materials consisted of rigid plates of fixed sizes.

The segmented drawer design allowed experimenters to measure the reactivity worth of the reference and expanded configurations in one reactor run. Performing all required measurements in one reactor run minimized experimental uncertainty by minimizing the reproducibility uncertainty and ensuring that the only difference between the reference state and the expansion configuration was the introduction of small gaps between segments.

3.1 ZPPR-15 Axial Expansion Worth Experiments

3.1.1 ZPPR-15A L061 Axial Expansion Experiment

The first axial expansion experiment was performed in ZPPR-15A L061. The segmented drawer consisted of four segments with approximate lengths of 6 in, 6 in, 6 in and 18 in. The lengths listed here are approximate because they ignore the 0.030 in (0.0762 cm) stainless steel plates attached to the front and back of each drawer segment to prevent plates from moving axially within the segments. Gaps of length 0.635 cm (0.25 in) were introduced between segments at 6 in, 12 in and 18 in (nominal positions).

After analysis of the ZPPR-15A axial expansion experiment was completed, the ZPPR staff concluded that the axial expansion experiment in ZPPR-15A was not representative of axial expansion in an LMFR for two reasons. First, the drawer used for the ZPPR-15A axial expansion experiment had only one column of Pu-U-Mo fuel plates and, consequently, had an average composition with much lower fissile content and reactivity worth than one would find in a typical LMFR. Second, the gap at 18 inches was a gap between the core and the axial blanket. The ZPPR staff concluded that this core-axial blanket gap was neither realistic nor representative of an actual LMFR case. Because the axial expansion experiment in ZPPR-15A was not representative of axial expansion in a real LMFR, no model was generated for the experiment in ZPPR-15A L061.

3.1.2 ZPPR-15B L117 Axial Expansion Experiment

Analysis of the ZPPR-15A axial expansion experiment caused the ZPPR staff to modify the experimental technique for subsequent axial expansion experiments in ZPPR-15B and ZPPR-15D to a) eliminate the unrealistic gap at the core-axial blanket interface and b) use an expansion drawer loading with two fuel columns. Using an expansion drawer with two fuel columns resulted in an average drawer composition that was more representative of a typical LMFR fuel assembly. In addition, the location of the expansion apparatus was moved to matrix position 150-40 (row 50, column 40 in half 1 of the matrix) for the axial expansion measurements in ZPPR-15B and ZPPR-15D.

The core matrix maps were created for ZPPR-15B L117 and ZPPR-15D L206, the core loadings in which the ZPPR-15B and ZPPR-15D axial expansion experiments were conducted.

With the exception of the segmented expansion drawer, all drawer masters used in ZPPR-15B L117 and ZPPR-15D L206 were standard drawers for which descriptions were available in the ZPPR-15 drawer master library. The axial expansion drawers, 15-1-207 and 15-1-879, were not available in the ZPPR-15 drawer master library. Available ZPPR reports and the collected notes of R. W. Schaefer, a former ZPPR staff analyst, were reviewed to determine how the segmented expansion drawers were constructed [6]. Those sources were sufficient to allow modeling of the expansion drawers for the ZPPR-15B and ZPPR-15D axial expansion experiments.

The segmented drawer for ZPPR-15B L117 was divided into three parts. The first part consisted of the first 6 in of the core (0 – 6 in), and the second part consisted of the second 6 in of the core (6 – 12 in). The third segment consisted of the remainder of the core (12 – 18 in) plus the axial blanket (18 – 31 in) and axial reflector (31 – 36 in). All plates used for the core in the segmented drawer were 6 in long. The plates used for the axial blanket and axial reflector in the segmented drawer were identical in size and type to the plates used for the axial blanket and reflector in the remainder of the core.

A 0.030 in (0.0762 cm) steel plate was fixed to the open end(s) of each segment to prevent axial motion of the plates in that segment. No explicit details regarding construction of the segmented drawer have been found, but it is believed that a normal 36 in. drawer was cut into segments of the required length to make the segmented drawer. That would have been the easiest way to make a segmented drawer and would have provided the best match for the other drawers in the core. The segments were connected by mylar tape.

Axial expansion consisted of introducing 6.4 mm gaps in the core at 152 mm and 305 mm from the front of the segmented drawer. Note that these are rounded metric values in the original reports. The gaps were introduced 6 in and 12 in from the front of the drawer, and it is likely that the actual gap width was 0.25 in or 6.35 mm.

The measured worth of axial expansion in ZPPR-15B L117 was -0.1907% with a one-sigma statistical uncertainty of 0.4%. The value of β_{eff} computed by the ZPPR staff for ZPPR-15B was 0.003361.

3.1.3 ZPPR-15D L206 Axial Expansion Experiments

The expansion drawer was divided into nine segments for the ZPPR-15D L206 axial expansion measurements. The nominal segment length was 2 in for each of the first eight core segments. The remaining 2 in of the core, the 13 in axial blanket and the 5 in axial reflector made up the ninth segment which had a total length of 20 in. There was a 0.020 in (0.0508 cm) steel plate fixed to the open end of each segment to prevent axial motion of the plates in that segment. Figure 3.1 shows the segmented drawer used in the ZPPR-15D axial expansion measurement.

All plates used for the core in the segmented drawer were 2 in long. Plates used for the axial blanket and axial reflector in the segmented drawer were identical in size and type to the plates used for the axial blanket and reflector in the remainder of the core.

Figure 3.1 Axial Expansion Configurations for ZPPR-15D Measurements

When ZPR-6 and ZPR-9 were shut down, the HEU plates in their inventory were shipped to ZPPR. These plates consisted of HEU metal coated with Kel-F, a paint-like coating used to inhibit corrosion and material loss during handling. The ZPPR staff sealed these HEU plates in stainless steel cans with nominal lengths of 4 – 8 in. These canned HEU plates were much too long to fit into the 2-in long segments in the expansion drawer. Consequently, eighteen 1/16x2x2 in HEU metal plates were removed from the cans, cleaned and coated with Kel-F for use in the axial expansion experiments. Eighteen HEU plates were required to load nine segments with two HEU fuel columns per segment.

