Experimental Breeder Reactor II Benchmark Evaluation

Mission Supporting Nuclear Energy: Integral Benchmark Evaluations

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Recipient:  Idaho State University

Project Title:  Experimental Breeder Reactor II Benchmark Evaluation

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Reporting period:  October 1, 2014 – September 30, 2017
The Experimental Breeder Reactor II (EBR-II) reactor physics benchmark evaluation project officially finished September 30, 2017. Nonetheless, work has subsequently proceeded to address technical committee review comments received after September 30, 2017. The overarching project goal was to prepare a reactor physics benchmark evaluation of the EBR-II Run 138B core configuration (April 1986) suitable for inclusion in the International Reactor Physics Evaluation Project (IRPhEP) handbook. That goal was reached when the benchmark evaluation report was delivered to the IRPhEP coordinator on August 18, 2017.

During the third and final year of the project, the benchmark evaluation report was assembled, an internal review was completed and comments were resolved, an external review was completed and the comments were resolved. The benchmark evaluation report was submitted to the IRPhEP coordinator August 18, 2017.

The IRPhEP technical review meeting was held in Washington DC on October 25, 2017. Comments from the IRPhEP technical review were received November 20, 2017. Resolution of IRPhEP technical review comments was completed December 28, 2017 and the EBR-II reactor physics benchmark evaluation was delivered to the IRPhEP coordinator for subcommittee review of the comment resolutions.

The EBR-II reactor physics benchmark evaluation report delivered to the IRPhEP coordinator on December 28, 2017 is provided on the following pages and serves as the project final report.
EVALUATION OF RUN 138B AT EXPERIMENTAL BREEDER REACTOR II, A PROTOTYPIC LIQUID METAL FAST BREEDER REACTOR

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Independent Reviewer(s)

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## Status of Compilation / Evaluation / Peer Review

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EVALUATION OF RUN 138B AT EXPERIMENTAL BREEDER REACTOR II, A PROTOTYPIC LIQUID METAL FAST BREEDER REACTOR

IDENTIFICATION NUMBER: EBR2-LMFR-RESR-001
CRIT

KEY WORDS: fast reactor, HEX-Z, Stainless-steel 304L reflected, fast, sodium coolant, uranium metal fuel

SUMMARY INFORMATION (summary file to be provided by author – will be linked as a separate document)

1.0 DETAILED DESCRIPTION

The Experimental Breeder Reactor-II (EBR-II) was a test reactor operated by Argonne National Laboratory. The reactor was operational between 1964 and 1994. From 1964 to 1969, the original purpose of EBR-II was to show a sodium-cooled fast reactor could be used as a power station which utilized an on-site reprocessing facility. The initial mission was accomplished in September 1969 and would later be referred to as phase I. EBR-II had four of these phases; each phase was started at different a time but continued until the reactor was shut down in September of 1994. Figure 1.0.1 shows a chart of the phases.
EBR-II achieved dry critical on September 30th, 1960. Tests were done in a dry critical condition to confirm calculations and to write procedures for both wet critical and approach to power. Two years later the sodium plant was completed and wet critical was established in November of 1962. In the following years, the reactor operating power was slowly increased until September 1969 when 62.5 MWt was achieved.

During the early years of EBR-II, it was primarily used as a demonstration facility for a liquid metal fast reactor with onsite reprocessing. In May 1965, the reactor used recycled fuel for the first time. This lead to the demonstration of a closed fuel cycle in September of 1969. After 1965, the facility initiated phase II where it was used as an irradiation test facility irradiating experimental assemblies. EBR-II continued in this role until early 1978 when it was concluded that continued experimental irradiations would decrease utilization of the reactor. It was at this point that phase III was initiated and new programs were proposed to test design basis accident conditions for future Liquid Metal Reactors (LMR).

One of the most important set of experiments in LMR history was part of these new proposals. The tests which became known as the Shutdown Heat Removal Tests (SHRT) were to test an LMR during catastrophic failures of heat removal at full power. The purpose of these experiments was to prove that EBR-II had enough passive safety features that it could shut itself down without any significant damage. There were dozens of SHRT experiments but, the most severe of these was SHRT 45 conducted on April 3rd, 1986. The conditions of the plant during SHRT 45 were 100% power, 100% initial primary flow, 104% secondary flow. During the experiment, both the secondary and primary pumps were coasted down to zero percent and the reactor SCRAM mechanism was disabled. The result of this experiment was a shutdown to approximately zero percent power within fifteen minutes. Peak fuel element temperature remained within safe limits and post-analysis showed only minimal damage to the fuel with no detectable cladding breach. That experiment not only proved the
inherit safety of the reactor but also was proof that a commercial LMR power reactor can withstand catastrophic failure without significant damage.

EBR-II continued to operate and perform experiments until August 1994. EBR-II last operated on September 27th, 1994.

1.1 Description of the Critical and / or Subcritical Configuration

1.1.1 Overview of Experiment.

The SHRT tests were originally conceived in 1974, where proposals were issued to study various upset conditions. The upset conditions focused on thermal hydraulic phenomena that would demonstrate the ability of EBR-II to remove decay heat from the core without causing damage. The most extreme test was the SHRT 45 (Run 138B core configuration) test conducted on April 3rd, 1986.

SHRT 45 was the most extreme experiment because it encompassed all accident scenarios into one experiment. Table 1.1.1 lists the plant conditions during the test. The test started with EBR-II at 100% power during normal operating conditions. The circuit breaker for the primary and secondary sodium pumps was tripped, which lead to the pumps coasting down. The only pump that was operational was the auxiliary pump which controlled the sodium flow to the ambient heat exchanger. This pump was operated on battery power. These conditions effectively simulate the worst aspects of a station blackout scenario.

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<th>Initial power (% of rated)</th>
<th>Initial primary flow (% of rated)</th>
<th>Initial secondary flow (% of nominal)</th>
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<td>68</td>
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EBR-II had to be modified to conduct SHRT 45. The reason for the modification was to ensure there were still mechanisms in place to shut the reactor down in case of unexpected behavior. The goal was to preserve the original plant so the tests would be as analogous to station blackout as possible, but also to provide a means to shut down the reactor if it deviated from calculated predictions.
One of the systems modified was the primary coolant system. Pump coast-down is a critical characteristic when determining peak temperature. The shape and duration of the coast-down were analyzed to find what configuration would yield the best results during a loss-of-flow-without-scram (LOFWS) test. Preliminary investigation of SHRT showed the coolant pump controllers were insufficient to provide a variety of coast-down methods. A passive method was required to simulate true blackout. This meant opening the 2400V circuit breaker to the pumps. The active method would simulate the coast-down by controlling the pump to reduce speed in a manner which simulated a coast-down while keeping power to the pump.

1.1.2 Geometry of the Experiment Configuration and Measurement Procedure

The dimensions obtained from engineering drawings were reported in inches and feet. Where referenced in this report, the original dimensions are then followed by their converted values in units of meters or centimeters, in parentheses. Information from Section 1 this report was taken from the engineering drawings of EBR-II reactor found in appendix B.1.

1.1.2.1 In Vessel

EBR-II was a sodium cooled fast reactor operating from 1964 through 1994. It had a maximum heat output of 62.5 MW (about 20 MW electric). Although initially designed to breed more fuel than it consumed, it was later reconfigured to operate as an irradiation facility where a variety of fuels and structural materials were tested.

The EBR-II consisted of 637 vertical, hexagonally shaped, removable assemblies. As shown in Figure 1.1.1, these assemblies were divided into three regions (moving outward from the middle): the core, an inner blanket, and an outer blanket. The number of assemblies within each region varied over the years with changing configurations, due to the experimental nature of the reactor. Driver assemblies containing 91 fuel elements each were located in the core region. The fuel was enriched uranium metal, alloyed with a small percentage of other elements to improve fuel performance properties, and clad within stainless-steel. Also in the core region were 10 moveable assemblies used for reactivity control. The moveable assemblies contained 61 fuel elements each and were raised into the core to increase reactor power or lowered from the core to reduce the reactor power. Other assemblies in this region included stainless-steel dummies, half worth drivers, and experimental/instrumentation assemblies. The inner blanket region initially consisted of assemblies which contained depleted uranium, for breeding new fissile material, as well as reflecting neutrons back toward the center of the core. After proving the breeding concept, these depleted uranium assemblies were replaced with stainless-steel reflectors more compatible with the goal of an irradiation facility. The outer blanket region consisted almost entirely of depleted uranium assemblies, again for breeding and reflection.
Assembly locations were denoted by three parameters: row, section, and position within the core. If a horizontal slice of the core was taken, the central assembly would be row 1. Row 2 follows with six assemblies immediately surrounding row 1. Row 3 and on follow the same pattern until row 14 of the core is reached. The last two rows, 15 and 16, have 66 and 24 assemblies, respectively. The core is then subdivided into six sections labeled A through F, as shown in Figure 1.1.2. A line is drawn from the central assembly and through each assembly towards the outside edge, in approximately 60-degree angles, which split the core evenly. An
assembly position is determined by the number of assemblies from each line of the six sectors. For example, in Figure 1.1.3, position 12A05 contains a blanket assembly. To find it on the map, the first section (which corresponds to A) is selected. This is followed by moving up five assemblies on the 180-degree line, starting with the central assembly. This will be assembly 12A01; then move to the right four assemblies starting with 12A05. Figure 1.1.3 also shows additional assemblies and their corresponding position references.

Figure 1.1.2. EBR-II core segments.
The assemblies were approximately 92 inches long, although only about 14 inches was uranium fuel. Above and beneath the fuel were neutron reflectors, which began as depleted uranium but was later replaced with stainless-steel. At the top of each assembly was fixture for assembly removal, and at the bottom was an adapter which fit into a grid plenum support structure. Orifices at the bottom of each assembly allowed sodium coolant to flow upward, with larger holes (and therefore greater flow) for those assemblies in the center region which produced the greatest heat.

Each assembly was fixed in the reactor via a lower adapter which connected into the grid plates, which was supported by a stainless-steel reactor vessel. Surrounding the core region was the stainless-steel reactor vessel which was comprised of a grid plenum assembly, reactor vessel shell, and the reactor vessel cover. Surrounding
the reactor vessel was a radial neutron shield, which was comprised of graphite and borated graphite blocks shown in Figure 1.1.5\textsuperscript{a}. The entire reactor vessel was in the lower central area of the primary tank and was submerged below approximately 10 feet (3 m) of sodium. Above the reactor vessel was a top cover which also contained a neutron shield. The top cover could be removed when required to enable replacement and handling of assemblies, and contained penetrations to allow for the control rod drive mechanisms. Surrounding the reactor vessel was the remainder of the primary sodium tank. The reactor core, two primary coolant centrifugal pumps, and intermediate heat exchanger were all contained within the primary sodium tank which was filled with 337,000 liters of sodium coolant. With the pool type design, any leaks within the primary coolant piping would simply drain into the primary coolant pool. While such a leak would impact plant efficiency, no leakage of primary sodium coolant outside the vessel would occur. Heat from the primary coolant was transferred to a secondary sodium loop through a heat exchanger submerged within the primary pool. Thus, heat from the reactor was removed to the secondary sodium loop while minimizing neutron activation of the secondary sodium. Finally, the secondary sodium was used to generate superheated steam for electricity generation. Figure 1.1.4 provides a cut-away view of the reactor.\textsuperscript{b}

\textsuperscript{a} R. L. McVean, et al., EBR-II Dry Critical Experiments, ANL-6462 (Feb 1962)

Figure 1.1.4 EBR-II cross-sectional view.
1.1.2.2 Assemblies

The EBR-II reactor assemblies are hexagonally shaped and consists of upper extension, lower extension and core region. There were driver, control, safety, reflector, outer blanket, dummy, instrument, and experiment assemblies.

1.1.2.3 Core Driver Assemblies

There were two types of driver assemblies used in the EBR-II core region for Run 138B, MK-II and MK-IIA. Their overall dimensions did not differ and they have the same composition. The difference between the two are the manufacturer and the fuel element length. MK-II AI was a MK-II assembly manufactured by Atomics International and MK-IIA was manufactured by Argonne National Laboratory with longer fuel elements. The following description applies to both assembly types with the different fuel element length noted. The assembly was comprised of three sections, the upper preassembly, core region and the lower extension. The three sections shared the same stainless-steel 304L hexagonal duct with an outside flat-to-flat distance of 2.29 in (5.8166 cm)

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and a wall thickness of 0.04 ± 0.001 in (0.1016 ± 0.00254 cm). The overall length of the duct was 65.796 ± 0.062 in (167.1218 ± 0.15748 cm). Figure 1.1.6 shows a segmented photograph of a driver assembly.
Figure 1.1.6. Assembly photos.
The upper preassembly hexagonal duct had a length above the top of the fuel elements to the upper pole piece of 17.312 in (43.9725 cm). The upper pole piece was a cylindrical piece of stainless-steel 304L with a total length of 5.609 in (14.2469 cm) and a diameter of 0.1248 in (0.3169 cm).

The core region hexagonal duct length that contained the fuel elements was 25.94 in (65.8876 cm) long and made of stainless-steel 304L. A total of 91 fuel elements were arranged in a hexagonal lattice within the core region of the assembly. The pitch of the elements was 0.2229 in (0.5661 cm).

The MK-II fuel element is shown in Figure 1.1.7. Each fuel element consisted of a fuel slug containing 66.72% enriched uranium at the beginning of life. The diameter of the fuel slug was 0.130 ± 0.003 in (0.3302 ± 0.0076 cm) and had a length of 13.5 ± 0.1 in (34.29 ± 0.254 cm). The fuel slug was surrounded by sodium which filled the void between the outer diameter of the fuel slug and the inner diameter of the cladding. The length of the sodium was 13.75 ± 0.35 in (34.925 ± 0.889 cm). Above the sodium was a helium gas plenum which filled the rest of the internal volume of the cladding. The cladding was made of stainless-steel 316 which had an outer diameter of 0.1740 ± 0.0005 in (0.4420 ± 0.00127 cm) and an inner diameter of 0.1500 ± 0.0005 in (0.3810 ± 0.00127 cm). The length of the cladding from the bottom of the fuel slug to the top of the element for a MK-II A was 24.3 in (61.72 cm) and for a MK-II/MKIIAI was 24.425 in (62.0395 cm). The cladding had an outer wire wrap with a diameter of 0.0490 ± 0.0005 in (0.1245 ± 0.00127 cm) and a length of 23.820 ± 0.031 in (60.5028 ± 0.07874 cm). The pitch of the wire wrap was 6.000 ± 0.250 in (15.24 ± 0.635 cm).

The hexagonal duct of the lower extension had a length of 24.625 ± 0.031 in (62.5475 ± 0.07874 cm) from the bottom of the fuel slug to the top of reactor grid plate. Inside of the lower extension were stainless-steel 304L channels for the sodium to flow up to the fuel elements.

There were half worth core drivers that were geometrically identical to the drivers but had 46 fuel elements and 45 solid stainless-steel dummy elements. The pattern of loading was starting from the top vertex of the assembly and moving in line 30 degrees down to the right. Every other element was a dummy element starting with a normal element. This pattern continued to the end of the row and then starting again with the next row and subsequent fuel element.
High flow drivers were also used which were geometrically identical to full worth drivers but had more holes drilled into the lower extension and upper preassembly to facilitate higher sodium flow through the assembly.

1.1.2.4 Control Assemblies

EBR-II had three types of moveable control assemblies, 7 high-worth control rods (HWCR), 1 control rod, and 2 safety rods. In general, the difference between the two types of control rods was the addition of $\text{B}_4\text{C}$ followers to the HWCRs. The HWCRs were comprised of two sections; a fueled region and a poison region. The combination of the fueled section and the poison region was 57.725 in (146.6215 cm) long. The poison region, as shown in Figure 1.1.8, was 36.093 ± 0.078 in (91.6762 ± 0.1981 cm) long and was comprised of 7 poison elements in a hexagonal array. Movement of the control rods was performed using independent control rod drive mechanisms located above the core. The safety rod drive mechanism was located below the core and moved the two safety rods in tandem. For the safety rods and control rod, when the rod is inserted the fueled region of the assembly is placed within the core region of the reactor. This is counter to typical control rods where insertion means the poison region is placed in the core. The HWCRs follow a similar nature. When the HWCR is inserted, the fueled region is placed within the core region of the reactor and when the HWCR was retracted the poison region of the assembly was within the core region of the reactor.

Each poison element was made up of a steel cap on top, gas, stainless-steel shielding, spring, boron carbide poison, and a lower steel cap all surrounded by steel cladding. The top steel cap was 2.406 in (6.1112 cm) long. The gas took up 9.750 in (24.765 cm) between the upper steel cap and the stainless-steel shield. The stainless-steel shield was 8 in (20.32 cm) with a diameter of 0.5490 in (1.3945 cm). The spring below the stainless-steel shield was 1.375 in (3.4925 cm) long with an inner diameter of 0.465 in (1.1811 cm) and an outer diameter of 0.54 in (1.3716 cm). The $\text{B}_4\text{C}$ poison was 14 in (35.56 cm) long with a diameter of 1.4728 in (3.7410 cm). The steel cap below it was 0.5 in (1.27 cm). The cladding that surrounded each poison element had an inner diameter of 0.555 (0.554/0.556) in (1.4097 cm) and an outer diameter of 0.625 (0.627/0.623) in (1.5875 cm).

The fueled region of all 7 HWCRs was 21.05 in (53.467 cm) long and comprised of 61 MK-IIS fuel elements in a hexagonal array. The only difference of MK-IIS fuel elements from MK-II fuel elements was the element height. Each fuel element was made up of a fuel slug of 0.130 ± 0.003 in (0.33020 ± 0.00762 cm) diameter and 13.500 ± 0.100 in (34.290 ± 0.254 cm) long. Each fuel element was filled with sodium to 13.75 ± 0.25 in (34.925 ± 0.635 cm). There was a sodium bond between the fuel slug and the inner diameter of the stainless-steel cladding. The inner diameter of the cladding is 0.1500 ± 0.0005 in (0.381 ± 0.00127 cm) and the outer diameter of the cladding is 0.1740 ± 0.0005 in (0.4420 ± 0.00127 cm).

The assembly lower extension was 28.340 in (71.9836 cm) long in total from the bottom of the fueled section to the top of the reactor grid plate. Below the lower extension was the lower adapter which slid between the upper and lower grid plate and had a length of 1.4081 ft (0.4292 m).

The single EBR-II control assembly was hexagonally-shaped. It was comprised of three sections; an upper extension, a fueled region, and a lower extension; with a combined length of 7.2136 ft (2.1987 m). The upper extension was 1.6862 ft (0.5140 m) long. It was comprised of stainless-steel with 6 holes to allow for sodium coolant flow.
Figure 1.1.8. B\textsubscript{4}C capsule in high worth control rod.
The fueled region was 2.0873 ft (0.6362 m) long and was comprised of 61 MK-IIA fuel elements in a hexagonal array. The lower extension was 3.2019 ft (0.9759 m) long and was comprised of a hexagonal portion and a cylindrical portion. The hexagonal duct was 1.3413 ft (0.4088 m) long and the cylindrical portion is 1.4375 ft (0.4382 m) long. The outer diameter of the cylindrical portion is 1.36 in (3.4544 cm).

Safety assemblies were similar to the single control assembly with the exception of using MK-II fuel elements rather than MK-IIA fuel elements and the drive mechanism was located at the bottom of the core.

1.1.2.5 Reflector Assemblies

The EBR-II stainless-steel reflector assemblies were hexagonally-shaped components. They were comprised of two sections; a core region, and a lower extension, with a combined length of 7.6537 ft (2.3328 m).

The core region was 65.796 ± 0.062 in (167.1218 ± 0.1575 cm) and comprised of a stainless-steel core. The stainless-steel core was separated into three separate pieces as shown in Figure 1.1.9. The lower piece was 20.5 in (52.07 cm) while the top was 5.5479 in (14.0913 cm).

The lower extension was comprised of a hexagonal portion and a cylindrical portion. The hexagonal portion was 1.8125 in (4.6038 cm) long, with a flat to flat width of 2.29 in (5.817 cm), and the cylindrical portion was 1.7043 in (41.95 cm) long. The outer diameter of the cylindrical portion changes at points along the length. The cylindrical portion of the top 3.952 in (10.04 cm) had an outer diameter of 1.508 in (3.83 cm). The second portion was 10.5 in (26.67 cm) in length and had an outer diameter of 1.469 in (3.73 cm). The third portion was 2.000 in (5.08 cm) in length and had an outer diameter of 1.469 in (3.73 cm). The final cylindrical portion was 4.000 in (10.16 cm) in length and had an outer diameter of 1.437 in (3.65 cm).

The second stainless-steel reflector type had minor differences only in the lower extension. The second type of reflector had a total lower extension length of 22.315 in (56.68 cm) and was comprised of a hexagonal portion and cylindrical portion. The hexagonal portion was 1.861 in (4.727 cm) long. The cylindrical portion changes along the length. The top cylindrical portion of the lower extension was 3.953 in (10.04 m) long and had a diameter of 1.726 in (4.384 m). The second portion was 12.5 in (31.75 cm) long and had a diameter of 1.585 in (4.206 cm).

The sectional view of the reflector assembly is shown in Figure 1.1.10.
Figure 1.1.9. Reflector assembly.
1.1.2.6 Outer Blanket Assemblies

The EBR-II depleted uranium outer blanket assemblies were hexagonally shaped components. The blanket assemblies were comprised of two sections; a core region and lower extension, with a combined length of 7.654 ft (2.3328 m). The lower extension, core region and upper extension had a flat-to-flat distance of 2.29 in (5.817 cm).

The core region was 5.168 ft (1.5753 m) long and was comprised of 19 blanket fuel elements. The blanket element slug height was 4.583 ft (1.397 m) with a diameter of 0.433 in (1.100 cm). The fuel elements were
filled with sodium up to 4.698 ft (1.4318 m). There was a sodium bond between uranium slug and the inner diameter of the stainless-steel cladding. The inner diameter of the cladding was 0.457 in (1.162 cm). The outer diameter of the cladding was 0.493 in (1.252 cm).

The lower adapter had a length of 24.4 in (61.98 cm) and was comprised of a hexagonal portion and a cylindrical portion. The hexagonal portion was 13.61 in (34.57 cm) long. The first cylindrical portion from the top was 3.953 in (10.04 cm) long and had a diameter of 1.508 in (3.83 cm). The second portion was 3.949 in (10.03 cm) long and had a diameter of 14.68 in (37.29 cm). The final portion was 6.00 in (15.24 cm) long and had a diameter of 1.437 in (3.65 cm).

### 1.1.2.7 Core Dummy Assemblies

The EBR-II core dummy assemblies were hexagonally shaped components. They were comprised of two sections; a core region and a lower extension with a combined length of 7.638 ft (2.3281 m) as shown in Figure 1.1.11. The lower extension, core region and upper extension had a flat-to-flat distance of 2.29 in (5.817 cm).

The core region was 5.340 ft (1.6276 m) long and was comprised of 7 solid stainless-steel elements. The elements were 4.983 ft (1.5189 m) long and had a diameter of 0.785 in (1.994 cm). There was a gap between the bottom of the rods and the upper reactor grid plate 1.653 in (4.199 cm) long. The upper reactor grid plate was 17.181 in (43.64 cm) long.

The lower extension was a total length of 20.437 in (51.91 cm) and was cylindrical. The diameter of the lower extension changed in size at certain lengths. The upper portion of the lower extension was 1.936 in (4.917 cm) in diameter and was 4.126 in (10.48 cm) in height. The second portion was 1.750 in (4.445 cm) in diameter and was 8.126 in (20.64 cm) long. The final portion was 1.875 in (4.763 cm) in diameter and was 8.189 in (20.80 cm) long. Figure 1.1.12 shows the sectional view of the dummy assembly.
Figure 1.1.11. Dummy assembly.
1.1.2.8 Instrumented Assemblies

There were two types of instrumented assemblies in EBR-II reactor core during Run 138B. One was a driver type (XX09), and the other was a blanket type (XX10). Both assemblies were designed to fit in the control rod positions. The instrumented assembly consisted of the assembly, an extension tube, and a terminal box. The XX09 instrumented rod was made the same as a standard EBR-II driver. The extension tube connects the assembly to outside the primary tank.\(^a\)

The XX10 is a 19-element unfueled instrumented assembly.\(^b\) Eighteen elements were solid SS316 rods with the remaining position being used as a conduit tube for the passage of instrument leads. Each rod has an outer

\(^a\) R. L. McVean, et al., EBR-II Dry Critical Experiments, ANL-6462 (Feb 1962)

\(^b\) P. R. Betten et al., Conceptual Design Basis and Temperature Predictions in a Simulated Instrumented LMFBR Blanket Assembly (Oct 1985).
diameter of 0.881 cm and was 61.2 cm long. Figure 1.1.13 shows the details of the in-core thermocouple positioning.
Figure 1.1.13. XX10 in-core thermocouple loading.
1.1.2.9 Experimental Assemblies

There were several experiments loaded into the core during Run 138B. While the experiments constituted special use assemblies, their main difference was material loading. C2776A was a driver assembly that had xenon gas tags loaded into the fuel elements to detect cladding breach. X412 and X402A were driver assemblies. XY-16 was a driver that had 61 fuel elements and was placed into a control rod position. X320C was a dummy assembly.

