Sodium Void Worth and Control Rod Worth Measurements in ZPPR-15

Nuclear Science and Engineering Division

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ABSTRACT

Sodium void worth and control rod worth were measured in Phases A, B, C and D of the ZPPR-15 experimental program. Sodium voiding was simulated by replacing stainless steel cans containing sodium by empty stainless steel cans of the same sizes. The control rod worth measurements were measurements of simulated control rods (CRs) and simulated empty control rod positions (CRPs). A CRP consisted of a 2 x 2 array of drawers filled with sodium plates. A CR consisted of a 2 x 2 array of drawers containing alternating columns of boron carbide plates and sodium plates in the front 18 inches and just sodium plates in the back 18 inches.

The ZPPR staff published the measured sodium void worths and control rod worths and the statistical uncertainties in the measured values. In reality, the published uncertainty for each of these measurements is only one component of the total uncertainty. There are additional contributions from uncertainties related to measurement technique, plate compositions and reproducibility. However, the dominant uncertainty for the sodium void worth and control rod worth measurements is the uncertainty in β_{eff} which is required to convert from the natural measurement units, cents, to the calculation units, pcm or Δ/k_1k_2 .

A full uncertainty analysis was performed for the sodium void worth and control rod worth measurements. The significant uncertainties were quantified, and a total uncertainty was derived for each sodium void worth or control rod worth measurement.

The ZPPR-15 experimental records were used to create detailed as-built Monte Carlo models of the sodium void worth and control rod worth configurations. These models were used to compute the sodium void worths and control rod worths. $(C/E - 1)$ and the related uncertainty in $(C/E - 1)$ were derived for the measured worths.

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1 Introduction

The sodium void worth and control rod worth are important aspects of safety for a sodium-cooled fast reactor, so experimental measurements are useful to reduce the uncertainties associated with these parameters in reactor design calculations. The sodium void worth and the worth of simulated control rods were measured in the ZPPR-15 program. A description of the Zero Power Plutonium Reactor (ZPPR) facility can be found in Ref. 1.

2 Sodium Void Worth Measurements in ZPPR-15

The sodium void worth was measured in ZPPR-15A, ZPPR-15B, ZPPR-15C and ZPPR-15D. The void region consisted of the central 148 drawers in each matrix half, i.e., table, in ZPPR-15A. In phases B, C and D, the void region consisted of the central 52 drawers in each half. Void regions of 8 inches, 14 inches and 18 inches in each half were simulated. ZPPR-15A also simulated a 31-in void in each half (18 inch core plus 13 inch axial blanket in each half).

In addition, sodium voiding was simulated in a special high zirconium zone constructed during the transition from ZPPR-15A to ZPPR-15B and in twelve blanket drawers in each half near the core-blanket interface in ZPPR-15B.

ZPPR operated at low power, so all sodium void measurements were performed at room temperature. The sodium cans were sealed, and the sodium in the cans was solid. It was not possible to change the density of the sodium in the cans, so it was not possible to perform experiments with reduced sodium density. Consequently, sodium void experiments in ZPPR-15 consisted of complete sodium voiding in the void region. This was accomplished by replacing cans filled with sodium with empty cans in the void region.

After the establishment of a reference critical configuration for each phase of the ZPPR-15 program, several operational measurements were performed. These operational measurements focused on the reactor temperature coefficient, the ^{241}Pu decay coefficient, the interface gap coefficient and the worth of each operational control rod. These operational measurements were used for reactor operations and to support the experimental program, but they were not part of the experimental program measurements.

The ZPPR staff used the modified source multiplication technique described below to perform all sodium void worth and control rod worth measurements in ZPPR-15. After the reference critical configuration was established and the required operational measurements were performed for a phase of ZPPR-15 (A, B, C or D), a subcritical reference configuration was established for that phase. The subcritical reference configuration was slightly subcritical with all operational control rods in their fully withdrawn positions. In some cases, a separate, lower subcritical reference was established for a particular sequence of measurements such as a sequence of sodium void worth measurements or control rod worth measurements if there was a possibility that some of the experimental configurations could have positive reactivity worth.

Establishing the subcritical reference configuration required reducing the excess reactivity of the reference critical configuration. This reduction could be accomplished by replacing core

drawers with radial blanket drawers or radial reflector drawers (if there was no radial blanket) at the outer edge of the core.

The more common practice for adjusting excess reactivity was to change the contents of some core drawers. A core drawer containing one fuel column was referred to as a single fuel column (SCF) drawer, and a core drawer containing two fuel columns was referred to as a double fuel column (DCF) drawer. Replacing DCF drawers with SCF drawers at symmetric locations in the outer core reduced the excess reactivity. Replacing SCF drawers with DCF drawers at symmetric locations in the outer core increased the excess reactivity.

The ZPPR staff referred to converting DCF drawers to SCF drawers to reduce reactivity as a “despike.” Conversely, converting SCF drawers to DCF drawers to increase reactivity was referred to as a “spike.”

The experimenters replaced DCF drawers with SCF drawers to establish the reference subcritical configurations for the sodium void worth and control rod worth measurements in ZPPR-15.

2.1 Sodium Void Worth Experimental Technique

A sodium-voided zone was simulated in ZPPR by replacing sodium-filled stainless steel cans, i.e., sodium plates, with empty stainless steel cans (void cans) in the drawers within a selected region of the core. The worth per kilogram for stainless steel is much larger than the worth per kilogram for sodium, so any mismatch between the mass of stainless steel removed in the sodium cans and the mass of steel added in the void cans could introduce a significant experimental uncertainty.

To minimize this experimental uncertainty, the experimenters attempted to match the amount of steel in the sodium plate to be removed with the amount of steel in the void can which replaced that sodium plate. In practice, matching the stainless steel in the sodium plates to be removed with the stainless steel in the void cans to be inserted meant that each sodium plate was replaced by a void can with the same dimensions. For example, a 1/2x2x8 inch sodium plate was replaced by a 1/2x2x8 inch void can. This is clear from the drawer master figures or templates used by the ZPPR technicians as guides to load plates into drawers.

Note that only the sodium plates were replaced in core drawers in the voided zone. No other plates in the affected drawers were changed in the measurement in order to minimize experimental uncertainty.

Changing the core loading required shutting down the reactor, separating the matrix halves, making the desired changes in the core loading, bringing the matrix halves together again and moving the operational control rods to establish the desired configuration. There was some ²⁴¹Pu decay during the elapsed time, and the average reactor temperature could change slightly as a result of the time required to establish the new configuration. Also, there could be a small difference in the interface gap between the reference configuration and the modified configuration. Measuring the sodium void worth for multiple configurations could span several days and require several modified configurations. In order to minimize experimental

uncertainty and facilitate analysis of the experiments, the experimenters adjusted the measured values for the sodium void worth to a common decay date, temperature and interface gap using measured ^{241}Pu decay, temperature and interface gap coefficients. These coefficients were measured during the operational measurements performed after the reference critical configuration was established. The common decay date, temperature and interface gap for the sodium void worth measurements were normally the values determined for the reference subcritical configuration.

2.2 Sodium Void Worth Reactivity Measurement

Sodium void worth measurements in ZPPR-15 were performed with the modified source multiplication (MSM) technique. The MSM technique was the standard technique used at ZPPR for measuring sodium void worth and control rod worth when the ZPPR-15 experiments were performed in 1985 – 1986.

The MSM technique provided several advantages over previous reactivity measurement techniques used at ZPPR. The MSM technique was applicable over a wider range of subcritical states (up to -50\$) than reactivity measurements based upon measurements of reactor period or calibrated B_4C shim rod position which had been used for excess reactivity measurements at ZPPR prior to adoption of the MSM technique

The MSM technique allowed measurements to be made with all operational rods and shim rods fully withdrawn which is a significant advantage because the presence of one or more partially inserted control rods affected the flux distribution and the measured worths.

Measurements based on reactor period or calibrated control rods sometimes required the addition or removal of core drawers at the core-radial blanket interface to adjust reactivity. No core changes were required for the MSM technique, so there were no shifts in the flux distribution with the MSM technique and no delays to establish the required core configuration.

The first step in the MSM technique is the establishment of a very slightly subcritical reference configuration (typically -10¢ to -30¢) with all operational control rods fully withdrawn. 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 reactivity is being determined.

There was a large spontaneous fission source in ZPPR-15 due to the ^{240}Pu in the Pu-U-Mo fuel plates (~11% of the total plutonium). The fuel for ZPPR-15A and ZPPR-15B consisted entirely of Pu-U-Mo plates. The fuel for ZPPR-15C consisted of 50% Pu-U-Mo plates and 50% HEU plates uniformly distributed in the core. For ZPPR-15D, the core contained predominantly HEU plates with ~10% Pu-U-Mo plates in the outer core to provide the distributed neutron source for the MSM technique. The neutron source was well distributed in the core fuel in ZPPR-15, so the flux distribution was predominantly fundamental mode, even for configurations that were far subcritical.

If the reactivity of the reference subcritical configuration is known, then the reactivity of the perturbed (sodium-voided) 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 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 sodium-voided configuration in this particular case. S and ϵ were computed with XYZ nodal diffusion theory adjoints and XYZ nodal transport theory by the ZPPR staff as part of the data reduction for ZPPR-15. Data reduction refers to processing the raw measurements to produce the final published experimental data.

The best choice for the subcritical reference is the configuration that is closest to critical because this configuration will be closest to the fundamental spatial mode which will minimize experimental uncertainty in the MSM technique. If all perturbed states are known to have negative worth (as is the case when inserting simulated control rods), then the subcritical reference can be established as close to the reference critical configuration as possible. On the other hand, if some perturbed states may have positive worth (as is the case for sodium voiding), then the subcritical reference state may require a greater degree of subcriticality to ensure that all 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 control rods in symmetric positions were scrammed. 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.

The subcritical reference configuration was modified to create the experimental configuration of interest. For the sodium void worth measurements, the modification consisted of replacing sodium plates with empty cans in the designated void region. All operational control rods were fully withdrawn in the subcritical reference configuration and in the experimental configuration of interest, which eliminated any distortion of the flux or worth measurements due to control rod effects.

After the experimental configuration of interest was established, several operational rods in symmetric positions were scrammed to provide the data to determine C_2 and ρ_2 for the perturbed configuration.

When ZPPR-15 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. These 64 detectors were widely distributed in the core, radial blanket and radial reflector in both halves of the matrix. Each detector for MSM measurements in ZPPR-15 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 reflector block behind a detector drawer.

2.3 Sodium Void Worth Uncertainties

The ZPPR staff published the measured ZPPR-15 sodium void worths and associated uncertainties. The published uncertainties include a) the statistical uncertainty in the actual measurement, b) the correlated uncertainty related to the reactivity measurement for the reference configuration, reactivity scale calibration, and source ratio uncertainty and c) small uncertainties related to adjustment to a common measurement configuration (common ^{241}Pu decay date, temperature and interface gap). Additional uncertainties contribute to the total uncertainty for the sodium void worth measurement.

2.3.1 Experimental Technique for Sodium Void Worth Measurements

Sodium void worth measurements at ZPPR were straightforward in concept, but the uncertainties associated with those measurements depend strongly on the details of the experimental procedures. The sodium void worth was obtained from the measured sub-critical multiplications in the reference configuration and the voided configuration. Because some of the sodium void worths were small, much care had to be taken when building the reference and void configurations to avoid introducing unintended reactivity effects of comparable size.

One important part of this procedure was to minimize drawer handling and changes within drawers. Only the sodium plates in the affected drawers were changed because the plate-to-plate mass variations among plates of a given type, especially fuel, would introduce an additional reactivity change. Consequently, each normal drawer in the voiding zone was removed from the matrix, modified by replacing sodium-filled cans with empty void cans and reloaded into the matrix at its original location.

Handling only the drawers to be modified also minimized unintentional changes in the positions of plates in the drawers, particularly axial changes near the drawer fronts. Unintentional changes in plate positions introduce additional experimental uncertainty which could be significant in some cases. In fact, plate shifting was a dominant experimental uncertainty for some of the sodium void worth measurements performed in ZPPR-12. Minimizing drawer handling minimized this source of uncertainty.

Another significant issue was the mismatch between the mass of steel in the sodium cans removed from the assembly and the mass of steel in the void cans inserted into the assembly. The steel mass difference between individual cans is small, but the mismatch can be significant in terms of reactivity because a) the total steel mass difference between all of the sodium plates removed and all of the void cans inserted in a large void zone is not necessarily small and b) the worth per kilogram for sodium is much lower than the worth per kilogram for stainless steel.

ZPPR had a large inventory of stainless steel “void cans” that were identical in design to the sodium-filled cans except that the void cans were empty. Each can had a unique serial number, and the steel mass of each can was recorded in a database at the time of manufacture. The experimenters could have used this database to select a set of void cans whose steel mass most

closely matched that of the sodium cans they were replacing. The inventory was large enough that this could be done to a level where the steel mass difference was insignificant.

Although the experimenters could have used the inventory database to select the specific void can that most closely matched each sodium can to be replaced, no records have been found to confirm this practice was followed in the ZPPR-15 experiments. There are two additional arguments against matching sodium plates and void cans at the level of individual plates. First, an experimenter confirmed that this was not the practice at Argonne's ZPR-6 and ZPR-9 critical experiment facilities [5]. Second, matching sodium plates and void cans at the individual plate level would significantly increase the time, effort and cost required to perform each measurement.

On the other hand, the ZPPR-15 drawer master descriptions (drawings or templates used by the technicians to load drawers) clearly show that sodium cans and replacement void cans were matched at least at the level of external dimensions. For example, a 1/2x2x8 inch sodium can was replaced by a 1/2x2x8 inch void can. This applies to all sodium cans replaced in the sodium void worth experiments.

The masses of steel in the sodium cans and in the void cans were known, so the total steel mass difference could be computed. The worth of the difference in steel masses could be determined from the steel mass difference and the measured worth per unit mass for stainless steel which was determined during the small sample worth measurements. It was standard practice at ZPR-6, ZPR-9 and ZPPR to correct the measured sodium void worth for the difference between the total stainless steel mass in the cans of the sodium plates removed and the total stainless steel mass in the void cans inserted in a sodium void worth experiment.

Variation in how deeply drawers were inserted into the matrix tubes introduces an additional uncertainty in the axial positions of the plates. The experimenters would have made sure that the fronts of all drawers in the voiding zones were exactly flush with the front edge of the matrix. Tabs on the drawer fronts mated with notches in the sides of the matrix tubes to ensure consistent positioning. Drawers were inserted into matrix tubes slowly to minimize plate shifting. The procedure for loading drawers into matrix tubes minimized unintentional changes in the axial position of the core material within each matrix half. Springs inserted in the backs of the drawers to push the plates forward also minimized unintentional changes in plate positions in the drawers.

The preceding paragraphs describe the general procedure for minimizing experimental uncertainties, but there were some residual uncertainties related to the experimental technique. The most obvious uncertainty in this category is the statistical uncertainty in the measurements. There were statistical uncertainties in the detector count rates for each measurement and in the process to convert the measured count rates to a reactivity worth.

In addition to these statistical uncertainties, there were small uncertainties related to the adjustment of measured reactivities to a common date, temperature and interface gap, i.e., the corrections for ^{241}Pu decay and for any differences in the temperature or the interface gap

between the reference configuration and the sodium void configuration. The reported statistical uncertainty from the experimenters includes all of these effects.

There is also a correlated uncertainty from the establishment of the reference subcritical configuration including the reactivity scale calibration and source ratio.

Another experimental uncertainty is reproducibility uncertainty. In this context, reproducibility uncertainty refers to the small difference in measured results when the experimenter attempts to reconstruct a previous experimental configuration as faithfully as possible. For example, a subcritical reference configuration was constructed for the sodium void worth measurements. The various void configurations were measured, and then the subcritical reference configuration was rebuilt. The small difference in reactivity between the original subcritical reference configuration and the reconstructed subcritical reference configuration is the reproducibility uncertainty. The reproducibility uncertainty arises because it is not possible to recreate the original configuration exactly (plate positions, reactor temperature distribution, interface gap, control rod positions, etc.).

In the ideal case with no cost or schedule constraints, the experimenters would build the reference configuration, measure the excess reactivity or subcriticality, and then disassemble the reference configuration. By repeating this process a number of times, e.g., 10 – 20 times, it would be possible to perform a statistical analysis on the measured values. The mean measured value would be the measured excess reactivity or subcriticality, and the standard deviation would be a measure of the reproducibility. For consistency, it would also be necessary to repeat this process for each void configuration or other experimental measurement to determine a mean measured experimental worth and associated standard deviation.