The total width of the core plates in each segment was less than the nominal 2-in interior width of the drawer segment. The existence of a small amount of free space would allow plate motion in the X-direction when the expansion drawer was loaded into the matrix and when the segments were moved during the experiment. Any plate shifting in the X-direction would introduce an additional experimental uncertainty. To eliminate free space and plate motion in the expansion drawer, the experimenters placed small, curved shims on each side of the core plates in the segments. The curved shims acted like springs to make any plate motion in the X-direction negligible.

In ZPPR-15D L206, six expansion measurements were made in five reactor runs. Table 3.1 shows the experimental results for the ZPPR-15D measurements. In the measurements with two gaps, approximately 2 g of mylar tape held the segments together. The gap spacing was determined by small staples that connected adjacent segments for the cases with no mylar tape.

Table 3.1 Axial Expansion Experiments in ZPPR-15D L206

Data File	Reactor Run Number	Number of Gaps	Total Expansion, mm	Mylar Present	Experimental Worth, ϵ^a
47	349	8	19.05	No	-0.1050 ± 0.0002
50	350	2	19.05	Yes	-0.1077 ± 0.0012
51	350	2	19.05	Yes	-0.1062 ± 0.0006
52	351	2	12.70	Yes	-0.0705 ± 0.0005
54	352	8	19.05	Yes	-0.0889 ± 0.0006
56	353	8	19.05	No	-0.1017 ± 0.0005

a) The uncertainty listed is just the measurement uncertainty.

Note that the six measurements in Table 3.1 do not represent six separate cases for modeling purposes. The ZPPR staff believed that there was an unidentified problem with the measurement in data file 54 (reactor run 352) and that the measurement in data file 54 should be rejected.

Data files 50 and 51 for reactor run 350 were two measurements of the same quantity performed in tandem during the same reactor run. They agree after allowing for the drift correction and statistical uncertainty in the measurement.

The file 56 measurement is a repetition of the file 47 measurement to determine the random error associated with reproducibility.

The final value of β_{eff} computed by the ZPPR staff for ZPPR-15D was 0.006564.

Experimenters varied the number and size of the gaps in ZPPR-15D L206 to determine whether discrete gaps of the sizes used in the ZPPR-15 experiments were an adequate approximation of the uniform expansion that would actually occur in an LMFR. The ZPPR staff concluded that the ZPPR-15B and ZPPR-15D axial expansion experiments were an adequate representation of the axial expansion in an LMFR.

3.2 ZPPR-15 Axial Expansion Measurement Uncertainties

The measured axial expansion reactivity for ZPPR-15B L117 was $-0.1907\epsilon \pm 0.00076\epsilon$ where 0.00076ϵ corresponds to the 0.4% measurement uncertainty listed in Section 3.1.2. The measured axial expansion reactivities and associated measurement uncertainties for the ZPPR-15D axial expansion measurements are shown in Table 3.1. The largest uncertainty in Table 3.1 is 1.1% for data file 50 (reactor run 350).

The uncertainties discussed in the preceding paragraph and listed in Table 3.1 above are measurement uncertainties, but they are not the total uncertainties for the measured axial expansion worths. Almost all uncertainties that are applicable to analysis of the reference critical configurations are fully correlated between the reference critical configurations and expansion configurations in ZPPR-15B L117 and ZPPR-15D L206 due to the experimental procedure used for the axial expansion measurements. Consequently, those uncertainties drop

out of the reactivity difference measurements. However, there are a few uncertainties that remain to be considered.

Conversion from the natural measurement units, cents, to the calculation units of $\Delta k/k_1 k_2$ or pcm requires knowledge of the delayed neutron kinetics parameters, particularly β_{eff} . However, β_{eff} is uncertain, and that uncertainty should be included in the total uncertainty for the axial expansion worth expressed in $\% \Delta k$ or pcm. The estimated uncertainty in β_{eff} is 5% which is the value assumed for ICSBEP/IRPhEP benchmarks of ZPR and ZPPR assemblies [3,4] as discussed in Section 2. The 5% uncertainty in β_{eff} applies to all of the measured axial expansion worths.

Reactor run 353 (data file 56) was a reconstruction of reactor run 349 (data file 47) to determine the random error associated with reproducibility of the experimental configurations. If it were possible to reproduce the earlier configuration and measurement conditions exactly, the measured worths in data file 56 and data file 47 would be identical within the statistical uncertainty of the measurements. Table 3.1 shows that there is ~3% difference between the measured values in reactor run 349 and reactor run 353. This 3% difference is much larger than the statistical uncertainty in the measurements. Consequently, the reproducibility uncertainty for the ZPPR-15 axial expansion experiments is assumed to be 3%. Although the reproducibility uncertainty was measured for one configuration, this uncertainty is assumed to apply to all of the axial expansion measurements.

The exact amount of mylar tape used in the experiments is not listed although it was estimated to be ~2 g by the ZPPR staff. The ZPPR staff computed the expansion worth for data file 52 with and without mylar tape present in their model. The expansion worth was only 0.5% larger with the mylar tape present. Based on the calculation by the ZPPR staff, the total worth of the mylar tape is believed to be much less than the 5% uncertainty in β_{eff} or the 3% reproducibility uncertainty, so the mylar tape will be neglected and the associated uncertainty will be 0.5% for any configuration where mylar tape was present.

The statistical uncertainty, the β_{eff} uncertainty, the reproducibility uncertainty and the mylar tape uncertainty are independent, so they are added in quadrature to give the total uncertainty for the axial expansion measurements. Table 3.2 gives the individual uncertainty components and the total uncertainties for the axial expansion measurements in ZPPR-15B and ZPPR-15D.