1.1.2.10 Fuel Element Swelling

Radiation induced swelling affected the metal fuel slug, cladding, and hexagonal flow duct. At the time of manufacture, the 0.25-mm radial gap between the metal fuel slug and the cladding was filled with sodium metal to enhance heat transfer. After ~3.2 at. % burnup, the metal fuel slug swells to the point where it comes into contact with the cladding. Most of the sodium bonding between the metal fuel slug and cladding was pushed up above the top of the metal fuel slug. The initial gap between the metal fuel slug and cladding, along with the swelling property, is part of the overall fuel design. Once the metal fuel slug swells ~30%, interconnection of pores within the slug occurs, which provides a release pathway for fission product gases to the volume above the slug. The initial gap coupled with the eventual slug swelling and pore interconnection led to fuel lifetimes in the 80,000 to 150,000 MWd per MTHM range. The fuel element cladding also swells as a function of burnup. The cladding diameter swollen ~3% at 9.4 at. % burnup. Finally, the hexagonal flow duct also swells slightly as a result of irradiation.

1.1.3 Material Data

Sodium Coolant

The main reactor vessel and primary cooling systems of EBR-II were all submerged in liquid sodium. This provided many advantages both from a thermodynamics perspective and a safety perspective. In 1967, chemical analysis was done on the pool sodium to assess chemical contaminates and impurities. The sodium contaminates were grouped into three categories, non-metals, trace metals and radionuclides. Table 1.1.2, Table 1.1.3, and Table 1.1.4 show the results of the chemical analysis of the sodium.

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Date: December 28, 2017
Table 1.1.2. Non-Metal Trace Elements in Pool Sodium

<table>
<thead>
<tr>
<th>Element</th>
<th>Primary Loop Concentration (ppm)</th>
<th>Secondary Loop Concentration (ppm)</th>
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</thead>
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<tr>
<td>C</td>
<td>&lt;2.0</td>
<td>&lt;2.0</td>
</tr>
<tr>
<td>Cl</td>
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<td>&lt;5.0</td>
</tr>
<tr>
<td>CN</td>
<td>&lt;0.2</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>H</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>N</td>
<td>~0.2</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>O</td>
<td>&lt;2.0</td>
<td>&lt;2.0</td>
</tr>
<tr>
<td>S</td>
<td>&lt;2.0</td>
<td>&lt;2.0</td>
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</table>
Table 1.1.3. Metal Trace Elements in Pool Sodium

<table>
<thead>
<tr>
<th>Element</th>
<th>Primary Loop Concentration (ppm)</th>
<th>Secondary Loop Concentration (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag</td>
<td>0.04</td>
<td>0.01</td>
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<td>Al</td>
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<td>&lt;0.06</td>
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<tr>
<td>Bi</td>
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<td>&lt;0.1</td>
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<td>Ca</td>
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<td>&lt;0.02</td>
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<td>Cd</td>
<td>0.08</td>
<td>&lt;0.02</td>
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<tr>
<td>Co</td>
<td>&lt;0.02</td>
<td>&lt;0.02</td>
</tr>
<tr>
<td>Cr</td>
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<tr>
<td>Cu</td>
<td>&lt;0.02</td>
<td>&lt;0.02</td>
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<tr>
<td>Fe</td>
<td>0.1-1.0</td>
<td>0.1-1.0</td>
</tr>
<tr>
<td>In</td>
<td>&lt;0.06</td>
<td>&lt;0.06</td>
</tr>
<tr>
<td>Mg</td>
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<td>0.005-0.05</td>
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<tr>
<td>Mn</td>
<td>&lt;0.005</td>
<td>0.005-0.05</td>
</tr>
<tr>
<td>Mo</td>
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<td>&lt;0.07</td>
</tr>
<tr>
<td>Ni</td>
<td>&lt;0.04</td>
<td>0.01-0.2</td>
</tr>
<tr>
<td>Pb</td>
<td>10.0</td>
<td>0.6</td>
</tr>
<tr>
<td>Sn</td>
<td>20.0</td>
<td>&lt;0.3</td>
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<tr>
<td>Zn</td>
<td>&lt;0.06</td>
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Table 1.1.4. Radionuclides in Pool Sodium

<table>
<thead>
<tr>
<th>Element</th>
<th>Primary Loop Activity, μCi/g</th>
<th>Secondary Loop Activity, μCi/g</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{24}\text{Na}$</td>
<td>1400</td>
<td>4.0E-2</td>
</tr>
<tr>
<td>$^{23}\text{Na}$</td>
<td>5E-2</td>
<td></td>
</tr>
<tr>
<td>$^{137}\text{Cs}$</td>
<td>1.2E-2</td>
<td></td>
</tr>
<tr>
<td>$^{131}\text{I}$</td>
<td>7.0E-4</td>
<td></td>
</tr>
</tbody>
</table>
The radionuclide content of the sodium coolant has two origins. The Cs and I radioisotopes are the result of intentional and unintentional cladding breach occurrences during years of power operation. The Na radioisotopes are the result of neutron activation occurring during power operation. Note that the location of the primary to secondary sodium heat exchanger away from the core results in secondary loop sodium activation four orders of magnitude lower than the primary sodium activation.

**Stainless-steel**

EBR-II used two different types of stainless-steel, SS316, and SS304L. Most of the internal structure of the reactor was SS304L. After irradiation experiments, it was determined that SS316 was more appropriate to use in the cladding of the fuel elements due to fuel-cladding interactions. During run 138B, only the fuel cladding was made of SS316, while the remainder of the core used SS304L.

Table 1.1.5 lists the minima and maxima composition for the two types of stainless-steels.

![Table 1.1.5. SS304L and SS316 Compositions](image)

**Plenum Gas**

The inert gas that was primarily used for EBR-II operation was argon; however, the engineering drawings for fuel elements indicate that a mix of 75 wgt. % helium, 25 wgt. % argon was also acceptable. There are no records which indicate what the mix was on an individual fuel element basis. The plenum gas was tagged with various xenon isotope mixtures in some fuel elements to identify cladding breaches during operation. Table 1.1.6 provides a list of maximum impurities in the plenum gas.

---

Table 1.1.6. Acceptance Criteria for Inert Atmosphere in Plenum Gas

<table>
<thead>
<tr>
<th>Element</th>
<th>Maximum Impurity (ppm)</th>
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<tbody>
<tr>
<td>N</td>
<td>5000</td>
</tr>
<tr>
<td>O</td>
<td>50</td>
</tr>
<tr>
<td>H₂O</td>
<td>50</td>
</tr>
</tbody>
</table>

**Beginning of Life Fuel Composition**

It is important to note EBR-II Run 138B used fuel with varying degrees of burnup, discussed below. Nonetheless, the beginning of life fuel composition is provided as background information.

The fueled assemblies, regardless of type, were fueled with similar beginning of life compositions. The uranium was 66.72% enriched with total fuel composition consisting of 95.00 ± 1.0 wgt. % uranium and 5.00 ± 0.32 wgt. % fissium. Fissium was comprised of elements meant to simulate dominant mid-cycle fission products. Table 1.1.7 provides a list of the beginning of life fuel composition with the respective uncertainties. Niobium and tantalum are difficult to analyze separately and therefore were combined. The uncertainties were measured analytically using an unknown method. The acceptance criteria allowed for the use of average chemical sample values meaning that elements that breach acceptance can still be allowed such that the average of the batch fell within criteria. Table 1.1.8 provides a list of the composition of the uranium isotopes. The ²³⁵U content was explicitly defined, while the remaining uranium isotopes, ²³⁴U, ²³⁶U, and ²³⁸U were grouped together with an upper bound listed for the sum of the ²³⁴U and ²³⁶U.

The impurities acceptance criteria were based upon exceeding any specific element in Table 1.1.9 but also state that a total impurity amount exceeding 1600 ppm would be unacceptable.

Table 1.1.7. Beginning of Life Fuel Composition

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight Percent</th>
<th>Weight Percent Uncertainty</th>
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<tbody>
<tr>
<td>Mo</td>
<td>2.44</td>
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<tr>
<td>Ru</td>
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<tr>
<td>Rh</td>
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<td>0.05</td>
</tr>
<tr>
<td>Pd</td>
<td>0.19</td>
<td>0.04</td>
</tr>
<tr>
<td>Zr</td>
<td>0.085</td>
<td>0.06</td>
</tr>
<tr>
<td>Nb + Ta</td>
<td>0.02</td>
<td>0.012</td>
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<tr>
<td>Si</td>
<td>0.054</td>
<td>0.031</td>
</tr>
<tr>
<td>U</td>
<td>95.00</td>
<td>1.00</td>
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Table 1.1.8. Uranium Composition

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<th>Isotope</th>
<th>Weight Percent</th>
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<td>$^{235}\text{U}$</td>
<td>66.72</td>
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</tr>
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<td>$^{234}\text{U} + ^{236}\text{U} + ^{238}\text{U}$</td>
<td>33.28</td>
<td>0.50</td>
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<tr>
<td>$^{234}\text{U} + ^{236}\text{U}$</td>
<td>&lt; 1.0</td>
<td>NA</td>
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Table 1.1.9. Uranium Impurities List

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<tr>
<td>Th</td>
<td>100</td>
</tr>
<tr>
<td>Y</td>
<td>100</td>
</tr>
</tbody>
</table>

Depleted Fuel Mass Uncertainty

The EBR-II Run 138B core configuration used fuel with varying degrees of burnup, thus the initial mass uncertainty must be combined with the depletion analysis mass uncertainty. Figure 1.1.14 shows the burnup values per assembly.
Figure 1.1.14. EBR-II Run 138B assembly burnup values.

The initial mass uncertainty is based on discussions with D. L. Porter, an expert associated with EBR-II fuel manufacturing activities, and reported manufacturing data. Nearly 30,000 Mk-II fuel elements were

---

* Personal communication with D. L. Porter


manufactured at ANL-W. According to D. L. Porter, the Mk-II driver slug mass manufacturing specification was quite broad at 50.7 g to 54.7 g per slug. The slug mass inspection limits were set at 50.7 g to 52.7 g indicating a reduction of 2 g per slug below the upper fuel slug mass manufacturing specification value noted by D. L. Porter.

An excessively conservative initial mass uncertainty assumption would be to assume an initial mass uncertainty of ± 4% based on the 52.7 g ± 2 g fuel slug mass manufacturing specification stated by D. L. Porter. A more realistic initial mass uncertainty of ± 2% could be used based on the 51.7 g ± 1 g inspection limit. However, consideration should be given to the reduction of the fuel slug manufacturing specification mass range (50.7 g to 54.7 g) to the fuel slug acceptance mass limit (50.7 g to 52.7 g), indicating a manufacturing bias toward lower fuel slug mass values. Additionally, it must be recognized that the manufacturing process involved injection casting of metal slugs which is prone to slug internal and external defects resulting in reduced slug mass. Manufacturing rejection rates of slugs following shearing slugs to length were approximately 15%. Rejections following shearing were due almost exclusively to internal and external defects which resulted in unacceptably low slug mass values.

Considering the reduced slug mass acceptance limit range, a manufacturing technique which produces slug defects resulting in reduced slug mass, and slug rejections dominated by unacceptably low mass values; a reduced and skewed initial mass uncertainty of -1.0% and +0.5% was selected.

The EBR-II core depletion analysis process and associated mass uncertainty was documented by R. D. McKnight. In the early 1990s, detailed core-follow depletion analysis for EBR-II was performed by Argonne National Laboratory using the Argonne National Laboratory developed REBUS-3 computer code. The REBUS-3 EBR-II model explicitly modeled each assembly as a homogenized unit with three axial depletion zones. The neutronics solution was performed using DIF3D and ENDF/B version V.2 cross-sections. Region dependent cross sections with 9 energy groups were generated for each reactor run. The full core model contained 33 x 33 x 35 mesh intervals and 1360 depletion zones.

The Argonne National Laboratory detailed core-follow analysis using REBUS-3 was performed starting with EBR-II Run 130A which started in August 1984. The core-follow analysis continued to EBR-II Run 154F ending in September 1990 for a total of 67 reactor including Run 138B which occurred in March and April 1986. For each reactor run, a single constant power burn step was used. All core configurations changes including control rod positions were included with each depletion calculation. Material compositions at the end of the previous run were carried forward into the next depletion run.

As discussed by R. D. McKnight, burnup measurements were obtained using chemistry measurements of $^{139}$La and $^{148}$Nd from destructive analysis of three assemblies. The chemistry measurement uncertainty was estimated to be ± 4%. Additionally, the reactor power measurement uncertainty was estimated to be ± 4%. The agreement between the calculated burnup value and the measured burnup value was therefore limited to ± 6%. That is, there is a 6% uncertainty in the burnup prediction when using REBUS-3 for EBR-II core-follow

---


depletion analysis. However, as noted by R. D. McKnight, the mass uncertainty component due to the burnup calculation is significantly mitigated by the fact most of the initial heavy metal atoms do not undergo fission. For example, if the burnup was 10%, and the initial mass uncertainty was 1%, the post burnup mass uncertainty would be 1.06%. For EBR-II Run 138B, the maximum driver assembly burnup was 6.08% and the average burnup was just 1.64%. Since the burnup contribution to the overall mass uncertainty is small compared to the initial mass uncertainty, a bounding 10% burnup assumption was used. Thus, when the mass uncertainty associated with the burnup is combined with the skewed initial mass uncertainty, identified above; the EBR-II Run 138B mass uncertainty is -1.06% and +0.56%. The blanket assembly initial mass uncertainty and burnup mass uncertainty is not known. However, the blanket assembly burnup values are trivial compared to driver assemblies. The driver assembly related mass uncertainty was applied to the blanket assembly mass uncertainty based on engineering judgement. An example of a driver assembly fuel composition and a blanket assembly fuel composition is provided in section 3.1.3. The complete listing of fuel data is in a separate folder labeled “Benchmark CSV”.

Element Bond

The element bond was the sodium that filled the gap between the fuel slug and the cladding. The oxygen and water content were of particular importance. The manufacturer was given the instruction that “If there is any question at any time that the sodium in the equipment has been contaminated with oxygen or H₂O or impurities beyond allowable limits, that sodium shall be disposed of or repurified.”

Table 1.1.10 provides the limits to the impurities acceptable in the element bond sodium.

<table>
<thead>
<tr>
<th>Element</th>
<th>Limit Maximum, ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>25</td>
</tr>
<tr>
<td>Ca</td>
<td>10</td>
</tr>
<tr>
<td>C</td>
<td>30</td>
</tr>
<tr>
<td>Cl</td>
<td>30</td>
</tr>
<tr>
<td>Li</td>
<td>5</td>
</tr>
<tr>
<td>K</td>
<td>1000</td>
</tr>
<tr>
<td>S</td>
<td>10</td>
</tr>
<tr>
<td>O</td>
<td>100</td>
</tr>
</tbody>
</table>

*EBR-II Specification E0288-0002-SF-06*
Boron Carbide

B$_4$C was used as a poison in the high worth control rods. The only information reported as to its composition is from the engineering drawing. It states that the $^{10}$B content per 14-inch-stack must be 18.04 ± 0.500 g. It was also reported that the boron was naturally enriched.$^a$

No impurities or acceptance criteria were reported.

1.1.4 Temperature Data

1.1.4.1 Bulk Sodium Temperature

The critical stamp located in the reactor operator’s logbook stated the bulk experiment temperature to be 650.6°F (616.82 K). The change in temperature from room temperature to zero power critical temperature was 343 oK.

1.1.4.2 Thermal Expansion

Thermal expansion in EBR-II produces significant reactivity effects. Some direct measurements of these effects were made, but many of the effects were calculated. Table 1.1.11 shows a list of reactivity coefficients calculated for Run 138B. These values were used in supporting safety analyses associated with the SHRT experiments performed during Run 138B. They represent the best approximations of the most dominate thermal expansion reactivity effects associated with EBR-II Run 138B. All of the reactivity effect values are negative with the exception of subassembly thermal bowing which was positive under the initial reactor heating and then also becomes negative like the other components. The most dominate thermal expansion component is associated with the upper grid plate expansion. The upper grid plate sets the fuel assembly pitch.

---

Table 1.1.11. Thermal Expansion Coefficients Used for the Safety Analysis of EBR-II Run 138B

<table>
<thead>
<tr>
<th>Calculated Negative Reactivity Component</th>
<th>Values Used in Analysis ((10^{-4} \text{$/°C$})) (a)</th>
<th>Estimated Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper grid plate expansion</td>
<td>-14.5</td>
<td>20</td>
</tr>
<tr>
<td>Driver steel expansion</td>
<td>-2.2</td>
<td>7</td>
</tr>
<tr>
<td>Subassembly thermal bowing</td>
<td>+9.8</td>
<td>25</td>
</tr>
<tr>
<td>Control-rod bank extension</td>
<td>-7.16</td>
<td>5</td>
</tr>
<tr>
<td>Driver fuel expansion</td>
<td>-4.91</td>
<td>11</td>
</tr>
<tr>
<td>Doppler effect</td>
<td>-0.671</td>
<td>10</td>
</tr>
</tbody>
</table>

(a) These values were calculated using a beta effective of 0.0068.

1.1.5 Additional Information Relevant to Critical and Subcritical Measurements

For Run 138B, the critical control rods positions can be found in Table 1.1.12. The EBR-II controls rods were fueled rather than poisoned. Thus, full insertion provides the maximum positive reactivity effect. In EBR-II, 14 inches was the maximum insertion.
Table 1.1.12 Critical Rod Heights of Run 138B.

<table>
<thead>
<tr>
<th>Control Rod</th>
<th>Insertion (inch/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>03D01 Safety</td>
<td>14.0 / 35.56</td>
</tr>
<tr>
<td>03A01 Safety</td>
<td>14.0 / 35.56</td>
</tr>
<tr>
<td>05C03 HWCR</td>
<td>0.0 / 0.0</td>
</tr>
<tr>
<td>05D01 Control</td>
<td>14.0 / 35.56</td>
</tr>
<tr>
<td>05E01 HWCR</td>
<td>14.0 / 35.56</td>
</tr>
<tr>
<td>05E03 HWCR</td>
<td>3.01 / 7.65</td>
</tr>
<tr>
<td>05F01 HWCR</td>
<td>14.0 / 35.56</td>
</tr>
<tr>
<td>05A01 HWCR</td>
<td>14.0 / 35.56</td>
</tr>
<tr>
<td>05B01 HWCR</td>
<td>0.0 / 0.0</td>
</tr>
<tr>
<td>05B03 HWCR</td>
<td>14.0 / 35.56</td>
</tr>
</tbody>
</table>

1.2 **Description of Buckling and Extrapolation Length Measurements**
Buckling and extrapolation length measurements were not made.

1.3 **Description of Spectral Characteristics Measurements**
Spectral Characteristics Measurements were not made.

1.4 **Description of Reactivity Effects Measurements**
Reactivity Effects Measurements were not made.

1.5 **Description of Reactivity Coefficient Measurements**
Reactivity Coefficient Measurements were not made.

1.6 **Description of Kinetics Measurements**
Kinetics Measurements were not made.

1.7 **Description of Reaction-Rate Distribution Measurements**
Reaction-Rate Distribution Measurements were not made.

1.8 **Description of Power Distribution Measurements**
Power Distribution Measurements were not made.
1.9 **Description of Isotopic Measurements**

Isotopic Measurements were not made.

1.10 **Description of Other Miscellaneous Types of Measurements**

Other Miscellaneous Types of Measurements were not made.
2.0 EVALUATION OF EXPERIMENTAL DATA

2.1 Evaluation of Critical and / or Subcritical Configuration Data

Statistical uncertainties for all runs were between 0.00005 and 0.00006 leading to a Δk statistical uncertainty of 0.000078. The cross-section file used was ENDF/B-VII.0.

Scaling factors were often increased to yield a greater than 1σ uncertainty and then subsequently used to adjust the calculated k_{eff} back to a 1σ. Uncertainty in k_{eff} was assessed using the stochastic uncertainty and then combined in quadrature to determine total uncertainty from a set of k_{eff} values.

Perturbations were done using a plus and minus deviation from as-built model k_{eff} unless otherwise limited by model boundaries.

Almost all perturbations used information gathered from manufacturing tolerances and were considered strictly enforced. Assemblies found to be non-conforming according to the engineering design were sent back to the manufacturer to be refabricated. Specifically, the dimensional perturbations were considered to have a normal distribution such that high or low dimensional values within the uncertainty would be undesirable.

Fuel material compositions were obtained from Argonne National Laboratory. The compositions resulted from detailed core follow analysis performed in the early 1990s using the REBUS-3 computer code developed by Argonne National Laboratory. The core follow analysis addressed individual assembly burnup for all assemblies in the Run 138B core configuration. The compositions for each specific fuel assembly were divided into three axial slug regions. The fuel mass uncertainty results from beginning of life mass uncertainty coupled with depletion analysis uncertainty. The beginning of life mass uncertainty is -1.0% and +0.5% based on manufacturing measurements and guidance from an expert, D. L. Porter, directly involved in the manufacturing EBR-II fuel. The mass uncertainty associated with depletion analysis uncertainty was obtained from published report from an EBR-II depletion analysis expert, R. D. McKnight. The depletion analysis mass uncertainty (~0.06%) is a very small contributor to the overall fuel mass uncertainty because the vast majority of atoms do not undergo fission. The overall fuel mass uncertainty used a uniform distribution ranging from -1.06% to +0.56%.

Little measured data is available to be used for the benchmark. Subsequently a random component to the uncertainty is unavailable for most measurements. Each perturbation was assessed for the ratio of systematic to random components of the uncertainty. Given that little measured data was available the systematic component dominated the uncertainty. Ubiquitous identical structures like fuel element cladding and assembly pitch had a larger random component applied. The ratio of random versus systematic and the number of components perturbed for each perturbation is annotated in Table 2.1.80.

Various regions within the core are referred to in the following perturbations. They are defined as follows:

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Assembly refers to everything inside of the hexagonal duct and the lower adapter. The hexagonal duct height plus the lower adapter height equals the total length of the assembly.

Upper extension refers to the stainless-steel sodium homogenization located inside the inner wall diameter of the hexagonal duct, above the core region height, and below the inner wall of the assembly.

Core region height refers to the region inside the inner wall diameter of the hexagonal duct, below the upper extension, above the lower extension. It contains the fuel elements and its height is defined separately from the fuel elements.

Fuel element refers to cladding, wire wrap, fuel slug, and sodium bond. The cladding height is the total height of fuel element and the wire wrap plus the cladding outer diameter equals the total diameter of the fuel element.

Fuel slug refers to the uranium cylinder located inside of the inner diameter of the cladding and is submerged in the sodium bond.

The lower extension refers to the stainless-steel sodium homogenization located inside of the inner diameter of the hexagonal duct, above the lower adapter and below the core region height.

Dimensions that change due to thermal expansion were not measured for the experiment. This was primarily due to the complex structural interactions that occur from thermal expansion. To account for thermal expansion, coefficients that were reported for the experiments were applied as a bias in section 3.1.1.6.

2.1.1 Experimental Uncertainties

2.1.1.1 Temperature

The temperature reported for the experiment was 650°F (~343°C or ~616 K). The MCNP data library cross sections were thermally broadened using NJOY\textsuperscript{a} to 616 K. The uncertainty in the measured temperature was unavailable. An uncertainty related to the thermocouples used in the assembly XX09 was reported to be ±0.7 K.\textsuperscript{b} This value was used as a typical uncertainty for the thermocouple used for the logbook reported value of 650°F. It was then increased by a factor of 10 to account for the unknown source of the logbook value and assessed as a uniform distribution. The temperature perturbation was applied to the mass densities of all the materials apart from fuel. No thermal expansion was applied to the model from the temperature perturbation. The structural expansion due to temperature was applied as a bias in section 3.1.1.6.


Table 2.1.1. Uncertainty in $k$ due to Temperature

<table>
<thead>
<tr>
<th>Deviation</th>
<th>$\Delta k$</th>
<th>$\pm$</th>
<th>$\sigma_{\Delta k}$</th>
<th>Scaling Factor</th>
<th>$\Delta k_{\text{eff}}(1\sigma)$</th>
<th>$\pm$</th>
<th>$\sigma_{\Delta k_{\text{eff}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 7 K (10 × limit)</td>
<td>-0.00017</td>
<td>$\pm$</td>
<td>0.00007</td>
<td>$10\sqrt{3}$</td>
<td>-0.00001</td>
<td>$\pm$</td>
<td>0.00000</td>
</tr>
<tr>
<td>- 7 K (10 × limit)</td>
<td>0.00021</td>
<td>$\pm$</td>
<td>0.00007</td>
<td>$10\sqrt{3}$</td>
<td>0.00001</td>
<td>$\pm$</td>
<td>0.00000</td>
</tr>
</tbody>
</table>

2.1.1.2 Control Rod Positions

The control rod positions were evaluated using the reported drive mechanism uncertainty. The total drive stroke was 35.56 cm denoted in the engineering drawings for all movable rods. Even with the differences in engineering design, the uncertainty reported for both drive mechanisms was $\pm 0.102$ cm and considered to be a $3\sigma$ uncertainty. The accumulative effects that lead to the total control rod position uncertainty are thermal expansion of the rod drive mechanism and the manufacturing tolerance of the length of the mechanism. Neither of these were evaluated in the benchmark because a reference for each was not available. The control rod drive mechanism uncertainty is negligible given the entire benchmark and the control rod bank thermal expansion. The bank expansion was assessed as a bias in section 3.1.1.6.