Cost and schedule constraints precluded repeated measurements. An experimental configuration such as a sodium void configuration was measured once. The original subcritical reference configuration was rebuilt once at the end of a series of experimental measurements. The difference between the reactivity of the original subcritical reference configuration and the rebuilt subcritical reference configuration was defined to be the reproducibility uncertainty. This reproducibility uncertainty was assumed to apply to all of the experimental worth measurements in the series.

The principal component of the reproducibility uncertainty for ZPPR-15 was generally plate shifting. Sometimes there were slight changes in plate positions despite the procedures for plate loading and drawer handling.

2.3.2 Reactivity Adjustments for Sodium Void Worth Measurements

The standard practice at ZPPR when the ZPPR-15 sodium void worth experiments were performed was to adjust each configuration to the ^{241}Pu decay date, core average temperature, and matrix interface gap width of the subcritical reference configuration.

In general, the uncertainty in the measured ^{241}Pu decay coefficient at ZPPR was approximately 10%. This uncertainty is correlated for all loadings in the same assembly/phase (ZPPR-15A,

ZPPR-15B, ZPPR-15C or ZPPR-15D) and is eliminated in reactivity differences such as the step worths or the cumulative worths for sodium voiding.

There is a 0.5°C temperature uncertainty from calibration of the in-core thermocouples and an estimated 1°C temperature uncertainty in the average core temperature. Table 2.1 shows the temperature coefficients for ZPPR-15 Phases A – D. Ref. 1 discusses the sources for the temperature uncertainty and the temperature coefficients.

Table 2-1 ZPPR-15 Assembly Temperature Coefficients.

Assembly	ρ , ¢/K	σ , ¢/K
ZPPR-15A	-1.05	0.1
ZPPR-15B	-1.05	0.1
ZPPR-15C	-0.575	0.11
ZPPR-15D	-0.39	0.1

Table 2.2 shows the interface gap coefficients and the published values of β_{eff} for the four phases of ZPPR-15 [1]. The interface gap coefficient was measured for ZPPR-15A. The published gap coefficient is listed for ZPPR-15C. There was a footnote stating that the published interface gap coefficient for ZPPR-15C was the interface gap coefficient for ZPPR-15B scaled by the relative values of β_{eff} , so the value listed for ZPPR-15B in Table 2.2 is the published ZPPR-15C value scaled by the relative values of β_{eff} for ZPPR-15B and ZPPR-15C. No published value was found for ZPPR-15D, so the gap coefficient listed in Table 2.2 for ZPPR-15D is the ZPPR-15B value scaled by the relative values of β_{eff} for ZPPR-15B and ZPPR-15D.

Table 2.2 shows the interface gap uncertainties for the sodium void worth measurements in all four phases of ZPPR-15. The maximum gap difference in Table 2.2 is the largest difference in the average gap closure readings determined from the ZPPR-15 logbook [2] for the sodium void worth measurement loadings in each phase of ZPPR-15. The interface gap uncertainties shown in Table 2.2 make a negligible contribution to the total uncertainties for the sodium void worth measurements, so any assumptions made here concerning the values of the interface gap are unimportant.

Table 2-2 Interface Gap Uncertainties for ZPPR-15.

Assembly	β_{eff}	Gap Coefficient, ¢/mil	Gap Coefficient σ , ¢/mil	Maximum Gap Difference, mils	σ , ¢	σ , pcm
ZPPR-15A	0.003357	-0.13	0.02	1.00	0.020	0.067
ZPPR-15B	0.003361	-0.132	0.02	1.20	0.024	0.081
ZPPR-15C	0.005207	-0.0852	0.013	1.52	0.020	0.103
ZPPR-15D	0.006564	-0.0676	0.01	1.20	0.012	0.079

The experimenters included the uncertainties in the reactivity adjustments in the reported statistical uncertainties for the measurements. All of the uncertainties related to the reactivity adjustment are small compared to the uncertainty related to reactivity conversion discussed below.

2.3.3 *Effects of Material Composition Uncertainties for Measurements of Sodium Void Worth*

For the sodium void worth measurements, the subcritical reference configuration and the voided configurations were identical except for the replacement of sodium plates by void cans in the successive void steps. Consequently, the uncertainty contributions of any plates or steel components to the uncertainties in the measured values would be highly correlated between the subcritical reference configuration and the corresponding void configurations for practical purposes except for the sodium plates removed and the void cans inserted. The uncertainty contributions of plates, drawers and matrix tubes will change slightly between the subcritical reference configuration and the void configuration due to the changes in neutron spectrum and leakage, but these changes are negligible compared to the uncertainties discussed below.

For the ZPPR-15B reference critical configuration, the computed total uncertainty related to sodium mass and sodium impurities was 1.65 pcm. There were approximately 896 core drawers per half including the normal core drawers, detectors drawers in the core and the PSR control rod drawers. The void zone consisted of 52 drawers per half, the maximum void region length was 45.72 cm, and the total length of the sodium columns in the core drawers was 78.74 cm. To a first order approximation, the maximum worth of the sodium mass and composition uncertainties for the ZPPR-15B sodium void worth measurements is $1.65 \times (52/896) \times (45.72/78.74) = 0.055$ pcm which is negligible.

For the ZPPR-15D reference critical configuration, the computed total uncertainty related to the sodium mass and sodium impurities was 1.53 pcm. The computed uncertainty for the sodium mass and sodium impurities in ZPPR-15C was significantly smaller than the 1.53 pcm value for ZPPR-15D, so the total uncertainty related to sodium mass and sodium impurities for ZPPR-15C is assumed to be 1.53 pcm to provide a conservative uncertainty estimate. The core sizes are essentially identical for all four phases of ZPPR-15, and the sizes of the voided regions were identical in ZPPR-15B, -15C and -15D. Consequently, to a first approximation, the maximum worth of the sodium mass and composition uncertainties for the sodium void worth measurements in ZPPR-15C and ZPPR-15D is $1.53 \times (52/896) \times (45.72/78.74) = 0.052$ pcm which is negligible.

For the ZPPR-15A reference critical configuration, the computed total uncertainty related to the sodium mass and sodium impurities was 1.55 pcm. The void zone in ZPPR-15A consisted of 148 drawers, and the maximum void length was 78.74 cm. To a first order approximation, the worth of the sodium mass and composition uncertainties for the sodium void worth measurements in ZPPR-15A is $1.55 \times (148/896) \times (78.74/78.74) = 0.256$ pcm which is negligible.

The contribution of the mass and composition uncertainties for the steel in the cans is much smaller than the sodium contribution because the steel mass change between the total stainless steel mass of the sodium cans removed and the total stainless steel mass of the void cans inserted is only ~4% of the total stainless steel mass of the sodium cans removed in the sodium void worth measurements.

These calculations could be refined, but the contributions of the sodium uncertainty and steel mass uncertainty would still be negligible, so the matter is not worth pursuing.

The discussion above covers the uncertainties in the measurement of the sodium void worth. However, there is an indirect (and largely second-order) source of uncertainties related to the effect of uncertainties in plate compositions on the calculated values. The effects of uncertainties in plate compositions on k_{eff} were computed for loading 91, the reference case, and loading 94 for all of the uncertainties in plate compositions in ZPPR-15B. The difference in the total composition uncertainty between loading 91 and loading 94 was 0.6 pcm. This is the contribution of the plate composition uncertainties to the total uncertainty for the sodium void worth measurement in loading 94. The corresponding contributions for loadings 92 and 93 would be slightly smaller because the extent of the voided region was smaller in loadings 92 and 93.

ZPPR-15A is almost identical to ZPPR-15B except for the replacement of some stainless steel plates in the inner core zone of ZPPR-15A by zirconium plates in ZPPR-15B. Thus, the uncertainty contribution of the plate composition for ZPPR-15A should be similar to the 0.6 pcm value calculated for ZPPR-15B. The main differences for ZPPR-15C and ZPPR-15D with respect to ZPPR-15B is the replacement of Pu-U-Mo fuel plates by HEU plates in ZPPR-15C and ZPPR-15D. The uncertainty contribution of the Pu-U-Mo plates and HEU plates in ZPPR-15C is approximately 10% lower than the uncertainty contribution of the Pu-U-Mo plates in ZPPR-15B, so the plate composition uncertainty for ZPPR-15C would be slightly smaller than 0.6 pcm. The uncertainty contribution for the Pu-U-Mo and HEU plates in ZPPR-15D is approximately 26% larger than the uncertainty contribution for the Pu-U-Mo plates in ZPPR-15B, so the plate composition uncertainty for ZPPR-15D would be slightly larger than 0.6 pcm (~ 0.7 pcm). The 0.6 pcm value was assumed to apply to all four phases because the difference in the plate composition uncertainty between the four phases is not large and because the plate composition uncertainty is not a dominant uncertainty for the sodium void worth measurements in ZPPR-15.

2.3.4 Reactivity Conversion for Sodium Void Worth Measurements

The sodium void worth in ZPPR-15 was measured in units of cents. Calculated worths and the associated uncertainties are typically expressed in units of $\Delta k/k_{1k2}$ or pcm. Conversion from the measurement units, cents, to pcm or from pcm to cents requires β_{eff} which was typically calculated by the experimenters. The calculation or measurement of β_{eff} is uncertain, and its estimated uncertainty is 5%. This is the uncertainty in β_{eff} assumed in all ICSBEP and IRPhEP benchmarks of ZPR and ZPPR assemblies and is a value that is frequently used in other ICSBEP/IRPhEP benchmarks [3,4]. The 5% uncertainty in β_{eff} contributes an additional uncertainty to the final sodium void worth. In general, the 5% uncertainty in β_{eff} is the dominant uncertainty for the sodium void worth measurements.

3 Measured Sodium Void Worths and Total Uncertainties

Sodium void worth was measured in all four phases of the ZPPR-15 program. The most extensive sodium void worth measurements were performed in ZPPR-15A and ZPPR-15B.

3.1 Sodium Void Worths and Total Uncertainties for ZPPR-15A

The initial subcritical reference for the ZPPR-15A sodium void worth measurements was loading 16 (L016). An 8-in (20.32 cm) void zone was established in 148 drawers per half in L017. Because the measured void worth was large and positive in L017, eight double fuel column (DCF) drawers were converted to single fuel column (SCF) drawers in symmetric locations to create a second subcritical reference in L018. L018 had an 8-in (20.32 cm) void in 148 drawers per half because the only change from L017 to L018 was conversion of eight DCF drawers in L017 to eight SCF drawers in L018.

In loadings 19, 20 and 21, the void zones were 14 in (35.56 cm), 18 in (45.72 cm) and 31 in (78.74 cm), respectively, in 148 drawers per half. In L022, all void cans in the void zone in half 2 were replaced by sodium cans. In L023, all void cans in the void zone in half 1 were replaced by sodium cans to return to a subcritical flooded reference configuration.

Figures 3.1 – 3.16 show the core loading maps or matrix maps for ZPPR-15A loadings 16 – 23. The outer ring of light blue cells is the radial reflector, and the ring of dark blue cells is the radial blanket. Green cells are normal DCF core drawers, and white cells are normal SCF core drawers. Brown cells are PSR control rod drawers, and orange cells are detector drawers. Yellow cells are sodium-voided drawers in the void region. Empty cells outside of the radial reflector are empty matrix tubes.

The numbers in the top row are the column numbers in the matrix, and the numbers in the first (leftmost) column are the row numbers. The number in each core, radial blanket or radial reflector cell is an abbreviation for the drawer master in that cell or matrix tube (see Ref. 1). For example, 201 is the abbreviation for 15-0-201, the full identifier for that drawer master.

Detector drawers and drawers opposite detector drawers were not voided in ZPPR-15A. Consequently, there are some normal, non-voided SCF core drawers within the sodium-voided zone in ZPPR-15A.

Table 3.1 shows the measured reactivities for the individual loadings as reported by the ZPPR staff. In addition to statistical and correlated uncertainties for the measurements, there is a reproducibility uncertainty for the measurements. The reproducibility uncertainty for the sodium void worth measurements consists of several components. First, the two halves of the matrix were neither perfectly flat nor perfectly parallel due to normal manufacturing and machining tolerances. In addition, the weight of the drawers in the matrix tubes could cause a small deflection in the support plates below the matrix tubes. Consequently, there was a small, non-uniform gap between the matrix halves even at the nominal full closure position when the two halves were touching at some points. This interface gap was not perfectly reproducible when the matrix halves were driven apart and then brought together again.

Second, the temperature distribution in the matrix tubes was not perfectly reproducible during repeated or successive measurements.

Third, the PSR (control rod) positions were not perfectly reproducible.

The fourth and generally largest component of the reproducibility uncertainty for sodium void worth measurements was the unintentional shifting of plates in the drawers during drawer loading, unloading and handling operations. Despite the drawer handling precautions discussed above, small plate shifts did occur.

Figure 3-1 ZPPR-15A Loading 16 – Half 1

Sodium Void Worth and Control Rod Worth Measurements in ZPPR-15
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Figure 3-2 ZPPR-15A Loading 16 – Half 2

Sodium Void Worth and Control Rod Worth Measurements in ZPPR-15
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Figure 3-3 ZPPR-15A Loading 17 – Half 1

Sodium Void Worth and Control Rod Worth Measurements in ZPPR-15

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Figure 3-4 ZPPR-15A Loading 17 - Half 2

Sodium Void Worth and Control Rod Worth Measurements in ZPPR-15

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Figure 3-5 ZPPR-15A Loading 18 - Half 1

Sodium Void Worth and Control Rod Worth Measurements in ZPPR-15
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Figure 3-6 ZPPR-15A Loading 18 – Half 2

Sodium Void Worth and Control Rod Worth Measurements in ZPPR-15
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Figure 3-7 ZPPR-15A Loading 19 – Half 1

Sodium Void Worth and Control Rod Worth Measurements in ZPPR-15

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Figure 3-8 ZPPR-15A Loading 19 – Half 2

Sodium Void Worth and Control Rod Worth Measurements in ZPPR-15
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Figure 3-9 ZPPR-15A Loading 20 – Half 1

Sodium Void Worth and Control Rod Worth Measurements in ZPPR-15

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Figure 3-10 ZPPR-15A Loading 20 – Half 2

Sodium Void Worth and Control Rod Worth Measurements in ZPPR-15
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Figure 3-11 ZPPR-15A Loading 21 – Half 1

Sodium Void Worth and Control Rod Worth Measurements in ZPPR-15

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Figure 3-12 ZPPR-15A Loading 21 – Half 2

Sodium Void Worth and Control Rod Worth Measurements in ZPPR-15
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Figure 3-13 ZPPR-15A Loading 22 – Half 1

Sodium Void Worth and Control Rod Worth Measurements in ZPPR-15
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Figure 3-14 ZPPR-15A Loading 22 – Half 2

Sodium Void Worth and Control Rod Worth Measurements in ZPPR-15
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Figure 3-15 ZPPR-15A Loading 23 – Half 1

Sodium Void Worth and Control Rod Worth Measurements in ZPPR-15
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Figure 3-16 ZPPR-15A Loading 23 - Half 2

No published reproducibility uncertainty has been found for ZPPR-15A. However, ZPPR-15A and ZPPR-15B are identical except for replacement of stainless steel plates in the central part of ZPPR-15A by zirconium plates in the central part of ZPPR-15B, so the 0.13¢ reproducibility uncertainty for ZPPR-15B is assumed to apply to ZPPR-15A. The reproducibility uncertainty does not make a significant contribution to the total uncertainty for ZPPR-15A sodium void measurements, so attempting to refine this value is not worthwhile.

Table 3-1 Measured Sodium Void Worths in ZPPR-15A.

Loading	Configuration	ρ , ϕ (1)	σ_{stat} , ϕ (2)	σ_{corr} , ϕ (3)	σ_{repro} , ϕ	σ_{total} , ϕ
16	Initial subcritical reference	-77.82	0.18	0.64	0.13	0.68
17	8-in void					
18	Second subcritical reference with 8-in void	-30.08	0.10	0.25	0.13	0.30
19	14-in void	-33.40				0.27
20	18-in void	-10.47	0.10	0.085	0.13	0.18
21	31-in void	-33.00	0.07	0.27	0.13	0.31
22	Reflood half 2	-87.52	0.14	0.71	0.13	0.74
23	Reflood	-140.52	0.21	1.15	0.13	1.18

- 1) The reactivity changes in column 3 were derived relative to L019, the 14-in void configuration with the second subcritical reference loading. The reactivity of L019 was determined by inverse kinetics analysis to be $-33.40\phi \pm 0.27\phi$.
- 2) The statistical uncertainty includes count rate plus the corrections for temperature, interface gap and ^{241}Pu decay.
- 3) Correlated uncertainty is due to the reactivity scale calibration and the source ratio uncertainty.