Table 3.2 Uncertainty Components and Total Uncertainties for ZPPR-15 Axial Expansion Measurements^a

Uncertainty	ZPPR-15B	ZPPR-15D Data File				
		47	50	51	52	56
Statistical, %	0.4	0.19	1.11	0.56	0.71	0.49
β_{eff} , %	5	5	5	5	5	5
Reproducibility, %	3	3	3	3	3	3
Mylar Tape, %	0.50	0	0.50	0.50	0.50	0
Total, %	5.87	5.83	5.96	5.88	5.90	5.85

a) All uncertainties are percent of the measured value.

Table 3.3 gives the measured axial expansion worths and total uncertainties for ZPPR-15B and ZPPR-15D.

Table 3.3 Axial Expansion Worths and Total Uncertainties for ZPPR-15B and ZPPR-15D

Case ^a	Assembly/ Loading	Data File/ Reactor Run	ρ , pcm	σ , %
1	ZPPR-15B L117		-0.641	5.87
2	ZPPR-15D L206	47/349	-0.689	5.83
3	ZPPR-15D L206	50/350	-0.707	5.96
4	ZPPR-15D L206	51/350	-0.697	5.88
5	ZPPR-15D L206	52/351	-0.463	5.90
6	ZPPR-15D L206	56/353	-0.668	5.85

a) Cases 2 – 6 correspond to configurations in Table 3.1.

3.3 ZPPR-15B and ZPPR-15D Axial Expansion Models

Two MCNP models and associated files were created for ZPPR-15B L117. The first ZPPR-15B L117 model is the reference case with no gaps in the segmented drawer. The second ZPPR-15B L117 model, Case 1 in Table 3.3, introduced 0.25 in (6.35 mm) gaps at 6 in (152.4 mm) and 12 in (304.8 mm) from the drawer front. Note that the axial positions where the gaps were introduced are nominal values that do not account for the thin stainless steel plates at the ends of each segment that prevent axial shifting of the materials in the segments. This applies to all axial expansion measurements in ZPPR-15.

For the ZPPR-15B L117 axial expansion MCNP models, the experimental axial expansion drawer is universe 35 in matrix position 150-40 (row 50, column 40 in half 1).

Four MCNP models and associated files were created for the axial expansion measurements in ZPPR-15D L206. The first ZPPR-15D L206 model is the reference case with no gaps in the segmented drawer.

The second ZPPR-15D L206 model corresponds to files 47 and 56 in Table 3.1 (Cases 2 and 6 in Table 3.3). For the second ZPPR-15D L206 model, eight gaps were introduced between the nine 2-in core segments. The total width of these eight gaps was 0.75 in (19.05 mm), so the width of each gap was 0.09375 in (2.38125 mm). Case 6 in Table 3.3 was a reconstruction of Case 2, so it is reasonable to use the average of the two measured values, -0.678 pcm, as the axial expansion worth for that configuration.

The third ZPPR-15D L206 model corresponds to files 50 and 51 in Table 3.1 (Cases 3 and 4 in Table 3.3). For the third ZPPR-15D L206 model, there were two gaps. One gap was located at 6 in (152.4 mm) from the drawer front, and the second gap was located at 12 in (304.8 mm) from the drawer front. The total width of these two gaps was 0.75 in (19.05 mm), so the width of each gap was 0.375 in (9.525 mm). Cases 3 and 4 were repeated measurements of the same configuration in the same reactor run, so it is reasonable to use the average of the two measured values, -0.702 pcm, as the axial expansion worth for that configuration.

The fourth ZPPR-15D L206 model corresponds to file 52 in Table 3.1 (Case 5 in Table 3.3). For the fourth ZPPR-15D L206 model, there were two gaps. One gap was located at 6 in (152.4

mm) from the drawer front, and the second gap was located at 12 in (304.8 mm) from the drawer front. The total width of these two gaps was 0.5 in (12.70 mm), so the width of each gap was 0.25 in (6.35 mm).

For the four ZPPR-15D L206 MCNP axial expansion models, the experimental axial expansion drawer is universe 124 in matrix location 150-40 (row 50, column 40 in half 1).

All of the MCNP models were run for enough histories to verify that they run correctly without losing neutrons. However, no attempt was made to calculate the measured axial expansion worths because it would be very difficult to compute reactivity worths on the 0.4 pcm – 0.7 pcm range with MCNP. It is assumed that the MCNP models and associated files would be used to create deterministic models for which meaningful calculations can be performed.

4 Radial Bowing Measurements

The worth of radial fuel bowing was measured in ZPPR-15, but the results were never reported because the ZPPR staff regarded them as unsatisfactory for unspecified reasons. The worth of radial bowing was measured using two different techniques in ZPPR-17A. The published ZPPR-17A radial bowing measurements will be described here in place of the unpublished ZPPR-15 radial bowing measurement. The ZPPR plates are rigid and do not bend and thus the bowing measurements in ZPPR-17A were based on moving groups of plates to simulate bowing rather than actually inducing true bowing in the drawers or matrix tubes. It is important to note that ZPPR-17A, unlike ZPPR-15, simulated a large internal blanket and simulated oxide fuel rather than binary or ternary metal fuel.

The first bowing measurement in ZPPR-17A was based upon rearranging the plates in 96 core drawers near the outer boundary of the core to move fuel and structural material outward toward the core-radial blanket interface. The second ZPPR-17A bowing measurement used a new oscillator device to lift the core plates in one drawer a small distance toward the core-radial blanket interface.

4.1 Plate Rearrangement Measurement of Bowing Worth in ZPPR-17A

This experiment simulated bowing of core fuel assemblies. The simulation included outward radial motion of the duct and all of its contents, which resulted in a corresponding inward movement of the inter-subassembly sodium due to the change in the gap width between subassemblies.

Bowing was simulated by rearranging the columns of plates in 4 x 6 arrays of drawers on the left and right sides of each matrix half near the core-radial blanket interface. This rearrangement moved fuel and structural material outward and moved sodium inward to occupy the vacated space.