Table 2.1.2. Control Rod Mechanism Uncertainty

<table>
<thead>
<tr>
<th>Deviation</th>
<th>$\Delta k$</th>
<th>$\pm$</th>
<th>$\sigma_{\Delta k}$</th>
<th>Scaling Factor</th>
<th>$\Delta k_{\text{eff}}(1\sigma)$</th>
<th>$\pm$</th>
<th>$\sigma_{\Delta k_{\text{eff}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pm 0.102$ cm (3$\sigma$)</td>
<td>0.00000</td>
<td>$\pm$</td>
<td>0.00007</td>
<td>1</td>
<td>0.00000</td>
<td>$\pm$</td>
<td>0.00007</td>
</tr>
</tbody>
</table>

2.1.1.3 Measured Value of $k_{\text{eff}}$

There was no specific reference to $k_{\text{eff}}$ made during the experiment. The reactor log only shows when the reactor went critical with associated control rod positions. No uncertainty was reported.

2.1.2 Geometrical Properties

2.1.2.1 Driver Assemblies

EBR-II Run 138B reactor configuration used depleted fuel which involved both fuel slug and fuel element swelling. The swelling was taken into consideration for the as-built model.

For all perturbations not directly involving the fuel slug, the mass was not preserved because dimensional uncertainties represent the manufacturer adding or subtracting material.
2.1.2.2 Experimental Assemblies

EBR-II had seven experimental assemblies during Run 138B. These experimental assemblies often lack detailed engineering drawing, and often were only described in writing. Due to this lack of information, the experimental assemblies were perturbed as if they were any other core assemblies. The uncertainties were derived from the type of assembly which most resembled the experimental configuration.

2.1.2.3 Core Assemblies

Fuel Slug: Height

Measured data was available for the fuel slug height. These data were taken from the fuel element that went into experimental assembly XX09. XX09 was not a typical assembly, however the fuel elements that were used in the assembly were typical MK-IIA fuel slugs. Each slug was measured in length, and an uncertainty was found to be ± 0.02159 cm with a uniform distribution.

There are 7,578 total fuel slugs.

Table 2.1.3. Uncertainty in k due to Fuel Slug Height

<table>
<thead>
<tr>
<th>Deviation</th>
<th>$\Delta k$</th>
<th>±</th>
<th>$\sigma_{\Delta k}$</th>
<th>Scaling Factor</th>
<th>$\Delta k_{\text{eff}} (1\sigma)$</th>
<th>±</th>
<th>$\sigma_{\Delta k_{\text{eff}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 0.02159 cm (3σ)</td>
<td>-0.00006</td>
<td>±</td>
<td>0.00007</td>
<td>3</td>
<td>-0.00002</td>
<td>±</td>
<td>0.00002</td>
</tr>
<tr>
<td>- 0.02159 cm (3σ)</td>
<td>0.00005</td>
<td>±</td>
<td>0.00007</td>
<td>3</td>
<td>0.00002</td>
<td>±</td>
<td>0.00002</td>
</tr>
</tbody>
</table>

Fuel Slug: Diameter

The uncertainty the diameter was found to be ± 0.000545 cm with a uniform distribution. This represents the uncertainty in the measured diameter.

There are 7,578 total fuel slugs.

Table 2.1.4. Uncertainty in k due to Fuel Slug Diameter

<table>
<thead>
<tr>
<th>Deviation</th>
<th>$\Delta k$</th>
<th>±</th>
<th>$\sigma_{\Delta k}$</th>
<th>Scaling Factor</th>
<th>$\Delta k_{\text{eff}} (1\sigma)$</th>
<th>±</th>
<th>$\sigma_{\Delta k_{\text{eff}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 0.00055 cm (3σ)</td>
<td>0.00007</td>
<td>±</td>
<td>0.00007</td>
<td>$3\sqrt{3}$</td>
<td>0.00001</td>
<td>±</td>
<td>0.00001</td>
</tr>
<tr>
<td>- 0.00055 cm (3σ)</td>
<td>0.00004</td>
<td>±</td>
<td>0.00007</td>
<td>$3\sqrt{3}$</td>
<td>0.00001</td>
<td>±</td>
<td>0.00001</td>
</tr>
</tbody>
</table>
Fuel Element: Sodium Level Above Fuel Slug

The uncertainty in the height of the sodium above the fuel slug varies depending on the type of fuel element in the assembly. The values in Table 2.1.5 are representative of the minimum amount of sodium above the fuel slug for each type of assembly. Due to this being a minimum allowable amount, only the addition of sodium (0.635cm) was perturbed. If the uncertainty in sodium was removed from the minimum allowable amount, the fuel slugs would have been exposed for a majority of the assemblies. Table 2.1.6 shows the delta k and uncertainty due to perturbing each assembly.

Table 2.1.5. Uncertainty in the Height of Sodium Above the Fuel Slug by Assembly

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Height of Sodium Above Fuel Slug (cm)</th>
<th>Uncertainty (cm) (3σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MK-II</td>
<td>0.635</td>
<td>0.635</td>
</tr>
<tr>
<td>MK-II Half-Worth</td>
<td>0.635</td>
<td>0.635</td>
</tr>
<tr>
<td>Safety Rod</td>
<td>3.175</td>
<td>0.635</td>
</tr>
<tr>
<td>HWCR</td>
<td>0.635</td>
<td>0.635</td>
</tr>
<tr>
<td>Control Rod</td>
<td>0.635</td>
<td>0.635</td>
</tr>
<tr>
<td>C2776A</td>
<td>0.635</td>
<td>0.635</td>
</tr>
<tr>
<td>XX09</td>
<td>3.175</td>
<td>0.635</td>
</tr>
<tr>
<td>X412</td>
<td>0.635</td>
<td>0.635</td>
</tr>
<tr>
<td>X402A</td>
<td>0.635</td>
<td>0.635</td>
</tr>
</tbody>
</table>

Table 2.1.6. Uncertainty in k due to the Height of Sodium Above the Fuel Slug

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Δk ± σΔk</th>
<th>Scaling Factor</th>
<th>Δkeff (1σ) ± σΔkeff</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 0.635 (3σ)</td>
<td>0.00030 ± 0.00007</td>
<td>3</td>
<td>0.00010 ± 0.00002</td>
</tr>
</tbody>
</table>

Fuel Element Cladding Height

The fuel element height and uncertainty in the fuel element height varies by assembly. The values in Table 2.1.7 are representative of the manufacturing tolerance. Table 2.1.8 shows the delta k and uncertainty due to perturbing cladding height.
Table 2.1.7. Uncertainty in Fuel Element Height by Assembly

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Fuel Element Height (cm)</th>
<th>Uncertainty (cm) (3σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MK-II</td>
<td>61.722</td>
<td>0.08128</td>
</tr>
<tr>
<td>MK-II HW</td>
<td>61.722</td>
<td>0.08128</td>
</tr>
<tr>
<td>Safety Rod</td>
<td>59.944</td>
<td>0.08128</td>
</tr>
<tr>
<td>HWCR</td>
<td>51.562</td>
<td>0.08128</td>
</tr>
<tr>
<td>Control Rod</td>
<td>61.722</td>
<td>0.08128</td>
</tr>
<tr>
<td>C2776A</td>
<td>61.722</td>
<td>0.08128</td>
</tr>
<tr>
<td>XX09</td>
<td>59.944</td>
<td>0.08128</td>
</tr>
<tr>
<td>X412</td>
<td>61.722</td>
<td>0.08128</td>
</tr>
<tr>
<td>X402A</td>
<td>61.722</td>
<td>0.08128</td>
</tr>
</tbody>
</table>

Table 2.1.8. Uncertainty in k due to Fuel Element Height

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Δk</th>
<th>±</th>
<th>σΔk</th>
<th>Scalin g Factor</th>
<th>Δk eff (1σ)</th>
<th>±</th>
<th>σΔk eff</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 0.08128 cm (3σ)</td>
<td>-0.00001</td>
<td>±</td>
<td>0.00007</td>
<td>3</td>
<td>0.000000</td>
<td>±</td>
<td>0.00002</td>
</tr>
<tr>
<td>- 0.08128 cm (3σ)</td>
<td>-0.00003</td>
<td>±</td>
<td>0.00007</td>
<td>3</td>
<td>-0.00001</td>
<td>±</td>
<td>0.00002</td>
</tr>
</tbody>
</table>

Fuel Element Cladding Thickness

The uncertainty in the thickness (0.03048 cm) of the cladding is ±0.00254 cm. This value is representative of the manufacturing tolerance. The fuel element thickness carries for each type of assembly: MK-II driver, MK-II HW driver, safety rod, HWCR, control rod, C2776A, XX09, X412, and X402A. the cladding thickness.

Table 2.1.9 shows the uncertainty for each type of assembly. The inner diameter of the hexagonal duct limits the positive perturbation that can be performed. The fuel elements within the duct are in contact with the inner diameter of the hexagonal duct. This prevented any positive perturbation from being performed. Table 2.1.10 shows delta k and uncertainty due to perturbing the cladding thickness.
Table 2.1.9. Uncertainty in Fuel Element Cladding Thickness by Assembly

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Fuel Element Cladding Thickness (cm)</th>
<th>Uncertainty (cm) ($3\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MK-II</td>
<td>0.3048</td>
<td>0.00254</td>
</tr>
<tr>
<td>MK-II HW</td>
<td>0.3048</td>
<td>0.00254</td>
</tr>
<tr>
<td>Safety Rod</td>
<td>0.3048</td>
<td>0.00254</td>
</tr>
<tr>
<td>HWCR</td>
<td>0.3048</td>
<td>0.00254</td>
</tr>
<tr>
<td>Control Rod</td>
<td>0.3048</td>
<td>0.00254</td>
</tr>
<tr>
<td>C2776A</td>
<td>0.3048</td>
<td>0.00254</td>
</tr>
<tr>
<td>XX09</td>
<td>0.3048</td>
<td>0.00254</td>
</tr>
<tr>
<td>X412</td>
<td>0.3048</td>
<td>0.00254</td>
</tr>
<tr>
<td>X402A</td>
<td>0.3048</td>
<td>0.00254</td>
</tr>
</tbody>
</table>

Table 2.1.10. Uncertainty in $k$ due to Fuel Element Cladding Thickness

<table>
<thead>
<tr>
<th>Deviation</th>
<th>$\Delta k$</th>
<th>$\pm$</th>
<th>$\sigma_{\Delta k}$</th>
<th>Scaling Factor</th>
<th>$\Delta k_{\text{eff}}$ ($1\sigma$)</th>
<th>$\pm$</th>
<th>$\sigma_{\Delta k_{\text{eff}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.00254 cm ($3\sigma$)</td>
<td>-0.00073</td>
<td>$\pm$</td>
<td>0.00007</td>
<td>3</td>
<td>-0.00024</td>
<td>$\pm$</td>
<td>0.00002</td>
</tr>
</tbody>
</table>

**Fuel Element Cladding Outer Diameter**

The uncertainty in the outer diameter (0.44196 cm) of the fuel element is $\pm 0.00127$ cm. This value is representative of the manufacturing tolerance. The fuel element outer diameter carries for each type of assembly: MK-II driver, MK-II half-worth (MK-II HW) driver, safety rod, HWCR, control rod, C2776A, XX09, X412, and X402A. Table 2.1.11 shows the uncertainty for each type of assembly. The inner diameter of the hexagonal duct limits the positive perturbation that can be performed. The fuel element within the duct are in contact with the inner diameter of the hexagonal duct. This prevented any positive perturbation from being performed. Table 2.1.12 shows delta $k$ and uncertainty due to perturbing each assembly.
Table 2.1.11. Uncertainty in Fuel Element Outer Diameter by Assembly

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Fuel Element Outer Diameter (cm)</th>
<th>Uncertainty (cm) (1σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MK-II</td>
<td>0.44196</td>
<td>0.00127</td>
</tr>
<tr>
<td>MK-II HW</td>
<td>0.44196</td>
<td>0.00127</td>
</tr>
<tr>
<td>Safety Rod</td>
<td>0.44196</td>
<td>0.00127</td>
</tr>
<tr>
<td>HWCR</td>
<td>0.44196</td>
<td>0.00127</td>
</tr>
<tr>
<td>Control Rod</td>
<td>0.44196</td>
<td>0.00127</td>
</tr>
<tr>
<td>C2776A</td>
<td>0.44196</td>
<td>0.00127</td>
</tr>
<tr>
<td>XX09</td>
<td>0.44196</td>
<td>0.00127</td>
</tr>
<tr>
<td>X412</td>
<td>0.44196</td>
<td>0.00127</td>
</tr>
<tr>
<td>X402A</td>
<td>0.44196</td>
<td>0.00127</td>
</tr>
</tbody>
</table>

Table 2.1.12. Uncertainty in $k$ due to Fuel Element Outer Diameter

<table>
<thead>
<tr>
<th>Deviation</th>
<th>$Δk$ ± $σ_{Δk}$</th>
<th>Scaling Factor</th>
<th>$Δk_{effective}(1σ)$ ± $σ_{Δk_{effective}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.00127 cm (3σ)</td>
<td>-0.00017 ± 0.00007</td>
<td>3</td>
<td>0.00006 ± 0.00002</td>
</tr>
</tbody>
</table>

**Wire Wrap: Height**

The height and uncertainty in the wire wrap height varies by assembly. This values in Table 2.1.13 are representative of the manufacturing tolerance. Table 2.1.14 shows delta $k$ and uncertainty due to perturbing each assembly.
Table 2.1.13. Uncertainty of Wire Wrap Height by Assembly

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Wire Wrap Height (cm)</th>
<th>Uncertainty (cm) (3σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MK-II</td>
<td>61.722</td>
<td>0.08128</td>
</tr>
<tr>
<td>MK-II HW</td>
<td>61.722</td>
<td>0.08128</td>
</tr>
<tr>
<td>Safety Rod</td>
<td>59.944</td>
<td>0.08128</td>
</tr>
<tr>
<td>HWCR</td>
<td>52.324</td>
<td>0.08128</td>
</tr>
<tr>
<td>Control Rod</td>
<td>61.722</td>
<td>0.08128</td>
</tr>
</tbody>
</table>

Table 2.1.14. Uncertainty in k due to Wire Wrap Height

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Δk ± σΔk</th>
<th>Scaling Factor</th>
<th>Δk_{eff} (1σ) ± σΔk_{eff}</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 0.08128 cm (3σ)</td>
<td>0.00000 ± 0.00007</td>
<td>3</td>
<td>0.00000 ± 0.00002</td>
</tr>
<tr>
<td>- 0.08128 cm (3σ)</td>
<td>0.00000 ± 0.00007</td>
<td>3</td>
<td>0.00000 ± 0.00002</td>
</tr>
</tbody>
</table>

**Wire Wrap: Diameter**

The uncertainty in the diameter (0.12446cm) of the wire wrap is ±0.00127cm. This value is representative of the manufacturing tolerance for the wire wrap. The wire wrap diameter carries for each type of assembly: MK-II driver, MK-II HW driver, safety rod, HWCR, and control rod. Table 2.1.15 shows the uncertainty for each type of assembly. Table 2.1.16 shows delta k and uncertainty due to perturbing each assembly.
Table 2.1.15. Uncertainty in the Wire Wrap Diameter by Assembly

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Wire Wrap Diameter (cm)</th>
<th>Uncertainty (cm (3σ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>MK-II</td>
<td>0.12446</td>
<td>0.00127</td>
</tr>
<tr>
<td>MK-II HW</td>
<td>0.12446</td>
<td>0.00127</td>
</tr>
<tr>
<td>Safety Rod</td>
<td>0.12446</td>
<td>0.00127</td>
</tr>
<tr>
<td>HWCR</td>
<td>0.12446</td>
<td>0.00127</td>
</tr>
<tr>
<td>Control Rod</td>
<td>0.12446</td>
<td>0.00127</td>
</tr>
</tbody>
</table>

Table 2.1.16. Uncertainty in k due to the Wire Wrap Diameter

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Δk</th>
<th>±</th>
<th>σΔk</th>
<th>Scaling Factor</th>
<th>Δkeff(1σ)</th>
<th>±</th>
<th>σΔkeff</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 0.00127 cm (3σ)</td>
<td>0.00016</td>
<td>±</td>
<td>0.00007</td>
<td>3</td>
<td>0.00005</td>
<td>±</td>
<td>0.00002</td>
</tr>
<tr>
<td>- 0.00127 cm (3σ)</td>
<td>-0.00023</td>
<td>±</td>
<td>0.00007</td>
<td>3</td>
<td>0.00008</td>
<td>±</td>
<td>0.00002</td>
</tr>
</tbody>
</table>

2.1.2.4 Blanket Assemblies

Blanket Fuel Slug: Height

From drawing EB-1-2506-D, the height (139.7 cm) of the blanket fuel slug had no uncertainty specified. No perturbation was performed on the blanket fuel slug height. Using the fuel slug height uncertainty as a reference, an uncertainty for the blanket slug height could be assumed to be in proportion. This led to an uncertainty of ±0.08796 cm. Given the overall length of the blanket slug and the Δk calculated for the blanket slug diameter, the uncertainty in blanket slug height was assessed to be negligible.

Blanket Fuel Slug: Diameter

From drawing EB-1-25648-D, the uncertainty in the diameter (1.1506 cm) of the blanket slug is ±0.00127 cm. This value is representative of the manufacturing tolerance for the blanket fuel slug. Table 2.1.17 shows the uncertainty for the blanket fuel slug diameter, while Table 2.1.18 shows delta k and uncertainty due to perturbing the blanket fuel slug diameter.
Table 2.17. Uncertainty in the Blanket Slug Diameter

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Blanket Fuel Slug Diameter (cm)</th>
<th>Uncertainty (cm) (1σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blanket</td>
<td>1.09982</td>
<td>0.00127</td>
</tr>
</tbody>
</table>

Table 2.18. Uncertainty in k due to Blanket Slug Diameter

<table>
<thead>
<tr>
<th>Deviation</th>
<th>( \Delta k ) ± ( \sigma_{\Delta k} )</th>
<th>Scaling Factor</th>
<th>( \Delta k_{\text{eff}} (1\sigma) ) ± ( \sigma_{\Delta k_{\text{eff}}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 0.00127 cm (3σ)</td>
<td>0.00009 ± 0.00007</td>
<td>3</td>
<td>0.00003 ± 0.00002</td>
</tr>
<tr>
<td>- 0.00127 cm (3σ)</td>
<td>-0.00005 ± 0.00007</td>
<td>3</td>
<td>0.00002 ± 0.00002</td>
</tr>
</tbody>
</table>

Blanket Fuel Element: Sodium Level Above Fuel Slug

From drawing EB-1-25061-D, the uncertainty in the height (3.048 cm) of the sodium level above the blanket fuel slug is ±1.27 cm. Table 2.19 shows the uncertainty for the sodium level above the blanket fuel slug, while Table 2.20 shows delta k and uncertainty due to perturbing the sodium level above the blanket fuel slug.

Table 2.19. Uncertainty in Sodium Level Above Blanket Fuel Slug

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Blanket Fuel Slug Diameter (cm)</th>
<th>Uncertainty (cm) (3σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blanket</td>
<td>1.09982</td>
<td>1.27</td>
</tr>
</tbody>
</table>

Table 2.20. Uncertainty in k due to Sodium Level Above Blanket Fuel Slug

<table>
<thead>
<tr>
<th>Deviation</th>
<th>( \Delta k ) ± ( \sigma_{\Delta k} )</th>
<th>Scaling Factor</th>
<th>( \Delta k_{\text{eff}} (1\sigma) ) ± ( \sigma_{\Delta k_{\text{eff}}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 1.27 cm (3σ)</td>
<td>-0.00002 ± 0.00007</td>
<td>3</td>
<td>-0.00001 ± 0.00002</td>
</tr>
<tr>
<td>- 1.27 cm (3σ)</td>
<td>0.00000 ± 0.00007</td>
<td>3</td>
<td>0.00000 ± 0.00002</td>
</tr>
</tbody>
</table>
Blanket Fuel Element: Outer Diameter

From drawing EB-1-25061-D, the uncertainty in the outer diameter (3.048 cm) of the blanket fuel element is ±0.00127 cm. This value is representative of the manufacturing tolerance. Table 2.1.21 shows the uncertainty for the blanket fuel element diameter, while Table 2.1.22 shows Δk and uncertainty due to perturbing the blanket fuel element outer diameter.

Table 2.1.21. Uncertainty in Blanket Fuel Element Outer Diameter

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Blanket Fuel Slug Diameter (cm)</th>
<th>Uncertainty (cm) (3σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blanket</td>
<td>3.048</td>
<td>0.00254</td>
</tr>
</tbody>
</table>

Table 2.1.22. Uncertainty in k due to Blanket Fuel Outer Diameter

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Δk ± σΔk</th>
<th>Scaling Factor</th>
<th>Δk eff (1σ) ± σΔk eff</th>
</tr>
</thead>
<tbody>
<tr>
<td>+0.00254 cm (3σ)</td>
<td>0.00010 ± 0.00007</td>
<td>3</td>
<td>0.00003 ± 0.00002</td>
</tr>
<tr>
<td>-0.00254 cm (3σ)</td>
<td>-0.00002 ± 0.00007</td>
<td>3</td>
<td>-0.00001 ± 0.00002</td>
</tr>
</tbody>
</table>

2.1.2.5 Dummy Assemblies

Dummy Element: Diameter

From drawing E0503-0025-DB, the uncertainty in the diameter (2.0447 cm) of the dummy element is ±0.00254 cm. This value is representative of the manufacturing tolerance. Table 2.1.23 shows the uncertainty for the dummy element diameter, while Table 2.1.24 shows delta k and uncertainty due to perturbing the dummy element diameter. Assembly X320C is included in this perturbation because it was loaded with the same type of dummy elements as the dummy assembly.
Table 2.1.23. Uncertainty in the Dummy Element Diameter

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Dummy Element Diameter (cm)</th>
<th>Uncertainty (cm) (3σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dummy</td>
<td>2.0447</td>
<td>0.00254</td>
</tr>
<tr>
<td>X320C</td>
<td>2.0447</td>
<td>0.00254</td>
</tr>
</tbody>
</table>

Table 2.1.24. Uncertainty in k due to Dummy Element Diameter

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Δk ± σΔk</th>
<th>Scaling Factor</th>
<th>Δk_{eff}(1σ) ± σΔk_{eff}</th>
</tr>
</thead>
<tbody>
<tr>
<td>- 0.00254 cm (3σ)</td>
<td>0.00000 ± 0.00007</td>
<td>1</td>
<td>0.00000 ± 0.00007</td>
</tr>
</tbody>
</table>

2.1.2.6 Moveable Rods

*Inner Hex Duct: Flat-To-Flat Width*

The uncertainty in the flat-to-flat width (4.826 cm) of the inner hex duct is ±0.01078 cm. This value is representative of the manufacture tolerance. This uncertainty is not affected in the same way as the hexagonal outer duct because the structures that move inside of the assembly have gap tolerances that allow the inner duct to move. The uncertainty is an overestimation of the true uncertainty because the positive perturbation would have exceeded the inner diameter of the outer hexagonal duct. Given that only 13 of the 637 assemblies are affected by this perturbation, the overestimation becomes a negligible change in the overall uncertainty. The flat-to-flat width of the assemblies carries for each type of assembly: Safety, HWCR, control rod, XX10, XX09, and XY-16. Table 2.1.25 shows the uncertainty for each type of assembly. Table 2.1.26 shows Δk and uncertainty due to perturbing each assembly.
Table 2.1.25. Uncertainty in the Inner Hex Duct Flat-to-Flat Width

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Inner Hex Duct Lower Cylinder Diameter (cm)</th>
<th>Uncertainty (cm) (3σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety</td>
<td>4.826</td>
<td>0.01078</td>
</tr>
<tr>
<td>HWCR</td>
<td>4.826</td>
<td>0.01078</td>
</tr>
<tr>
<td>Control</td>
<td>4.826</td>
<td>0.01078</td>
</tr>
<tr>
<td>XX10</td>
<td>4.826</td>
<td>0.01078</td>
</tr>
<tr>
<td>XX09</td>
<td>4.826</td>
<td>0.01078</td>
</tr>
<tr>
<td>XY-16</td>
<td>4.826</td>
<td>0.01078</td>
</tr>
</tbody>
</table>

Table 2.1.26. Uncertainty in k due to the Inner Hex Duct Flat-to-Flat Width

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Δk   ±   σΔk</th>
<th>Scaling Factor</th>
<th>Δk_{eff} (1σ) ± σΔk_{eff}</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 0.01078 cm (3σ)</td>
<td>0.00010 ± 0.00007</td>
<td>3</td>
<td>0.00003 ± 0.00002</td>
</tr>
<tr>
<td>- 0.01078 cm (3σ)</td>
<td>-0.00007 ± 0.00007</td>
<td>3</td>
<td>-0.00002 ± 0.00002</td>
</tr>
</tbody>
</table>

**Inner Hex Duct: Wall Thickness**

The uncertainty in the thickness (0.09652 cm) of the inner hex duct varies with the assembly. This value is representative of the manufacture tolerance. The thickness of the hex duct carries for each type of assembly: Safety, HWCR, control rod, XX10, XX09, XY-16.