Table 3.2 shows the reported reactivity changes for the individual void steps.

Table 3-2 Experimental Reactivity Changes for Sodium Void Steps in ZPPR-15A

Loading (1)	Step (1)	Mass of Na, kg (2)	ρ_{meas} , ϕ (3)	ρ_{steel} , ϕ (4)	$\rho_{\text{corrected}}$, ϕ (5)	σ_{stat} , ϕ	σ_{corr} , ϕ	σ_{repro} , ϕ	σ_{total} , ϕ	ρ_{spec} , $\phi/\text{kg Na}$ (6)
L016 - L017	8 in (7)	57.086	110.29	0.86	111.20	0.36	0.91	0.13	0.987	1.948
L018 - L019	8 - 14 in	41.069	30.08	1.33	31.41	0.45	0.25	0.13	0.531	0.7648
L019 - L020	14 - 18 in	27.955	-10.47	0.19	-10.28	0.12	0.09	0.13	0.198	-0.3677
L020 - L021	18 - 31 in	100.971	-22.53	-0.05	-22.53	0.12	0.19	0.13	0.260	-0.2236
L021 - L022	Void H1	113.541	-54.52	1.165	-53.36	0.41	0.44	0.13	0.615	0.4905
L021 - L023	Reflood H1, H2	227.081	-53.00	2.33	-50.67	0.81	0.88	0.13	1.203	0.4837

- 1) Column 1 specifies the core loadings for the reactivity change; column 2 is the configuration change for that step.
- 2) Column 3 is the mass of sodium voided in that step.
- 3) Column 4 is the measured reactivity.
- 4) Column 5 is the reactivity correction for the difference in steel masses between the sodium cans and void cans in the void zone.
- 5) Column 6 is the measured reactivity corrected for the steel mismatch. The -22.53ϕ values in columns 4 and 6 for the L020 – L021 difference are the values listed in the original source document.
- 6) The last column is the specific reactivity, i.e., reactivity per kg of sodium voided.

- 7) The first step (8-in void) is relative to the first subcritical reference, L016, so the correct pairing is L016 – L017. The remaining steps are relative to the second subcritical reference, L018.

The reported reactivities for individual loadings in Table 3.1 can be converted to values of k_{eff} using the reported β_{eff} value for ZPPR-15A, 0.003357. Table 3.3 shows the values of k_{eff} determined from the reactivities for the individual loadings in Table 3.1. The adjusted k_{eff} values in Table 3.3 include a positive bias of 33.63 pcm to account for features of the actual ZPPR-15A assembly such as room return that are not included in the as-built ZPPR-15 models (see Ref. 1). In some cases, the adjusted k_{eff} may be greater than 1.0 due to this bias even though the reactor was subcritical for all of the sodium void worth measurements.

Table 3-3 Reactivity and k_{eff} for ZPPR-15A Loadings 16 – 23

Loading	Measured ρ , $\%$ (1)		Measured ρ , pcm		Bias ρ , pcm (2)		Adjusted ρ , pcm		Adjusted k_{eff}	σ
	ρ , $\%$	σ_{total} , $\%$	ρ , pcm	σ_{total} , pcm	ρ , pcm	σ , pcm	ρ_{adj} , pcm	σ , pcm		
16	-111.22	0.68	-373.366	2.274	33.63	13.68	-339.74	13.87	0.99661	0.00014
17										
18	-63.48	0.30	-213.102	1.004	33.63	13.68	-179.47	13.72	0.99821	0.00014
19	-33.40	0.27	-112.124	0.906	33.63	13.68	-78.49	13.71	0.99922	0.00014
20	-43.87	0.18	-147.272	0.620	33.63	13.68	-113.64	13.69	0.99886	0.00014
21	-66.40	0.31	-222.905	1.033	33.63	13.68	-189.27	13.72	0.99811	0.00014
22	-120.92	0.74	-405.928	2.468	33.63	13.68	-372.30	13.90	0.99629	0.00014
23	-173.92	1.18	-583.849	3.949	33.63	13.68	-550.22	14.24	0.99453	0.00014

- 1) The measured reactivity values for loadings 16, 18, and 20 – 23 in Table 3.1 were added to the measured reactivity for loading 19 to produce the values shown in column 2.
- 2) Bias exists because room return, impurities in the depleted uranium (DU) plates and the Kel-F coating on the DU plates are neglected in the as-built models. The bias values shown in Table 3.3 were determined as part of the uncertainty analysis for the ZPPR-15A reference critical configuration.

Table 3.4 shows the measured and calculated sodium void worths for ZPPR-15A. Column 4 shows the total measured sodium void worth in units of pcm. Conversion of the measured reactivity from cents to pcm introduces a small uncertainty due to uncertainties in plate compositions and a larger reactivity uncertainty due to the 5% β_{eff} uncertainty (column 6). The total uncertainty for the measured sodium void worth after conversion from cents to pcm is shown in column 8. The worths of the individual sodium void steps in ZPPR-15A were calculated with MCNP6.1 and ENDF/B-VII.0 cross sections.

Table 3-4 Measured and Calculated Sodium Void Worths in ZPPR-15A

Step (1)	Measured ρ , $\%$ (2)		Measured ρ , pcm (3)		$\sigma(\beta)$, pcm (3)	σ_{comp} , pcm (4)	σ_{total} , pcm (5)	Calculated ρ , pcm (6)		C/E - 1, % (7)	
	ρ_{meas} , $\%$	σ_{meas} , $\%$	ρ_{meas} , pcm	σ_{meas} , pcm				ρ , pcm	σ , pcm	C/E - 1, %	σ , %
L016 - L017	110.29	0.99	370.24	3.314	18.51	0.60	18.82	354.24	2.84	-4.3	4.9
L018 - L019	30.08	0.53	100.98	1.782	5.05	0.60	5.39	84.52	2.84	-16.3	5.3
L019 - L020	-10.47	0.20	-35.15	0.666	-1.76	0.60	1.97	-35.20	2.84	0.2	9.8
L020 - L021	-22.53	0.26	-75.63	0.872	-3.72	0.60	3.93	-73.50	2.84	-2.8	6.3
L022 - L023	-54.52	0.62	-183.02	2.066	9.15	0.60	9.40	-170.56	2.84	-6.8	5.0
L022 - L023	-53.00	1.20	-177.92	4.039	8.90	0.60	9.79	-159.98	2.25	-10.0	5.1

- 1) Steps correspond to Table 3.2.
- 2) The measured reactivity does not include the correction for the steel mismatch.
- 3) This is the uncertainty resulting from the 5% uncertainty in the β_{eff} used to convert the reactivity from cents to pcm.
- 4) This is the uncertainty resulting from the uncertainty in plate compositions.
- 5) The σ_{total} value in column 8 is the final total uncertainty for the measured reactivity expressed in pcm.

The measured reactivities in Table 3.4 do not include the correction for the steel mismatch between sodium cans removed and void cans inserted in a sodium void measurement. The as-built ZPPR-15 models and any deterministic models derived from the as-built models explicitly represent the sodium plates (or cans) and the void cans. Any mismatch in the steel content of the sodium cans and void cans is included in the as-built models, so it would be incorrect to apply the correction for the steel mismatch. The steel correction reactivity is included in Table 3.2 only to show that the steel correction is small.

3.2 Sodium Void Worths and Total Uncertainties for ZPPR-15B

The reference critical configuration for ZPPR-15B was L088, and the subcritical reference configuration for ZPPR-15B was L089. It was necessary to reduce the core reactivity further for the sodium void worth measurements. This was accomplished in L091 by replacing drawers containing two fuel columns (double column fuel or DCF drawers) by drawers containing one fuel column (single column fuel or SCF drawers) at symmetric locations in the outer core (despike).

The subcritical reference for ZPPR-15B sodium void worth measurements was L091. In ZPPR-15B L092, an 8-in (20.32 cm) sodium void was introduced in the central 52 drawers per half. In ZPPR-15B L093, the sodium void zone was increased to 14 inches (35.56 cm) in the central 52 drawers per half, and the sodium void zone was increased to 18 inches (45.72 cm) in the central 52 drawers per half in L094. In L095, all sodium void cans in the void zone were replaced by sodium plates to reconstruct L091. Figures 3.17 – 3.24 show the core loading maps or matrix maps for ZPPR-15B loadings 91 – 94. The interpretation of the colors in Figures 3.17 – 3.24 is identical to the interpretation of colors in Figures 3.1 – 3.16 for ZPPR-15A.

Sodium Void Worth and Control Rod Worth Measurements in ZPPR-15
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Figure 3-18 ZPPR-15B Loading 91 – Half 2

Sodium Void Worth and Control Rod Worth Measurements in ZPPR-15
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Figure 3-19 ZPPR-15B Loading 92 – Half 1

Sodium Void Worth and Control Rod Worth Measurements in ZPPR-15
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Figure 3-20 ZPPR-15B Loading 92 – Half 2

Sodium Void Worth and Control Rod Worth Measurements in ZPPR-15
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Figure 3-21 ZPPR-15B Loading 93 - Half 1

Sodium Void Worth and Control Rod Worth Measurements in ZPPR-15
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Figure 3-22 ZPPR-15B Loading 93 – Half 2

Sodium Void Worth and Control Rod Worth Measurements in ZPPR-15
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Figure 3-23 ZPPR-15B Loading 94 – Half 1

Sodium Void Worth and Control Rod Worth Measurements in ZPPR-15
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Figure 3-24 ZPPR-15B Loading 94 – Half 2

Table 3.5 shows the measured reactivities for the individual loadings as reported by the ZPPR staff. The 0.13¢ difference between the measured excess reactivities in L091 and L095 is the reproducibility uncertainty.

Table 3-5 Measured Sodium Void Worths in ZPPR-15B

Loading	Measurement	ρ , ϕ (1)	σ_{stat} , ϕ (2)	σ_{corr} , ϕ (3)	σ_{repro} , ϕ	σ_{total} , ϕ
91	Despike	-47.11	0.085	0.382	0.13	0.412
92	203 mm Void	-3.89	0.034	0.038	0.13	0.140
93	356 mm Void	7.45	0.071	0.060	0.13	0.160
94	457 mm Void	3.27	0.093	0.030	0.13	0.163
95	Reflood	-47.24	0.133	0.383	0.13	0.426

- 1) The reactivities in column 3 were determined relative to L096, the subcritical reference for the control rod worth measurements in ZPPR-15B. The reactivity of L096 (reactor run 178) was determined by inverse kinetics analysis to be $-17.33\phi \pm 0.14\phi$.
- 2) The statistical uncertainty includes count rate plus the corrections for temperature, interface gap and ^{241}Pu decay.
- 3) Correlated uncertainty is due to reactivity scale calibration and the source ratio uncertainty.

Table 3.6 shows the reported reactivity changes for the individual void steps.

Table 3-6 Experimental Reactivity Changes for Sodium Void Steps in ZPPR-15B

Loading (1)	Step (1)	Mass of Na, kg (2)	ρ_{meas} , ϕ (3)	Steel ρ , ϕ (4)	$\rho_{\text{corrected}}$, ϕ (5)	σ_{stat} , ϕ	σ_{corr} , ϕ	σ_{repro} , ϕ	σ_{total} , ϕ	ρ_{spec} , $\phi/\text{kg Na}$ (6)
L91-L92	0 - 203 mm	20.804	43.22	0.11	43.33	0.10	0.35	0.13	0.387	2.083
L91-L93	0 - 356 mm	35.843	54.56	0.60	55.16	0.21	0.06	0.13	0.254	1.539
L91-L94	0 - 457 mm	46.080	50.38	0.50	50.88	0.19	0.03	0.13	0.232	1.104
L92-L93	203 - 356 mm	15.039	11.34	0.49	11.83	0.18	0.10	0.13	0.244	0.787
L93-L94	356 - 457 mm	10.237	-4.18	-0.10	4.28	0.12	0.03	0.13	0.179	-0.418

- 1) Column 1 specifies the core loadings for the reactivity change; column 2 is the configuration change for that step.
- 2) Column 3 is the mass of sodium voided in that step.
- 3) Column 4 is the measured reactivity.
- 4) Column 5 is the reactivity correction for the difference in steel masses between the sodium cans and void cans in the void zone.
- 5) Column 6 is the measured reactivity corrected for the steel mismatch.
- 6) The last column is the specific reactivity, i.e., reactivity per kg of sodium voided.

The reported reactivities for individual loadings in Table 3.5 can be converted to values of k_{eff} using the reported β_{eff} value for ZPPR-15B, 0.003361. Table 3.7 shows the values of k_{eff} determined from the reactivities for the individual loadings in Table 3.5. The adjusted k_{eff} values in Table 3.7 include a positive bias of 41.76 pcm to account for features of the actual

ZPPR-15B assembly such as room return that are not included in the as-built ZPPR-15 models (see Ref. 1). In some cases, the adjusted k_{eff} may be greater than 1.0 due to this bias although all of the measured configurations in Table 3.7 were subcritical.

Table 3-7 Reactivity and k_{eff} for ZPPR-15B Loadings 91 – 96

Loading	Measured ρ , ϕ (1)		Measured ρ , pcm		Bias ρ , pcm (2)		Adjusted ρ , pcm		Adjusted k_{eff}	σ
	ρ , ϕ	σ_{total} , ϕ	ρ , pcm	σ_{total} , pcm	ρ , pcm	σ , pcm	ρ_{adj} , pcm	σ , pcm		
91	-64.44	0.41	-216.58	1.39	41.76	13.92	-174.82	13.99	0.99825	0.00014
92	-21.22	0.14	-71.32	0.47	41.76	13.92	-29.56	13.93	0.99970	0.00014
93	-9.88	0.16	-33.21	0.54	41.76	13.92	8.55	13.93	1.00009	0.00014
94	-14.06	0.16	-47.26	0.55	41.76	13.92	-5.50	13.93	0.99995	0.00014
95	-64.57	0.43	-217.02	1.43	41.76	13.92	-175.26	13.99	0.99825	0.00014
96	-17.33	0.14	-58.25	0.47	41.76	13.92	-16.49	13.93	0.99984	0.00014

- 1) The measured reactivity values for L091 – L095 in Table 3.5 were added to the measured reactivity for L096 to produce the values shown in column 2 for L091 – L095.
- 2) Bias exists because room return, impurities in the depleted uranium plates and the Kel-F coating on the depleted uranium plates are neglected in the as-built models. The bias values shown in Table 3.7 were determined as part of the uncertainty analysis for the ZPPR-15B reference critical configuration.

Table 3.8 shows the measured and calculated sodium void worths for ZPPR-15B. Column 4 shows the total measured sodium void worth in units of pcm. Conversion of the measured reactivity from cents to pcm introduces a small uncertainty due to uncertainties in the plate compositions and a larger reactivity uncertainty due to the 5% β_{eff} uncertainty (column 6). The total uncertainty for the measured sodium void worths after conversion from cents to pcm is shown in column 8. The worth of each sodium void step in ZPPR-15B were calculated with MCNP6.1 and ENDF/B-VII.0 cross sections.

The measured reactivities in Table 3.8 do not include the correction for the steel mismatch between sodium cans removed and void cans inserted in a sodium void measurement. The as-built models and any deterministic models derived from the as-built models explicitly represent the sodium plates (or cans) and the void cans. Any mismatch in the steel content of the sodium cans and void cans is included in the as-built models, so it would be incorrect to apply the correction for the steel mismatch. The steel correction reactivity is included in Table 3.6 only to show that the steel correction is small.

Table 3-8 Measured and Calculated Sodium Void Worths in ZPPR-15B.