4.1.1 Plate Rearrangement Configurations

The plate rearrangement experiment was performed in ZPPR-17A loadings 71 – 74. Loading 71 was the initial subcritical reference configuration. The plate rearrangements were performed in loadings 72 and 73. Loading 74 was a reconstruction of loading 71. The reactivity difference between loading 71 and loading 74 is a measure of the reproducibility uncertainty for the experiment. In this context, reproducibility uncertainty results from several factors.

The surfaces of the two matrix halves are neither perfectly flat nor perfectly parallel, so there were small gaps at some points on the surfaces of the matrix interface, even at the nominal full closure position. It was not possible to reproduce this interface gap between matrix halves to an arbitrary degree of precision. Likewise, it was not possible to reproduce control rod positions or reactor temperature distribution to an arbitrary degree of precision. The drawer handling and motion required to change drawer contents and matrix loadings could introduce small lateral or axial shifts in plate positions within the affected drawers. The combination of the uncertainty in the interface gap, uncertainties in control rod positions, uncertainty in reactor temperature distribution and the effects of plate shifting combine to form a reproducibility uncertainty for the experiment.

Figures 4.1 through 4.6 show the matrix maps for half 1 and half 2, respectively, of ZPPR-17A loadings 72, 73 and 74. Loadings 71 and 74 have identical matrix maps, so separate maps were not created for loading 71. The plates were rearranged in 4 x 6 arrays of core drawers on the left and right sides of the core in both matrix halves to simulate bowing, so plates were rearranged in a total of 96 drawers.

ZPPR-17A was divided into an inner core zone and an outer core zone. In the outer core zone, the Pu-U-Mo fuel extended over the full height of the core, 20 in. (50.8 cm) in each matrix half. In the inner core zone, there was a 6 in. (15.24 cm) axial blanket followed by 14 in. (35.56 cm) of fuel plates in each matrix half.

The ZPPR-17A core contained single column fuel (SCF) drawers and double column fuel (DCF) drawers. Each SCF drawer contained a single fuel column in the center of the drawer, and each DCF drawer contained two fuel columns separated by a 0.5 in. (1.27 cm) column of sodium carbonate plates. Figure 4.7 shows the 17-0-107 drawer master, the most common SCF drawer master in the inner core zone. Note that a drawer master was a figure used by the ZPPR technicians as a guide when loading drawers (see Ref. 2). Figure 4.8 shows the 17-0-205 drawer master, the most common DCF drawer master in the inner core zone. The central axial blanket zone of depleted uranium plates (UD) is clearly visible on the left hand side in Figures 4.7 and 4.8. The Pu-U-Mo fuel plates are the “PUMN” columns in all of the drawer master figures.

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Figure 4.1 ZPPR-17A Loading 72 - Half 1

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Figure 4.3 ZPPR-17A Loading 73 – Half 1

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Figure 4.5 ZPPR-17A Loading 74 - Half 1

Figure 4.6 ZPPR-17A Loading 74 – Half 2.

Figure 4.7 Drawer Master 17-0-107 - Inner Core SCF Drawer

Figure 4.8 Drawer Master 17-0-205 - Inner Core DCF Drawer

In the reference SCF configuration in loadings 71 and 74, there was a 0.125 in (0.3175 cm) iron oxide column, a 0.5 in (1.27 cm) sodium column and a 0.25 in (0.635 cm) depleted U_3O_8 column on either side of the fuel column in the SCF drawer; the contents of the SCF drawer were symmetric about the central fuel column.

Each DCF drawer contained two fuel columns separated by a 0.5 in (1.27 cm) column of sodium carbonate plates. In the reference DCF configuration in loadings 71 and 74, there was a fuel column, a 0.25 in (0.635 cm) sodium column and a 0.25 in (0.635 cm) depleted U_3O_8 column on either side of the central 0.5 in (1.27 cm) sodium carbonate column; the contents of the DCF drawer were symmetric about the central sodium carbonate column.

Figure 4.9 shows drawer master 17-0-103, a reference SCF drawer in the outer core zone in loadings 71 and 74. Figure 4.10 shows drawer master 17-0-203, a reference DCF drawer in the outer core zone in loadings 71 and 74.

Figure 4.9 Drawer Master 17-0-103 - Outer Core SCF Reference Configuration

Figure 4.10 Drawer Master 17-0-203 - Outer Core DCF Reference Configuration

The standard SCF drawers only contained 0.5 in (1.27 cm) sodium plates, so it was necessary to change the drawer configurations in the plate shifting zones as a preliminary step prior to the plate shifting experiment. In loading 72, each 0.5 in (1.27 cm) sodium plate column in the core region of the SCF drawers in the plate shifting zone was replaced by two 0.25 in (0.635 cm) sodium plate columns, and the 0.25 in (0.635 cm) depleted U_3O_8 column and the sodium columns were rearranged to place the depleted U_3O_8 column between the two 0.25 in (0.635 cm) sodium columns. This change placed 0.25 in (0.635 cm) sodium columns along the left and right edges of the drawer.

The DCF drawers in the plate shifting zone also were rearranged in loading 72. The rearrangement for the DCF drawers consisted of interchanging the columns of 0.25 in (0.635 cm) sodium plates and 0.25 in (0.635 cm) depleted U_3O_8 in the core region to place 0.25 in (0.635 cm) sodium columns along the left and right edges of the drawer. These rearrangements for the SCF and DCF drawers in the plate shifting zone in loading 72 produced the initial configuration for the plate shifting experiment in loading 73.

Loading 73 was the simulated bowing configuration. In loading 73, the 0.25 in (0.635 cm) sodium column closest to the radial blanket in each drawer in the plate shifting zone was moved inward to the inner side of the drawer, i.e., the side closest to the core center, and all of the other plate columns in the drawer were shifted 0.25 in (0.635 cm) outward toward the radial blanket to simulate bowing. Figure 4.11 shows drawer master 17-0-144, a rearranged SCF drawer master in loading 73. Figure 4.12 shows drawer master 17-0-222, a rearranged DCF drawer master in loading 73.