Table 2.1.27 shows the uncertainty for each type of assembly. Table 2.1.28 shows delta k and uncertainty due to perturbing each assembly.
Table 2.1.27. Uncertainty in the Inner Hex Duct Thickness

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Inner Hex Duct Thickness (cm)</th>
<th>Uncertainty (cm) (3σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety</td>
<td>0.09652</td>
<td>0.00762</td>
</tr>
<tr>
<td>HWCR</td>
<td>0.09652</td>
<td>0.00762</td>
</tr>
<tr>
<td>Control</td>
<td>0.09652</td>
<td>0.00762</td>
</tr>
<tr>
<td>XX10</td>
<td>0.09652</td>
<td>0.00254</td>
</tr>
<tr>
<td>XX09</td>
<td>0.09652</td>
<td>0.00254</td>
</tr>
<tr>
<td>XY-16</td>
<td>0.09652</td>
<td>0.00254</td>
</tr>
</tbody>
</table>

Table 2.1.28. Uncertainty in $k$ due to the Inner Hex Duct Thickness

<table>
<thead>
<tr>
<th>Deviation</th>
<th>$\Delta k$</th>
<th>±</th>
<th>$\sigma_{\Delta k}$</th>
<th>Scaling Factor</th>
<th>$\Delta k_{\text{eff}}(1\sigma)$</th>
<th>±</th>
<th>$\sigma_{\Delta k_{\text{eff}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ (a) (3σ)</td>
<td>-0.00006</td>
<td>±</td>
<td>0.00007</td>
<td>3</td>
<td>-0.00002</td>
<td>±</td>
<td>0.00002</td>
</tr>
<tr>
<td>- (a) (3σ)</td>
<td>-0.00001</td>
<td>±</td>
<td>0.00007</td>
<td>3</td>
<td>0.00000</td>
<td>±</td>
<td>0.00002</td>
</tr>
</tbody>
</table>

(a) This uncertainty varies by assembly.

### 2.1.2.7 Poison Assemblies

**Poison Element Cladding Height**

From drawing EB-1-52068-D, the uncertainty in the height (91.6762 cm) of the poison element is ±0.19812 cm. This value is representative of the manufacture tolerance. Table 2.1.29 shows the uncertainty for the poison element height. Table 2.1.30 shows delta k and uncertainty due to perturbing each assembly.
Table 2.1.29. Uncertainty in Poison Element Height

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Poison Element Height (cm)</th>
<th>Uncertainty (cm) (3σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HWCR</td>
<td>91.6762</td>
<td>0.19812</td>
</tr>
</tbody>
</table>

Table 2.1.30. Uncertainty in k due to Poison Element Height

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Δk   ± σΔk</th>
<th>Scaling Factor</th>
<th>Δk_{eff} (1σ) ± σΔk_{eff}</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 0.19812 cm (3σ)</td>
<td>-0.00003 ± 0.00007</td>
<td>3</td>
<td>-0.00001 ± 0.00002</td>
</tr>
<tr>
<td>- 0.19812 cm (3σ)</td>
<td>-0.00001 ± 0.00007</td>
<td>3</td>
<td>0.00000 ± 0.00002</td>
</tr>
</tbody>
</table>

**Poison Element Cladding Diameter**

From drawing EB-1-52070-B, the uncertainty in the diameter (1.5875 cm) of the poison element is ±0.00508 cm. This value is representative of the manufacture tolerance. Table 2.1.31 shows the uncertainty for the poison element diameter. Table 2.1.32 shows Δk and uncertainty due to perturbing each assembly.

Table 2.1.31. Uncertainty in Poison Element Diameter

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Poison Element Diameter (cm)</th>
<th>Uncertainty (cm) (3σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HWCR</td>
<td>1.5875</td>
<td>0.00508</td>
</tr>
</tbody>
</table>

Table 2.1.32. Uncertainty in k due to Poison Element Diameter

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Δk   ± σΔk</th>
<th>Scaling Factor</th>
<th>Δk_{eff} (1σ) ± σΔk_{eff}</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 0.00508 cm (3σ)</td>
<td>0.00011 ± 0.00007</td>
<td>3</td>
<td>0.00004 ± 0.00002</td>
</tr>
<tr>
<td>- 0.00508 cm (3σ)</td>
<td>0.00009 ± 0.00007</td>
<td>3</td>
<td>0.00003 ± 0.00002</td>
</tr>
</tbody>
</table>

**Poison Element: Shield Block Height**

From drawing EB-1-52073-B, the uncertainty in the height (20.32 cm) of the poison element shield block is ±0.07874 cm. This value is representative of the manufacture tolerance. Table 2.1.33 shows the uncertainty for the poison element shield block height. Table 2.1.34 shows delta k and uncertainty due to perturbing each assembly.

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Date: December 28, 2017
Table 2.1.33. Uncertainty in Poison Element Shield Block Height

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Poison Element Shield Block Height (cm)</th>
<th>Uncertainty (cm) (3σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HWCR</td>
<td>20.32</td>
<td>0.07874</td>
</tr>
</tbody>
</table>

Table 2.1.34. Uncertainty in k due to Poison Element Shield Block Height

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Δk ± σ_{Δk}</th>
<th>Scaling Factor</th>
<th>Δk_{eff} (1σ) ± σ_{Δk_{eff}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 0.07874 cm (3σ)</td>
<td>0.00004 ± 0.00007</td>
<td>3</td>
<td>0.00001 ± 0.00002</td>
</tr>
<tr>
<td>- 0.07874 cm (3σ)</td>
<td>0.00003 ± 0.00007</td>
<td>3</td>
<td>-0.00001 ± 0.00002</td>
</tr>
</tbody>
</table>

**Poison Element: Cladding Wall Thickness**

From drawing EB-1-52070-B, the uncertainty in the wall thickness (0.08899 cm) of the poison element cladding is ±0.00762 cm. This value is representative of the manufacture tolerance. Table 2.1.35 shows the uncertainty for the poison element cladding thickness. Table 2.1.36 shows delta k and uncertainty due to perturbing each assembly.

Table 2.1.35. Uncertainty in Poison Element Cladding Wall Thickness

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Poison Element Cladding Thickness (cm)</th>
<th>Uncertainty (cm) (3σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HWCR</td>
<td>0.08899</td>
<td>0.00762</td>
</tr>
</tbody>
</table>

Table 2.1.36. Uncertainty in k due to Poison Element Cladding Wall Thickness

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Δk ± σ_{Δk}</th>
<th>Scaling Factor</th>
<th>Δk_{eff} (1σ) ± σ_{Δk_{eff}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 0.00762 cm (3σ)</td>
<td>0.00012 ± 0.00007</td>
<td>3</td>
<td>0.00004 ± 0.00002</td>
</tr>
<tr>
<td>- 0.00762 cm (3σ)</td>
<td>-0.00003 ± 0.00007</td>
<td>3</td>
<td>-0.00001 ± 0.00002</td>
</tr>
</tbody>
</table>
Poison Element: Wire Wrap Height

From drawing EB-1-52068, the uncertainty in the height (91.6762 cm) of the poison element wire wrap is ±0.19812 cm. This value is representative of the manufacture tolerance. Table 2.1.37 shows the uncertainty for the poison element wire wrap height. Table 2.1.38 shows delta k and uncertainty due to perturbing each assembly.

### Table 2.1.37. Uncertainty in Poison Element Wire Wrap Height

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Poison Element Wire Wrap Height (cm)</th>
<th>Uncertainty (cm) (3σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HWCR</td>
<td>91.6762</td>
<td>0.19812</td>
</tr>
</tbody>
</table>

### Table 2.1.38. Uncertainty in k due to Poison Element Wire Wrap Height

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Δk</th>
<th>±</th>
<th>σΔk</th>
<th>Scaling Factor</th>
<th>Δk_{eff} (1σ)</th>
<th>±</th>
<th>σΔk_{eff}</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 0.19812 cm (3σ)</td>
<td>-0.00001</td>
<td>±</td>
<td>0.00007</td>
<td>3</td>
<td>0.00000</td>
<td>±</td>
<td>0.00002</td>
</tr>
<tr>
<td>- 0.19812 cm (3σ)</td>
<td>0.00004</td>
<td>±</td>
<td>0.00007</td>
<td>3</td>
<td>0.00001</td>
<td>±</td>
<td>0.00002</td>
</tr>
</tbody>
</table>

Poison Element: Wire Wrap Diameter

From drawing EB-1-52068, the uncertainty in the diameter (0.0762 cm) of the poison element wire wrap is ±0.00127 cm. This value is representative of the manufacture tolerance. Table 2.1.39 shows the uncertainty for the poison element wire wrap diameter. Table 2.1.40 shows delta k and uncertainty due to perturbing each assembly.
Table 2.1.39. Uncertainty in the Poison Element Wire Wrap Diameter

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Poison Element Wire Wrap Diameter (cm)</th>
<th>Uncertainty (cm) (3σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HWCR</td>
<td>0.0762</td>
<td>0.00127</td>
</tr>
</tbody>
</table>

Table 2.1.40. Uncertainty in k due to the Poison Element Wire Wrap Diameter

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Δk     ±      σΔk</th>
<th>Scaling Factor</th>
<th>Δk_{eff} (1σ) ± σΔk_{eff}</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 0.00127 cm (3σ)</td>
<td>-0.00004 ± 0.00007</td>
<td>3</td>
<td>-0.00001 ± 0.00000</td>
</tr>
<tr>
<td>- 0.00127 cm (3σ)</td>
<td>0.00000 ± 0.00007</td>
<td>3</td>
<td>0.00000 ± 0.00000</td>
</tr>
</tbody>
</table>

Poison Slug: Diameter

Measurements were taken from a MK-I high-worth control rod poison slugs. There were differences between the MK-II and MK-I rods, but the poison slugs themselves were identical. The main difference between the rods was the type of fuel elements that were used. A MK-I high worth control rod used MK-I fuel elements. The diameter uncertainty from the measurements is ±0.0127 cm with a normal distribution. Table 2.1.41 shows the uncertainty for the poison slug diameter. Table 2.1.42 shows delta k and uncertainty due to perturbing each assembly.

Table 2.1.41. Uncertainty in Poison Slug Diameter

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Poison Slug Diameter (cm)</th>
<th>Uncertainty (cm) (1σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HWCR</td>
<td>1.37541</td>
<td>0.0127</td>
</tr>
</tbody>
</table>

Table 2.1.42. Uncertainty in k due to Poison Slug Diameter

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Δk     ±      σΔk</th>
<th>Scaling Factor</th>
<th>Δk_{eff} (1σ) ± σΔk_{eff}</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 0.0127 cm (1σ)</td>
<td>0.00016 ± 0.00007</td>
<td>1</td>
<td>0.00016 ± 0.00007</td>
</tr>
<tr>
<td>- 0.0127 cm (1σ)</td>
<td>-0.00011 ± 0.00007</td>
<td>1</td>
<td>-0.00011 ± 0.00007</td>
</tr>
</tbody>
</table>
**Poison Slug: Height**

The height uncertainty from the measurements is ± 0.01778 cm with a uniform distribution. Table 2.1.43 shows the uncertainty for the poison slug height. Table 2.1.44 shows delta k and uncertainty due to perturbing each assembly.

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Poison Slug Height (cm)</th>
<th>Uncertainty (cm) (3σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HWCR</td>
<td>35.56</td>
<td>0.01778</td>
</tr>
</tbody>
</table>

**Table 2.1.44. Uncertainty in k due to Poison Slug Height**

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Δk</th>
<th>±</th>
<th>σΔk</th>
<th>Scaling Factor</th>
<th>Δk_{eff} (1σ)</th>
<th>±</th>
<th>σΔk_{eff}</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 0.01778 cm (3σ)</td>
<td>0.00005</td>
<td>±</td>
<td>0.00007</td>
<td>3√3</td>
<td>0.00001</td>
<td>±</td>
<td>0.00002</td>
</tr>
<tr>
<td>- 0.01778 cm (3σ)</td>
<td>0.00001</td>
<td>±</td>
<td>0.00007</td>
<td>3√3</td>
<td>0.00000</td>
<td>±</td>
<td>0.00002</td>
</tr>
</tbody>
</table>

**2.1.2.8 Assembly Structure**

**Assembly Pitch**

The pitch of the assemblies was 5.8877 cm with an uncertainty of ± 0.00762 cm. The pitch perturbation was assessed by increasing/decreasing the spacing between assemblies. The uncertainty was assessed to be a uniform distribution.
Table 2.1.45. Uncertainty in Pitch of the Assemblies

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Pitch (cm)</th>
<th>Uncertainty (cm) (1σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch</td>
<td>5.8877</td>
<td>0.00762</td>
</tr>
</tbody>
</table>

Table 2.1.46. Uncertainty in $k$ due to Pitch of the Assemblies

<table>
<thead>
<tr>
<th>Deviation</th>
<th>$\Delta k$</th>
<th>$\pm \sigma_{\Delta k}$</th>
<th>Scaling Factor</th>
<th>$\Delta k_{\text{eff}}$ (1σ)</th>
<th>$\pm \sigma_{\Delta k_{\text{eff}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 0.00762 cm (1σ)</td>
<td>-0.00085</td>
<td>$\pm 0.00007$</td>
<td>1</td>
<td>-0.00085</td>
<td>$\pm 0.00007$</td>
</tr>
<tr>
<td>- 0.00762 cm (1σ)</td>
<td>0.00098</td>
<td>$\pm 0.00007$</td>
<td>1</td>
<td>0.00098</td>
<td>$\pm 0.00007$</td>
</tr>
</tbody>
</table>

Lower Adapter Hole Position

The upper reactor grid plate was a hand-marked and drilled piece of steel. There was an uncertainty of (0.0129 cm) the diameter of the hole drilled for the lower adapters. The hole locations set the assembly pitch. Assessing the perturbation moved all subassemblies radially out within the uncertainty.

Table 2.1.47. Uncertainty in Lower Adapter Hole Position

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Position (cm)</th>
<th>Uncertainty (cm) (1σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Adapter Hole Position</td>
<td>Origin</td>
<td>0.00508</td>
</tr>
</tbody>
</table>

Table 2.1.48. Uncertainty in $k$ due to Lower Adapter Hole Position

<table>
<thead>
<tr>
<th>Deviation</th>
<th>$\Delta k$</th>
<th>$\pm \sigma_{\Delta k}$</th>
<th>Scaling Factor</th>
<th>$\Delta k_{\text{eff}}$ (1σ)</th>
<th>$\pm \sigma_{\Delta k_{\text{eff}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 0.00508 cm (1σ)</td>
<td>-0.00008</td>
<td>$\pm 0.00007$</td>
<td>1</td>
<td>-0.00008</td>
<td>$\pm 0.00007$</td>
</tr>
<tr>
<td>- 0.00508 cm (1σ)</td>
<td>0.00016</td>
<td>$\pm 0.00007$</td>
<td>1</td>
<td>0.00016</td>
<td>$\pm 0.00007$</td>
</tr>
</tbody>
</table>
Fuel Assembly Hex Duct: Flat-To-Flat Width

The uncertainty in the flat-to-flat width (5.8166 cm) of the assemblies is ±0.08076 cm. This value is representative of the manufacture tolerance. The flat-to-flat width of the assemblies carries for each type of assembly: MK-II driver, MK-II HW driver, safety rod, HWCR, control rod, dummy, reflector, C2776A, XX09, X412, X402A, X320C, XX10, and XY-16. This perturbation could not be performed because information was not available for the overall reactor liner diameter. Treating the hex duct: flat-To-flat width uncertainty as-is would have created a large unrealistic perturbation. Changing the outer diameter of the hexagonal ducts without a restraining value would lead to a large change in pitch. This problem affects both the positive and negative perturbation. The overall pitch change when all rows are combined is ±1.3 cm. Both perturbations would have led to large changes in k-effective which were not possible inside of the real core. The pitch perturbation has been assessed separately.

Table 2.1.49. Uncertainty in Flat-to-Flat Width of Fuel Assembly Hex Duct by Assembly

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Assembly Hex Duct Flat-to-Flat Width (cm)</th>
<th>Uncertainty (cm) (1σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MK-II</td>
<td>5.8166</td>
<td>0.08076</td>
</tr>
<tr>
<td>MK-II HW</td>
<td>5.8166</td>
<td>0.08076</td>
</tr>
<tr>
<td>Safety Rod</td>
<td>5.8166</td>
<td>0.08076</td>
</tr>
<tr>
<td>HWCR</td>
<td>5.8166</td>
<td>0.08076</td>
</tr>
<tr>
<td>Control Rod</td>
<td>5.8166</td>
<td>0.08076</td>
</tr>
<tr>
<td>Dummy</td>
<td>5.8166</td>
<td>0.08076</td>
</tr>
<tr>
<td>Reflector</td>
<td>5.8166</td>
<td>0.08076</td>
</tr>
<tr>
<td>C2776A</td>
<td>5.8166</td>
<td>0.08076</td>
</tr>
<tr>
<td>XX09</td>
<td>5.8166</td>
<td>0.08076</td>
</tr>
<tr>
<td>X412</td>
<td>5.8166</td>
<td>0.08076</td>
</tr>
<tr>
<td>X402A</td>
<td>5.8166</td>
<td>0.08076</td>
</tr>
<tr>
<td>X320C</td>
<td>5.8166</td>
<td>0.08076</td>
</tr>
<tr>
<td>XX10</td>
<td>5.8166</td>
<td>0.08076</td>
</tr>
<tr>
<td>XY-16</td>
<td>5.8166</td>
<td>0.08076</td>
</tr>
</tbody>
</table>

Fuel Assembly Hex Duct: Wall Thickness

The uncertainty in the wall thickness (0.1016 cm) of the assembly hex duct is ±0.00254 cm. This value is representative of the manufacture tolerance. The thickness of the assemblies carries for each type of assembly: MK-II driver, MK-II HW driver, safety rod, HWCR, control rod, dummy, reflector, C2776A, XX09, X412,
X402A, X320C, XX10, and XY-16. Table 2.1.50 shows the uncertainty for each type of assembly. To achieve the perturbation for thickness the inner flat-to-flat width was perturbed to prevent changing the pitch of the assemblies. Table 2.1.51 shows delta k and uncertainty due to perturbing each assembly.

Table 2.1.50. Uncertainty in the Thickness of the Assembly Hex Duct by Assembly

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Fuel Element Cladding Thickness (cm)</th>
<th>Uncertainty (cm) (3σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MK-II</td>
<td>0.1016</td>
<td>0.00254</td>
</tr>
<tr>
<td>MK-II HW</td>
<td>0.1016</td>
<td>0.00254</td>
</tr>
<tr>
<td>Safety Rod</td>
<td>0.1016</td>
<td>0.00254</td>
</tr>
<tr>
<td>HWCR</td>
<td>0.1016</td>
<td>0.00254</td>
</tr>
<tr>
<td>Control Rod</td>
<td>0.1016</td>
<td>0.00254</td>
</tr>
<tr>
<td>Dummy</td>
<td>0.1016</td>
<td>0.00254</td>
</tr>
<tr>
<td>Reflector</td>
<td>0.1016</td>
<td>0.00254</td>
</tr>
<tr>
<td>C2776A</td>
<td>0.1016</td>
<td>0.00254</td>
</tr>
<tr>
<td>XX09</td>
<td>0.1016</td>
<td>0.00254</td>
</tr>
<tr>
<td>X412</td>
<td>0.1016</td>
<td>0.00254</td>
</tr>
<tr>
<td>X402A</td>
<td>0.1016</td>
<td>0.00254</td>
</tr>
<tr>
<td>X320C</td>
<td>0.1016</td>
<td>0.00254</td>
</tr>
<tr>
<td>XX10</td>
<td>0.1016</td>
<td>0.00254</td>
</tr>
<tr>
<td>XY-16</td>
<td>0.1016</td>
<td>0.00254</td>
</tr>
</tbody>
</table>

Table 2.1.51. Uncertainty in k due to Thickness in the Hex Duct

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Δk</th>
<th>±</th>
<th>σ_Δk</th>
<th>Scaling Factor</th>
<th>Δk_{eff} (1σ)</th>
<th>±</th>
<th>σ_Δk_{eff}</th>
</tr>
</thead>
<tbody>
<tr>
<td>- 0.00254 cm (3σ)</td>
<td>-0.00059</td>
<td>±</td>
<td>0.00007</td>
<td>3</td>
<td>-0.00020</td>
<td>±</td>
<td>0.00002</td>
</tr>
</tbody>
</table>

**Lower Extension: Height**

The lower extension height and uncertainty varies by assembly. This values in Table 2.1.52 are representative of the manufacturing tolerance. Table 2.1.53 shows Δk and uncertainty due to perturbing each assembly.
Table 2.1.52. Uncertainty in Lower Extension Height by Assembly

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Lower Extension height (cm)</th>
<th>Uncertainty (cm) (3σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MK-II</td>
<td>61.3537</td>
<td>0.07874</td>
</tr>
<tr>
<td>MK-II HW</td>
<td>61.3537</td>
<td>0.07874</td>
</tr>
<tr>
<td>Safety Rod</td>
<td>61.7525</td>
<td>0.07874</td>
</tr>
<tr>
<td>HWCR</td>
<td>52.23</td>
<td>0.0381</td>
</tr>
<tr>
<td>Control Rod</td>
<td>61.2839</td>
<td>0.03962</td>
</tr>
<tr>
<td>C2776A</td>
<td>61.3537</td>
<td>0.07874</td>
</tr>
<tr>
<td>XX09</td>
<td>52.23</td>
<td>0.0381</td>
</tr>
<tr>
<td>X412</td>
<td>61.3537</td>
<td>0.07874</td>
</tr>
<tr>
<td>X402A</td>
<td>61.3537</td>
<td>0.07874</td>
</tr>
<tr>
<td>XX10</td>
<td>52.23</td>
<td>0.0381</td>
</tr>
<tr>
<td>XY-16</td>
<td>52.23</td>
<td>0.0381</td>
</tr>
</tbody>
</table>

Table 2.1.53. Uncertainty in k due to the Lower Extension Height

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Δk ± σ_{Δk}</th>
<th>Scaling Factor</th>
<th>Δk_{eff (1σ)} ± σ_{Δk_{eff}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ (a) (3σ)</td>
<td>0.00001 ± 0.00007</td>
<td>3</td>
<td>0.00000 ± 0.00002</td>
</tr>
<tr>
<td>- (a) (3σ)</td>
<td>0.00004 ± 0.00007</td>
<td>3</td>
<td>0.00001 ± 0.00002</td>
</tr>
</tbody>
</table>

(a) This uncertainty varies by assembly.

Upper Extension: Height

The upper extension height and uncertainty varies by assembly. This values in Table 2.1.54 are representative of the manufacturing tolerance. Table 2.1.55 shows delta k and uncertainty due to perturbing each assembly.
Table 2.1.54. Uncertainty in Upper Extension Height by Assembly

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Upper Extension Height (cm)</th>
<th>Uncertainty (cm) (1σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MK-II</td>
<td>40.5968</td>
<td>0.36088</td>
</tr>
<tr>
<td>MK-II HW</td>
<td>40.5968</td>
<td>0.36088</td>
</tr>
<tr>
<td>Safety Rod</td>
<td>37.3050</td>
<td>0.16203</td>
</tr>
<tr>
<td>HWCR</td>
<td>96.4413</td>
<td>0.19812</td>
</tr>
<tr>
<td>Control Rod</td>
<td>66.5640</td>
<td>0.25230</td>
</tr>
<tr>
<td>C2776A</td>
<td>40.5968</td>
<td>0.36088</td>
</tr>
<tr>
<td>XX09</td>
<td>40.5968</td>
<td>0.36088</td>
</tr>
<tr>
<td>X412</td>
<td>40.5968</td>
<td>0.36088</td>
</tr>
<tr>
<td>X402A</td>
<td>40.5968</td>
<td>0.36088</td>
</tr>
<tr>
<td>XX10</td>
<td>40.5968</td>
<td>0.36088</td>
</tr>
<tr>
<td>XY-16</td>
<td>66.5547</td>
<td>0.25230</td>
</tr>
</tbody>
</table>

Table 2.1.55. Uncertainty in k due to Upper Extension Height

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Δk</th>
<th>±</th>
<th>σΔk</th>
<th>Scaling Factor</th>
<th>Δk_{eff} (1σ)</th>
<th>±</th>
<th>σΔk_{eff}</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ (a) (3σ)</td>
<td>-0.00002</td>
<td>±</td>
<td>0.00007</td>
<td>3</td>
<td>-0.00001</td>
<td>±</td>
<td>0.00002</td>
</tr>
<tr>
<td>- (a) (3σ)</td>
<td>0.00005</td>
<td>±</td>
<td>0.00007</td>
<td>3</td>
<td>0.00002</td>
<td>±</td>
<td>0.00002</td>
</tr>
</tbody>
</table>

(a) This uncertainty varies by assembly.