Step (1)	Measured ρ , ϕ (2)		Measured ρ , pcm					Calculated ρ , pcm		C/E – 1, %	
	ρ , ϕ	σ_{meas} , ϕ	ρ_{meas} , pcm	σ_{exp} , pcm	$\sigma(\beta)$, pcm (3)	σ_{comp} , pcm (4)	σ_{total} , pcm (5)	ρ , pcm	σ , pcm	C/E-1, %	σ , %
L91 - L92	43.22	0.39	145.26	1.30	7.26	0.60	7.40	133.93	2.84	-7.8	5.1
L91 - L93	54.56	0.25	183.38	0.85	9.17	0.60	9.23	171.12	2.84	-6.7	4.9
L91 - L94	50.38	0.23	169.33	0.78	8.47	0.60	8.52	154.04	2.84	-9.0	4.9
L92 - L93	11.34	0.24	38.11	0.82	1.91	0.60	2.16	37.19	2.84	-2.4	9.3
L93 - L94	-4.18	0.18	-14.05	0.60	0.70	0.60	1.10	-17.09	2.84	-21.6	22.3

- 1) Steps correspond to Table 3.6.
- 2) The measured reactivity does not include the correction for the steel mismatch.
- 3) This is the uncertainty resulting from the 5% uncertainty in the β_{eff} used to convert the reactivity from cents to pcm.
- 4) This is the uncertainty resulting from the uncertainty in plate compositions.
- 5) The σ_{total} value in column 8 is the final total uncertainty for the measured reactivity expressed in pcm.

3.3 Sodium Void Worths and Total Uncertainties for ZPPR-15C

The subcritical reference configuration for ZPPR-15C was L165. It was necessary to reduce the core reactivity for the sodium void worth measurements, so selected DCF drawers in the outer core were converted to SCF drawers in L167, the despike loading. In ZPPR-15C L168, an 8-in (20.32 cm) sodium void zone was introduced in the central 52 drawers per half. In ZPPR-15C L169, the sodium void zone was increased to 18 inches (45.72 cm) in the central 52 drawers per half. All of the void cans in the void zone were replaced by sodium plates in L170, the reflood configuration, to rebuild L167. Figures 3.25 – 3.30 show the core loading maps or matrix maps for ZPPR-15C loadings 167 – 169. The interpretation of the colors in Figures 3.25 – 3.30 is identical to the interpretation of colors in Figures 3.1 – 3.16 for ZPPR-15A with one exception. In Figures 3.25 – 3.30, the salmon-colored cells contain HEU fuel plates rather than Pu-U-Mo fuel plates.

Table 3.9 shows the measured reactivities for the individual loadings as reported by the ZPPR staff. The 0.15¢ difference between the measured sub-criticality of L167 and L170 is the reproducibility uncertainty.

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Figure 3-25 ZPPR-15C Loading 167 – Half 1

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Figure 3-26 ZPPR-15C Loading 167 – Half 2

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Figure 3-27 ZPPR-15C Loading 168 – Half 1

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Figure 3-28 ZPPR-15C Loading 168 – Half 2

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Figure 3-29 ZPPR-15C Loading 169 – Half 1

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Figure 3-30 ZPPR-15C Loading 169 – Half 2

Table 3-9 Measured Sodium Void Worths in ZPPR-15C

Loading	Measurement	ρ , β (1)	σ_{stat} , β (2)	σ_{corr} , β (3)	σ_{repro} , β	σ_{total} , β
167	Despike	-24.57	0.070	0.222	0.15	0.277
168	203 mm Void	-8.58	0.058	0.090	0.15	0.184
169	457 mm Void	-10.17	0.053	0.103	0.15	0.190
170	Reflood	-24.72	0.079	0.223	0.15	0.280

- 1) The reactivities in column 3 were determined relative to L165, the subcritical reference for ZPPR-15C. The reactivity of L165 was determined by inverse kinetics analysis to be $-11.268\beta \pm 0.089\beta$.
- 2) The statistical uncertainty includes count rate plus the corrections for temperature, interface gap and ^{241}Pu decay.
- 3) Correlated uncertainty is due to reactivity scale calibration and the source ratio uncertainty.

Table 3.10 shows the reported reactivity changes for the individual void steps.

Table 3-10 Experimental Reactivity Changes for Sodium Void Steps in ZPPR-15C

Loading (1)	Step (1)	Mass of Na, kg (2)	ρ_{meas} , β (3)	Steel ρ , β (4)	$\rho_{\text{corrected}}$, β (5)	σ_{stat} , β	σ_{corr} , β	σ_{repro} , β	σ_{total} , β	ρ_{spec} , $\beta/\text{kg Na}$ (6)
L167-L168	0 - 203 mm	20.804	15.99	0.07	16.06	0.091	0.132	0.15	0.220	0.772
L167-L169	0 - 457 mm	46.080	14.40	0.32	14.72	0.088	0.119	0.15	0.211	0.319
L168-L169	203 - 457 mm	25.276	-1.59	0.25	-1.34	0.079	0.013	0.15	0.170	-0.051

- 1) Column 1 specifies the core loadings for the reactivity change; column 2 is the configuration change for that step.
- 2) Column 3 is the mass of sodium voided in that step.
- 3) Column 4 is the measured reactivity.
- 4) Column 5 is the reactivity correction for the difference in steel masses between the sodium cans and void cans in the void zone.
- 5) Column 6 is the measured reactivity corrected for the steel mismatch.
- 6) The last column is the specific reactivity, i.e., reactivity per kg of sodium voided.

The reported reactivities for individual loadings in Table 3.9 can be converted to values of k_{eff} using the reported β_{eff} value for ZPPR-15C, 0.005207. Table 3.11 shows the values of k_{eff} determined from the reactivities for the individual loadings in Table 3.9. The adjusted k_{eff} values in Table 3.11 include a positive bias of 54.55 pcm to account for features of the actual ZPPR-15C assembly such as room return that are not included in the as-built ZPPR-15 models (see Ref. 1). In some cases, the adjusted k_{eff} may be greater than 1.0 due to this bias although all loadings in Table 3.11 were subcritical.

Table 3-11 Reactivity and k_{eff} for ZPPR-15C Loadings 165 – 170

Loading	Measured ρ , ϕ (1)		Measured ρ , pcm		Bias ρ , pcm		Adjusted ρ , pcm		Adjusted k_{eff}	σ
	ρ , ϕ	σ_{total} , ϕ	ρ , pcm	σ_{total} , pcm	ρ , pcm	σ , pcm	ρ_{adj} , pcm	σ , pcm		
165	-11.27	0.09	-58.67	0.46	54.55	17.10	-4.12	17.11	0.99996	0.00017
167	-35.84	0.28	-186.61	1.44	54.55	17.10	-132.06	17.16	0.99868	0.00017
168	-19.85	0.18	-103.35	0.96	54.55	17.10	-48.80	17.13	0.99951	0.00017
169	-21.44	0.19	-111.63	0.99	54.55	17.10	-57.08	17.13	0.99943	0.00017
170	-35.99	0.28	-187.39	1.46	54.55	17.10	-132.84	17.16	0.99867	0.00017

- 1) The measured reactivity values for L167 – L170 in Table 3.11 were added to the measured reactivity for L165 to produce the values shown in column 2 for L167 – L170.
- 2) Bias exists because room return, impurities in the DU plates, Kel-F coating on the DU plates, HEU impurities and corrosion in the HEU plates (leaking end caps) are neglected in the as-built models.

Table 3.12 shows the measured and calculated sodium void worths for ZPPR-15C. Column 4 shows the total measured sodium void worth in units of pcm. Conversion of the measured reactivity from cents to pcm introduces a small uncertainty due to uncertainties in the plate compositions and a larger reactivity uncertainty due to the 5% β_{eff} uncertainty (column 6). The total uncertainty for the measured sodium void worths after conversion from cents to pcm is shown in column 8. The worths of the sodium void steps in ZPPR-15C were calculated with MCNP6.1 and ENDF/B-VII.0 cross sections.

Table 3-12 Measured and Calculated Sodium Void Worths in ZPPR-15C

Step (1)	Measured ρ , ϕ (2)		Measured ρ , pcm					Calculated ρ , pcm		C/E – 1, %	
	ρ , ϕ	σ_{exp} , ϕ	ρ_{meas} , pcm	σ_{exp} , pcm	$\sigma(\beta)$, pcm (3)	σ_{comp} , pcm (4)	σ_{total} , pcm (5)	ρ , pcm	σ , pcm	C/E-1, %	σ , %
L167 - L168	15.99	0.22	83.26	1.14	4.16	0.60	4.36	84.29	2.83	-1.2	6.3
L167 - L169	14.40	0.21	74.98	1.10	3.75	0.60	3.95	71.25	2.83	-5.0	6.3
L168 - L169	-1.59	0.17	-8.28	0.88	0.41	0.60	1.15	-13.04	2.83	57.4	40.6

- 1) Steps correspond to Table 3.10.
- 2) The measured reactivity does not include the correction for the steel mismatch.
- 3) This is the uncertainty resulting from the 5% uncertainty in the β_{eff} used to convert the reactivity from cents to pcm.
- 4) This is the uncertainty resulting from the uncertainty in plate compositions.
- 5) The σ_{total} value in column 8 is the final total uncertainty for the measured reactivity expressed in pcm.

The measured reactivities in Table 3.12 do not include the correction for the steel mismatch between sodium cans removed and void cans inserted in a sodium void measurement. The as-built models and any deterministic models derived from the as-built models explicitly represent the sodium plates (or cans) and the void cans. Any mismatch in the steel content of the sodium cans and void cans is included in the as-built models, so it would be incorrect to apply the correction for the steel mismatch. The steel correction reactivity is included in Table 3.10 only to show that the steel correction is small.

3.4 Sodium Void Worths and Total Uncertainties for ZPPR-15D

The subcritical reference for ZPPR-15D was L184. In ZPPR-15D L189, an 8-in (20.32 cm) sodium void was introduced in the central 52 drawers per half. In ZPPR-15D L190, the sodium void zone was increased to 18 in (45.72 cm) in the central 52 drawers per half. The measured reactivities in L189 and L190 are relative to L184, the subcritical reference configuration. All of the void cans in the void zone were replaced by sodium plates in L191, the reflood configuration, to rebuild L184. Figures 3.31 – 3.36 show the core loading maps or matrix maps for ZPPR-15D loadings 184, 189 and 190. The interpretation of the colors in Figures 3.31 – 3.36 is identical to the interpretation of colors in Figures 3.1 – 3.16 for ZPPR-15A with one exception. In Figures 3.31 – 3.36, the salmon-colored cells contain HEU fuel plates rather than Pu-U-Mo fuel plates.

Table 3.13 shows the measured reactivities for the individual loadings as reported by the ZPPR staff. The 0.13¢ difference between the excess reactivities of L184 and L191 is the reproducibility uncertainty.

Table 3-13 Measured Sodium Void Worths for ZPPR-15D

Loading	Measurement	ρ , ¢ (1)	σ_{stat} , ¢ (2)	σ_{corr} , ¢ (3)	σ_{repro} , ¢	σ_{total} , ¢
189	203 mm Void	4.79	0.04	0.04	0.13	0.142
190	457 mm Void	-0.65	0.01	0.01	0.13	0.131
191	Reflood	0.13	0.02	0.01	0.13	0.132

- 1) The reactivities in column 3 were determined relative to L184, the subcritical reference for ZPPR-15D. The reactivity of L184 was determined by inverse kinetics analysis to be $-7.075\text{¢} \pm 0.059\text{¢}$.
- 2) The statistical uncertainty includes count rate plus the corrections for temperature, interface gap and ^{241}Pu decay.
- 3) Correlated uncertainty is due to reactivity scale calibration and the source ratio uncertainty.

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Figure 3-31 ZPPR-15D Loading 184 – Half 1

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Figure 3-32 ZPPR-15D Loading 184 – Half 2

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Figure 3-33 ZPPR-15D Loading 189 – Half 1

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Figure 3-34 ZPPR-15D Loading 189 – Half 2

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Figure 3-35 ZPPR-15D Loading 190 – Half 1

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Figure 3-36 ZPPR-15D Loading 190 – Half 2

Table 3.14 shows the reported reactivity changes for the individual void steps.

Table 3-14 Experimental Reactivity Changes for Sodium Void Steps in ZPPR-15D

Loading (1)	Step (1)	Mass of Na, kg (2)	ρ_{meas} , ¢ (3)	Steel ρ , ¢ (4)	$\rho_{\text{corrected}}$, ¢ (5)	σ_{stat} , ¢	σ_{corr} , ¢	σ_{repro} , ¢	σ_{total} , ¢	ρ_{spec} , ¢/kg Na (6)
L184 - L189	0 - 203 mm	20.804	4.79	0.06	4.85	0.04	0.04	0.13	0.142	0.233
L184 - L190	0 - 457 mm	46.080	-0.65	0.26	-0.39	0.04	0.04	0.13	0.142	-0.008
L189 - L190	203 - 457 mm	25.276	-5.44	0.20	-5.24	0.06	0.06	0.13	0.155	-0.207

- 1) Column 1 specifies the core loadings for the reactivity change; column 2 is the configuration change for that step.
- 2) Column 3 is the mass of sodium voided in that step.
- 3) Column 4 is the measured reactivity.
- 4) Column 5 is the reactivity correction for the difference in steel masses between the sodium cans and void cans in the void zone.
- 5) Column 6 is the measured reactivity corrected for the steel mismatch.
- 6) The last column is the specific reactivity, i.e., reactivity per kg of sodium voided.

The reported reactivities for individual loadings in Table 3.13 can be converted to values of k_{eff} using the reported β_{eff} value for ZPPR-15D, 0.006564. Table 3.15 shows the values of k_{eff} determined from the reactivities for the individual loadings in Table 3.13. The adjusted k_{eff} values in Table 3.15 include a positive bias of 50.45 pcm to account for features of the actual ZPPR-15D assembly such as room return that are not included in the as-built ZPPR-15 models (see Ref. 1). In some cases, the adjusted k_{eff} may be greater than 1.0 due to this bias, but loadings 184, 189 and 190 were subcritical.

Table 3-15 Reactivity and k_{eff} for ZPPR-15D Loadings 184, 189 and 190

Loading	Measured ρ , ¢ (1)		Measured ρ , pcm		Bias ρ , pcm (2)		Adjusted ρ , pcm		Adjusted k_{eff}	σ
	ρ , ¢	σ_{total} , ¢	ρ , pcm	σ_{total} , pcm	ρ , pcm	σ , pcm	ρ_{adj} , pcm	σ , pcm		
184	-7.075	0.059	-46.44	0.39	50.45	18.76	4.01	18.76	1.00004	0.00019
189	-2.285	0.142	-15.00	0.93	50.45	18.76	35.45	18.78	1.00035	0.00019
190	-7.725	0.131	-50.71	0.86	50.45	18.76	-0.26	18.78	1.00000	0.00019

- 1) The measured reactivity values for L189 – L190 in Table 3.13 were added to the measured reactivity for L184 to produce the values shown in column 2 for L189 – L190.
- 2) Bias exists because room return, impurities in the DU plates, Kel-F coating on the DU plates, HEU impurities and corrosion in the HEU plates (leaking end caps) are neglected in the as-built models. The biases were determined as part of the uncertainty analysis for the ZPPR-15D reference critical configuration.

Table 3.16 shows the measured and calculated sodium void worths for ZPPR-15D. Column 4 shows the total measured sodium void worth in units of pcm. Conversion of the measured reactivity from cents to pcm introduces a small uncertainty due to uncertainties in plate

compositions and a larger reactivity uncertainty due to the 5% β_{eff} uncertainty (column 6). The total uncertainty for the measured sodium void worth after conversion from cents to pcm is shown in column 8. The sodium void worth in ZPPR-15D were calculated with MCNP6.1 and ENDF/B-VII.0 cross sections.

Table 3-16 Measured and Calculated Sodium Void Worths in ZPPR-15D

Step (1)	Measured ρ , ϕ (2)		Measured ρ , pcm					Calculated ρ , pcm		C/E - 1, %	
	ρ , ϕ	σ_{exp} , ϕ	ρ_{meas} , pcm	σ_{exp} , pcm	$\sigma(\beta)$, pcm (3)	σ_{comp} , pcm (4)	σ_{total} , pcm (5)	ρ , pcm	σ , pcm	C/E - 1, %	σ , %
L184 - L189	4.79	0.14	31.44	0.93	1.57	0.60	1.92	39.93	2.83	27.0	11.9
L184 - L190	-0.65	0.14	-4.27	0.93	0.21	0.60	1.13	8.99	2.83	-310.6	86.5
L189 - L190	-5.44	0.16	-35.71	1.02	1.78	0.60	2.14	-30.94	2.83	-13.4	9.5

- 1) Steps correspond to Table 3.14.
- 2) The measured reactivity does not include the correction for the steel mismatch.
- 3) This is the uncertainty resulting from the 5% uncertainty in the β_{eff} used to convert the reactivity from cents to pcm.
- 4) This is the uncertainty resulting from the uncertainty in plate compositions.
- 5) The σ_{total} value in column 8 is the final total uncertainty for the measured reactivity expressed in pcm.