Figure 4.11 Drawer Master 17-0-144 - SCF Rearranged Configuration - Loading 73

Figure 4.12 Drawer Master 17-0-222 - DCF Rearranged Configuration - Loading 73

In loading 74, the initial loading 71 configuration was reconstructed to measure the reproducibility uncertainty for the experiment.

4.1.2 Plate Rearrangement Reactivity Measurement Technique

Most reactivity worth measurements in ZPPR-17 were performed with the modified source multiplication (MSM) technique. The MSM technique had the advantage of being applicable over a much wider range of subcritical states (up to -50\$) than excess reactivity measurements based on measurements of reactor period or a calibrated B₄C shim rod position which had been used for excess reactivity measurements at ZPPR prior to adoption of the MSM technique. In addition, the MSM technique allowed measurements to be made with all operational rods and shim rods fully withdrawn, which was a significant advantage because the presence of one or more partially inserted rods affected the flux distribution and measured worth of these types of experiments.

It is necessary to establish a very slightly subcritical reference configuration ($\sim -10\phi$ to -30ϕ) as a first step in the MSM technique. The very slightly subcritical state is important because (a) the near critical state assures validity of the inverse kinetics technique used to determine the excess reactivity of the reference state, (b) the neutron flux is low enough that detectors do not require significant dead-time corrections and (c) the neutron flux is in a fundamental mode spatial distribution which ensures that fundamental mode-based reactivity is being measured. There was a spontaneous fission neutron source in the ZPPR-17A core due to the ²⁴⁰Pu in the Pu-U-Mo fuel plates ($\sim 11\%$ of the total plutonium in each plate was ²⁴⁰Pu). This source is distributed throughout the core fuel, so flux distributions in ZPPR-17A can be considered the fundamental mode, even for configurations that are far subcritical.

If the reactivity of the reference subcritical configuration is known, then the reactivity of the perturbed configuration can be determined from the following equation:

$$\rho_2 = \rho_1 \times (\epsilon_2/\epsilon_1) \times (C_1/C_2) \times (S_2/S_1) \times (\beta_1/\beta_2)$$

where ρ is subcritical reactivity in units of dollars (\$), ϵ is detector efficiency (ratio of detector count rate to total production rate by fission), C is the detector count rate, (S_1/S_2) is the change in the ratio of the adjoint-weighted inherent source to the adjoint-weighted fission source, and β is the effective delayed neutron fraction. Subscript 1 refers to the reference subcritical reactor state or configuration, and subscript 2 refers to the perturbed state, i.e., the plate rearrangement configuration in this particular case. S and ϵ were computed with XYZ nodal diffusion theory adjoints and XYZ nodal transport theory as part of the data reduction, i.e., processing the basic measured data, for ZPPR-17A.

The best choice for the subcritical reference is the configuration that is closest to critical because this configuration will be closest to the fundamental mode, which will minimize experimental uncertainty in the MSM technique. If all of the perturbed states are known to have negative worth, e.g., inserting simulated control rods to measure control rod worths, then the subcritical reference can be established as close to the critical reference as possible. On the other hand, if some of the perturbed states may have a positive worth, then the subcritical reference state should be subcritical enough to ensure that all of the perturbed configurations are subcritical.

After the subcritical reference configuration was established, the detector data were recorded and converted to count rates to form C_1 in the MSM equation. After the detector data were recorded, several operational rods in symmetric positions were scrambled. The initial reactivity, ρ_1 , of the subcritical reference configuration was determined from inverse kinetics analysis of the power history following this rod drop. The product $\rho_1 C_1$ calibrated the MSM technique. All control rods were then completely withdrawn, and no operational rods were inserted during any of the subsequent worth measurements except for the actual rod drop. This eliminates any distortion of the flux or follow-on worth measurements due to control rod effects.

When ZPPR-17A was built, the standard practice at ZPPR was to use 64 detectors for the MSM technique, so there would be 64 separate, but correlated, measurements. Each detector for MSM measurements in ZPPR-17A occupied a 1/2x2x6 in space at the front of the core, blanket or reflector drawer. The detector cables extended from the back of the drawer, so it was not possible to place a back drawer or a stainless steel axial reflector block behind a detector drawer.

4.1.3 *Plate Rearrangement Measured Reactivity and Uncertainty*

The measured worth for the plate rearrangement simulation of bowing was -6.02 cents. The reported uncertainty for the subcritical source multiplication analysis was 1.2%, and the reported configuration reproducibility uncertainty for the plate rearrangement experiment was 2.8%.

The total experimental uncertainty is obtained by adding the 1.2% and 2.8% uncertainties in quadrature to get the total experimental uncertainty of 3.1% or 0.19 cents. Thus the experimental worth of the plate rearrangement measurement is -6.02 ± 0.19 cents.

Any uncertainties related to the compositions or dimensions of the drawers and matrix tubes are fully correlated for loadings 71 – 74 because the drawers and matrix tubes were present for all loadings in this series. This is also true for all plate uncertainties except those related to replacement of 1.27 cm sodium plates by 0.635 cm sodium plates in the SCF drawers in the rearrangement zone. Consequently, all uncertainties related to dimensions or compositions of matrix tubes, drawers and plates cancel except for those related to the sodium plate replacement in the rearrangement zone. Analyses of many reference critical configurations of ZPR and ZPPR assemblies have shown that the reactivity effects of sodium plate uncertainties are small or negligible when all of the sodium plates in the entire assembly are included in the analysis. The effects of uncertainties for sodium plates in the SCF drawers in the 96-drawer rearrangement zone would be negligible compared to the other uncertainties considered here, particularly the uncertainty in β_{eff} , which is required to convert between the measurement reactivity units and the calculation reactivity units.