2.1.2.9 Core

Core: Button Height

From drawing EB-1-52141-C, the uncertainty in the height (0.03556 cm) of the button is ±0.00762 cm. The button height of the assemblies carries for each type of assembly: MK-II driver, MK-II HW driver, safety rod, HWCR, control rod, dummy, reflector, C2776A, XX09, X412, X402A, X320C, XX10, and XY-16. The button heights had a similar issue to the hexagonal ducts outer diameter. Any change in button height causes a large pitch change which is unrealistic given that all assemblies were touching inside of the core. This prevented any positive perturbation from being performed. The negative perturbation cannot be performed because of the drastic change in pitch. Only perturbing the height and not the pitch leads to a negligible change. The values in Table 2.1.56 are representative of the manufacture tolerance. Table 2.1.56 shows the uncertainty in the button height.
Table 2.1.56. Uncertainty in Button Height by Assembly

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Button Height (cm)</th>
<th>Uncertainty (cm) (1σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MK-II</td>
<td>0.03556</td>
<td>0.00762</td>
</tr>
<tr>
<td>MK-II HW</td>
<td>0.03556</td>
<td>0.00762</td>
</tr>
<tr>
<td>Safety</td>
<td>0.03556</td>
<td>0.00762</td>
</tr>
<tr>
<td>HWCR</td>
<td>0.03556</td>
<td>0.00762</td>
</tr>
<tr>
<td>Control</td>
<td>0.03556</td>
<td>0.00762</td>
</tr>
<tr>
<td>Reflector</td>
<td>0.03556</td>
<td>0.00762</td>
</tr>
<tr>
<td>Dummy</td>
<td>0.03556</td>
<td>0.00762</td>
</tr>
<tr>
<td>Blanket</td>
<td>0.03556</td>
<td>0.00762</td>
</tr>
<tr>
<td>C2776A</td>
<td>0.03556</td>
<td>0.00762</td>
</tr>
<tr>
<td>XX09</td>
<td>0.03556</td>
<td>0.00762</td>
</tr>
<tr>
<td>X412</td>
<td>0.03556</td>
<td>0.00762</td>
</tr>
<tr>
<td>X402A</td>
<td>0.03556</td>
<td>0.00762</td>
</tr>
<tr>
<td>XX10</td>
<td>0.03556</td>
<td>0.00762</td>
</tr>
<tr>
<td>XY-16</td>
<td>0.03556</td>
<td>0.00762</td>
</tr>
</tbody>
</table>

**Core: Region Height**

The height and the uncertainty of the core region varies by assembly. The values in Table 2.1.57 are representative of the manufacture tolerance in the core region height. Table 2.1.58 shows Δk and uncertainty due to perturbing each assembly.
Table 2.1.57. Uncertainty in Core Region Height by Assembly

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Core Region Height (cm)</th>
<th>Uncertainty (cm) (1σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MK-II</td>
<td>65.5422</td>
<td>0.05237</td>
</tr>
<tr>
<td>MK-II HW</td>
<td>65.5422</td>
<td>0.05237</td>
</tr>
<tr>
<td>Safety</td>
<td>65.6565</td>
<td>0.08227</td>
</tr>
<tr>
<td>HWCR</td>
<td>55.4965</td>
<td>0.08227</td>
</tr>
<tr>
<td>Control</td>
<td>65.5422</td>
<td>0.05237</td>
</tr>
<tr>
<td>Reflector</td>
<td>167.122</td>
<td>0.15748</td>
</tr>
<tr>
<td>Dummy</td>
<td>167.119</td>
<td>0.15748</td>
</tr>
<tr>
<td>Blanket</td>
<td>158.234</td>
<td>0.15748</td>
</tr>
<tr>
<td>C2776A</td>
<td>64.3153</td>
<td>0.05237</td>
</tr>
<tr>
<td>XX09</td>
<td>67.056</td>
<td>0.05237</td>
</tr>
<tr>
<td>X412</td>
<td>64.3153</td>
<td>0.05237</td>
</tr>
<tr>
<td>X402A</td>
<td>64.3153</td>
<td>0.05237</td>
</tr>
<tr>
<td>XX10</td>
<td>67.056</td>
<td>0.05237</td>
</tr>
<tr>
<td>XY-16</td>
<td>67.056</td>
<td>0.05237</td>
</tr>
<tr>
<td>X320C</td>
<td>167.119</td>
<td>0.15748</td>
</tr>
</tbody>
</table>

Table 2.1.58. Uncertainty in k due to Core Region Height

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Δk     ±</th>
<th>σ_Δk</th>
<th>Scaling Factor</th>
<th>Δk_{eff} (1σ) ±</th>
<th>σ_{Δk_{eff}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ (a) (3σ)</td>
<td>0.00004 ±</td>
<td>0.00007</td>
<td>3</td>
<td>0.00001 ±</td>
<td>0.00002</td>
</tr>
<tr>
<td>- (a) (3σ)</td>
<td>0.00003 ±</td>
<td>0.00007</td>
<td>3</td>
<td>0.00001 ±</td>
<td>0.00002</td>
</tr>
</tbody>
</table>

(a) This uncertainty varies by assembly.
2.1.3 Compositional Variations

2.1.3.1 Stainless-steel 316

Composition

The fabrication composition of stainless-steel 316 is provided in Table 1.1.1. An average composition is used to represent the benchmark model (Table 2.1.59). The perturbations were performed by maximizing each secondary constituent while using the iron for weight balance. The iron is simultaneously perturbed within its total tolerance using this procedure. This uncertainty is treated as a bounded limit with uniform probability distribution. The results are shown in Table 2.1.60.

Table 2.1.59. Stainless-Steel 316 Composition in the Benchmark Model

<table>
<thead>
<tr>
<th>Elements</th>
<th>Weight %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.008</td>
</tr>
<tr>
<td>Silicon</td>
<td>1.00</td>
</tr>
<tr>
<td>Chromium</td>
<td>17.00</td>
</tr>
<tr>
<td>Manganese</td>
<td>2.00</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>2.5</td>
</tr>
<tr>
<td>Nickel</td>
<td>12.00</td>
</tr>
<tr>
<td>Iron</td>
<td>65.42</td>
</tr>
</tbody>
</table>

Table 2.1.60. Uncertainty in the Stainless-Steel 316 Composition

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Δk</th>
<th>±</th>
<th>σΔk</th>
<th>Scaling Factor</th>
<th>Δk_{eff} (1σ)</th>
<th>±</th>
<th>σΔk_{eff}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Mn</td>
<td>-0.00015</td>
<td>± 0.00007</td>
<td>1</td>
<td>-0.00015</td>
<td>± 0.00007</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Cr</td>
<td>0.00054</td>
<td>± 0.00007</td>
<td>1</td>
<td>0.00054</td>
<td>± 0.00007</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum Cr</td>
<td>-0.00067</td>
<td>± 0.00007</td>
<td>1</td>
<td>-0.00067</td>
<td>± 0.00007</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Mo</td>
<td>-0.00035</td>
<td>± 0.00007</td>
<td>1</td>
<td>-0.00035</td>
<td>± 0.00007</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum Mo</td>
<td>0.00042</td>
<td>± 0.00007</td>
<td>1</td>
<td>0.00042</td>
<td>± 0.00007</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Ni</td>
<td>0.00062</td>
<td>± 0.00007</td>
<td>1</td>
<td>0.00062</td>
<td>± 0.00007</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum Ni</td>
<td>-0.00074</td>
<td>± 0.00007</td>
<td>1</td>
<td>-0.00074</td>
<td>± 0.00007</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Uncertainty</td>
<td>0.00109</td>
<td>± 0.00012</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Density

The density of stainless-steel 316 is reported to be 7.97 g/cm³ at benchmark temperatures. The uncertainty of density was varied by 0.1 g/cm³ with a uniform distribution. There was no data either measured or reported for the density of SS316. A reference density and uncertainty was used and 0.1 g/cm³ represents the bounding limit. The results are shown in Table 2.1.61.

Table 2.1.61. Uncertainty in the Stainless-Steel 316 Density

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Δk</th>
<th>±</th>
<th>σ_{Δk}</th>
<th>Scaling Factor</th>
<th>Δk_{eff} (1σ)</th>
<th>±</th>
<th>σ_{Δk_{eff}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>+0.1 g/cm³ (2×limit)</td>
<td>0.00000</td>
<td>±</td>
<td>0.00007</td>
<td>√3</td>
<td>0.00000</td>
<td>±</td>
<td>0.00002</td>
</tr>
<tr>
<td>+0.1 g/cm³ (2×limit)</td>
<td>0.00000</td>
<td>±</td>
<td>0.00007</td>
<td>√3</td>
<td>0.00000</td>
<td>±</td>
<td>0.00002</td>
</tr>
</tbody>
</table>

2.1.3.2 Stainless-steel 304L

The perturbations were performed by maximizing each secondary constituent while using the iron for weight balance. The iron is simultaneously perturbed within its total tolerance using this procedure.

Table 2.1.62. Stainless-Steel 304L Composition in the Benchmark Model

<table>
<thead>
<tr>
<th>Elements</th>
<th>Weight %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.07</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.5</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.011</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.006</td>
</tr>
<tr>
<td>Chromium</td>
<td>18.65</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.76</td>
</tr>
<tr>
<td>Iron</td>
<td>71.053</td>
</tr>
<tr>
<td>Nickel</td>
<td>8.95</td>
</tr>
</tbody>
</table>
### Table 2.1.63. Uncertainty in the Stainless-Steel 304L Composition

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Δk</th>
<th>±</th>
<th>σ_{Δk}</th>
<th>Scaling Factor</th>
<th>Δk_{eff} (1σ)</th>
<th>±</th>
<th>σ_{Δk_{eff}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Mn</td>
<td>-0.00044</td>
<td>± 0.00007</td>
<td></td>
<td>1</td>
<td>-0.00044</td>
<td>± 0.00007</td>
<td></td>
</tr>
<tr>
<td>Minimum Mn</td>
<td>0.00013</td>
<td>± 0.00007</td>
<td></td>
<td>1</td>
<td>0.00013</td>
<td>± 0.00007</td>
<td></td>
</tr>
<tr>
<td>Maximum Cr</td>
<td>0.00039</td>
<td>± 0.00007</td>
<td></td>
<td>1</td>
<td>0.00039</td>
<td>± 0.00007</td>
<td></td>
</tr>
<tr>
<td>Minimum Cr</td>
<td>-0.00021</td>
<td>± 0.00007</td>
<td></td>
<td>1</td>
<td>-0.00021</td>
<td>± 0.00007</td>
<td></td>
</tr>
<tr>
<td>Maximum Ni</td>
<td>0.00034</td>
<td>± 0.00007</td>
<td></td>
<td>1</td>
<td>0.00034</td>
<td>± 0.00007</td>
<td></td>
</tr>
<tr>
<td>Minimum Ni</td>
<td>-0.00030</td>
<td>± 0.00007</td>
<td></td>
<td>1</td>
<td>-0.00030</td>
<td>± 0.00007</td>
<td></td>
</tr>
<tr>
<td>Total Uncertainty</td>
<td>0.00060</td>
<td>± 0.00007</td>
<td></td>
<td>√3</td>
<td>0.00035</td>
<td>± 0.00002</td>
<td></td>
</tr>
</tbody>
</table>

**Density**

The density of stainless-steel 304L is reported to be 7.86 g/cm³ at benchmark temperatures. The uncertainty of density was varied by 0.1 g/cm³ with a uniform distribution. There was no data either measured or reported for the density of SS304L. A reference density and uncertainty was used and 0.1 g/cm³ represents the bounding limit. The results are shown in Table 2.1.64.

Table 2.1.64. Uncertainty in the Stainless-Steel 304L Density

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Δk</th>
<th>±</th>
<th>σ_{Δk}</th>
<th>Scaling Factor</th>
<th>Δk_{eff} (1σ)</th>
<th>±</th>
<th>σ_{Δk_{eff}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>+0.1 g/cm³ (2×limit)</td>
<td>0.00060</td>
<td>± 0.00007</td>
<td></td>
<td>√3</td>
<td>0.00035</td>
<td>± 0.00002</td>
<td></td>
</tr>
<tr>
<td>-0.1 g/cm³ (2×limit)</td>
<td>-0.00068</td>
<td>± 0.00007</td>
<td></td>
<td>√3</td>
<td>-0.00039</td>
<td>± 0.00002</td>
<td></td>
</tr>
</tbody>
</table>

#### 2.1.3.3 Sodium Coolant

**Density**

The density of the liquid sodium is determined entirely by the temperature of the sodium. Perturbing the temperature accomplishes perturbing the mass density of the sodium. Nominal operating sodium temperature at 616K is 0.8729 g/cm³. Applying a ± 0.7 K perturbation to the sodium leads to a ± 0.0017 g/cm³ density perturbation for the sodium. The temperature perturbation results account for the sodium density perturbation and are located in section 2.1.1.1.
2.1.3.4 Plenum Gas

Density

The plenum gas consists of 75% weight helium and 25% weight argon. The density of the plenum gas was calculated to be 0.00058 g/cm³. The density uncertainty was not reported. An uncertainty was assumed to be 0.01 g/cm³. This was a large estimate for the uncertainty but it was shown to still be insignificant. The results are reported in Table 2.1.65.

Table 2.1.65. Uncertainty in Plenum Gas Density

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Δk</th>
<th>±</th>
<th>σ_Δk</th>
<th>Scaling Factor</th>
<th>Δk_{eff} (1σ)</th>
<th>±</th>
<th>σ_{Δk_{eff}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 0.01 g/cm³ (1σ)</td>
<td>0.00000</td>
<td>±</td>
<td>0.00007</td>
<td>1</td>
<td>0.00000</td>
<td>±</td>
<td>0.00007</td>
</tr>
<tr>
<td>- 0.01 g/cm³ (1σ)</td>
<td>0.00000</td>
<td>±</td>
<td>0.00007</td>
<td>1</td>
<td>0.00000</td>
<td>±</td>
<td>0.00007</td>
</tr>
</tbody>
</table>

2.1.3.5 Driver Fuel Assemblies

Fuel Slugs

Fuel Slug: Isotopic Distribution

The uncertainty in the mass of the fuel slugs is discussed in section 1.1.3. The uncertainty in slug mass was applied to individual isotope masses. To conserve total slug mass, the other constituents of the composition were uniformly adjusted to compensate for the perturbation of the single isotope. Each isotope was perturbed using a uniform distribution. The positive perturbation is +0.56% composition change and -1.06% for the negative perturbation. The asymmetry is due to the manufacturing process systematically producing low weight slugs. The results are shown in Table 2.1.66.
Table 2.1.66. The Uncertainty in the Isotopic Distribution of the Fuel Slugs

<table>
<thead>
<tr>
<th>Deviation</th>
<th>$\Delta k$ $\pm \sigma_{\Delta k}$</th>
<th>Scaling Factor</th>
<th>$\Delta k_{\text{eff}} (1\sigma)$$ \pm \sigma_{\Delta k_{\text{eff}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>+0.56% $^{235}$U</td>
<td>0.00276 $\pm$ 0.00007</td>
<td>1</td>
<td>0.00276 $\pm$ 0.00007</td>
</tr>
<tr>
<td>-1.06% $^{235}$U</td>
<td>-0.00539 $\pm$ 0.00007</td>
<td>1</td>
<td>-0.00539 $\pm$ 0.00007</td>
</tr>
<tr>
<td>+0.56% $^{238}$U</td>
<td>0.00005 $\pm$ 0.00007</td>
<td>1</td>
<td>0.00005 $\pm$ 0.00007</td>
</tr>
<tr>
<td>-1.06% $^{238}$U</td>
<td>-0.00014 $\pm$ 0.00007</td>
<td>1</td>
<td>-0.00014 $\pm$ 0.00007</td>
</tr>
<tr>
<td>+0.56% $^{234}$U</td>
<td>0.00018 $\pm$ 0.00007</td>
<td>1</td>
<td>0.00018 $\pm$ 0.00007</td>
</tr>
<tr>
<td>-1.06% $^{234}$U</td>
<td>0.00001 $\pm$ 0.00007</td>
<td>1</td>
<td>0.00001 $\pm$ 0.00007</td>
</tr>
<tr>
<td>+0.56% $^{236}$U</td>
<td>0.00006 $\pm$ 0.00007</td>
<td>1</td>
<td>0.00006 $\pm$ 0.00007</td>
</tr>
<tr>
<td>-1.06% $^{236}$U</td>
<td>0.00002 $\pm$ 0.00007</td>
<td>1</td>
<td>0.00002 $\pm$ 0.00007</td>
</tr>
<tr>
<td>+0.56% $^{239}$Pu</td>
<td>0.00014 $\pm$ 0.00007</td>
<td>1</td>
<td>0.00014 $\pm$ 0.00007</td>
</tr>
<tr>
<td>-1.06% $^{239}$Pu</td>
<td>-0.00006 $\pm$ 0.00007</td>
<td>1</td>
<td>-0.00006 $\pm$ 0.00007</td>
</tr>
<tr>
<td>+0.56% $^{236}$Pu</td>
<td>-0.00006 $\pm$ 0.00007</td>
<td>1</td>
<td>-0.00006 $\pm$ 0.00007</td>
</tr>
<tr>
<td>-1.06% $^{236}$Pu</td>
<td>0.00010 $\pm$ 0.00007</td>
<td>1</td>
<td>0.00010 $\pm$ 0.00007</td>
</tr>
<tr>
<td>+0.56% $^{238}$Pu</td>
<td>-0.00010 $\pm$ 0.00007</td>
<td>1</td>
<td>-0.00010 $\pm$ 0.00007</td>
</tr>
<tr>
<td>-1.06% $^{238}$Pu</td>
<td>0.00004 $\pm$ 0.00007</td>
<td>1</td>
<td>0.00004 $\pm$ 0.00007</td>
</tr>
<tr>
<td>+0.56% $^{240}$Pu</td>
<td>-0.00003 $\pm$ 0.00007</td>
<td>1</td>
<td>-0.00003 $\pm$ 0.00007</td>
</tr>
<tr>
<td>-1.06% $^{240}$Pu</td>
<td>0.00001 $\pm$ 0.00007</td>
<td>1</td>
<td>0.00001 $\pm$ 0.00007</td>
</tr>
<tr>
<td>+0.56% $^{241}$Pu</td>
<td>-0.00004 $\pm$ 0.00007</td>
<td>1</td>
<td>-0.00004 $\pm$ 0.00007</td>
</tr>
<tr>
<td>-1.06% $^{241}$Pu</td>
<td>0.00007 $\pm$ 0.00007</td>
<td>1</td>
<td>0.00007 $\pm$ 0.00007</td>
</tr>
</tbody>
</table>

Fuel Slug: Fissium Composition

The fuel consists of 95 wgt. % uranium and 5 wgt. % fissium. The composition of fissium in the driver fuel slugs at beginning of life is given in Table 2.1.67. The isotopic distribution of the fissium elements are natural abundances.
Table 2.1.67. Fuel Slug Beginning of Life (BOL) Content

<table>
<thead>
<tr>
<th>Element</th>
<th>Wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mo</td>
<td>2.44 ± 0.17</td>
</tr>
<tr>
<td>Ru</td>
<td>1.94 ± 0.25</td>
</tr>
<tr>
<td>Rh</td>
<td>0.28 ± 0.05</td>
</tr>
<tr>
<td>Pa</td>
<td>0.19 ± 0.04</td>
</tr>
<tr>
<td>Zr</td>
<td>0.085 ± 0.060</td>
</tr>
<tr>
<td>Nb</td>
<td>0.020 ± 0.012</td>
</tr>
<tr>
<td>Si</td>
<td>0.054 ± 0.031</td>
</tr>
<tr>
<td>U</td>
<td>95.00 ± 1.00</td>
</tr>
</tbody>
</table>

To assess the uncertainty associated with the fissium composition, each element’s weight percent was increased or decreased by its tolerance and the other element’s weight percent was decreased or increased within its tolerance limit, such that total mass was unchanged. Then a bridging depletion analysis was performed on a single fuel assembly to obtain the resulting fission product values since the composition data from Argonne National Laboratory used a simplified lumped fission product value. The range of fuel assembly burnup values was 0% to 6.1% with an average 1.6%. The fission products were applied to the model fuel compositions to assess the uncertainty in k due to fissium composition uncertainty. The results are shown in Table 2.1.68 and Table 2.1.69.
### Table 2.168. Uncertainty in Fissium

<table>
<thead>
<tr>
<th>Deviation</th>
<th>$\Delta k$ ± $\sigma_{\Delta k}$</th>
<th>Scaling Factor</th>
<th>$\Delta k_{\text{eff}}$ (1σ) ± $\sigma_{\Delta k_{\text{eff}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Mo</td>
<td>0.00000 ± 0.00007</td>
<td>1</td>
<td>0.00000 ± 0.00007</td>
</tr>
<tr>
<td>Minimum Mo</td>
<td>0.00000 ± 0.00007</td>
<td>1</td>
<td>0.00000 ± 0.00007</td>
</tr>
<tr>
<td>Maximum Ru</td>
<td>0.00000 ± 0.00007</td>
<td>1</td>
<td>0.00000 ± 0.00007</td>
</tr>
<tr>
<td>Minimum Ru</td>
<td>0.00000 ± 0.00007</td>
<td>1</td>
<td>0.00000 ± 0.00007</td>
</tr>
<tr>
<td>Maximum Rh</td>
<td>0.00000 ± 0.00007</td>
<td>1</td>
<td>0.00000 ± 0.00007</td>
</tr>
<tr>
<td>Minimum Rh</td>
<td>0.00000 ± 0.00007</td>
<td>1</td>
<td>0.00000 ± 0.00007</td>
</tr>
<tr>
<td>Maximum Pa</td>
<td>0.00000 ± 0.00007</td>
<td>1</td>
<td>0.00000 ± 0.00007</td>
</tr>
<tr>
<td>Minimum Pa</td>
<td>0.00000 ± 0.00007</td>
<td>1</td>
<td>0.00000 ± 0.00007</td>
</tr>
<tr>
<td>Maximum Zr</td>
<td>0.00000 ± 0.00007</td>
<td>1</td>
<td>0.00000 ± 0.00007</td>
</tr>
<tr>
<td>Minimum Zr</td>
<td>0.00000 ± 0.00007</td>
<td>1</td>
<td>0.00000 ± 0.00007</td>
</tr>
<tr>
<td>Maximum Nb</td>
<td>0.00000 ± 0.00007</td>
<td>1</td>
<td>0.00000 ± 0.00007</td>
</tr>
<tr>
<td>Minimum Nb</td>
<td>0.00000 ± 0.00007</td>
<td>1</td>
<td>0.00000 ± 0.00007</td>
</tr>
<tr>
<td>Maximum Si</td>
<td>0.00000 ± 0.00007</td>
<td>1</td>
<td>0.00000 ± 0.00007</td>
</tr>
<tr>
<td>Minimum Si</td>
<td>0.00000 ± 0.00007</td>
<td>1</td>
<td>0.00000 ± 0.00007</td>
</tr>
</tbody>
</table>
Table 2.1.69. Uncertainty in the Fuel Slugs Actinides

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Δk</th>
<th>±</th>
<th>σ_{Ak}</th>
<th>Scaling Factor</th>
<th>Δk_{eff} (1σ)</th>
<th>±</th>
<th>σ_{Δk_{eff}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>+0.56% 241Am</td>
<td>-0.00001</td>
<td>± 0.00007</td>
<td>1</td>
<td>-0.00001</td>
<td>± 0.00007</td>
<td>1</td>
<td>± 0.00007</td>
</tr>
<tr>
<td>-1.06% 241Am</td>
<td>0.00008</td>
<td>± 0.00007</td>
<td>1</td>
<td>0.00008</td>
<td>± 0.00007</td>
<td>1</td>
<td>± 0.00007</td>
</tr>
<tr>
<td>+0.56% 242Am</td>
<td>-0.00001</td>
<td>± 0.00007</td>
<td>1</td>
<td>-0.00001</td>
<td>± 0.00007</td>
<td>1</td>
<td>± 0.00007</td>
</tr>
<tr>
<td>-1.06% 242Am</td>
<td>0.00007</td>
<td>± 0.00007</td>
<td>1</td>
<td>0.00007</td>
<td>± 0.00007</td>
<td>1</td>
<td>± 0.00007</td>
</tr>
<tr>
<td>+0.56% 243Am</td>
<td>-0.00003</td>
<td>± 0.00007</td>
<td>1</td>
<td>-0.00003</td>
<td>± 0.00007</td>
<td>1</td>
<td>± 0.00007</td>
</tr>
<tr>
<td>-1.06% 243Am</td>
<td>0.00005</td>
<td>± 0.00007</td>
<td>1</td>
<td>0.00005</td>
<td>± 0.00007</td>
<td>1</td>
<td>± 0.00007</td>
</tr>
<tr>
<td>+0.56% 242Cm</td>
<td>-0.00013</td>
<td>± 0.00007</td>
<td>1</td>
<td>-0.00013</td>
<td>± 0.00007</td>
<td>1</td>
<td>± 0.00007</td>
</tr>
<tr>
<td>-1.06% 242Cm</td>
<td>0.00001</td>
<td>± 0.00007</td>
<td>1</td>
<td>0.00001</td>
<td>± 0.00007</td>
<td>1</td>
<td>± 0.00007</td>
</tr>
<tr>
<td>+0.56% 243Cm</td>
<td>-0.00006</td>
<td>± 0.00007</td>
<td>1</td>
<td>-0.00006</td>
<td>± 0.00007</td>
<td>1</td>
<td>± 0.00007</td>
</tr>
<tr>
<td>-1.06% 243Cm</td>
<td>0.00017</td>
<td>± 0.00007</td>
<td>1</td>
<td>0.00017</td>
<td>± 0.00007</td>
<td>1</td>
<td>± 0.00007</td>
</tr>
<tr>
<td>+0.56% 244Cm</td>
<td>-0.00003</td>
<td>± 0.00007</td>
<td>1</td>
<td>-0.00003</td>
<td>± 0.00007</td>
<td>1</td>
<td>± 0.00007</td>
</tr>
<tr>
<td>-1.06% 244Cm</td>
<td>0.00008</td>
<td>± 0.00007</td>
<td>1</td>
<td>0.00008</td>
<td>± 0.00007</td>
<td>1</td>
<td>± 0.00007</td>
</tr>
<tr>
<td>+0.56% 245Cm</td>
<td>-0.00003</td>
<td>± 0.00007</td>
<td>1</td>
<td>-0.00003</td>
<td>± 0.00007</td>
<td>1</td>
<td>± 0.00007</td>
</tr>
<tr>
<td>-1.06% 245Cm</td>
<td>0.00002</td>
<td>± 0.00007</td>
<td>1</td>
<td>0.00002</td>
<td>± 0.00007</td>
<td>1</td>
<td>± 0.00007</td>
</tr>
<tr>
<td>+0.56% 246Cm</td>
<td>0.00001</td>
<td>± 0.00007</td>
<td>1</td>
<td>0.00001</td>
<td>± 0.00007</td>
<td>1</td>
<td>± 0.00007</td>
</tr>
<tr>
<td>-1.06% 246Cm</td>
<td>0.00001</td>
<td>± 0.00007</td>
<td>1</td>
<td>0.00001</td>
<td>± 0.00007</td>
<td>1</td>
<td>± 0.00007</td>
</tr>
<tr>
<td>+0.56% 237Np</td>
<td>0.00002</td>
<td>± 0.00007</td>
<td>1</td>
<td>0.00002</td>
<td>± 0.00007</td>
<td>1</td>
<td>± 0.00007</td>
</tr>
<tr>
<td>-1.06% 237Np</td>
<td>0.00002</td>
<td>± 0.00007</td>
<td>1</td>
<td>0.00002</td>
<td>± 0.00007</td>
<td>1</td>
<td>± 0.00007</td>
</tr>
</tbody>
</table>

**Upper and Lower Extension**

The upper and lower extensions of the driver fuel assemblies consist of a homogenized sodium and stainless-steel. The weight of the sodium in homogenized upper and lower extensions was increased or decreased by 0.1% and compensated the same amount by decreasing or increasing the stainless-steel weight.