The measured reactivities in Table 3.16 do not include the correction for the steel mismatch between sodium cans removed and void cans inserted in a sodium void measurement. The as-built models and any deterministic models derived from the as-built models explicitly represent the sodium plates (or cans) and the void cans. Any mismatch in the steel content of the sodium cans and void cans is included in the as-built models, so it would be incorrect to apply the correction for the steel mismatch. The steel correction reactivity is included in Table 3.14 only to show that the steel correction is small.

3.5 Sodium Void Worth and Total Uncertainty for the ZPPR-15B High Zr Zone

During the transition from ZPPR-15A to ZPPR-15B, a high zirconium zone was constructed in the central part of the core by replacing two 1/16 inch columns of depleted uranium and two 1/16 inch columns of stainless steel with two 1/8 inch columns of zirconium in a central zone of 132 drawers per half. A subcritical reference was established for the high zirconium zone core in L076. In L077, an 8-in (20.32 cm) void zone was established in 52 drawers per half, and the worth of sodium voiding was measured. L078 was a reconstruction of L076. The 0.47¢ difference between the subcriticality of L076 and L078 is the reproducibility uncertainty. Table 3.17 shows the measured reactivities for the individual loadings as reported by the ZPPR staff.

Table 3-17 Measured Sodium Void Worth for the High Zr Zone

Loading	Measurement	ρ , β (1)	σ_{stat} , β (2)	σ_{corr} , β (3)	σ_{repro} , β (5)	σ_{total} , β
76	Subcritical Reference	-36.12	0.134	0.824	0.47	0.958
77	203 mm Void	-32.36				0.260
78	Subcritical Reference	-36.59	0.166	0.822	0.47	0.961

- 1) The reactivities for L076 and L078 in column 3 were determined relative to L077. The reactivity of L077 was determined by inverse kinetics analysis to be $-32.36\beta \pm 0.26\beta$.
- 2) The statistical uncertainty includes count rate plus the corrections for temperature, interface gap and ^{241}Pu decay.
- 3) Correlated uncertainty is due to reactivity scale calibration and the source ratio uncertainty.

Table 3.18 shows the reported reactivity change for the sodium void worth measurement in the high Zr zone.

Table 3-18 Experimental Reactivity Change for Sodium Voiding in the High Zr Zone

Loading	ρ_{meas} , β (1)	σ_{stat} , β	σ_{corr} , β	σ_{repro} , β	σ_{total} , β
L076/L078 - L077	36.35	0.166	0.822	0.47	0.961

- 1) The measured reactivity is the average of the measured values for L076 and L078.

The reported reactivities for individual loadings in Table 3.17 can be converted to values of k_{eff} using the reported β_{eff} value for ZPPR-15B, 0.003361. Table 3.19 shows the values of k_{eff} determined from the reactivities for the individual loadings in Table 3.17. The adjusted k_{eff} values in Table 3.19 include a positive bias of 41.76 pcm to account for features of the actual ZPPR-15B assembly such as room return that are not included in the as-built ZPPR-15 models (see Ref. 1). In some cases, the adjusted k_{eff} may be greater than 1.0 due to this bias.

Table 3.20 shows the measured and calculated sodium void worths for the ZPPR-15B high Zr zone configuration. Column 4 shows the total measured sodium void worth in units of pcm. Conversion of the measured reactivity from cents to pcm introduces a small uncertainty due to uncertainties in the plate compositions and a larger reactivity uncertainty due to the 5% β_{eff} uncertainty (column 6). The total uncertainty for the measured sodium void worths after conversion from cents to pcm is shown in column 8. The sodium void worth in ZPPR-15B high Zr zone were calculated with MCNP6.1 and ENDF/B-VII.0 cross sections.

Table 3-19 Reactivity and k_{eff} for ZPPR-15B Loadings 76 – 78

Loading	Measured ρ , $\%$ (1)		Measured ρ , pcm		Bias ρ , pcm (2)		Adjusted ρ , pcm		Adjusted k_{eff}	σ
	ρ , $\%$	σ_{total} , $\%$	ρ , pcm	σ_{total} , pcm	ρ , pcm	σ , pcm	ρ_{adj} , pcm	σ , pcm		
76	-68.48	0.96	-230.16	3.22	41.76	13.7 0	-188.40	14.07	0.99812	0.00014
77	-32.36	0.26	-108.76	0.87	41.76	13.7 0	-67.00	13.73	0.99933	0.00014
78	-68.95	0.96	-231.74	3.23	41.76	13.7 0	-189.98	14.08	0.99810	0.00014

- 1) The measured reactivity values for L076 and L078 in Table 3.17 were added to the measured reactivity for L077 to produce the values shown in column 2 for L076 – L078.
- 2) Bias exists because room return, impurities in the depleted uranium plates and the Kel-F coating on the depleted uranium plates are neglected in the as-built models. The bias values shown in Table 3.19 were determined as part of the uncertainty analysis for the ZPPR-15B reference critical configuration.

Table 3-20 Measured and Calculated Sodium Void Worths in the High Zr Zone

Step	Measured ρ , $\%$		Measured ρ , pcm					Calculated ρ , pcm		C/E – 1, %	
	ρ , $\%$	σ_{meas} , $\%$	ρ_{meas} , pcm	σ_{exp} , pcm	$\sigma(\beta)$, pcm (1)	σ_{comp} , pcm (2)	σ_{total} , pcm (3)	ρ , pcm	σ , pcm	C/E-1, %	σ , %
L76 - L77	36.35	0.96	122.17	3.23	6.11	0.60	6.94	108.61	2.84	-11.1	5.6

- 1) This is the uncertainty resulting from the 5% uncertainty in the β_{eff} used to convert the reactivity from cents to pcm.
- 2) This is the uncertainty resulting from the uncertainty in plate compositions.
- 3) The σ_{total} value in column 8 is the final total uncertainty for the measured reactivity expressed in pcm.

3.6 Sodium Void Worth and Total Uncertainty for the ZPPR-15B Sodium Manometer Experiments

In ZPPR-15B loadings 109 – 112, the worth of a simulated sodium manometer was measured. A sodium manometer is a tube containing gas that is trapped between a sealed end at the top and liquid sodium below. Under normal operating conditions the gas is compressed at the top, and the liquid sodium nearly fills the tube. The pressure drop in a loss-of-flow accident causes the sodium to be expelled from the tube which reduces reactivity.

L109 was the subcritical reference configuration. In L110 the manometer was simulated by replacing twelve blanket drawers in each half by drawers filled with sodium plates. The sodium plates in the manometer drawers were replaced with void cans in half 1 in L111. In L112 the sodium plates in the manometer drawers in half 2 were replaced with void cans. L113 was a

rebuild of the subcritical reference. The 0.47% difference between the excess reactivities of L109 and L113 is the reproducibility uncertainty. Table 3.21 shows the measured reactivities as reported by the ZPPR staff.

Table 3-21 Measured Worths for the ZPPR-15B Sodium Manometer Experiment

Loading	Measurement	$\rho, \%$ (1)	$\sigma_{\text{stat}}, \%$ (2)	$\sigma_{\text{corr}}, \%$ (3)	$\sigma_{\text{repro}}, \%$	$\sigma_{\text{tot}}, \%$
109	Subcritical Reference	0.30	0.057	0.017	0.47	0.474
110	Sodium Manometers Replacing Blanket	-4.75	0.057	0.076	0.47	0.480
111	Manometers Voided in Half-1	-13.49	0.072	0.142	0.47	0.496
112	Manometers Voided in Both Halves	-21.96	0.104	0.212	0.47	0.526
113	Return to Subcritical Reference	-0.17	0.066	0.016	0.47	0.475

- 1) The reactivities in column 3 were determined relative to L096, the subcritical reference for control rod worth measurements in ZPPR-15B. The reactivity of L096 (reactor run 178) was determined by inverse kinetics analysis to be $-17.33\% \pm 0.14\%$. L109 and L113 were identical to L096.
- 2) The statistical uncertainty includes count rate plus the corrections for temperature, interface gap and ^{241}Pu decay.
- 3) Correlated uncertainty is due to reactivity scale calibration and the source ratio uncertainty.

Table 3.22 shows the reported reactivity changes for the individual steps in the sodium manometer experiment.

Table 3-22 Experimental Reactivity Changes for Steps in the ZPPR-15B Sodium Manometer Experiment

Loading	Measurement	$\rho, \%$	$\sigma_{\text{stat}}, \%$ (1)	$\sigma_{\text{corr}}, \%$ (2)	$\sigma_{\text{repro}}, \%$	$\sigma_{\text{tot}}, \%$
L109 - L110	Sodium Manometers Replacing Blanket	-5.05	0.081	0.093	0.47	0.486
L110 - L111	Manometers Voided in Half-1	-8.74	0.092	0.066	0.47	0.483
L110 - L112	Manometers Voided in Both Halves	-17.21	0.119	0.136	0.47	0.504

- 1) The statistical uncertainty includes count rate plus the corrections for temperature, interface gap and ^{241}Pu decay.
- 2) Correlated uncertainty is due to reactivity scale calibration and the source ratio uncertainty.

The reported reactivities for individual loadings in Table 3.21 can be converted to values of k_{eff} using the reported β_{eff} value for ZPPR-15B, 0.003361. Table 3.23 shows the values of k_{eff} determined from the reactivities of the individual loadings in Table 3.21. The adjusted k_{eff}

values in Table 3.23 include a positive bias of 41.76 pcm to account for features of the actual ZPPR-15B assembly such as room return that are not included in the as-built ZPPR-15 models (see Ref. 1). In some cases, the adjusted k_{eff} may be greater than 1.0 due to this bias.

Table 3-23 Reactivity and k_{eff} for the ZPPR-15B Sodium Manometer Experiment

Loading	Measured ρ , ϕ (1)		Measured ρ , pcm		Bias ρ , pcm (2)		Adjusted ρ , pcm		Adjusted k_{eff}	σ
	ρ , ϕ	σ_{total} , ϕ	ρ , pcm	σ_{total} , pcm	ρ , pcm	σ , pcm	ρ_{adj} , pcm	σ , pcm		
96	-17.33	0.14	-58.25	0.47	41.76	13.70	-16.49	13.71	0.99984	0.00014
109	-17.03	0.47	-57.24	1.59	41.76	13.70	-15.48	13.79	0.99985	0.00014
110	-22.08	0.48	-74.21	1.61	41.76	13.70	-32.45	13.79	0.99968	0.00014
111	-30.82	0.50	-103.59	1.67	41.76	13.70	-61.83	13.80	0.99938	0.00014
112	-39.29	0.53	-132.05	1.77	41.76	13.70	-90.29	13.81	0.99910	0.00014

- 1) The measured reactivity values for L109 – L112 in Table 3.21 were added to the measured reactivity for L096 to produce the values shown in column 2 for L109 – L112.
- 2) Bias exists because room return, impurities in the depleted uranium plates and the Kel-F coating on the depleted uranium plates are neglected in the as-built models. The bias values shown in Table 3.23 were determined as part of the uncertainty analysis for the ZPPR-15B reference critical configuration.

Table 3.24 shows the measured and calculated sodium void worths for the ZPPR-15B manometer experiment. Column 4 shows the total measured sodium void worth in units of pcm. Conversion of the measured reactivity from cents to pcm introduces a small uncertainty due to uncertainties in plate compositions and a larger reactivity uncertainty due to the 5% β_{eff} uncertainty (column 6). The total uncertainty for the measured sodium void worth after conversion from cents to pcm is shown in column 8. The sodium void worth in the ZPPR-15B manometer experiment were calculated with MCNP6.1 and ENDF/B-VII.0 cross sections.

Table 3-24 Measured and Calculated Worths in the ZPPR-15B Sodium Manometer Experiment.

Step (1)	Measured ρ , ¢		Measured ρ , pcm					Calculated ρ , pcm		C/E - 1, %	
	ρ_{meas} , ¢	σ_{meas} , ¢	ρ_{meas} , pcm	σ_{meas} , pcm	$\sigma(\beta)$, pcm (2)	σ_{comp} , pcm (3)	σ_{total} , pcm (4)	ρ , pcm	σ , pcm	C/E - 1, %	σ , %
L109 - L110	-5.05	0.49	-16.97	1.63	0.85	0.60	1.94	-19.10	2.84	12.6	21.1
L110 - L111	-8.74	0.48	-29.38	1.62	1.47	0.60	2.27	-34.20	2.84	16.4	13.2
L110 - L112	- 17.21	0.50	-57.84	1.69	2.89	0.60	3.40	-55.34	2.84	-4.3	7.5

- 1) Steps correspond to Table 3.22.
- 2) This is the uncertainty resulting from the 5% uncertainty in the β_{eff} used to convert the reactivity from cents to pcm.
- 3) This is the uncertainty resulting from the uncertainty in plate compositions.
- 4) The σ_{total} value in column 8 is the final total uncertainty for the measured reactivity expressed in pcm.

4 Control Rod Worth Measurements in ZPPR-15

The worth of simulated control rods was measured in ZPPR-15A, ZPPR-15B, ZPPR-15C and ZPPR-15D although the measured control rod worths for ZPPR-15C were not reported. It should be noted that the control rod worths measured in these experiments were not the worths of the operational control rods used to control ZPPR. The operational control rods used in ZPPR were narrow stainless-steel clad boron carbide blades located within stainless steel guide tubes. Each guide tube was 0.5 in (1.27 cm) wide and was placed at the side of a matrix tube. The remaining space in the matrix tube containing a guide tube was occupied by a narrow drawer filled with normal plates of core, axial blanket and axial reflector materials. The nominal interior width of a narrow drawer was 1.5 in (3.81 cm).

Operational control rods in ZPPR were poison safety rods and poison shim rods (PSRs in both cases). Four safety rods were located at symmetric locations in the inner core in each matrix half of ZPPR-15. These rods were fully withdrawn during normal operations. Eight shim rods were located at symmetric positions in the outer core in each matrix half of ZPPR-15. These shim rods were used for normal reactor control purposes and were positioned as required to maintain the desired critical or subcritical configuration.

The mockup control rods used in these experiments simulated control rods in an LMFR. In ZPPR-15, a mockup control rod (CR) or control rod position (CRP) consisted of a 2 x 2 array of 36-inch drawers. For a CR, the first 18 in (45.72 cm) of each drawer was filled with columns of boron carbide plates and sodium plates; the remainder of each CR drawer was filled with sodium plates. Each CRP drawer was completely filled with sodium plates. A CR simulated

an inserted LMFR control rod, and a CRP simulated a withdrawn LMFR control rod, i.e., an empty control rod channel filled with sodium.

There was a single CR or CRP in the center of the core for the ZPPR-15A measurements. For ZPPR-15B and ZPPR-15D, there were 13 CR/CRP positions in the inner core. The CR/CRP at the center of the core was designated CR/CRP 1. The six CR/CRP positions in a ring at the outer edge of the inner core were designated CRs/CRPs 8 – 13. The six CR/CRP positions in a ring between the center CR/CRP and the outer ring of CRs/CRPs were designated CRs/CRPs 2 – 7.

Figure 4.1 shows the positions of CRs and CRPs in ZPPR-15. The seven CRs in Figure 4.1 are red. The six CRPs in this figure are the 2 x 2 arrays of lighter green cells between the inner and outer CRs. The CRs in Figure 4.1 are in positions 1 (center) and 8 – 13 (outer ring); the CRPs in this figure are in positions 2 – 7. CRs in positions 1 and 8 – 13 were designated as primary CRs, and CRs in positions 2 – 7 were designated as secondary CRs for the ZPPR-15 control rod worth measurements.

Figure 4-1 ZPPR-15 – CR/CRP Positions

The 13 CR/CRP positions shown in Figure 4.1 apply to all control rod worth measurements in ZPPR-15A, ZPPR-15B and ZPPR-15D. Various patterns of inserted CRs and CRPs were measured in ZPPR-15A, ZPPR-15B and ZPPR-15D. In most experiments, a CR was placed in half 1 and half 2 to simulate a fully inserted control rod, or a CRP was placed in both matrix halves to simulate a fully withdrawn control rod. In a few cases, a CR was placed in one matrix half and a CRP was placed in the other matrix half to simulate a partially inserted control rod.