The natural unit of reactivity for measurement is cents, but the natural reactivity unit for calculations is pcm. Conversion between cents and pcm requires β_{eff} . The β_{eff} calculated by the ZPPR staff for ZPPR-17A was 0.003385, so the measured reactivity is -20.4 pcm. The experimental uncertainty is 3.1%, but β_{eff} is also uncertain. The standard assumed uncertainty in β_{eff} for ICSBEP/IRPhEP benchmarks is 5%, and the 5% uncertainty has been used for all ICSBEP/IRPhEP benchmarks of ZPR and ZPPR experiments [3,4]. If the 3.1% experimental uncertainty and 5% uncertainty in β_{eff} are added in quadrature, the resulting uncertainty for the measured worth expressed in pcm is 5.9% or 1.2 pcm. The worth of the plate rearrangement

measurement expressed in pcm is -20.4 ± 1.2 pcm. This can be calculated by direct Monte Carlo or by a deterministic model.

4.2 Bowing Oscillator Measurement of Bowing Worth in ZPPR-17A

The bowing measurement in ZPPR-15 used a pin tilting oscillator that raised one end of a group of pins in one matrix tube to simulate bowing. The bowing measurement in ZPPR-15 did not produce useful data according to the ZPPR staff.

A new bowing oscillator mechanism was developed for ZPPR-17A. This mechanism simulated bowing in a special drawer divided into two parts. The oscillator mechanism raised the core plates and the front part of the special drawer vertically within the matrix tube containing the bowing oscillator. The distance available for vertical motion was limited to the small space between the tops of the plates and the top of the matrix tube.

For clarification purposes, the convention for ZPPR is that the axial direction is along the axis of the matrix tube, which is normal to the surface in matrix map figures such as Figure 4.1 earlier. Consider a $\frac{1}{4} \times 2 \times 4$ inch Pu-U-Mo plate in ZPPR-17A. The 4 inch length of the plate is oriented along the Z-axis which is normal to the surface of Figure 4.1. The $\frac{1}{4}$ inch thickness of the plate is oriented along the X-axis which runs from left to right in Figure 4.1. The 2 inch height of the plate is oriented along the Y-axis which runs from bottom to top in Figure 4.1. The bowing oscillator raised the core plates and the front part of the special drawer a small distance along the Y-axis.

4.2.1 Bowing Oscillator Configuration in ZPPR-17A

The bowing oscillator measurement was made in loading 69 and was repeated in loading 75 to measure the reproducibility uncertainty. Figures 4.13 and 4.14 show the matrix maps for half 1 and half 2, respectively, of ZPPR-17A loading 75, reactor run 82 which was the reactor run in which the bowing oscillator measurement was performed.

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Figure 4.13 ZPPR-17A Loading 75 – Half 1

Figure 4.14 ZPPR-17A Loading 75 – Half 2.

The bowing oscillator was drawer master 17-0-841 which was located at row 26, column 49 of matrix half 1 (shorthand notation of 126-49). The bowing oscillator was located near the peak of the radial core worth gradient at a position corresponding to the outermost fuel assembly adjacent to the radial blanket.

There were actually four oscillator mechanisms in half 1 of ZPPR-17A loading 75. In addition to the bowing oscillator located in 126-49, an axial expansion oscillator was installed in 166-55, a plate column oscillator was installed in 148-31, and another plate column oscillator was installed in 148-68.

Figure 4.15 shows drawer master 17-0-841 for the bowing oscillator. The front 21 inches or 53.34 cm of the bowing oscillator was the section that moved vertically in the matrix tube. This section was made from a standard drawer that was cut to 53.34 cm length. The standard 0.031 inch-thick drawer bottom was replaced with a 0.010 inch-thick bottom. The reason for the

replacement is not listed, but the most likely explanation is that the reduced bottom thickness creates an additional 0.021 inches of space for the vertical motion of the bowing device. The clearance between the tops of the plates in the drawer and the top of the matrix tube was small, so reducing the thickness of the drawer bottom is an obvious way to gain more space for vertical motion of the oscillator. The front portion of the oscillator was raised 0.133 cm or 0.0524 in in the experiment, so the 0.021 in gained by reducing the drawer bottom thickness represents 40% of the total vertical motion of the oscillator.

Figure 4.15 Drawer Master 17-0-841 – Bowing Oscillator.

The nominal length of the core plates in the front part of the bowing oscillator was 19 inches or 48.26 cm. There were several gaps in the front section of the oscillator to accommodate structures related to the oscillator. The drawer master shows a 0.46 cm gap at the front of the plates (B in Fig. 4.15) that contained approximately 8 g of stainless steel and 1.7 g of plastic from the potentiometer. It seems likely that the 0.46 cm is a rounded value and that the actual value was 0.18 inches or 0.4572 cm, so the likely gap dimensions are 1.875 x 2 x 0.18 inch.

There was a 0.41 cm axial gap between the plate boundaries at 5 in, 10 in and 15 in (nominal positions) in the front part of the bowing oscillator (C in Fig. 4-15). Each of these gaps contained about 4 g of low carbon steel in the form of screws. It is assumed that the 0.41 cm is a rounded value and that the actual value is 0.16 inches or 0.4064 cm, so the likely gap dimensions are 1.875 x 2 x 0.16 in.

The first 2.54 cm (axially) of the 0.635 cm-wide depleted U_3O_8 column on the right side of the core region in the bowing oscillator (VOID in bottom left corner of Fig. 4.15) was absent because some of this space was occupied by the front potentiometer. The resulting gap (0.25 x 2 x 1 in.) was filled with approximately 1 g of crushed aluminum foil to prevent shifting of adjacent plates.

The gap at the back of the front section of the oscillator (D in Fig. 4.15) had a length of ~1.34 inches or 3.4036 cm (1.875 x 2 x 1.34 in.). This gap contained approximately 36 g of aluminum, 9 g of stainless steel, 40 g of low carbon steel and 5 g of plastic.

The depleted U_3O_8 column on the left side of the core region in the front part of the oscillator (upper side of Fig. 4.15) was 0.3175 cm thick. This allowed a 0.3175 cm gap on the left side of the core region that accommodated cables and a clamping bar to restrain the motion of the plates in the core region (A in Fig. 4.15). This gap extended over the entire length of the front section (0.125 x 2 x 21 in.). This gap contained approximately 477 g of stainless steel, 3 g of copper wire and 2 g of Teflon.