**Lower Extension: Sodium-to-Stainless-Steel Ratio**

The sodium content of the homogenized lower extension was calculated to be 11.6% ± 0.1%. Due to perturbation of sodium content, the smeared density of the lower extension changes. The results are shown in Table 2.1.70.
Table 2.1.70. Uncertainty in Sodium-to-Stainless-Steel Ratio in the Lower Extension

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Δk   ± σΔk</th>
<th>Scaling Factor</th>
<th>Δk_{eff} (1σ) ± σΔk_{eff}</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 1% Na</td>
<td>0.00045 ± 0.00007</td>
<td>10</td>
<td>0.00005 ± 0.00001</td>
</tr>
<tr>
<td>- 1% Na</td>
<td>-0.00043 ± 0.00007</td>
<td>10</td>
<td>-0.00004 ± 0.00001</td>
</tr>
</tbody>
</table>

Upper Extension: Sodium-to-Stainless-Steel Ratio

The sodium content of the homogenized lower extension was calculated to be 9.71% ± 1%.

Table 2.1.71. Uncertainty in Sodium-to-Stainless-Steel Ratio in the Upper Extension

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Δk   ± σΔk</th>
<th>Scaling Factor</th>
<th>Δk_{eff} (1σ) ± σΔk_{eff}</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 1% Na</td>
<td>0.00006 ± 0.00007</td>
<td>10</td>
<td>0.00001 ± 0.00001</td>
</tr>
<tr>
<td>- 1% Na</td>
<td>0.00045 ± 0.00007</td>
<td>10</td>
<td>0.00005 ± 0.00001</td>
</tr>
</tbody>
</table>

Fuel Element Wire Wrap:

Wire Wrap: Density

The fuel element has a stainless-steel wire wrap around it. The density of the wire wrap was calculated to be 8.0154 g/cm³. The uncertainty in the wire wrap density is ±0.1 g/cm³. The results are shown in Table 2.1.72.

Table 2.1.72. Uncertainty in the Density of Fuel Element Wire Wrap

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Δk   ± σΔk</th>
<th>Scaling Factor</th>
<th>Δk_{eff} (1σ) ± σΔk_{eff}</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 0.1 g/cm³ (1σ)</td>
<td>0.00000 ± 0.00007</td>
<td>√3</td>
<td>0.00000 ± 0.00002</td>
</tr>
<tr>
<td>- 0.1 g/cm³ (1σ)</td>
<td>0.00000 ± 0.00007</td>
<td>√3</td>
<td>0.00000 ± 0.00002</td>
</tr>
</tbody>
</table>
2.1.3.6 High Worth Control Rod

The high worth control rod has poison rods which consists of B$_4$C, stainless-steel cladding and stainless-steel wire wrap.

Poison Element: $B_4C$ Density

The density of the $B_4C$ is 2.5 g/cm$^3$. The uncertainty in the $B_4C$ density is ±0.1 g/cm$^3$. The results are shown in Table 2.1.73.

<table>
<thead>
<tr>
<th>Deviation</th>
<th>$\Delta k$</th>
<th>$\pm$</th>
<th>$\sigma_{\Delta k}$</th>
<th>Scaling Factor</th>
<th>$\Delta k_{\text{eff}} (1\sigma)$</th>
<th>$\pm$</th>
<th>$\sigma_{\Delta k_{\text{eff}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 0.1 g/cm$^3$ (1σ)</td>
<td>-0.00021</td>
<td>±</td>
<td>0.00007</td>
<td>1</td>
<td>-0.00021</td>
<td>±</td>
<td>0.00007</td>
</tr>
<tr>
<td>- 0.1 g/cm$^3$ (1σ)</td>
<td>0.00034</td>
<td>±</td>
<td>0.00007</td>
<td>1</td>
<td>0.00034</td>
<td>±</td>
<td>0.00007</td>
</tr>
</tbody>
</table>

Poison Element: $^{10}$B-to-$^{11}$B ratio

The engineering drawing EB-1-52069 states that each poison element has 18.04 g of $^{10}$B and the uncertainty of ±0.5 g. The weight of $^{10}$B isotope was increased or decreased by 0.5 g by decreasing or increasing $^{11}$B isotope weight, respectively. The results are shown in Table 2.1.74.

<table>
<thead>
<tr>
<th>Deviation</th>
<th>$\Delta k$</th>
<th>$\pm$</th>
<th>$\sigma_{\Delta k}$</th>
<th>Scaling Factor</th>
<th>$\Delta k_{\text{eff}} (1\sigma)$</th>
<th>$\pm$</th>
<th>$\sigma_{\Delta k_{\text{eff}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 0.5 g $^{10}$B</td>
<td>0.00052</td>
<td>±</td>
<td>0.00007</td>
<td>1</td>
<td>0.00052</td>
<td>±</td>
<td>0.00007</td>
</tr>
<tr>
<td>- 0.5 g $^{10}$B</td>
<td>-0.00059</td>
<td>±</td>
<td>0.00007</td>
<td>1</td>
<td>-0.00059</td>
<td>±</td>
<td>0.00007</td>
</tr>
</tbody>
</table>

Poison Element Wire Wrap: Density

The poison element has a stainless-steel wire wrap around it. The density of the wire wrap was calculated to be 7.8611 g/cm$^3$. The uncertainty in the wire wrap density is ±0.1 g/cm$^3$. The results are shown in Table 2.1.75.
Table 2.1.75. Uncertainty in the Density of the Poison Element Wire Wrap

<table>
<thead>
<tr>
<th>Deviation</th>
<th>$\Delta k$</th>
<th>$\pm$</th>
<th>$\sigma_{\Delta k}$</th>
<th>Scaling Factor</th>
<th>$\Delta k_{\text{eff}} (1\sigma)$</th>
<th>$\pm$</th>
<th>$\sigma_{\Delta k_{\text{eff}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 0.1 g/cm$^3$ (1\sigma)</td>
<td>0.00000 ± 0.00007</td>
<td>1</td>
<td>0.00000</td>
<td>±</td>
<td>0.000002</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 0.1 g/cm$^3$ (1\sigma)</td>
<td>0.00000 ± 0.00007</td>
<td>1</td>
<td>0.00000</td>
<td>±</td>
<td>0.000002</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Poison Element Shield Block: Sodium-to-Stainless-Steel Ratio

The poison element in high worth control rod has stainless-steel shield and retaining spring above B$_4$C poison elements. This volume is homogenized and the density is 7.73152 g/cm$^3$. It consists of 1.88 wt. % of sodium and rest is stainless-steel. The sodium weight is increased or decreased by 1% and the stainless-steel weight was decreased or increased by same amount of weight to keep the total weight at 100%. The density was recalculated based on the composition of the smeared material. The results are shown in Table 2.1.76.

Table 2.1.76. Uncertainty in the Sodium-to-Stainless-Steel Ratio in the Poison Element Shield Block

<table>
<thead>
<tr>
<th>Deviation</th>
<th>$\Delta k$</th>
<th>$\pm$</th>
<th>$\sigma_{\Delta k}$</th>
<th>Scaling Factor</th>
<th>$\Delta k_{\text{eff}} (1\sigma)$</th>
<th>$\pm$</th>
<th>$\sigma_{\Delta k_{\text{eff}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 1% Na</td>
<td>0.00011 ± 0.00007</td>
<td>10</td>
<td>0.00001</td>
<td>±</td>
<td>0.00001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 1% Na</td>
<td>-0.00002 ± 0.00007</td>
<td>10</td>
<td>0.00000</td>
<td>±</td>
<td>0.00001</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.1.3.7 Safety Rod

Safety Rod Upper Extension: Sodium-to-Stainless-Steel Ratio

The upper extension of the safety rod was homogenized. It consists of 8.64 wgt. % sodium and rest is stainless-steel. The weight of sodium was increased or decreased by 1% and the stainless-steel weight was decreased or increased to keep the total weight at 100%. The density of the smeared material was recalculated in every perturbation. Results are shown in Table 2.1.77.
Table 2.1.77. Uncertainty in the Sodium-to-Stainless-Steel Ratio in the Homogenized Upper Extension of Safety Rod

<table>
<thead>
<tr>
<th>Deviation</th>
<th>$\Delta k$</th>
<th>$\pm$</th>
<th>$\sigma_{\Delta k}$</th>
<th>Scaling Factor</th>
<th>$\Delta k_{\text{eff}} (1\sigma)$</th>
<th>$\pm$</th>
<th>$\sigma_{\Delta k_{\text{eff}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 1% Na</td>
<td>0.00003</td>
<td>$\pm$</td>
<td>0.00007</td>
<td>10</td>
<td>0.00000</td>
<td>$\pm$</td>
<td>0.00001</td>
</tr>
<tr>
<td>- 1% Na</td>
<td>0.00015</td>
<td>$\pm$</td>
<td>0.00007</td>
<td>10</td>
<td>0.00002</td>
<td>$\pm$</td>
<td>0.00001</td>
</tr>
</tbody>
</table>

2.1.3.8 Reflectors

Stainless-steel Reflector: Sodium-to-Stainless-steel Ratio

The inside of the hexagonal duct of stainless-steel reflectors was homogenized and consist of 1.8 wgt. % sodium and 98.2 wgt. % either stainless-steel 316 or stainless-steel 304L. The sodium weight was increased or decreased by 1% and stainless-steel weight was decreased or increased to keep the total weight at 100%. The density was recalculated in every perturbation. The results of sodium-to-stainless-steel ratio perturbation of SS316 and SS304L reflectors are shown in Table 2.1.78 and Table 2.1.79, respectively.

Table 2.1.78. Uncertainty in the Sodium-to-Stainless-Steel Ratio in the SS316 Reflector

<table>
<thead>
<tr>
<th>Deviation</th>
<th>$\Delta k$</th>
<th>$\pm$</th>
<th>$\sigma_{\Delta k}$</th>
<th>Scaling Factor</th>
<th>$\Delta k_{\text{eff}} (1\sigma)$</th>
<th>$\pm$</th>
<th>$\sigma_{\Delta k_{\text{eff}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 1% Na</td>
<td>0.00072</td>
<td>$\pm$</td>
<td>0.00007</td>
<td>10</td>
<td>0.00007</td>
<td>$\pm$</td>
<td>0.00001</td>
</tr>
<tr>
<td>- 1% Na</td>
<td>-0.00072</td>
<td>$\pm$</td>
<td>0.00007</td>
<td>10</td>
<td>-0.00007</td>
<td>$\pm$</td>
<td>0.00001</td>
</tr>
</tbody>
</table>

Table 2.1.79. Uncertainty in the Sodium-to-Stainless-Steel Ratio in the SS304L Reflector

<table>
<thead>
<tr>
<th>Deviation</th>
<th>$\Delta k$</th>
<th>$\pm$</th>
<th>$\sigma_{\Delta k}$</th>
<th>Scaling Factor</th>
<th>$\Delta k_{\text{eff}} (1\sigma)$</th>
<th>$\pm$</th>
<th>$\sigma_{\Delta k_{\text{eff}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 1% Na</td>
<td>0.00074</td>
<td>$\pm$</td>
<td>0.00007</td>
<td>10</td>
<td>0.00007</td>
<td>$\pm$</td>
<td>0.00001</td>
</tr>
<tr>
<td>- 1% Na</td>
<td>-0.00063</td>
<td>$\pm$</td>
<td>0.00007</td>
<td>10</td>
<td>-0.00066</td>
<td>$\pm$</td>
<td>0.00001</td>
</tr>
</tbody>
</table>

2.1.4 Systemic Biases and Uncertainties

Most uncertainties that did not have measured data were assessed as 70% systematic and 30% random. This ratio provided some random component to the unknown uncertainties but not large enough to make the entire uncertainty negligible.
2.1.5 Total Experiment Uncertainty

Table 2.1.80 lists the results of all the perturbations for EBR-II Run 138B. Each result that had a positive and negative change were calculated from critical and then the higher perturbation was used in the overall uncertainty calculation. Uncertainties that were evaluated to be less than 0.00005 were considered negligible (neg). Total uncertainty was derived by combining all evaluated uncertainties in quadrature.
<table>
<thead>
<tr>
<th>Varied Parameter</th>
<th>Evaluated Uncertainty ±Δk_{eff} (1σ)</th>
<th>Systematic Uncertainty ±Δk_{eff} (1σ)</th>
<th>% sys</th>
<th>Number of Components</th>
<th>% rand</th>
<th>Random Uncertainty ±Δk_{eff} (1σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assembly Pitch</td>
<td>0.00098</td>
<td>0.0001</td>
<td>10</td>
<td>637</td>
<td>90</td>
<td>neg</td>
</tr>
<tr>
<td>Lower Adapter Org Change</td>
<td>0.00016</td>
<td>neg</td>
<td>10</td>
<td>637</td>
<td>90</td>
<td>neg</td>
</tr>
<tr>
<td>Hex Duct Wall Thickness</td>
<td>0.00020</td>
<td>0.00014</td>
<td>70</td>
<td>637</td>
<td>30</td>
<td>neg</td>
</tr>
<tr>
<td>Inner Hex Duct Outer Diameter</td>
<td>neg</td>
<td>neg</td>
<td>70</td>
<td>13</td>
<td>30</td>
<td>neg</td>
</tr>
<tr>
<td>Inner Hex Duct Wall Thickness</td>
<td>neg</td>
<td>neg</td>
<td>70</td>
<td>13</td>
<td>30</td>
<td>neg</td>
</tr>
<tr>
<td>Upper Extension Height</td>
<td>neg</td>
<td>neg</td>
<td>70</td>
<td>99</td>
<td>30</td>
<td>neg</td>
</tr>
<tr>
<td>Core Region Height</td>
<td>neg</td>
<td>neg</td>
<td>70</td>
<td>637</td>
<td>30</td>
<td>neg</td>
</tr>
<tr>
<td>Lower Extension Height</td>
<td>neg</td>
<td>neg</td>
<td>70</td>
<td>93</td>
<td>30</td>
<td>neg</td>
</tr>
<tr>
<td>Poison Element Height</td>
<td>neg</td>
<td>neg</td>
<td>70</td>
<td>49</td>
<td>30</td>
<td>neg</td>
</tr>
<tr>
<td>Poison Element Outer Diameter</td>
<td>neg</td>
<td>neg</td>
<td>70</td>
<td>49</td>
<td>30</td>
<td>neg</td>
</tr>
<tr>
<td>Poison Element Shield Block Height</td>
<td>neg</td>
<td>neg</td>
<td>70</td>
<td>49</td>
<td>30</td>
<td>neg</td>
</tr>
<tr>
<td>Poison Element Cladding Thickness</td>
<td>neg</td>
<td>neg</td>
<td>70</td>
<td>49</td>
<td>30</td>
<td>neg</td>
</tr>
<tr>
<td>Poison Element Wire Wrap Diameter</td>
<td>neg</td>
<td>neg</td>
<td>70</td>
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Table 2.1.80 (cont’d). Total Experiment Uncertainty EBR-II Run 138B

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<th>Evaluated Uncertainty ±Δk_{eff} (1σ)</th>
<th>Systematic Uncertainty ±Δk_{eff} (1σ)</th>
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<th>Number of Components</th>
<th>% rand</th>
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### Table 2.1.80 (cont’d). Total Experiment Uncertainty EBR-II Run 138B

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<th>Varied Parameter</th>
<th>Evaluated Uncertainty $\pm \Delta k_{\text{eff}}$ (1σ)</th>
<th>Systematic Uncertainty $\pm \Delta k_{\text{eff}}$ (1σ)</th>
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<th>Number of Components</th>
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</table>
2.2 **Evaluation of Buckling and Extrapolation Length Data**

Buckling and Extrapolation Length Data measurements were not made.

2.3 **Evaluation of Spectral Characteristics Measurements**

Spectral Characteristics measurements were not made.

2.4 **Evaluation of Reactivity Effects Measurements**

Reactivity Effects measurements were not made.

2.5 **Evaluation of Reactivity Coefficient Measurements**

Reactivity Coefficient measurements were not made.

2.6 **Evaluation of Kinetics Measurements**

Kinetics measurements were note made.

2.7 **Evaluation of Reaction-Rate Distribution Measurements**

Reaction-Rate Distribution measurements were not made.

2.8 **Evaluation of Power Distribution Measurements**

Power Distribution measurements were not made.

2.9 **Evaluation of Isotopic Measurements**

Isotopic measurements were not made.

2.10 **Evaluation of Other Miscellaneous Types of Measurements**

Other Miscellaneous Types of measurements were note made.

3.0 **BENCHMARK SPECIFICATIONS**

3.1 **Benchmark-Model Specifications for Critical and / or Subcritical Measurements**

For nearly each type of assembly in EBR-II, detailed engineering drawings were utilized to find exact dimensions. These drawings contained dimensions regarding both the assemblies themselves, and any fuel elements, or stainless-steel blocks which were placed into the assemblies. The information gained from the engineering drawings was translated as closely as possible into the as built model of the EBR-II core.

There were certain assemblies which were not well documented and consequently were not modeled as accurately. Along with this, the assemblies contained complicated geometries which could not be accurately modeled. During the Run 138B, there were seven custom assemblies which varied slightly from a typical driver
assembly. These assemblies did not have accompanying engineering drawings, and were created from the physical descriptions. The upper and lower extensions inside the hex ducts were complicated geometrically and could not be accurately modeled. Based on engineering judgment, they were homogenized into a stainless-steel and sodium hexagonal prism representation. A similar practice was done on the lower adapter using a homogenization of stainless-steel and sodium in a cylinder. Many of these simplifications were performed in low importance areas of the core, and as a result were not expected to have any significant impact on the physics occurring.

3.1.1 Description of the Benchmark Model Simplifications

The EBR-II reactor was surrounded by rings of a stainless-steel and sodium mixture, which comprised the neutron shield blocks. These blocks were not modeled as borated graphite, which was the real composition, due to the low importance of the material composition. It was found in a parametric study that outside of the blanket assemblies, a material change had no effect on $k_{eff}$.

The upper pole piece in each assembly was not included due to its lack of effect on the $k_{eff}$.

The geometry of the upper and lower assembly extensions was not modeled exactly, but instead was modeled as a homogeneous mixture of stainless-steel and sodium. This homogenization was determined to retain the physics needed to model the system, without needing to generate the sections geometry precisely. To determine the volume of stainless-steel, there were two approaches. The first was an experimental set up, and the second was modeling in CAD.

For the experimental set up, an unirradiated unfueled-driver assembly was obtained and the stainless-steel volume was found by dipping a specified section into water to find the volume displaced by the section. The lower extension, outer hexagonal duct lower cylinder, and inner hexagonal duct lower cylinder for the high worth control rod were found via this method. These were not included as a bias and were only used as an uncertainty.

In CAD, a model was developed following the engineering diagrams, and the volume was found using a built-in volume finder function. The components found via this method were the upper extension for the safety assembly, upper extension for the driver assembly, B$_4$C shield block element, and reflector hexagonal blocks. These were not included as a bias and were only used as an uncertainty.

For both methods, once the stainless-steel volume ratio was found, a homogenized geometry was used to replace the specific component in the model.

All assemblies contained hexagonal ducts with stainless-steel spacer buttons to provide a small gap between assemblies. The buttons were small and were not explicitly modeled due to their size. The addition of the button stainless steel was considered negligible in comparison to the overall benchmark uncertainty.

The moveable assemblies contained movement structures and a locking mechanism inside the outer hexagonal duct. Due to the extreme complexity, the structures were not modeled. There was no information available to assess a bias or an uncertainty, however these internal structures were small in comparison to the overall assembly and were determined to have a negligible effect.
The instrumented assemblies contained sodium flow measuring devices and thermocouples which were not modeled. These devices did not change the geometry nor had any physics effect. They were designed specifically to have no impact on the neutron physics nor the thermal hydraulics.

Each element of the driver assemblies had a wire which wrapped helically up the length of the fuel element. Due to the complexity of modeling a toroid, it was determined that a single cylinder was attached to the side of the wire wrap. This cylinder had a higher atom density of stainless-steel to compensate for the loss of mass due to modeling a cylinder versus a toroid. It was not included as a bias and considered only an uncertainty. This method was chosen to retain a similar structure to the wire wrap.

Each fuel/poison element had a spade at the bottom which attached to a grid plate in the assembly. This spade was not modeled explicitly due to its complexity, but additional stainless-steel was added to the bottom of each fuel element to maintain the appropriate amount of stainless-steel. The grid plate was homogenized into the lower extension. The homogenization took place to maintain the stainless-steel importance in the material. This was included in the uncertainty of the stainless-steel to sodium ratio.

Each fuel/poison element had a plug which was welded onto the cladding. The plug was not modeled explicitly due to complexity, but additional stainless-steel was added to the top of the fuel element to maintain the appropriate amount of stainless-steel. These add a negligible amount of stainless-steel and were not included as a bias or uncertainty.

Due to a difficulty in modeling complex lattice structures, the origin of each fuel element had to be adjusted to fit the wire wrap inside the hexagonal lattice structure. If this adjustment did not take place, the wire wrap would have been partially cut out of the lattice. The entire core was moved slightly in one direction. Since this movement was the entire core, it was determined that the effect would be negligible in comparison to the overall benchmark uncertainty.

Inside the B₄C poison elements there was a retention spring which held the slugs in place inside the cladding. Along with the springs, a stainless-steel shield block was also present above each poison slug. The spring and shield block were homogenized with the surrounding sodium into one section above the poison slug. This was included as an uncertainty in the sodium to stainless-steel ratio of the poison element shield block.

Most of the driver and control assemblies had depleted fuel during Run 138B. To account for swelling due irradiation, the fuel slug and fuel element models were adjusted from the beginning of life dimensions. This had the potential to cause geometry errors and potentially cut off sections of the fuel slug. To account for this, swelling corresponding to 3% burnup was used.⁴ There was some fuel with higher burnup, which was accounted for in the material composition. The burnup swelling cap of 3% was selected because the swelling associated with 3% burnup results in the fuel slug coming into contact with the inner wall of the cladding.

Fuel element and fuel slug swelling was assessed as a bias and not an uncertainty. The data used to determine the swelling functions were plots showing the relationship between burnup and dimension change. The relationship was determined from measurements taken post-irradiation of MK-II(A) fuel elements. Both fuel

element and fuel slug swelling are addressed in section 3.1.1.1 and their $\Delta k_{\text{eff}}$ effects were $0.00118 \pm 0.00007$ and $0.00490 \pm 0.00007$ respectively.

Smearing of blanket rows 13-16 was addressed in section 3.1.1.2 and $\Delta k_{\text{eff}}$ was determined to be $-0.00025 \pm 0.00007$, this was assessing to be a bias.

Removal of the lower adapters was done due to their geometric complexity. A smear was originally utilized in their place, but due to the uncertainty in the sodium to steel ratio and their distance from the core, they were considered a bias (section 3.1.1.3). The $\Delta k_{\text{eff}}$ for their removal was $-0.00095 \pm 0.00007$.

No information was known about the burnup of boron in run 138B. A calculation was performed using the fuel burnup of the particular HWCR to determine the boron burnup of each HWCR. This provided some basis for the effect of boron burnup. This effect was assessed as a bias. Section 3.1.1.4 shows the resultant $\Delta k_{\text{eff}}$ of $0.00013 \pm 0.00007$.

No information was known about the sodium level above the fuel slug aside from the engineering design. The engineering drawing is created at room temperature sodium. The fuel element then undergoes a change in temperature of $343^\circ$K to reach operating temperature. This introduces a significant thermal expansion effect on the sodium bond inside of the fuel element. The new sodium level was never measured. A calculation was performed to determine the new sodium level. The change in sodium level due to thermal expansion was assessed as a bias. Section 3.1.1.5 shows the resultant $\Delta k_{\text{eff}}$ of $0.00013 \pm 0.00007$.

Other thermal expansion coefficients existed. Due to the complexity of structural expansion in EBR-II run 138B, no measurements were taken for the experiment. Coefficients were calculated for the experiment and used for safety determination. These values are reported in Table 1.1.11. The reported values were assessed as biases to the benchmark model. The values reported in Table 1.1.11 were multiplied by the change in temperature ($343^\circ$K) and beta effective (0.0068) leading to a values in units of $\Delta k/k$. The density changes that occur during these structural expansion need to be removed because the density changes are perturbed separately. Removal of the density changes isolates the geometric reactivity changes. The bias due to the density change of stainless-steel for a temperature change of ($343^\circ$K) was $-0.0027 \Delta k/k$.