Only one control rod worth measurement was performed in ZPPR-15C, and the results of that measurement were not reported for unknown reasons.

ZPPR operated at low power, so all control rod worth measurements were performed at room temperature.

4.1 Control Rod Worth Measurement Technique

After the subcritical reference configuration was established for the control rod worth measurements, normal core drawers at some or all of the CR/CRP positions shown in Figure 4.1 were replaced with CR drawers and/or CRP drawers to create the control rod insertion pattern of interest. The change in subcriticality of the experimental configuration relative to the subcritical reference configuration was measured with the modified source multiplication technique as described in Section 2.2.

Changing the core loading required shutting down the reactor, separating the matrix halves, making the desired changes in the core loading, bringing the matrix halves together again and moving the operational control rods to establish the desired configuration. The full sequence of measurements could extend over several days. There was some ^{241}Pu decay during the elapsed time, and the average reactor temperature could change slightly as a result of the time required to establish the new configuration. There could also be a small difference in the interface gap between the reference configuration and the modified configuration. In order to minimize experimental uncertainty and facilitate analysis, the experimenters adjusted the measured values of the control rod worth to a common decay date, temperature and interface gap using the measured ^{241}Pu decay, temperature and interface gap coefficients.

4.2 Control Rod Worth Uncertainties

The published uncertainties for the control rod worth measurements include a) the statistical uncertainty in the actual measurement, b) the correlated uncertainty related to the criticality measurement of the reference configuration, the reactivity calibration, and source ratio uncertainty and c) small uncertainties related to the adjustment to common measurement conditions (common ^{241}Pu decay date, temperature and interface gap). Additional uncertainties contribute to the total uncertainty for the control rod worth measurement.

4.2.1 Experimental Technique for Control Rod Worth Measurements

Control rod worth measurements were simpler than sodium void worth measurements in ZPPR for several reasons. In sodium void worth measurements, each core drawer in the void zone was removed from the matrix, modified by replacing sodium plates with empty void cans, and reloaded into the matrix in its original location. In the control rod worth experiments, configuration changes were direct replacements of one set of drawers by another set of drawers. For example, a 2 x 2 array of normal core drawers in each half was replaced by another 2 x 2 array of drawers to create a CR or CRP, a CR was replaced by a CRP, or a CRP was replaced by a CR. This direct replacement reduces the problems associated with changes in plate positions due to in-drawer plate substitution and drawer handling. In addition, changes for CR/CRP configurations generally involved less drawers than changes for the sodium void worth configurations. Changes in the CR/CRP configurations involved 4 – 52 drawers per half, depending upon the configuration of interest. Changes for the sodium void worth measurements involved 148 drawers per half in ZPPR-15A and 52 drawers per half in ZPPR-15B, ZPPR-15C and ZPPR-15D. Consequently, plate shifting is much less important for the control rod worth measurements than for sodium void worth measurements. Plate shifting is

frequently a major component of reproducibility uncertainty, so reproducibility uncertainty is likely to be much smaller for control rod worth measurements than for sodium void worth measurements.

There was a small mismatch between the amount of stainless steel in the canned boron carbide plates and sodium plates in a CR drawer and the amount of stainless steel in the sodium plates in a CRP drawer. Likewise, there was likely a small mismatch between the masses of stainless steel in individual drawers. The mismatch for the drawer mass applies to all CR drawers, CRP drawers and normal core drawers that were replaced by the CR and CRP drawers. Note that this particular mismatch does not apply to the sodium void measurements because the same drawers were used in the subcritical reference configuration and in the sodium void configurations.

The ZPPR staff apparently did not regard any correction or uncertainty for the mismatch in steel masses to be important for the control rod worth measurements. The steel mismatch and the associated reactivity correction were reported for the sodium void worth measurements. Reports for the control rod worth experiments do not mention any steel mismatch, and there is no evidence that any reactivity correction for the steel mismatch was applied in the control rod worth measurements.

This mismatch in the steel mass is not important for the control rod worth measurements. The worth of sodium is small, and the worth of stainless steel per kilogram is much greater than the worth of sodium per kilogram. Consequently, correction for the mismatch in steel masses could have a small but discernible effect (approximately $0.2\text{¢} - 2\text{¢}$) for sodium void measurements. For measurements of CR worth and CRP worth, the worth of replacing normal core drawers with CR drawers and/or CRP drawers is large. Likewise, the worth of replacing CRPs by CRs or vice versa is large. Any small correction or uncertainty related to the steel mismatch in the control rod worth measurements would be negligible compared to the total uncertainty for the measurement, which is generally dominated by the 5% uncertainty in the reactivity conversion from the measurement units, cents, to the calculation units, $\Delta k/k_1 k_2$ or pcm.

Standard drawer-loading and drawer-handling procedures applied to all ZPPR-15 experiments. The experimenters would have made certain that all drawer fronts were exactly flush with the front edge of the matrix. Tabs on the drawer fronts mated with notches in the sides of the matrix tubes to ensure consistent positioning. Drawers were inserted into matrix tubes slowly to minimize plate shifting. The procedure for loading drawers into the matrix tubes minimized unintentional changes in the axial position of the core material within each matrix half. Springs inserted in the backs of the drawers pushed the plates forward to minimize unintentional changes in the plate positions.

The preceding paragraphs cover general procedures for minimizing experimental uncertainties, but there are residual uncertainties related to experimental technique. There is a statistical uncertainty in individual detector count rates for the measurement and an additional statistical uncertainty associated with processing the data from the 64 detectors used in the MSM technique.

Another uncertainty is the reproducibility uncertainty. Reproducibility uncertainty refers to the small difference in measured results when the experimenter attempts to reconstruct a previous experimental configuration. For example, at the end of a series of control rod worth experiments, the experimenter might reconstruct the subcritical reference configuration. The difference between the excess reactivity of the original subcritical reference configuration and the excess reactivity of the reconstructed subcritical reference configuration is the reproducibility uncertainty.

The ZPPR staff reported the reproducibility uncertainty for the sodium void worth measurements, but they did not report any reproducibility uncertainty for the control rod worth measurements. The contribution of the reproducibility uncertainty to the total uncertainty for the control rod worth measurements would be much smaller than the contribution of the reproducibility uncertainty to the total uncertainty for the sodium void worth measurements because the plate shifting component of reproducibility uncertainty is much smaller for control rod worth measurements.

There is a correlated uncertainty for all measurements related to the measurement of the reference subcritical configuration, reactivity scale calibration and source ratio uncertainty.

All uncertainty components related to the experimental technique are small compared to the contribution from reactivity conversion.

4.2.2 Reactivity Adjustments for Control Rod Worth Measurements

The uncertainties associated with adjustment to a common decay date, temperature and interface gap were discussed in Section 2.3.2 and apply here as well.

The experimenters adjusted each measured control rod worth configuration to the temperature, ²⁴¹Pu decay date and matrix interface gap width of the subcritical reference configuration. This adjustment simplified analysis by providing a common basis for comparing configurations and measured values. These adjustments add small uncertainties because the measured temperature coefficient, interface gap coefficient and ²⁴¹Pu decay coefficient used for the adjustments had small associated uncertainties. The uncertainties associated with the adjustments are very small compared to the uncertainty associated with reactivity conversion, so further refinement of these values is not warranted.

4.2.3 Effects of Material Composition Uncertainties for Measurements of Control Rod Worth

For the control rod worth measurements, the subcritical reference configuration and the CR/CRP insertion configurations were identical except for replacement of core drawers by CR/CRP drawers in 4 – 52 matrix tubes per half. Consequently, the uncertainty contributions of the plates, drawers, and matrix tubes to the uncertainties in the measured values would be highly correlated between the subcritical reference configuration and the corresponding CR/CRP configurations excluding the materials in the drawers that are changed. The uncertainty contributions of plates, drawers, and matrix tubes will change slightly between the subcritical reference configuration and the CR/CRP configuration due to small changes in the neutron spectrum, but these changes are negligible compared to other uncertainties discussed below.

There is a 0.15% uncertainty in the masses of the sodium plates and boron carbide plates in the CRs and CRPs [1]. Uncertainty analysis for the ZPPR-15 sodium void measurements showed that the worth of uncertainties in the sodium mass and impurities was ~ 0.05 pcm. The number of sodium plates changed in the sodium void measurements are comparable to or larger than the numbers of sodium plates in the CR/CRP drawers. The contribution to the total control rod worth uncertainty from uncertainties in the sodium plate masses and sodium impurities is in the 0.05 – 0.15 pcm range. This value is negligible compared to the total uncertainty for the control rod worth measurements, so refinement of the sodium plate contribution is not worth pursuing.

The worth of the 0.15% uncertainty in the mass of the boron carbide plates was computed for ZPPR-15B loading 102 (L102). This loading was chosen because L102 had 13 inserted CRs which is the maximum number of CRs used in the ZPPR-15 control rod worth measurements. Consequently, L102 has the maximum number of boron carbide plates among the measured ZPPR-15 configurations. The computed worth of the uncertainty in the mass of the boron carbide plates for L102 is 11.2 pcm.

The boron in the boron carbide plates was 18.32 wt.% ^{10}B and 81.68 wt.% ^{11}B . It is likely that these were measured values, but there are no details of the measurements and no way to quantify the measurement uncertainty. Because there is no other information, it is assumed here that the worth of the uncertainty in the boron isotopics is no larger than the worth of the 0.15% mass uncertainty, i.e., 11.2 pcm for L102. For other ZPPR-15 control rod worth measurements, the worth of the 0.15% boron carbide mass uncertainty and the uncertainty in the boron isotopics are each assumed to be the 11.2 pcm values for L102 scaled for the differences in the numbers of boron carbide plates present relative to L102. All simulated control rods in ZPPR-15 had the same types of columns of boron carbide plates, so the mass of boron carbide present in any CR worth loading is directly proportional to the number of boron carbide plates present in that loading.

This is equivalent to assuming a 0.15% uncertainty in the ^{10}B weight percent and is an overestimate of the $^{10}\text{B}/\text{B}$ uncertainty. Because the total uncertainty for the control rod worth measurements is dominated by the uncertainty in reactivity conversion, the effect of this approximation for the $^{10}\text{B}/\text{B}$ uncertainty is small.

4.2.4 *Reactivity Conversion for Control Rod Worth Measurements*

The control rod worths were measured in units of cents. The calculated worths and associated uncertainties are expressed in units of $\Delta k/k_{1k2}$ or pcm. Conversion from cents to pcm or from pcm to cents requires β_{eff} which was calculated by the experimenters. However, β_{eff} is uncertain, and its estimated uncertainty is 5% (see Section 2.3.4). The 5% uncertainty in β_{eff} contributes an additional uncertainty to the final control rod worths. In general, the 5% uncertainty in β_{eff} is the dominant uncertainty for the control rod worth measurements.

5 Measured Control Rod Worths and Total Uncertainties

Control rod worths were measured in all four phases of the ZPPR-15 program, but the ZPPR staff only published results for ZPPR-15A, ZPPR-15B and ZPPR-15D.

5.1 Control Rod Worths and Total Uncertainties for ZPPR-15A

Control rod worths in ZPPR-15A were limited to measurements of a single CR or CRP at the center of the core. The following configurations were measured in ZPPR-15A:

L025 – Loading 25 was the subcritical reference configuration for control rod worth measurements in ZPPR-15A.

L026 – One CRP was placed at the center of the core in both matrix halves.

L027 – One CR was placed at the center of the core in both matrix halves. The first 45.72 cm of each CR drawer was filled with boron carbide plates; the remainder of each CR drawer was filled with sodium plates.

L028 – One CR was placed at the center of the core in both matrix halves. The first 45.72 cm of each CR drawer contained alternating columns of boron carbide plates and sodium plates (50 vol.% boron carbide plates, 50 vol.% sodium plates); the remainder of each CR drawer was filled with sodium plates.

Figures 5.1 – 5.8 show the core loading maps or matrix maps for ZPPR-15A loadings 25 – 28. The interpretation of the colors in these figures is identical to the interpretation of the colors in Figures 3.1 – 3.16 with two exceptions. The four lighter green cells in the centers of Figures 5.3 and 5.4 are a CRP. The four red cells in the centers of Figures 5.5 – 5.8 are the two versions of a CR in loadings 27 and 28.

Sodium Void Worth and Control Rod Worth Measurements in ZPPR-15
April 30, 2020

Figure 5-1 ZPPR-15A Loading 25 – Half 1

Sodium Void Worth and Control Rod Worth Measurements in ZPPR-15
April 30, 2020

Figure 5-2 ZPPR-15A Loading 25 – Half 2

Sodium Void Worth and Control Rod Worth Measurements in ZPPR-15
April 30, 2020

Figure 5-3 ZPPR-15A Loading 26 – Half 1

The CRP consists of the four lighter green cells at the core center (drawer master 601) in Figures 5.3 and 5.54.

Sodium Void Worth and Control Rod Worth Measurements in ZPPR-15
April 30, 2020

Figure 5-4 ZPPR-15A Loading 26 – Half 2

Sodium Void Worth and Control Rod Worth Measurements in ZPPR-15
April 30, 2020

Figure 5-5 ZPPR-15A Loading 27 – Half 1.

The CR consists of the four red cells at the center of Figures 5.5 – 5.8 (drawer master 602 or 603).

Sodium Void Worth and Control Rod Worth Measurements in ZPPR-15

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Figure 5-6 ZPPR-15A Loading 27 – Half 2

Sodium Void Worth and Control Rod Worth Measurements in ZPPR-15
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Figure 5-7 ZPPR-15A Loading 28 – Half 1

Figure 5-8 ZPPR-15A Loading 28 – Half 2

The published reports do not list a reproducibility uncertainty for the control rod measurements, but it is likely that there was a small reproducibility uncertainty because a ZPPR configuration cannot be reproduced to an arbitrary degree of precision. A reproducibility uncertainty of 0.13¢ is assumed here to match the value for sodium void measurements in ZPPR-15A. The total uncertainty is dominated by the 5% uncertainty associated with reactivity conversion, so further refinement of the reproducibility uncertainty is not warranted. Table 5.1 shows the measured reactivities for L025 – L028 as reported by the ZPPR staff.

Table 5-1 Measured Control Rod Worths in ZPPR-15A

Loading	State (1)	ρ , \$	σ_{stat} , \$ (2)	σ_{corr} , \$ (3)	σ_{repro} , \$ (4)	σ_{total} , \$	σ_{total} , %
25	Subcritical Reference	- 0.210					
26	CRP	- 0.479	0.00115	0.00355	0.0013	0.00396	0.826
27	CR – 100% B ₄ C (5)	- 3.890	0.00428	0.02610	0.0013	0.02648	0.681
28	CR – 50% B ₄ C (6)	- 2.976	0.00298	0.02032	0.0013	0.02058	0.691

- 1) Reactivity changes for loadings 26 – 28 were derived relative to L031 (reactor run 50) which was a rebuild of L025. The reactivity of L031 or L025 was -0.210\$ as determined by inverse kinetics analysis.
- 2) The statistical uncertainty includes detector statistics plus the adjustments for temperature, ²⁴¹Pu decay and the interface gap.
- 3) The correlated uncertainty is due to reactivity scale calibration and the source ratio uncertainty.
- 4) A reproducibility uncertainty of 0.13¢ was assumed for consistency with the sodium void worth measurements.
- 5) The 18 in (45.72 cm) control rod section of the CR drawers consisted entirely of B₄C plates.
- 6) The 18 in (45.72 cm) control rod section of the CR drawers consisted of 50% B₄C plates and 50% sodium plates by volume.

The reported reactivities for individual loadings in Table 5.1 can be converted to values of k_{eff} using the reported β_{eff} value for ZPPR-15A, 0.003357. Table 5.2 shows the values of k_{eff} determined from the reactivities for the individual loadings in Table 5.1. The adjusted k_{eff} values in Table 5.2 include a positive bias of 33.63 pcm to account for features of the actual ZPPR-15A assembly such as room return that are not included in the as-built ZPPR-15 models (see Ref. 1). In some cases, the adjusted k_{eff} may be greater than 1.0 due to this bias although all experimental configurations were subcritical.