The figure for drawer master 17-0-841 and the available reports do not provide any additional information regarding the geometry or composition of the front portion of the bowing oscillator drawer or of the oscillator components. The compositions of the front plate, bottom and sides of the modified drawer were assumed to be identical to the compositions of the corresponding components of standard drawers since the modified drawer was created from a standard drawer.

The stainless steel components inside the modified drawer were assumed to be Type 304 stainless steel because this type of stainless steel was commonly used at ZPPR. The matrix tubes, drawers and stainless steel plates used at ZPPR were made of Type 304 stainless steel. The low carbon steel in the modified drawer was assumed to be generic carbon steel containing 0.5 wt.% carbon and 99.5 wt.% iron (see LA-UR-09-00380, *Criticality Calculations with MCNP: A Primer*). The type of plastic in the plastic components was not specified in any available records. It is unlikely that this plastic was Teflon because Teflon was listed specifically for the 0.125 x 2 x 21 in gap on the left side of the front section. In the absence of any other evidence, the plastic was assumed to be nylon because nylon was a very common plastic at that time.

The axial blanket in the stationary part of the oscillator was the standard axial blanket for ZPPR-17A except for the replacement of one column of standard 0.25 in (0.635 cm) wide depleted U_3O_8 plates by two columns of stainless steel plates on the left side of the drawer. The replacement stainless steel plates had a height of 1.0 in (2.54 cm) rather than the normal 2.0 in (5.08 cm); the reduced height left space for cables from the oscillator mechanism.

The normal steel axial reflector had a length of 5.0 in (12.7 cm) and height of 2.0 in (5.08 cm) in ZPPR-17A. The stainless steel reflector plates in drawer master 17-0-841 had a total length of 4.75 in (12.065 cm), and the stainless steel plates in the leftmost 0.25 in (0.635 cm) of the reflector were 1.0 in (2.54 cm) high to make space for the cables.

4.2.2 Bowing Oscillator Modeling in MCNP

Drawer master 17-0-841 (see Fig. 4.15) was used to model the bowing oscillator. The geometry of the MCNP model of the bowing oscillator matches the geometry shown in Fig. 4.15. The materials in the five gaps in the front part of the bowing oscillator that were described above

are not part of the standard ADEN library used to model ZPPR assemblies. The compositions for these materials were derived from the known dimensions and material masses in drawer master 17-0-841 with the assumptions that a) the stainless steel was Type 304 stainless steel, b) the low carbon steel contained 0.5 wt.% carbon and 99.5 wt.% iron, and c) the unspecified plastic was standard nylon. The resulting compositions were calculated and then added directly to the MCNP models. The MCNP material numbers for these five materials in the models are:

1. 601 – 1.875 x 2 x 0.18 inch gap at front containing 8 g of stainless steel and 1.7 g of plastic (B in Fig. 4.15),
2. 602 – 1.875 x 2 x 0.16 inch gap between axial plate boundaries (at 5 in, 10 in and 15 in nominal) containing 4 g of mild steel (C in Fig. 4.15),
3. 603 – 0.25 x 2 x 1 inch gap in depleted U_3O_8 column containing 1 g of crushed aluminum foil (VOID in lower left corner in Fig. 4.15),
4. 604 – 1.875 x 2 x 1.34 inch gap at the back of the front section of the oscillator containing 36 g of aluminum, 9 g of stainless steel, 40 g of mild steel and 5 g of plastic (D in Fig. 4.15),
5. 605 – 0.125 x 2 x 21 inch gap for cables and clamping bar containing 477 g of stainless steel, 3 g of copper wire and 2 g of Teflon (A in Fig. 4.15).

4.2.3 *Bowing Oscillator Reactivity Measurement Technique*

The modified source multiplication technique was not used for the bowing oscillator measurement. The operational control rods were used to establish a critical configuration with all four oscillators in their reference configuration where the drawer rests on the bottom of the matrix tube.

For the bowing oscillator measurement, the reference configuration consisted of the bowing oscillator in the lower position in the matrix tube. The measurement consisted of raising the front part of the oscillator mechanism containing the core plates 0.133 cm or 0.0524 inches vertically in the matrix tube and measuring the associated change in reactivity. The measured reactivity was derived from inverse kinetics processing of the measured data.

The bowing oscillator measurement was performed in loading 69 and repeated in loading 75 to determine the experimental reproducibility. Because only the oscillator position changed during the measurement and because the measurement was performed during a single reactor run, many of the standard components of reproducibility uncertainty, such as plate shifting during drawer loading and handling, interface gap uncertainty and control rod position uncertainty, are not relevant for the bowing oscillator measurement. The reproducibility uncertainty for the bowing oscillator measurement is determined by the reproducibility of plate positions in the oscillator mechanism and reproducibility of the vertical motion of the oscillator.

The oscillator mechanism was removed from the reactor, and the plate loading was loosened and clamped again between the two oscillator measurements to assess the reproducibility of plate positions. The movement indicator at the oscillator front failed before it could be calibrated for the measurement in loading 69, so the vertical motion during the measurement in loading 69 could not be determined precisely. The ZPPR staff concluded that the reproducibility uncertainty is not more than 5% but could not refine it any further.

Table 4.1 shows the motion for the bowing oscillator measurement in loading 75 as recorded at four measuring points on the oscillator drawer mechanism. The moving section of the oscillator mechanism cannot be assumed to act like a rigid body. The plates in the oscillator mechanism were rigid, but the drawer itself could flex slightly when it was lifted. Consequently, the recorded motions at the four measuring points are slightly different as shown in Table 4.1. The ZPPR staff concluded that it is legitimate to average the left and right measurements because there was no significant worth gradient across the width of the drawer. They also concluded that the axial worth gradient is sufficiently linear to justify averaging the front and back motions. The averaging yields an average motion of 0.132 cm where the ZPPR staff regarded 0.133 cm as the effective motion for the bowing oscillator measurement.