A uniform temperature of the sodium coolant directly surrounding the EBR-II core was utilized and set to 616 K. This was the temperature obtained from the log book as the bulk coolant temperature for the core. No other information was available to create a temperature profile.

The stainless-steel reflectors contained stainless-steel hexagonal blocks surrounded by a sodium bond, followed by a hexagonal duct. The hexagonal blocks and sodium were homogenized together for simplicity of the model, and the impact was negligible. This was accounted for the in sodium to stainless-steel ratio uncertainty.

All isotopic distributions were based on the 16th edition of the Chart of the Nuclides, unless otherwise noted.
3.1.1.1 Fuel Element and Slug Swelling.

Fuel element and slug swelling were assessed as biases. Fuel slug swelling involved swelling on the fuel slugs within the element. While fuel element swelling involved swelling only the fuel cladding, and leaving the fuel slugs untouched. Table 3.1.1 and Table 3.1.2 show the results of removing fuel element swelling and fuel slug swelling.

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Δk</th>
<th>±  σ_{Δk}</th>
<th>Scaling Factor</th>
<th>Δk_{eff} (1σ)</th>
<th>±  σ_{Δk_{eff}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Fuel Element Swelling</td>
<td>0.00206</td>
<td>±  0.00007</td>
<td>1</td>
<td>0.00206</td>
<td>±  0.00007</td>
</tr>
</tbody>
</table>

Table 3.1.2. Fuel Slug Swelling Removal

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Δk</th>
<th>±  σ_{Δk}</th>
<th>Scaling Factor</th>
<th>Δk_{eff} (1σ)</th>
<th>±  σ_{Δk_{eff}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Fuel Slug Swelling</td>
<td>0.00591</td>
<td>±  0.00007</td>
<td>1</td>
<td>0.00591</td>
<td>±  0.00007</td>
</tr>
</tbody>
</table>

3.1.1.2 Smeared Blankets Rows 13-16

Parametric study demonstrated that everything outside of the core liner was negligible. Homogenization of blanket assemblies in rows 13-16 was assessed as a bias. Table 3.1.3 shows the results of smearing each blanket assembly in rows 13-16.

<table>
<thead>
<tr>
<th>Deviation</th>
<th>Δk</th>
<th>±  σ_{Δk}</th>
<th>Scaling Factor</th>
<th>Δk_{eff} (1σ)</th>
<th>±  σ_{Δk_{eff}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blanket Rows 13-16 Smeared</td>
<td>-0.00063</td>
<td>±  0.00007</td>
<td>1</td>
<td>-0.00063</td>
<td>±  0.00007</td>
</tr>
</tbody>
</table>
3.1.1.3 Lower Adapters

The lower adapters distance away from the core led to their removal and replacement with sodium. This was assessed as a bias. Table 3.1.4 shows the results of removing and replacing all of the lower adapters with sodium.

Table 3.1.4. All Lower Adapters Removed and Replaced with Sodium

<table>
<thead>
<tr>
<th>Deviation</th>
<th>$\Delta k \pm \sigma_{\Delta k}$</th>
<th>Scaling Factor</th>
<th>$\Delta k_{\text{eff}}(1\sigma) \pm \sigma_{\Delta k_{\text{eff}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Adapter</td>
<td>-0.00005 $\pm$ 0.00007</td>
<td>1</td>
<td>-0.00005 $\pm$ 0.00007</td>
</tr>
<tr>
<td>Removal</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.1.1.4 Boron Burnup

Individual HWCR assemblies had a burnup of $^{10}$B that was calculated in accordance with their respective fuel burnup. This was assessed as a bias where depleted boron was replaced with BOL boron. Table 3.1.5 shows the results of replacing depleted boron with BOL boron. The change is large compared to the perturbation in section 2.1.3.6 due to the large amount of boron-10 that is removed from due to burnup.

Table 3.1.5. No Boron Burnup

<table>
<thead>
<tr>
<th>Deviation</th>
<th>$\Delta k \pm \sigma_{\Delta k}$</th>
<th>Scaling Factor</th>
<th>$\Delta k_{\text{eff}}(1\sigma) \pm \sigma_{\Delta k_{\text{eff}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Boron Burnup</td>
<td>-0.00049 $\pm$ 0.00007</td>
<td>1</td>
<td>-0.00049 $\pm$ 0.00007</td>
</tr>
</tbody>
</table>

3.1.1.5 Fuel Sodium Level Above Slug Thermal Correction

The fuel sodium level above the fuel slug was affected by the thermal expansion of the sodium bond inside of the fuel element. This was considered a bias. Table 3.1.6 shows the result of not correcting the sodium level above the slug for thermal expansion. This change is large compared to the perturbation in section 2.1.3.3, due to the large amount of sodium that takes place of the plenum gas.
### Table 3.1.6. Fuel Sodium Level Above Slug Thermal Expansion

<table>
<thead>
<tr>
<th>Deviation</th>
<th>$\Delta k$ $\pm$ $\sigma_{\Delta k}$</th>
<th>Scaling Factor</th>
<th>$\Delta k_{\text{eff}}(1\sigma) \pm \sigma_{\Delta k_{\text{eff}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Sodium Bond Thermal Expansion Correction</td>
<td>-0.00057 $\pm$ 0.00007</td>
<td>1</td>
<td>-0.00143 $\pm$ 0.00007</td>
</tr>
</tbody>
</table>

### 3.1.1.6 Other Expansion Coefficients

### Table 3.1.7. Structural Expansion Reactivity Coefficients

<table>
<thead>
<tr>
<th>Expansion Coefficient</th>
<th>Reported Values (10$^{-4}$$/°K$)</th>
<th>Total PRD ($)</th>
<th>Total PRD ($\Delta k/k$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper grid plate expansion</td>
<td>-14.5</td>
<td>-0.497</td>
<td>-0.00338</td>
</tr>
<tr>
<td>Driver Steel Expansion</td>
<td>-2.2</td>
<td>-0.076</td>
<td>-0.000513</td>
</tr>
<tr>
<td>Subassembly thermal bowing</td>
<td>+9.8</td>
<td>0.336</td>
<td>0.00229</td>
</tr>
<tr>
<td>Control-rod bank extension</td>
<td>-7.16</td>
<td>-0.246</td>
<td>-0.00167</td>
</tr>
<tr>
<td>Driver fuel expansion</td>
<td>-4.91</td>
<td>-0.168</td>
<td>-0.00115</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>-18.97</strong></td>
<td><strong>-0.651</strong></td>
<td><strong>-0.00442</strong></td>
</tr>
<tr>
<td><strong>Total bias minus stainless-steel density change</strong></td>
<td></td>
<td></td>
<td>0.00172</td>
</tr>
</tbody>
</table>
3.1.1.7 Total Biases for Benchmark Model

A summary of the benchmark model biases for run 138B can be found in Table 3.1.8.

Table 3.1.8. Summary of Benchmark Model Biases for Run 138B.

<table>
<thead>
<tr>
<th>Simplification</th>
<th>Δk_{eff}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron shield blocks not included</td>
<td>NA</td>
</tr>
<tr>
<td>Upper pole pieces not included</td>
<td>neg</td>
</tr>
<tr>
<td>Homogenization of upper and lower extensions</td>
<td>neg</td>
</tr>
<tr>
<td>Hexagonal duct buttons not included</td>
<td>neg</td>
</tr>
<tr>
<td>Internal moveable rod structures not included</td>
<td>neg</td>
</tr>
<tr>
<td>Instrumented assemblies measuring devices not included</td>
<td>neg</td>
</tr>
<tr>
<td>Fuel slug origin adjustment</td>
<td>neg</td>
</tr>
<tr>
<td>Fuel element swelling</td>
<td>0.00206</td>
</tr>
<tr>
<td>Fuel slug swelling</td>
<td>0.00591</td>
</tr>
<tr>
<td>Homogenization of blanket assemblies in rows 13-16</td>
<td>0.00063</td>
</tr>
<tr>
<td>Lower adapter removal</td>
<td>0.00005</td>
</tr>
<tr>
<td>BOL boron</td>
<td>-0.00049</td>
</tr>
<tr>
<td>Uncorrected sodium level above fuel slug</td>
<td>-0.00057</td>
</tr>
<tr>
<td>Thermal expansion bias</td>
<td>0.00172</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.009273</strong></td>
</tr>
</tbody>
</table>

3.1.2 Dimensions

The origin for the EBR-II Run 138B model is located at the interface between the driver lower extensions and the core regions.

3.1.2.1 Reactor Core

A vertical representation of the EBR-II core as modeled can be seen in Figure 3.1.1. This figure shows where the origin of the entire model is in reference to the model geometry. Figure 3.1.2 is a plot of the model at an axial height of 0 cm relative to the model. Figure 3.1.3 shows the position of the experimental assemblies. A reference for every assembly position and type is in appendix B.2.
Figure 3.1.1. XZ core slice.
Figure 3.1.2. XY core slice at Z=0 cm.
Figure 3.1.3. Experimental Assembly Positions.
3.1.2.2 Driver Assemblies

Driver Fuel Elements

EBR-II driver assemblies contained three different types of fuel elements for Run 138B. The three element types were MK-II, MK-IIA, MK-IIS and the only difference between them was the element height and the sodium bond height above the fuel slugs. Each fuel element consists of up to three fuel slugs, the sodium bond, and a gas plenum which are contained in a stainless-steel cladding. The upper and lower sections of the fuel element are solid stainless-steel pieces to model the stainless-steel plug and spade. Each driver fuel element also has a wire wrap, which runs vertically up the side of the fuel element. Dimensions for MK-II, MK-IIA, and MK-IIS are shown in Table 3.1.9.

Table 3.1.9. Dimensions for a Driver MK-II Fuel Element

<table>
<thead>
<tr>
<th>Component</th>
<th>Inner Diameter (cm)</th>
<th>Outer Diameter (cm)</th>
<th>Height (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Slug (x3)</td>
<td>--</td>
<td>0.3302</td>
<td>11.43</td>
</tr>
<tr>
<td>Sodium Around Slug</td>
<td>0.3302</td>
<td>0.3810</td>
<td>11.43</td>
</tr>
<tr>
<td>Sodium Above Slug</td>
<td>--</td>
<td>0.3810</td>
<td>0.0050 MK-II</td>
</tr>
<tr>
<td>Plug</td>
<td>--</td>
<td>0.4420</td>
<td>26.40 MK-II</td>
</tr>
<tr>
<td>Spade</td>
<td>--</td>
<td>0.4420</td>
<td>0.2700</td>
</tr>
<tr>
<td>Gas Plenum</td>
<td>--</td>
<td>0.3810</td>
<td>28.30 MK-II</td>
</tr>
<tr>
<td>Cladding</td>
<td>0.3810</td>
<td>0.4420</td>
<td>62.99 MK-II</td>
</tr>
<tr>
<td>Wire Wrap</td>
<td>--</td>
<td>0.1240</td>
<td>61.56 MK-IIS</td>
</tr>
</tbody>
</table>

Table 3.1.10 provides location references for the various components of a fuel element. The dimensions in Table 3.1.10 refer to a MKIIA fuel element unless otherwise noted.
Table 3.1.10. Dimension reference for Figure 3.1.4

<table>
<thead>
<tr>
<th>Reference</th>
<th>Length (cm)</th>
<th>Nomenclature</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.3175</td>
<td>Bottom Cladding(^{(a)})</td>
</tr>
<tr>
<td>B</td>
<td>11.43</td>
<td>Section 1 Fuel Slug</td>
</tr>
<tr>
<td>C</td>
<td>11.43</td>
<td>Section 2 Fuel Slug</td>
</tr>
<tr>
<td>D</td>
<td>11.43</td>
<td>Section 3 Fuel Slug</td>
</tr>
<tr>
<td>E</td>
<td>0.635 MK-IIA / 0.635 MK-IIS / 3.18 MK-II</td>
<td>Sodium Above Fuel Slug</td>
</tr>
<tr>
<td>F</td>
<td>24.56 MK-IIA / 21.48 MK-II / 15.63 MK-IIS</td>
<td>Gas Plenum</td>
</tr>
<tr>
<td>G</td>
<td>0.6858</td>
<td>Cladding Top Plug</td>
</tr>
<tr>
<td>H</td>
<td>0.3302</td>
<td>Fuel Slug Outer Diameter</td>
</tr>
<tr>
<td>I</td>
<td>0.442</td>
<td>Fuel Element Outer Diameter</td>
</tr>
<tr>
<td>J</td>
<td>0.1245</td>
<td>Wire Wrap Diameter</td>
</tr>
<tr>
<td>K</td>
<td>0.0254</td>
<td>Sodium Bond Thickness</td>
</tr>
<tr>
<td>L</td>
<td>0.5665</td>
<td>Pitch of Elements in Assembly</td>
</tr>
</tbody>
</table>

\(^{(a)}\) This dimension touches the origin and can be referenced from 0 cm in height.
Figure 3.1.4. Fuel Element Dimensions
**Driver Assembly**

The driver assemblies contained 91 fuel elements within a hexagonal lattice with a triangular pitch of 0.566 cm, within a hexagonal duct with an inner flat-to-flat distance of 5.6134 cm. The inner flat-to-flat distance of the hexagonal duct corresponded to the inner wall of the hex duct, which contained the entire driver assembly. This inner flat-to-flat distance of the hexagonal duct is 5.6134 cm, while the outer flat-to-flat distance is 5.8166 cm. The hexagonal duct also contained the homogenized upper and lower extensions and had a total height of 164.386 cm. The upper extension starts at the top of the fuel lattice and rises 40.59682 cm, while the lower extensions starts at the bottom of the fuel lattice and drops 61.3537 cm. Below the lower extensions is the homogenized lower adapter, which is a cylinder with a diameter of 4.7625 cm and a height of 51.9125 cm. Table 3.1.11 provides location references for the various components of a driver assembly, where Figure 3.1.5 provides a qualitative expansion.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Length (cm)</th>
<th>Nomenclature</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>65.54</td>
<td>Core Region Height (^{(a)})</td>
</tr>
<tr>
<td>B</td>
<td>106.139</td>
<td>Core Region Height + Upper Extension Height</td>
</tr>
<tr>
<td>C</td>
<td>0.1016</td>
<td>Hexagonal Duct Wall Thickness (^{(b)})</td>
</tr>
<tr>
<td>D</td>
<td>61.3537</td>
<td>Lower Extension (^{(a)})</td>
</tr>
<tr>
<td>E</td>
<td>113.368</td>
<td>Lower Extension + Hex Duct Wall Thickness</td>
</tr>
<tr>
<td>F</td>
<td>5.8166</td>
<td>Hexagonal Duct Flat to Flat Outer Diameter</td>
</tr>
<tr>
<td>G</td>
<td>5.6134</td>
<td>Hexagonal Duct Flat to Flat Inner Diameter</td>
</tr>
</tbody>
</table>

\(^{(a)}\) These dimensions touch the origin and can be referenced from 0 cm in height.

\(^{(b)}\) This dimension is the same thickness around the duct.
Figure 3.1.5. Driver assembly.
3.1.2.3 **Half-Worth Driver Assemblies**

The half-worth driver assemblies are modeled identically to the driver assemblies with the replacement of 46 fuel elements with solid stainless-steel dummy elements. The dimensions and position references are identical to the driver assembly. Figure 3.1.6 provides reference locations for various components in the half-worth driver assembly, where Table 3.1.11 provides the dimension and position reference.
3.1.2.4 Dummy Assemblies

**Dummy Elements**

The stainless-steel dummy elements had a diameter of 2.0447 cm, with a height of 145.2829 cm. These dummy elements were solid stainless-steel.

**Dummy Assembly**

The dummy assembly contained 7 dummy elements with a triangular pitch of 2.0447 cm. Surrounding these elements was sodium coolant. The elements were contained in a hexagonal duct with an inner flat-to-flat distance of 5.6314 cm, an outer flat-to-flat distance of 5.8166 cm, and a height of 164.385 cm. Below the dummy lattice was the lower adapter, which was a cylinder with a diameter of 4.907 cm and a height of 52.07 cm. Table 3.1.12 shows lengths and references for the dummy assembly components shown in Figure 3.1.7.

Table 3.1.12. Dimension reference for Figure 3.1.7

<table>
<thead>
<tr>
<th>Reference</th>
<th>Length (cm)</th>
<th>Nomenclature</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>62.5475</td>
<td>Distance form Origin (a)</td>
</tr>
<tr>
<td>B</td>
<td>52.1716</td>
<td>Hex Duct Wall Thickness + Lower Adapter Length</td>
</tr>
<tr>
<td>C</td>
<td>167.119</td>
<td>Core Region Height (b)</td>
</tr>
<tr>
<td>D</td>
<td>5.6134</td>
<td>Hexagonal Duct Flat to Flat Inner Diameter</td>
</tr>
<tr>
<td>E</td>
<td>5.8166</td>
<td>Hexagonal Duct Flat to Flat Outer Diameter</td>
</tr>
<tr>
<td>F</td>
<td>2.0447</td>
<td>Dummy Element Pitch</td>
</tr>
<tr>
<td>G</td>
<td>0.1016</td>
<td>Hexagonal Duct Wall Thickness (b)</td>
</tr>
</tbody>
</table>

(a) These dimensions touch the origin and can be referenced from 0 cm in height.

(b) This dimension does not include the hexagonal duct wall thickness that is above.
Figure 3.1.7. Dummy assembly.
3.1.2.5 Safety Assemblies

The safety assemblies contained 61 MK-IIA fuel elements in a triangular pitch of 0.566 cm, within an inner hexagonal duct with a flat-to-flat distance of 4.826 cm, where the remainder of the space was filled with sodium. The inner flat-to-flat distance of the hexagonal duct corresponded to the inner wall of the hex duct, which contained the entire driver assembly. Above and below the MK-IIA fuel elements were the upper and lower extensions, which had heights of 61.75248 cm and 37.30498 cm. The inner hexagonal duct had an outer flat-to-flat distance of 4.902 cm, and a height of 102.819 cm. The inner hexagonal duct also contained a homogenized lower adapter, which was a cylinder with a diameter of 4.291 cm and a height of 82.6287 cm. Depending on the position of the safety assembly, additional sodium was placed below the lower adapter to account for the voided space caused by moving the assembly. An outer hexagonal duct had a flat-to-flat distance of 5.6314 cm, an outer flat-to-flat distance of 5.8166 cm, a height of 103.266 cm, and contained the inner hexagonal duct. Table 3.1.13 shows lengths and references for the safety assembly components shown in Figure 3.1.8.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Length (cm)</th>
<th>Nomenclature</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>65.0215</td>
<td>Length from Origin to Bottom of the Upper Extension (a)</td>
</tr>
<tr>
<td>B</td>
<td>83.365</td>
<td>Hex Duct Wall Thickness + assembly Offset (see J) + Inner Lower Adapter Length</td>
</tr>
<tr>
<td>C</td>
<td>37.305</td>
<td>Upper Extension (b)</td>
</tr>
<tr>
<td>D</td>
<td>82.730</td>
<td>Outer Duct Lower Adapter Length</td>
</tr>
<tr>
<td>E</td>
<td>62.387</td>
<td>Distance from Origin to Bottom of the Outer Duct (b)</td>
</tr>
<tr>
<td>F</td>
<td>40.879</td>
<td>Outer Duct Height Above Origin</td>
</tr>
<tr>
<td>G</td>
<td>4.8260</td>
<td>Hexagonal Inner Duct Flat to Flat Outer Diameter</td>
</tr>
<tr>
<td>H</td>
<td>5.8166</td>
<td>Hexagonal Outer Duct Flat to Flat Outer Diameter</td>
</tr>
<tr>
<td>I</td>
<td>0.1016</td>
<td>Hexagonal Duct Wall Thickness</td>
</tr>
<tr>
<td>J</td>
<td>0.635</td>
<td>Assembly Offset from Origin</td>
</tr>
</tbody>
</table>

(a) The safety assembly is offset from the origin height. See J for offset distance.

(b) This dimension does not include the hexagonal duct wall thickness.
Figure 3.1.8. Safety assembly.
3.1.2.6 Control Assembly

The control assemblies contained 61 MK-IIA fuel elements in a triangular pitch of 0.566 cm, within an inner hexagonal duct with a flat-to-flat distance of 4.826 cm. The remainder of the space was filled with sodium. The inner flat-to-flat distance of the hexagonal duct corresponded to the inner wall of the hex duct, which contained the entire driver assembly. Above and below the MK-II fuel elements were the upper and lower extensions, which had heights of 66.5547 cm and 61.4621 cm. The inner hexagonal duct had an outer flat-to-flat distance of 4.902 cm, and a height of 159.822 cm. The inner hexagonal duct also contained a homogenized lower adapter, which was modeled as a cylinder with a diameter of 4.291 cm and a height of 80.486 cm. Depending on the position of the control assembly, additional sodium was placed below the lower adapter to account for the voided space caused by moving the assembly. The outer hexagonal duct had an inner flat-to-flat distance of 5.6314 cm, an outer flat-to-flat distance of 5.8166 cm, and a height of 159.822 cm. Table 3.1.14 shows lengths and references for the control assembly components shown in Figure 3.1.9

Table 3.1.14. Dimension reference for Figure 3.1.9

<table>
<thead>
<tr>
<th>Reference</th>
<th>Length (cm)</th>
<th>Nomenclature</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>75.431</td>
<td>Length from Origin to Bottom of the Upper Extension (a)</td>
</tr>
<tr>
<td>B</td>
<td>81.223</td>
<td>Hex Duct Wall Thickness + assembly Offset (see J) + Inner Lower Adapter Length</td>
</tr>
<tr>
<td>C</td>
<td>30.480</td>
<td>Shield Block Length (b)</td>
</tr>
<tr>
<td>D</td>
<td>57.142</td>
<td>Outer Duct Lower Adapter Length</td>
</tr>
<tr>
<td>E</td>
<td>61.436</td>
<td>Distance from Origin to Bottom of the Outer Duct (b)</td>
</tr>
<tr>
<td>F</td>
<td>98.386</td>
<td>Outer Duct Height Above Origin</td>
</tr>
<tr>
<td>G</td>
<td>4.8260</td>
<td>Hexagonal Inner Duct Flat to Flat Outer Diameter</td>
</tr>
<tr>
<td>H</td>
<td>5.8166</td>
<td>Hexagonal Outer Duct Flat to Flat Outer Diameter</td>
</tr>
<tr>
<td>I</td>
<td>0.1016</td>
<td>Hexagonal Duct Wall Thickness</td>
</tr>
<tr>
<td>J</td>
<td>0.635</td>
<td>Assembly Offset from Origin</td>
</tr>
<tr>
<td>K</td>
<td>36.075</td>
<td>Sodium Above Shield Block</td>
</tr>
</tbody>
</table>

(a) The safety assembly is offset from the origin height. See J for offset distance.
(b) This dimension does not include the hexagonal duct wall thickness.
3.1.2.7 **High Worth Control Rod Assembly**

**Poison Elements**

The poison element consisted of a poison slug, a sodium bond, a homogenized spring region, a homogenized shield block region, followed by a sodium plenum region, all of which were encompassed in stainless-steel cladding. The upper section of the element was a solid stainless-steel piece to model the plug. Each poison element also had a wire wrap, which ran vertically up the side of the fuel element. The poison element dimensions are shown in Table 3.1.15.

<table>
<thead>
<tr>
<th>Component</th>
<th>Inner Diameter (cm)</th>
<th>Outer Diameter (cm)</th>
<th>Height (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poison Slug</td>
<td>--</td>
<td>1.375</td>
<td>35.56</td>
</tr>
<tr>
<td>Sodium Around Slug</td>
<td>1.375</td>
<td>1.410</td>
<td>35.56</td>
</tr>
<tr>
<td>Sodium Above Slug</td>
<td>--</td>
<td>1.410</td>
<td>3.492</td>
</tr>
<tr>
<td>Plug</td>
<td>--</td>
<td>1.410</td>
<td>1.270</td>
</tr>
<tr>
<td>Spring Region</td>
<td>--</td>
<td>1.410</td>
<td>3.493</td>
</tr>
<tr>
<td>Shield Block Region</td>
<td>--</td>
<td>1.410</td>
<td>20.32</td>
</tr>
<tr>
<td>Gas Plenum</td>
<td>--</td>
<td>1.410</td>
<td>31.034</td>
</tr>
<tr>
<td>Cladding</td>
<td>1.410</td>
<td>1.588</td>
<td>91.68</td>
</tr>
<tr>
<td>Wire Wrap</td>
<td>--</td>
<td>0.030</td>
<td>91.68</td>
</tr>
</tbody>
</table>

Table 3.1.16 provides location references for the various components of a B4C poison element, which can be seen in Figure 3.1.10.
Table 3.1.16. Dimension reference for Figure 3.1.10

<table>
<thead>
<tr>
<th>Reference</th>
<th>Length (cm)</th>
<th>Nomenclature</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.27</td>
<td>Bottom Plug Length (a)</td>
</tr>
<tr>
<td>B</td>
<td>35.56</td>
<td>Poison Slug Height</td>
</tr>
<tr>
<td>C</td>
<td>3.493</td>
<td>Sodium Above Poison Slug Height</td>
</tr>
<tr>
<td>D</td>
<td>20.32</td>
<td>Shield Block</td>
</tr>
<tr>
<td>E</td>
<td>31.034</td>
<td>Gas Plenum (a)</td>
</tr>
<tr>
<td>F</td>
<td>1.664</td>
<td>Pitch</td>
</tr>
<tr>
<td>G</td>
<td>1.3754</td>
<td>Poison Slug Diameter</td>
</tr>
<tr>
<td>H</td>
<td>1.5875</td>
<td>Poison Element Outer Diameter</td>
</tr>
<tr>
<td>I</td>
<td>0.0762</td>
<td>Poison Element Wire Wrap Diameter</td>
</tr>
<tr>
<td>J</td>
<td>0.01715</td>
<td>Sodium Bond Gap</td>
</tr>
</tbody>
</table>

(a) The origin of this part is referenced from item A in Table 3.1.17.
Figure 3.1.10. B4C Poison Element
High Worth Control Rod Assembly

The high worth control rod assemblies contained 61 MK-IIS fuel elements in a triangular pitch of 0.657 cm, within an inner hexagonal duct with a flat-to-flat distance of 4.826 cm. The remainder of the space was filled with sodium. The inner flat-to-flat distance of the hexagonal duct corresponded to the inner wall of the hex duct, which contained the entire driver assembly. Above the fuel section was a lattice of 7 poison elements with a triangular pitch of 1.5875 cm. The lower extension was 52.23 cm in height. The inner hexagonal duct had an outer flat-to-flat distance of 4.902 cm and a height of 159.822 cm. The inner hexagonal duct also contained a lower adapter, which was modeled as a cylinder with a diameter of 4.291 cm and a height of 80.4863 cm. Depending on the position of the high worth control assembly, additional sodium was placed below the lower adapter to account for the voided space caused by moving the assembly. The outer hexagonal duct had an inner flat-to-flat distance of 5.6314 cm, an outer flat-to-flat distance of 5.8166 cm, and a height of 159.822 cm. Table 3.1.17 shows lengths and references for the high worth control assembly components shown in Figure 3.1.11.