Table 5-2 Measured Reactivity and k_{eff} for ZPPR-15A Loadings 25 – 28

Loading	Measured ρ , \$ (1)		Measured ρ , pcm		Bias ρ , pcm (2)		Adjusted ρ , pcm		Adjusted k_{eff}	σ
	ρ , \$	σ_{total} , \$	ρ , pcm	σ_{total} , pcm	ρ , pcm	σ , pcm	ρ_{adj} , pcm	σ , pcm		
25	-0.210		-70.50	0.00	33.63	13.68	-36.87	13.68	0.99963	0.00014
26	-0.689	0.004	-231.30	1.33	33.63	13.68	-197.67	13.74	0.99803	0.00014
27	-4.100	0.026	-1376.37	8.89	33.63	13.68	-1342.74	16.32	0.98675	0.00016
28	-3.186	0.021	-1069.54	6.91	33.63	13.68	-1035.91	15.32	0.98975	0.00015

- 1) The measured reactivity values for loadings 26 – 28 in Table 5.1 were added to the measured reactivity for L025, -0.210\$, to produce the values shown in column 2 for loadings 26 – 28.

- 2) Bias exists because room return, impurities in the depleted uranium (DU) plates and the Kel-F coating on the DU plates are neglected in the as-built models. The bias values shown in Table 5.2 were determined as part of the uncertainty analysis for the ZPPR-15A reference critical configuration.

The uncertainties listed in Table 5.1 are the uncertainties for the experimental measurement. There are additional uncertainties related to the plates and the interface gap. Table 5.3 shows the additional uncertainties for the plate compositions and the interface gap in the ZPPR-15A control rod worth measurements.

Table 5-3 Plate and Gap Uncertainties for the ZPPR-15A Control Rod Worth Measurements

Loading	σ_{gap} , pcm (1)	σ_{plates} , pcm (2)	σ_{Na} , pcm (3)	$\sigma_{\text{B4C Mass}}$, pcm (4)	$\sigma_{\text{B-10}}$, pcm (5)	σ_{total} , pcm
26	0.20	0.60	0.10	0.00	0.00	0.64
27	0.20	0.60	0.10	1.72	1.72	2.52
28	0.20	0.60	0.10	0.86	0.86	1.38

- 1) The maximum contribution of the interface gap uncertainty was less than 0.15 pcm for the sodium void worth measurements.
- 2) The contribution of the uncertainties in plate compositions was ~0.6 pcm in the sodium void worth measurements.
- 3) The contribution of the uncertainty in sodium plate masses and compositions was ~0.1 pcm for the sodium void worth measurements.
- 4) The B₄C plate mass uncertainty is 11.2 pcm (13 fully inserted CRs in L102) scaled by the number of fully inserted CRs or B₄C plates in each loading.
- 5) The uncertainty in the boron isotopics is assumed to be identical to the uncertainty in the B₄C plate mass.

The worths of the control rod configurations in ZPPR-15A were calculated with MCNP6.1 and ENDF/B-VII.0 cross sections. Table 5.4 shows the measured and calculated control rod worths in ZPPR-15A.

Table 5-4 Measured and Calculated Control Rod Worths in ZPPR-15A

Step (1)	Measured ρ , \$		Measured ρ , pcm		$\sigma(\beta)$, pcm (2)	σ_{plate} , pcm (3)	σ_{total} , pcm (4)	Calculated ρ , pcm		C/E - 1, %	
	ρ_{meas} , \$	σ_{meas} , \$	ρ_{meas} , pcm	σ_{meas} , pcm				ρ , pcm	σ , pcm	C/E - 1, %	σ , %
L025 - L026	-0.479	0.0040	-160.8	1.33	8.04	0.64	8.2	-157.9	2.8	-1.8	5.3
L025 - L027	-3.890	0.0265	-1305.9	8.89	65.29	2.52	65.9	-1258.5	2.9	-3.6	4.9
L025 - L028	-2.976	0.0206	-999.0	6.91	49.95	1.38	50.4	-916.9	2.8	-8.2	4.6

- 1) Steps correspond to Table 5.1.
- 2) This is the uncertainty resulting from the 5% uncertainty in the β_{eff} used to convert the reactivity from cents to pcm.

- 3) This is the uncertainty resulting from the uncertainty in plate compositions.
- 4) The σ_{total} value in column 8 is the final total uncertainty for the measured reactivity expressed in pcm.

5.2 Control Rod Worths and Total Uncertainties for ZPPR-15B

The subcritical reference and six CR/CRP configurations were modeled for ZPPR-15B. Each CRP consisted of a 2 x 2 array of drawers filled with sodium plates. Each CR consisted of a 2 x 2 array of drawers. The first 18 in (45.72 cm) of each CR drawer contained alternating columns of boron carbide plates and sodium plates (50 vol.% boron carbide, 50 vol.% sodium plates); the remainder of each CR drawer was filled with sodium plates.

In ZPPR-15B and ZPPR-15D, there were 13 possible CR/CRP locations (see Figure 4.1). CR1 was a CR in the center of the core. CR8 – CR13 consisted of an outer ring of CRs at the outer edge of the inner core zone, i.e., the zone containing zirconium plates. CR2 – CR7 consisted of an intermediate ring of rods between CR1 and the outer ring of CRs, i.e., CR8 – CR13. The primary CRs were CR1 and CR8 – CR13. The secondary CRs were CR2 – CR7.

The following configurations were modeled for ZPPR-15B:

L096 – Loading 96 was the subcritical reference configuration for the control rod worth measurements in ZPPR-15B.

L100 – Five primary CRs were inserted in positions 8 – 12.

L102 – All 13 CRs were inserted.

L103 – CR1 and CR8 – CR13 were inserted in half 1. The remaining 6 secondary positions in half 1 and all 13 positions in half 2 were occupied by CRPs.

L104 – CR1 and CR8 – CR13 were inserted in both halves. CRP2 – CRP7 were inserted in both halves.

L105 – All CRs were inserted except for position 6 which was occupied by a CRP.

L106 – All 13 positions were occupied by CRPs.

Figures 5.9 – 5.22 show the core loading maps or matrix maps for the ZPPR-15B control rod worth measurements. The interpretation of the colors in these figures is identical to the interpretation of the colors in Figures 3.1 – 3.16 with two exceptions. The four lighter green cells (drawer master 601) at various locations in these figures are CRPs. The four red cells (drawer master 622) at various locations in these figures are CRs.

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Figure 5-9 ZPPR-15B Loading 96 – Half 1

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Figure 5-10 ZPPR-15B Loading 96 - Half 2

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Figure 5-11 ZPPR-15B Loading 100 – Half 1

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Figure 5-12 ZPPR-15B Loading 100 – Half 2

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Figure 5-13 ZPPR-15B Loading 102 – Half 1

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Figure 5-14 ZPPR-15B Loading 102 – Half 2

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Figure 5-15 ZPPR-15B Loading 103 – Half 1

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Figure 5-16 ZPPR-15B Loading 103 – Half 2

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Figure 5-17 ZPPR-15B Loading 104 – Half 1

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Figure 5-18 ZPPR-15B Loading 104 – Half 2

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Figure 5-19 ZPPR-15B Loading 105 – Half 1

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Figure 5-20 ZPPR-15B Loading 105 – Half 2.

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Figure 5-21 ZPPR-15B Loading 106 – Half 1

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Figure 5-22 ZPPR-15B Loading 106 – Half 2

A reproducibility uncertainty of 0.13¢ is assumed here to match the value for the sodium void measurements in ZPPR-15B. The total uncertainty is dominated by the 5% uncertainty associated with reactivity conversion, so further refinement of the reproducibility uncertainty is not warranted. Table 5.5 shows the measured reactivities for L096 – L106 as reported by the ZPPR staff.

Table 5-5 Measured Control Rod Worths in ZPPR-15B

Loading	ρ , \$ (1)	σ_{stat} , \$ (2)	σ_{corr} , \$ (3)	σ_{repro} , \$ (4)	σ_{total} , \$	σ_{total} , %
96	-0.1733				0.0014	
100	-12.189	0.014	0.104	0.0013	0.105	0.865
102	-37.576	0.068	0.321	0.0013	0.328	0.873
103	-14.358	0.024	0.122	0.0013	0.124	0.866
104	-22.953	0.037	0.195	0.0013	0.199	0.866
105	-34.337	0.063	0.293	0.0013	0.300	0.873
106	-6.311	0.007	0.054	0.0013	0.054	0.859

- 1) Reactivity changes for loadings 100 – 106 were derived relative to L096 (reactor run 178). The reactivity of L096 was $-0.1733\$ \pm 0.0014\$$ as determined by inverse kinetics analysis.
- 2) The statistical uncertainty includes detector statistics plus the adjustments for temperature, ^{241}Pu decay and the interface gap.
- 3) The correlated uncertainty is due to the reactivity scale calibration and the source ratio uncertainty.
- 4) A reproducibility uncertainty of 0.13% was assumed for consistency with the sodium void worth measurements.

Reactivities for loadings in Table 5.5 can be converted to values of k_{eff} using the reported β_{eff} value for ZPPR-15B, 0.003361. Table 5.6 shows the values of k_{eff} determined from the reactivities for the loadings in Table 5.5. The adjusted k_{eff} values in Table 5.6 include a positive bias of 41.76 pcm to account for features of the actual ZPPR-15B assembly such as room return that are not included in the as-built ZPPR-15 models (see Ref. 1). In some cases, the adjusted k_{eff} may be greater than 1.0 due to this bias although all experimental configurations were subcritical.

Table 5-6 Measured Reactivity and k_{eff} for ZPPR-15B Loadings 96 – 106

Loading	Measured ρ , \$ (1)		Measured ρ , pcm		Bias ρ , pcm (2)		Adjusted ρ , pcm		Adjusted k_{eff}	σ
	ρ , \$	σ_{total} , \$	ρ , pcm	σ_{total} , pcm	ρ , pcm	σ , pcm	ρ_{adj} , pcm	σ , pcm		
96	-0.1733	0.0014	-58.2	0.47	41.76	13.70	-16.49	13.71	0.99984	0.00014
100	-12.362	0.105	-4155.0	35.44	41.76	13.70	-4113.21	38.00	0.96049	0.00038
102	-37.749	0.328	-12687.5	110.25	41.76	13.70	-12645.78	111.10	0.88774	0.00111
103	-14.531	0.124	-4884.0	41.79	41.76	13.70	-4842.21	43.98	0.95381	0.00044
104	-23.126	0.199	-7772.8	66.81	41.76	13.70	-7730.99	68.20	0.92824	0.00068
105	-34.510	0.300	-11598.9	100.75	41.76	13.70	-11557.15	101.68	0.89640	0.00102
106	-6.484	0.054	-2179.4	18.23	41.76	13.70	-2137.61	22.80	0.97907	0.00023

- 1) The measured reactivity values for loadings 100 – 106 in Table 5.5 were added to the measured reactivity for L096, $-0.1733\$$, to produce the values shown in column 2 for loadings 100 – 106.

- 2) Bias exists because some experimental features are neglected in as-built models. Bias values in Table 5.6 were determined for the ZPPR-15B reference critical configuration uncertainty analysis.

The uncertainties listed in Table 5.5 are the uncertainties for the experimental measurement. There are additional uncertainties related to the plates and the interface gap. Table 5.7 shows the additional uncertainties for the plate compositions and the interface gap in the ZPPR-15B control rod worth measurements.

Table 5-7 Plate and Gap Uncertainties for the ZPPR-15B Control Rod Worth Measurements.

Loading	σ_{gap} , pcm (1)	σ_{plates} , pcm (2)	σ_{Na} , pcm (3)	$\sigma_{\text{B}_4\text{C Mass}}$, pcm (4)	$\sigma_{\text{B-10}}$, pcm (5)	σ_{total} , pcm
L100	0.20	0.60	0.10	4.31	4.31	6.13
L102	0.20	0.60	0.10	11.20	11.20	15.85
L103	0.20	0.60	0.10	3.02	3.02	4.31
L104	0.20	0.60	0.10	6.03	6.03	8.55
L105	0.20	0.60	0.10	10.34	10.34	14.64
L106	0.20	0.60	0.10	0.00	0.00	0.64

- 1) The maximum contribution of the interface gap uncertainty was less than 0.15 pcm for the sodium void worth measurements.
- 2) The contribution of the uncertainties in plate compositions was ~0.6 pcm in the sodium void worth measurements.
- 3) The contribution of the uncertainty in sodium plate masses and compositions was ~0.1 pcm for the sodium void worth measurements.
- 4) The B₄C plate mass uncertainty is 11.2 pcm (13 fully inserted CRs in L102) scaled by the number of fully inserted CRs in each loading.
- 5) The uncertainty in the boron isotopics is assumed to be identical to the uncertainty in the B₄C plate mass.

The control rod worth configurations in ZPPR-15B were calculated with MCNP6.1 and ENDF/B-VII.0 cross sections. Table 5.8 shows the measured and calculated control rod worths in ZPPR-15B.

Table 5-8 Measured and Calculated Control Rod Worths in ZPPR-15B

Step (1)	Measured ρ , \$		Measured ρ , pcm					Calculated ρ , pcm		C/E - 1, %	
	ρ_{meas} , \$	σ_{meas} , \$	ρ_{meas} , pcm	σ_{meas} , pcm	$\sigma(\beta)$, pcm (2)	σ_{plate} , pcm (3)	σ_{total} , pcm (4)	ρ , pcm	σ , pcm	C/E - 1, %	σ , %
L096 - L100	-12.189	0.105	-4096.7	35.44	204.84	6.13	208.0	-3916.9	2.9	-4.4	4.9
L096 - L102	-37.576	0.328	-12629.3	110.25	631.46	15.85	641.2	-11775.6	3.0	-6.8	4.7
L096 - L103	-14.358	0.124	-4825.7	41.79	241.29	4.31	244.9	-4692.1	2.9	-2.8	4.9
L096 - L104	-22.953	0.199	-7714.5	66.81	385.73	8.55	391.6	-7375.2	2.9	-4.4	4.9
L096 - L105	-34.337	0.300	-11540.7	100.75	577.03	14.63	586.0	-11011.4	3.0	-4.6	4.8
L096 - L106	-6.311	0.054	-2121.1	18.23	106.06	0.64	107.6	-2034.9	2.9	-4.1	4.9

- 1) Steps correspond to Table 5.5.
- 2) This is the uncertainty resulting from the 5% uncertainty in the β_{eff} used to convert the reactivity from cents to pcm.
- 3) This is the uncertainty resulting from the uncertainty in plate compositions.
- 4) The σ_{total} value in column 8 is the final total uncertainty for the measured reactivity expressed in pcm.

5.3 Control Rod Worths and Total Uncertainties for ZPPR-15D

There was one control rod worth measurement in ZPPR-15C, but the results of that measurement were not reported. The following configurations were modeled in ZPPR-15D:

L193 – Loading 193 was the subcritical reference configuration for the control rod worth measurements in ZPPR-15D.

L194 – CRP1 was present in the center of the core. All other CR/CRP positions were occupied by normal core drawers.

L195 – CR1 was present in the center of the core. All other CR/CRP positions were occupied by normal core drawers.

L198 – CR1 was present in the center of the core and CR8 – CR13 were present in the outer ring. CR/CRP positions 2 – 7 in the intermediate ring were occupied by normal core drawers.

L199 – All 13 CRs were present in the core.

Figures 5.23 – 5.32 show the core loading maps or matrix maps for the ZPPR-15D control rod worth measurements in loadings 193 – 199. The interpretation of the colors in these figures is identical to the interpretation of the colors in Figures 3.1 – 3.16 with three exceptions. The four

lighter green cells (drawer master 601) at various locations in these figures are CRPs, the four red cells (drawer master 622) at various locations in these figures are CRs and the salmon-colored cells contain HEU fuel plates rather than Pu-U-Mo fuel plates. The white cells and green cells in the core are drawers containing Pu-U-Mo fuel. White cells contained one Pu-U-Mo fuel column, and green cells contained two Pu-U-Mo fuel columns. The Pu-U-Mo fuel in these drawers provided the distributed neutron source required for the MSM technique.