Table 4.1 Vertical Motion of the Bowing Oscillator in ZPPR-17A Loading 75

Axial Location	Motion (cm)		
	Left	Right	Average
Front (0.33 cm)	0.147	0.133	0.140
Back (51.03 cm)	0.122	0.127	0.125

4.2.4 Bowing Oscillator Measured Reactivity and Uncertainty

The measured worth for the bowing oscillator simulation of bowing was -0.01392 cents.

There were no changes in drawers, plates or other materials during the bowing oscillator measurement. Any uncertainties related to compositions or dimensions of matrix tubes, drawers, plates or other materials are fully correlated for the bowing oscillator measurement and, consequently, cancel. There were no changes in the positions of the matrix halves or of the operational rods, so uncertainties related to the interface gap or control rod positions are not relevant. The only motion during the measurement was the motion of the oscillator mechanism. The plates in the front part of the oscillator were clamped, so there is no uncertainty related to plates shifting in the drawer.

Inverse kinetics was used to process the data for the bowing oscillator measurement. The reported statistical uncertainty for the inverse kinetics data processing is 1.9%. In addition, there is an uncertainty in the calibration of the oscillator motion. The reported calibration uncertainty is approximately 2.9%. The combined uncertainty for the data processing and calibration uncertainties is 3.5%.

The repeated bowing oscillator measurements in loadings 69 and 75 were intended to quantify the reproducibility uncertainty for the experiment. The vertical motion in loading 69 could not be determined precisely because the movement indicator at the oscillator front failed before it could be calibrated for the measurement in loading 69. Consequently, the ZPPR staff concluded that the reproducibility uncertainty is not more than 5%, but the reproducibility uncertainty could not be refined further.

The reproducibility uncertainty range of 0 – 5% for the bowing oscillator measurement is appropriate but any value chosen in that range is arbitrary. Table 4.2 shows the range of experimental uncertainty based upon different values of the reproducibility uncertainty range.

Table 4.2 Experimental Uncertainty Range for the ZPPR-17A Bowing Oscillator Measurement

Reproducibility Uncertainty, %	Total Experimental Uncertainty, %
0	3.5
2.5	4.3
5	6.1

The measured bowing worth is -0.01392¢ so the experimental uncertainty range is 3.5% - 6.1% or $0.00049\text{¢} - 0.00085\text{¢}$.

The bowing worth was measured in reactivity units of cents, but the natural reactivity unit for calculations is pcm. Conversion between cents and pcm requires β_{eff} . The ZPPR staff calculated 0.003385 for β_{eff} , so the measured worth for the bowing oscillator is -0.047119 pcm . However, β_{eff} is uncertain, and the assumed uncertainty in β_{eff} is 5% (see Section 2.3). Table 4.3 shows the range of total uncertainty for the calculated bowing worth in units of pcm based upon the fact that the reproducibility was assessed as not greater than 5% by the ZPPR staff.

Table 4.3 Computational Uncertainty Range for the ZPPR-17A Bowing Oscillator Measurement

Reproducibility Uncertainty, %	Total Experimental Uncertainty, %	β_{eff} Uncertainty, %	Total Calculation Uncertainty, %
0	3.5	5	6.1
2.5	4.3	5	6.6
5	6.1	5	7.9

The worth of the ZPPR-17A bowing oscillator measurement expressed in pcm is -0.04712 pcm . The uncertainty range for the bowing oscillator measurement expressed in pcm is 6.1% – 7.9% or $0.00287\text{ pcm} - 0.00371\text{ pcm}$.

5 Summary

The Doppler sample worth measurements performed in ZPPR-15A, ZPPR-15B and ZPPR-15D were described and analyzed. Total uncertainties were derived for all ZPPR-15 Doppler sample worth measurements. As-built MCNP models were created for the Doppler sample worth configurations. The measured Doppler worths are in the 0.05 – 0.2 pcm range, so it seems impractical to perform Monte Carlo calculations for the Doppler sample worths. Previous deterministic calculations of the ZPPR-15 Doppler sample worth measurements produced results that ranged from good to excellent [5].

The axial expansion worth was measured in ZPPR-15A, ZPPR-15B and ZPPR-15D using special segmented drawers that could introduce small gaps between the segments. MCNP models were created for the axial expansion measurements in ZPPR-15B and ZPPR-15D. The ZPPR staff regarded the ZPPR-15A axial expansion experiment as unrealistic because a) the fuel content of the expansion drawer was too low and b) the experimental drawer allowed an unrealistic gap between the top of the core and the axial blanket, so no model was created for the ZPPR-15A experiment. Total uncertainties were derived for the axial expansion experiments in ZPPR-15B and ZPPR-15D. The measured axial expansion worths are in the 0.4 – 0.7 pcm range, so it seems impractical to compute these worths using Monte Carlo techniques.

It is assumed that the calculations of axial expansion worth will be done using deterministic methods.

The worth of radial bowing was measured in ZPPR-15 using a pin tilt oscillator, but the measured bowing worth was never reported because the ZPPR staff regarded the measured bowing worth as unsatisfactory for unspecified reasons. The worth of radial bowing was measured in ZPPR-17A, and the ZPPR-17A radial bowing experiments were presented here as a substitute for the missing ZPPR-15 radial bowing measurement. The worth of radial bowing was measured by a) rearranging the plate columns in 96 drawers near the outer core boundary and b) a new bowing oscillator. MCNP models were constructed for both sets of bowing measurements in ZPPR-17A, and the total uncertainties for the bowing measurements were determined.

The worth of the plate rearrangement measurement is -20.4 ± 1.2 pcm. This value can be computed by deterministic methods or by direct Monte Carlo. The measured worth of the plate oscillator experiment is -0.047 pcm, which cannot be done directly by Monte Carlo with any realistic amount of computational effort.

6 References

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