Figure 5-23 ZPPR-15D Loading 193 - Half 1

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Figure 5-24 ZPPR-15D Loading 193 – Half 2

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Figure 5-25 ZPPR-15D Loading 194 – Half 1

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Figure 5-26 ZPPR-15D Loading 194 - Half 2

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Figure 5-27 ZPPR-15D Loading 195 – Half 1

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Figure 5-28 ZPPR-15D Loading 195 – Half 2

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Figure 5-29 ZPPR-15D Loading 198 – Half 1

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Figure 5-30 ZPPR-15D Loading 198 – Half 2

Sodium Void Worth and Control Rod Worth Measurements in ZPPR-15

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Figure 5-31 ZPPR-15D Loading 199 – Half 1

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Figure 5-32 ZPPR-15D Loading 199 - Half 2

A reproducibility uncertainty of 0.13¢ is assumed here to match the value for sodium void measurements in ZPPR-15D. The total uncertainty is dominated by the 5% uncertainty associated with reactivity conversion, so further refinement of the reproducibility uncertainty is not warranted. Table 5.9 shows the measured reactivities for L193 – L199 as reported by the ZPPR staff.

Table 5-9 Measured Control Rod Worths in ZPPR-15D

Loading	ρ , \$ (1)	σ_{stat} , \$ (2)	σ_{corr} , \$ (3)	σ_{repro} , \$ (4)	σ_{total} , \$	σ_{total} , %
193	-0.0755				0.00054	
194	-0.158	0.0003	0.0013	0.0013	0.0019	1.197
195	-1.392	0.0027	0.0108	0.0013	0.0112	0.806
198	-9.726	0.0316	0.0751	0.0013	0.0815	0.838
199	-19.979	0.0897	0.1549	0.0013	0.1790	0.896

- 1) Reactivity changes for loadings 194 – 199 were derived relative to L193 (reactor run 326). The reactivity of L193 was $-0.0755\$ \pm 0.00054\$$ as determined by inverse kinetics analysis.
- 2) The statistical uncertainty includes detector statistics plus the adjustments for temperature, ^{241}Pu decay and the interface gap.
- 3) The correlated uncertainty is due to reactivity scale calibration and the source ratio uncertainty.
- 4) A reproducibility uncertainty of 0.13¢ was assumed for consistency with the ZPPR-15D sodium void worth measurements.

The reported reactivities for individual loadings in Table 5.9 can be converted to values of k_{eff} using the reported β_{eff} value for ZPPR-15D, 0.006564. Table 5.10 shows the values of k_{eff} determined from the reactivities for the individual loadings in Table 5.9. The adjusted k_{eff} values in Table 5.10 include a positive bias of 50.45 pcm to account for features of the actual ZPPR-15D assembly such as room return that are not included in the as-built ZPPR-15 models (see Ref. 1). In some cases, the adjusted k_{eff} may be greater than 1.0 due to this bias although all experimental configurations were subcritical.

Table 5-10 Measured Reactivity and k_{eff} for ZPPR-15D Loadings 193 – 199.

Loading	Measured ρ , \$ (1)		Measured ρ , pcm		Bias ρ , pcm (2)		Adjusted ρ , pcm		Adjusted k_{eff}	σ
	ρ , \$	σ_{total} , \$	ρ , pcm	σ_{total} , pcm	ρ , pcm	σ , pcm	ρ_{adj} , pcm	σ , pcm		
193	-0.0755	0.00054	-49.6	0.35	50.45	18.76	0.9	18.8	1.00001	0.00019
194	-0.234	0.0019	-153.3	1.24	50.45	18.76	-102.8	18.8	0.99897	0.00019
195	-1.468	0.0112	-963.3	7.37	50.45	18.76	-912.8	20.2	0.99095	0.00020
198	-9.802	0.0815	-6433.7	53.51	50.45	18.76	-6383.2	56.7	0.94000	0.00057
199	-20.054	0.1790	-13163.8	117.51	50.45	18.76	-13113.3	119.0	0.88407	0.00119

- 1) The measured reactivity values for loadings 194 – 199 in Table 5.9 were added to the measured reactivity for L193, $-0.0755\$$, to produce the values shown in column 2 for loadings 194 – 199.
- 2) Bias exists because room return, impurities in the depleted uranium (DU) plates, the Kel-F coating on the DU plates, HEU impurities and corrosion in the clad HEU plates (leaking end caps) are neglected in the as-built models. The bias values shown in Table

5.10 were determined as part of the uncertainty analysis for the ZPPR-15D reference critical configuration.

The uncertainties listed in Table 5.9 are the uncertainties for the experimental measurement. There are additional uncertainties related to the plates and the interface gap. Table 5.11 shows the additional uncertainties for the plates and interface gap in the ZPPR-15D control rod worth measurements.

Table 5-11 Plate and Gap Uncertainties for the ZPPR-15D Control Rod Worth Measurements

Loading	σ_{gap} , pcm (1)	σ_{plates} , pcm (2)	σ_{Na} , pcm (3)	$\sigma_{\text{B}_4\text{C Mass}}$, pcm (4)	$\sigma_{\text{B-10}}$, pcm (5)	σ_{total} , pcm
L194	0.20	0.60	0.10	0.00	0.00	0.64
L195	0.20	0.60	0.10	0.86	0.86	1.38
L198	0.20	0.60	0.10	6.03	6.03	8.55
L199	0.20	0.60	0.10	11.20	11.20	15.85

- 1) The maximum contribution of the interface gap uncertainty was less than 0.15 pcm for the sodium void worth measurements.
- 2) The contribution of the uncertainties in plate compositions was ~0.6 pcm in the sodium void worth measurements.
- 3) The contribution of the uncertainty in sodium plate masses and compositions was ~0.1 pcm for the sodium void worth measurements.
- 4) The B₄C plate mass uncertainty is 11.2 pcm (13 fully inserted CRs in L102) scaled by the number of fully inserted CRs in each loading.
- 5) The uncertainty in the boron isotopics is assumed to be identical to the uncertainty in the B₄C plate mass.

The worths of the control rod configurations in ZPPR-15D were calculated with MCNP6.1 and ENDF/B-VII.0 cross sections. Table 5.12 shows the measured and calculated control rod worths in ZPPR-15D.

Table 5-12 Measured and Calculated Control Rod Worths in ZPPR-15D

Step (1)	Measured ρ , \$		Measured ρ , pcm					Calculated ρ , pcm		C/E - 1, %	
	ρ_{meas} , \$	σ_{meas} , \$	ρ_{meas} , pcm	σ_{meas} , pcm	$\sigma(\beta)$, pcm (2)	σ_{plate} , pcm (3)	σ_{total} , pcm (4)	ρ , pcm	σ , pcm	C/E - 1, %	σ , %
L193 - L194	-0.158	0.0019	-103.7	1.24	5.19	0.64	5.4	-101.0	2.8	-2.7	5.7
L193 - L195	-1.392	0.0112	-913.7	7.37	45.69	1.38	46.3	-864.2	2.8	-5.4	4.8
L193 - L198	-9.726	0.0815	-6384.1	53.51	319.2 1	8.55	323.8	-5999.8	2.9	-6.0	4.8
L193 - L199	-19.979	0.1790	- 13114.2	117.5 1	655.7 1	15.8 5	666.4	-12193.7	3.0	-7.0	4.7

- 1) Steps correspond to Table 5.9.
- 2) This is the uncertainty resulting from the 5% uncertainty in the β_{eff} used to convert the reactivity from cents to pcm.
- 3) This is the uncertainty resulting from the uncertainty in plate compositions.
- 4) The σ_{total} value in column 8 is the final total uncertainty for the measured reactivity expressed in pcm.

5.4 Control Rod Worth and Total Uncertainty for the ZPPR-15D Segmented Control Rod Measurement

The worth of a special segmented control rod was measured at the core center in ZPPR-15D. In its fully inserted state, the segmented control rod consisted of three 8-in (20.32 cm) sections of B₄C separated by two sections of stainless steel and sodium plates. The steel segments separating the B₄C sections simulated links in the segmented control rod to allow it to be inserted in a distorted control rod channel. A reference control rod consisted of just B₄C plates in the front 18 in (45.72 cm) of the CR drawers was measured for comparison.

The following configurations were measured in ZPPR-15D loadings 208 – 210:

L208 – subcritical reference configuration for the segmented control rod measurement.

L209 – segmented control rod was present in the central 2 x 2 array of drawers in each half. The segmented control rod consisted of three 8-in (20.32 cm) sections of B₄C plates separated by two 6-in (15.24 cm) sections of stainless and sodium plates.

L210 – the segmented control rod drawers were replaced by drawers containing 18 in (45.72 cm) of B₄C plates in each matrix half.

A reproducibility uncertainty of 0.13¢ was assumed for consistency with the ZPPR-15D sodium void worth measurements. The total uncertainty is dominated by the 5% uncertainty associated with reactivity conversion, so further refinement of the reproducibility uncertainty is not

warranted. Table 5.13 shows the measured reactivities for L208 – L210 as reported by the ZPPR staff.

Table 5-13 Measured Control Rod Worths for the Segmented Control Rod Experiment

Loading	ρ , \$ (1)	σ_{stat} , \$ (2)	σ_{corr} , \$ (3)	σ_{repro} , \$ (4)	σ_{total} , \$	σ_{total} , %
208	-0.04036				0.00018	
209	-1.406	0.0025	0.0076	0.0013	0.0081	0.579
210	-1.953	0.0027	0.0105	0.0013	0.0109	0.558

- 1) Reactivity changes for loadings 209 and 210 were derived relative to L208. The reactivity of L208 was $-0.04036\$ \pm 0.00018\$$ as determined by inverse kinetics analysis.
- 2) The statistical uncertainty includes detector statistics plus the adjustments for temperature, ^{241}Pu decay and the interface gap.
- 3) The correlated uncertainty is due to reactivity scale calibration and the source ratio uncertainty.
- 4) Reproducibility uncertainty of 0.13¢ was assumed for the control rod worth measurements.

Reactivities for loadings in Table 5.13 can be converted to values of k_{eff} using the reported β_{eff} value for ZPPR-15D, 0.006564. Table 5.14 shows values of k_{eff} determined from reactivities for the loadings in Table 5.13. Adjusted k_{eff} values in Table 5.14 include a positive bias of 50.45 pcm to account for features of the actual ZPPR-15D assembly that are not included in the as-built ZPPR-15 models (see Ref. 1). In some cases, the adjusted k_{eff} may be greater than 1.0 due to this bias although all experimental configurations were subcritical.

Table 5-14 Measured Reactivity and k_{eff} for ZPPR-15D Loadings 208 – 210

Loading	Measured ρ , \$ (1)		Measured ρ , pcm		Bias ρ , pcm (2)		Adjusted ρ , pcm		Adjusted k_{eff}	σ
	ρ , \$	σ_{total} , \$	ρ , pcm	σ_{total} , pcm	ρ , pcm	σ , pcm	ρ_{adj} , pcm	σ , pcm		
208	-0.04036	0.00018	-26.5	0.12	50.45	18.76	24.0	18.8	1.00024	0.00019
209	-1.446	0.0081	-949.4	5.35	50.45	18.76	-898.9	19.5	0.99109	0.00020
210	-1.993	0.0109	-1308.4	7.15	50.45	18.76	-1258.0	20.1	0.98758	0.00020

- 1) The measured reactivity values for loadings 209 – 210 in Table 5.13 were added to the measured reactivity for L208, $-0.04036\$$, to produce the values shown in column 2 for loadings 209 – 210.
- 2) Bias exists because some experimental features are neglected in as-built models. The bias values in Table 5.14 were determined for the ZPPR-15D reference configuration uncertainty analysis [1].

The uncertainties listed in Table 5.13 are the uncertainties for the experimental measurement. There are additional uncertainties related to the plates and the interface gap. Table 5.15 shows the additional uncertainties for the plates and interface gap in the ZPPR-15D segmented control rod worth measurements.

Table 5-15 Plate and Gap Uncertainties for the ZPPR-15D Segmented Rod Worth Measurements.

Loading	σ_{gap} , pcm (1)	σ_{plates} , pcm (2)	σ_{Na} , pcm (3)	$\sigma_{\text{B4C Mass}}$, pcm (4)	$\sigma_{\text{B-10}}$, pcm (5)	σ_{total} , pcm
208	0.20	0.60	0.10	0.00	0.00	0.64
209	0.20	0.60	0.10	0.86	0.86	1.38
210	0.20	0.60	0.10	0.86	0.86	1.38

- 1) The maximum contribution of the interface gap uncertainty was less than 0.15 pcm for the sodium void worth measurements.
- 2) The contribution of the uncertainties in plate compositions was ~0.6 pcm in the sodium void worth measurements.
- 3) The contribution of the uncertainty in sodium plate masses and compositions was ~0.1 pcm for the sodium void worth measurements.
- 4) The B₄C plate mass uncertainty is 11.2 pcm (13 fully inserted CRs in L102) scaled by the number of fully inserted CRs in each loading.
- 5) The uncertainty in the boron isotopics is assumed to be identical to the uncertainty in the B₄C plate mass.

The worths of the control rod configurations in ZPPR-15D were calculated with MCNP6.1 and ENDF/B-VII.0 cross sections. Table 5.16 shows the measured and calculated control rod worth in the ZPPR-15D segmented control rod worth experiments.

Table 5-16 Measured and Calculated Control Rod Worths in the ZPPR-15D Segmented Control Rod Worth Experiment

Step (1)	Measured ρ , \$		Measured ρ , pcm		$\sigma(\beta)$, pcm (2)	σ_{plate} , pcm (3)	σ_{total} , pcm (4)	Calculated ρ , pcm		C/E - 1, %	
	ρ_{meas} , \$	σ_{meas} , \$	ρ_{meas} , pcm	σ_{meas} , pcm				ρ , pcm	σ , pcm	C/E - 1, %	σ , %
L208 - L209	-1.406	0.0081	-922.9	5.35	46.14	1.38	46.5	-872.5	2.8	-5.5	4.8
L208 - L210	-1.953	0.0109	-1281.9	7.15	64.10	1.38	64.5	-1209.2	2.8	-5.7	4.8

- 1) Steps correspond to Table 5.13.
- 2) This is the uncertainty resulting from the 5% uncertainty in the β_{eff} used to convert the reactivity from cents to pcm.
- 3) This is the uncertainty resulting from the uncertainty in plate compositions.
- 4) The σ_{total} value in column 8 is the final total uncertainty for the measured reactivity expressed in pcm.

6 Discussion and Summary

Measurements of sodium void worth were performed in all four phases of the ZPPR-15 program. In addition, sodium void worth measurements were performed in a high zirconium core constructed during the transition between ZPPR-15A and ZPPR-15B and in 96 drawers simulating a sodium manometer in ZPPR-15B. As-built MCNP models were constructed for all sodium void worth measurements performed in ZPPR-15, and total uncertainties were derived for all of the modeled configurations. Agreement between calculated and measured

sodium void worths was mixed. For measured sodium void worths above $\sim 10\%$, C/E values were generally reasonable. For measured sodium void worths below 10% , C/E values varied widely.

Several factors can affect the sodium void worth measurement, the associated total uncertainty and the difference between the actual experimental configuration and the model of that experimental configuration. First, as-built models are based on the average sodium plate and void can of each size used in the experiment. In reality, there were small plate-to-plate variations between plates of the same size due to normal manufacturing processes and tolerances. These plate-to-plate variations and the actual position of each plate in the assembly have a small effect on measured reactivity. Available records are not sufficient to model the specific plate or void can at each location in the assembly.

Second, although experimental procedures were designed to minimize plate shifting, i.e., small changes in plate positions in the drawers due to normal drawer loading/unloading operations and drawer handling, plate shifting could still occur. Small shifts in plate positions in the drawers affected measured reactivity.

Third, there is an uncertainty in control rod calibration that indirectly affects all the measured values due to the role of the control rods in the modified source multiplication technique. Fourth, there is a small uncertainty in the position of each control rod that affects the measured values for the same reason. Fifth, the interface gap is not a constant value. It could be affected by the weight of the loaded drawers in the matrix tubes.

The net effect of all of these factors is small. However, the importance of this net effect and its relative contribution to both the total experimental uncertainty and the difference between the measured and calculated worths would be greater for a small measured value than for a large measured value.

The worths of various configurations of simulated or mockup control rods and empty control rod channels were measured in ZPPR-15A, ZPPR-15B and ZPPR-15D. As-built MCNP models were constructed for a subset of the mockup control rod worth measurements, and total uncertainties were derived for all of the modeled configurations. Agreement between calculated and measured control rod worths for the modeled cases was generally good. C/E values for the control rod measurements were generally within one sigma of unity with no large outliers.

7 References

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