Table 3.1.17. Dimension reference for Figure 3.1.11

<table>
<thead>
<tr>
<th>Reference</th>
<th>Length (cm)</th>
<th>Nomenclature</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>55.496</td>
<td>Core Region Height</td>
</tr>
<tr>
<td>B</td>
<td>52.230</td>
<td>Distance from the Bottom of Fuel Elements to the Bottom of the Outer Duct</td>
</tr>
<tr>
<td>C</td>
<td>96.441</td>
<td>Poison Region (^{(a)})</td>
</tr>
<tr>
<td>D</td>
<td>52.230</td>
<td>Inner Hex Duct Lower Inner Lower Adapter</td>
</tr>
<tr>
<td>E</td>
<td>115.959</td>
<td>Bottom of Fuel Elements to the Outer Duct Lower Adapter (^{(a)})</td>
</tr>
<tr>
<td>F</td>
<td>107.592</td>
<td>Bottom of Fuel Elements to Top of Outer Hex Duct</td>
</tr>
<tr>
<td>G</td>
<td>4.8260</td>
<td>Hexagonal Inner Duct Flat to Flat Outer Diameter</td>
</tr>
<tr>
<td>H</td>
<td>5.8166</td>
<td>Hexagonal Outer Duct Flat to Flat Outer Diameter</td>
</tr>
<tr>
<td>I</td>
<td>0.5665</td>
<td>Pitch</td>
</tr>
<tr>
<td>J</td>
<td>8.255</td>
<td>Assembly Offset from Origin</td>
</tr>
</tbody>
</table>

\(^{(a)}\) This dimension does not include the hexagonal duct wall thickness.
Figure 3.1.11. High-worth control rod assembly.
3.1.2.8 Reflectors Assembly

The reflector assemblies consisted of hexagonally stacked blocks within a hexagonal duct. The blocks ran the entire length of the assembly, which had a height of 167.02024 cm. The blocks had a flat-to-flat distance of 5.6314 cm, which was identical to the inner hexagonal duct flat-to-flat distance. The outer flat-to-flat distance was 5.8166 cm. Table 3.1.18 shows lengths and references for the control assembly components shown in Figure 3.1.12.

Table 3.1.18. Dimension reference for Figure 3.1.12

<table>
<thead>
<tr>
<th>Reference</th>
<th>Length (cm)</th>
<th>Nomenclature</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>62.548</td>
<td>Distance from Origin to Bottom of Hexagonal Duct</td>
</tr>
<tr>
<td>B</td>
<td>163.909</td>
<td>Hexagonal Duct Length</td>
</tr>
<tr>
<td>C</td>
<td>52.07</td>
<td>Lower Adapter Length</td>
</tr>
<tr>
<td>J</td>
<td>0.1016</td>
<td>Hex Duct Wall Thickness</td>
</tr>
</tbody>
</table>

(a) This dimension does not include the hexagonal duct wall thickness
Figure 3.1.12. Reflector assembly.
3.1.2.9 Blanket Assembly

Blanket Elements

The blanket elements contain three fuel slugs, a sodium bond, and a plenum region, which are all contained in a stainless-steel cladding. The dimensions for a blanket element are found in Table 3.1.19.

Table 3.1.19. Dimensions of a Blanket Element

<table>
<thead>
<tr>
<th>Component</th>
<th>Inner Diameter (cm)</th>
<th>Outer Diameter (cm)</th>
<th>Height (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Slug (x3)</td>
<td>--</td>
<td>1.100</td>
<td>46.57</td>
</tr>
<tr>
<td>Sodium Around Slug</td>
<td>1.100</td>
<td>1.161</td>
<td>139.7</td>
</tr>
<tr>
<td>Sodium Above Slug</td>
<td>--</td>
<td>1.161</td>
<td>3.048</td>
</tr>
<tr>
<td>Plenum</td>
<td>--</td>
<td>1.161</td>
<td>12.83</td>
</tr>
<tr>
<td>Cladding</td>
<td>1.161</td>
<td>1.252</td>
<td>155.6</td>
</tr>
</tbody>
</table>

Table 3.1.20 provides location references for the various components of a B4C poison element, which can be seen in Figure 3.1.13.

Table 3.1.20. Dimension reference for Figure 3.1.10

<table>
<thead>
<tr>
<th>Reference</th>
<th>Length (cm)</th>
<th>Nomenclature</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.04572</td>
<td>Blanket Element Wall Thickness</td>
</tr>
<tr>
<td>B</td>
<td>46.567</td>
<td>Blanket Slug Section 1</td>
</tr>
<tr>
<td>C</td>
<td>46.567</td>
<td>Blanket Slug Section 2</td>
</tr>
<tr>
<td>D</td>
<td>46.567</td>
<td>Blanket Slug Section 3</td>
</tr>
<tr>
<td>E</td>
<td>3.048</td>
<td>Sodium Above Slug</td>
</tr>
<tr>
<td>F</td>
<td>12.781</td>
<td>Gas Plenum Length</td>
</tr>
<tr>
<td>G</td>
<td>1.0998</td>
<td>Blanket Slug Diameter</td>
</tr>
<tr>
<td>H</td>
<td>1.2522</td>
<td>Blanket Element Outer Diameter</td>
</tr>
<tr>
<td>I</td>
<td>0.03048</td>
<td>Sodium Bond Gap</td>
</tr>
</tbody>
</table>
Figure 3.1.13. Blanket Element
Blanket Assembly

The blanket assembly contained 19 blanket fuel elements with a triangular pitch of 1.255 cm, within an inner a flat-to-flat distance of 5.6314 cm, where the remainder of the space was filled with sodium. Below the blanket elements, there was a lower adapter with a diameter of 3.828 cm and a height of 52.07 cm. The outer hexagonal duct had an outer flat-to-flat distance of 5.8166 cm, and a height of 155.575 cm. Table 3.1.21 shows lengths and references for the control assembly components shown in Figure 3.1.14.

Table 3.1.21. Dimension reference for Figure 3.1.14

<table>
<thead>
<tr>
<th>Reference</th>
<th>Length (cm)</th>
<th>Nomenclature</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>62.5475</td>
<td>Distance form Origin (a)</td>
</tr>
<tr>
<td>B</td>
<td>52.1716</td>
<td>Hex Duct Wall Thickness + Lower Adapter Length</td>
</tr>
<tr>
<td>C</td>
<td>158.234</td>
<td>Core Region Height (b)</td>
</tr>
<tr>
<td>D</td>
<td>5.6134</td>
<td>Hexagonal Duct Flat to Flat Inner Diameter</td>
</tr>
<tr>
<td>E</td>
<td>5.8166</td>
<td>Hexagonal Duct Flat to Flat Outer Diameter</td>
</tr>
<tr>
<td>F</td>
<td>1.2522</td>
<td>Blanket Element Pitch</td>
</tr>
<tr>
<td>G</td>
<td>0.1016</td>
<td>Hexagonal Duct Wall Thickness (b)</td>
</tr>
</tbody>
</table>

(a) These dimensions touch the origin and can be referenced from 0 cm in height.

(b) This dimension does not include the hexagonal duct wall thickness that is above.
Figure 3.1.14. Blanket assembly.
3.1.2.10 Experimental Assemblies

C2776A

C2776A was identical to a driver assembly geometrically, with the only difference being a xenon gas tag in the assembly. Therefore, C2776A was modeled as a driver assembly. C2776A was located in 04C02.

X412

X412 was similar to a driver assembly, with only minor material differences. Therefore, X412 was modeled as a driver assembly. X412 was located in 06D01.

X320C

X320C was an assembly built for experimental materials to be irradiated, and was identical to a stainless-steel dummy assembly. Therefore, it was modeled as a stainless-steel dummy assembly. X320C was located in 04D02.

XX10

XX10 was an instrumented assembly which was similar to a control assembly, but it was not movable, and located in 05C01. XX10 contained 18 stainless-steel dummy elements along with 1 hollow stainless-steel element, all with a triangular pitch of 0.566 cm. Above the element lattice was an upper extension with a height of 40.597 cm. The elements and the upper extension were contained in an inner hexagonal duct with an inner flat-to-flat distance of 4.826 cm, an outer flat-to-flat distance of 4.902 cm, and a height of 159.822 cm. Below the inner hexagonal duct, there was a lower adapter, which was modeled as a cylinder with a diameter of 4.291 cm and a height of 36.444 cm. The inner hexagonal duct was contained in an outer hexagonal duct, which had an inner flat-to-flat distance of 5.6314 cm, an outer flat-to-flat distance of 5.8166 cm, and a height of 159.822 cm. Table 3.1.22 shows lengths and references for the control assembly components shown in Figure 3.1.15.
Table 3.1.22. Dimension reference for Figure 3.1.15

<table>
<thead>
<tr>
<th>Reference</th>
<th>Length (cm)</th>
<th>Nomenclature</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>68.428</td>
<td>Core Region Height</td>
</tr>
<tr>
<td>B</td>
<td>40.597</td>
<td>Upper Extension</td>
</tr>
<tr>
<td>C</td>
<td>52.23</td>
<td>Distance from the Origin to the Bottom of the Outer Hex Duct (^{(a)})</td>
</tr>
<tr>
<td>D</td>
<td>107.59</td>
<td>Distance from the Origin to the Top of the Outer Hex Duct</td>
</tr>
<tr>
<td>E</td>
<td>108.618</td>
<td>Distance from the Origin to the Bottom of the Outer Hex Duct Lower Adapter (^{(a)})</td>
</tr>
<tr>
<td>F</td>
<td>0.1016</td>
<td>Hex Duct Wall Thickness</td>
</tr>
<tr>
<td>G</td>
<td>4.8260</td>
<td>Hexagonal Inner Duct Flat to Flat Outer Diameter</td>
</tr>
<tr>
<td>H</td>
<td>5.8166</td>
<td>Hexagonal Outer Duct Flat to Flat Outer Diameter</td>
</tr>
<tr>
<td>I</td>
<td>1.0055</td>
<td>Pitch</td>
</tr>
</tbody>
</table>

\(^{(a)}\) This dimension does not include the hexagonal duct wall thickness
Figure 3.1.15. XX10 Assembly.
XX09 was an instrumented assembly which is similar to a control assembly, but was not moveable, and was located in 05D03. XX09 contained 59 MK-II fuel elements and 2 stainless-steel MK-II dummy elements in a triangular pitch of 0.566 cm. Above the fuel lattice was an upper extension with a height of 40.597 cm. The element lattice and the upper extension were contained in an inner hexagonal duct with an inner flat-to-flat distance of 4.826 cm, an outer flat-to-flat distance of 4.902 cm, and a height of 159.822 cm. Below the inner hexagonal duct was the lower adapter, which was modeled as a cylinder with a diameter of 4.291 cm and a height of 36.44 cm. The inner hexagonal duct was contained in an outer hexagonal duct, which had an inner flat-to-flat distance of 5.8166 cm, an outer flat-to-flat distance of 5.887 cm, and a height of 159.822 cm. Table 3.1.23 shows lengths and references for the control assembly components shown in Figure 3.1.16.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Length (cm)</th>
<th>Nomenclature</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>68.428</td>
<td>Core Region Height</td>
</tr>
<tr>
<td>B</td>
<td>40.597</td>
<td>Upper Extension</td>
</tr>
<tr>
<td>C</td>
<td>52.23</td>
<td>Distance from the Origin to the Bottom of the Outer Hex Duct (a)</td>
</tr>
<tr>
<td>D</td>
<td>107.59</td>
<td>Distance from the Origin to the Top of the Outer Hex Duct</td>
</tr>
<tr>
<td>E</td>
<td>108.618</td>
<td>Distance from the Origin to the Bottom of the Outer Hex Duct Lower Adapter (a)</td>
</tr>
<tr>
<td>F</td>
<td>0.1016</td>
<td>Hex Duct Wall Thickness</td>
</tr>
<tr>
<td>G</td>
<td>4.8260</td>
<td>Hexagonal Inner Duct Flat to Flat Outer Diameter</td>
</tr>
<tr>
<td>H</td>
<td>5.8166</td>
<td>Hexagonal Outer Duct Flat to Flat Outer Diameter</td>
</tr>
</tbody>
</table>

(a) This dimension does not include the hexagonal duct wall thickness.
Figure 3.1.16. XX09 Assembly
XY-16

XY-16 was an assembly built identical to a control assembly with the fuel elements being replaced with stainless-steel dummy elements. XY-16 was located in 05F03.

X402A

X402A was modeled as a driver assembly with the middle fuel element being replaced with a solid stainless-steel element with the same dimensions as a MK-II dummy element. X402A was located in 06B03.

3.1.2.11 Core Shield Block

The core shield boundary was modeled as a cylinder with an inner diameter of 83.6 cm and an outer diameter of 101.6 cm, with a length of 609.6 cm, where the bottom had a thickness of 25.4 cm, and the top had a thickness of 76.2 cm.

3.1.3 Material Data

3.1.3.1 Material Mass Densities

All materials in the core had their respective cross sections temperature corrected to 616K. Mass densities for materials other than fuel were temperature corrected to 616K. Table 3.1.24 shows the temperature corrected mass densities of materials other than fuel.
### Table 3.1.24. Temperature Corrected Mass Densities

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium</td>
<td>0.8692</td>
</tr>
<tr>
<td>Plenum Gas(a)</td>
<td>0.00058</td>
</tr>
<tr>
<td>SS304L</td>
<td>7.7285</td>
</tr>
<tr>
<td>Poison Element Wire Wrap</td>
<td>10.38</td>
</tr>
<tr>
<td>SS316</td>
<td>7.8763</td>
</tr>
<tr>
<td>Fuel Element Wire Wrap</td>
<td>7.9212</td>
</tr>
<tr>
<td>Boron Carbide(a)</td>
<td>2.5</td>
</tr>
<tr>
<td>Smeared Upper Extension</td>
<td>7.113</td>
</tr>
<tr>
<td>Smeared Lower Extension</td>
<td>6.9924</td>
</tr>
<tr>
<td>Smeared Safety Upper Extension</td>
<td>7.1815</td>
</tr>
<tr>
<td>Poison Element Smeared Shield Block</td>
<td>7.6099</td>
</tr>
<tr>
<td>Stainless Steel 304 Reflector Smear</td>
<td>7.6151</td>
</tr>
<tr>
<td>Stainless Steel 316 Reflector Smear</td>
<td>7.7493</td>
</tr>
</tbody>
</table>

(a) These materials did not have their densities adjusted because their thermal expansions were negligible.

#### 3.1.3.2 Driver Assemblies

**Driver Fuel Element**

The driver fuel was a uranium metal. The uranium was approximately 95 wgt. % uranium and 5 wgt. % fissium, where fissium was used to simulate the dominant mid-cycle fission product. As mentioned, the fuel for Run 138B was depleted.

The cladding was 316 stainless-steel and the compositions are shown in Table 3.1.25.
Table 3.1.25. Composition of Stainless-Steel 316

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Atomic Density (a/b-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>3.209E-04</td>
</tr>
<tr>
<td>Si</td>
<td>1.715E-03</td>
</tr>
<tr>
<td>Cr</td>
<td>1.714E-02</td>
</tr>
<tr>
<td>Mn</td>
<td>3.725E-04</td>
</tr>
<tr>
<td>Fe</td>
<td>5.643E-02</td>
</tr>
<tr>
<td>Ni</td>
<td>9.850E-03</td>
</tr>
<tr>
<td>Mo</td>
<td>1.256E-03</td>
</tr>
</tbody>
</table>

**Plenum Gas**

The gas plenum had a composition of helium and argon as seen in Table 3.1.26.

Table 3.1.26 Composition of Plenum Gas

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Atomic Density (a/b-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>6.540E-05</td>
</tr>
<tr>
<td>Ar</td>
<td>2.189E-06</td>
</tr>
</tbody>
</table>

**Sodium Bond**

The sodium bond was composed of sodium without impurities. The sodium bond had a composition of sodium as seen in Table 3.1.27.

Table 3.1.27 Composition of Sodium Bond

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Atomic Density (a/b-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na</td>
<td>2.478E-2</td>
</tr>
</tbody>
</table>

**Driver Assembly**

The outer hexagonal duct was made of stainless-steel 304L (Table 3.1.28). The upper extension, lower extension, and lower adapter were all homogenizations of stainless-steel 304L and sodium. Their compositions can be found in Table 3.1.29, Table 3.1.30, and Table 3.1.31. This composition is the same for the half-worth drivers and dummy assemblies.
Table 3.1.28 Composition of Stainless-Steel 304L

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Atomic Density (a/b-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>2.759E-04</td>
</tr>
<tr>
<td>Si</td>
<td>8.428E-04</td>
</tr>
<tr>
<td>P</td>
<td>1.681E-05</td>
</tr>
<tr>
<td>S</td>
<td>8.858E-06</td>
</tr>
<tr>
<td>Cr</td>
<td>1.698E-02</td>
</tr>
<tr>
<td>Mn</td>
<td>6.549E-04</td>
</tr>
<tr>
<td>Fe</td>
<td>6.024E-02</td>
</tr>
<tr>
<td>Ni</td>
<td>7.219E-03</td>
</tr>
</tbody>
</table>

Table 3.1.29. Composition of Homogenized Upper Extension

<table>
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</tr>
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<tbody>
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<tr>
<td>Na</td>
<td>1.829E-02</td>
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<tr>
<td>Si</td>
<td>6.959E-04</td>
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<td>P</td>
<td>1.388E-05</td>
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<td>S</td>
<td>7.314E-06</td>
</tr>
<tr>
<td>Cr</td>
<td>1.402E-02</td>
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<tr>
<td>Mn</td>
<td>5.408E-04</td>
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<td>Fe</td>
<td>4.973E-02</td>
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<tr>
<td>Ni</td>
<td>5.961E-03</td>
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</table>
Table 3.1.30. Composition of Homogenized Lower Extension

<table>
<thead>
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<th>Atomic Density (a/b-cm)</th>
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<td>Na</td>
<td>2.145E-02</td>
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<td>Mn</td>
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<td>Fe</td>
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<td>Ni</td>
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Table 3.1.31. Composition of Homogenized Lower Adapter

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<td>Si</td>
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<td>P</td>
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<td>S</td>
<td>7.971E-06</td>
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<tr>
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<td>1.528E-02</td>
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<td>Mn</td>
<td>5.894E-04</td>
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<td>Fe</td>
<td>5.421E-02</td>
</tr>
<tr>
<td>Ni</td>
<td>6.497E-03</td>
</tr>
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</table>
Driver Fuel Element Composition

The fuel composition for the individual driver assemblies are in a separate folder labeled “Benchmark CSV”. Within that folder, the general types of assemblies are further broken down into drivers MK-IIA, drivers MKIIAI, safeties, controls, experimentals, and blankets. Each folder has a set of “.csv” files which are titled by the assembly position in the core. Figure 1.1.3 shows the manner in which EBR-II assemblies positions were referenced. The separate folder system was included due to the excessive length of the materials used for the depleted core. Using the Argonne National Laboratory depletion analysis results produced in the early 1990s, each driver assembly has an individual data set associated with it, and each uniquely depleted assembly also has three unique axial fueled regions, each with their own material composition. Table 3.1.32 shows an example of one assembly fuel composition. The wire wrap remained constant between the driver fuel elements and are a derivative of stainless-steel 316 with a higher atom density, which can be seen in Table 3.1.33.
Table 3.1.32 Composition of Driver Subassembly 03C01

<table>
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<th>Slug 1 Atom Percent</th>
<th>Slug 2 Atom Percent</th>
<th>Slug 3 Atom Percent</th>
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<td>1.520E-23</td>
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<tr>
<td>243Cm</td>
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<td>1.350E-28</td>
<td>1.340E-28</td>
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<tr>
<td>244Cm</td>
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<td>1.030E-28</td>
<td>9.860E-29</td>
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<td>245Cm</td>
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<td>2.220E-33</td>
<td>2.240E-33</td>
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<td>246Cm</td>
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<td>2.240E-38</td>
<td>2.050E-38</td>
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<td>2.460E-19</td>
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<td>1.880E-24</td>
<td>1.840E-24</td>
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<td>3.880E-12</td>
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<td>2.650E-04</td>
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<td>5.580E-04</td>
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Table 3.1.33 Composition of Stainless-Steel 316 Wire Wrap

<table>
<thead>
<tr>
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<td>1.715E-03</td>
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<td>Cr</td>
<td>1.714E-02</td>
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<tr>
<td>Mn</td>
<td>3.725E-04</td>
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<td>Fe</td>
<td>5.643E-02</td>
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<td>Ni</td>
<td>9.850E-03</td>
</tr>
<tr>
<td>Mo</td>
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</table>

3.1.3.3 *Half-Worth Driver Assembly*

**Driver Fuel Element**

The half-worth driver fuel elements were identical to the driver fuel elements.

**Dummy Element**

The composition of the dummy elements was stainless-steel 316 (Table 3.1.25).

**Half-Worth Driver Assembly**

The outer hexagonal duct was made of stainless-steel 304L (Table 3.1.28). The upper extension, lower extension, and lower adapter were all homogenizations of stainless-steel 304L and sodium. Their compositions can be found in Table 3.1.29, Table 3.1.30, and Table 3.1.31.

**Half-Worth Driver Fuel Element Composition**

The fuel composition for the individual half-worth driver assemblies are in a separate folder labeled “Benchmark CSV.”

3.1.3.4 *Dummy Assembly*

**Dummy Element**

The composition of the dummy elements was stainless-steel 304L (Table 3.1.28).
**Dummy Assembly**

The composition of the hexagonal ducts was either stainless-steel 316 (Table 3.1.25) or stainless-steel 304L (Table 3.1.28) depending on placement in the core. The lower adapter consisted of homogenized stainless-steel 304L and sodium Table 3.1.31.

**3.1.3.5 Safety Rod Assembly**

**Safety Rod Fuel Element**

The safety rod fuel elements were identical to the driver fuel elements.

**Safety Rod Inner Assembly**

The upper extension and the lower adapter of the safety assembly inner hexagonal duct were homogenized mixtures of stainless-steel 304L and sodium, and their compositions are found in Table 3.1.34 and Table 3.1.35. The inner hexagonal duct was composed of stainless-steel 304L (Table 3.1.28).

**Safety Rod Outer Assembly**

The composition of the hexagonal duct was stainless-steel 304L (Table 3.1.28).

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Atomic Density (a/b-cm)</th>
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<tbody>
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<tr>
<td>Na</td>
<td>3.807E-03</td>
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<tr>
<td>Si</td>
<td>8.133E-04</td>
</tr>
<tr>
<td>P</td>
<td>1.622E-05</td>
</tr>
<tr>
<td>S</td>
<td>8.548E-06</td>
</tr>
<tr>
<td>Cr</td>
<td>1.639E-02</td>
</tr>
<tr>
<td>Mn</td>
<td>6.320E-04</td>
</tr>
<tr>
<td>Fe</td>
<td>5.812E-02</td>
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<tr>
<td>Ni</td>
<td>6.966E-03</td>
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</table>
Table 3.1.35. Composition of Safety Assembly Inner Hexagonal Duct Lower Adapter

<table>
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<td>P</td>
<td>1.529E-05</td>
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<tr>
<td>Cr</td>
<td>1.544E-02</td>
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<td>Mn</td>
<td>5.954E-04</td>
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<td>5.476E-02</td>
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<tr>
<td>Ni</td>
<td>6.563E-03</td>
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</table>

**Safety Rod Outer Assembly**

The volume between the inner and outer hexagonal assembly was composed of sodium without impurities. The outer hexagonal duct was composed of stainless-steel 304L (Table 3.1.28).

**Safety Rod Fuel Element Composition**

The fuel composition for the individual safety rod assemblies are in a separate folder labeled “Benchmark CSV”.

**3.1.3.6 Control Rod Assembly**

**Control Rod Fuel Element**

The control rod fuel elements were identical to the driver fuel elements.

**Control Rod Inner Assembly**

The control rod inner assembly composition was identical to the safety rod assembly.

**Control Rod Outer Assembly**

The control rod outer assembly composition was identical to the safety rod assembly.
Control Rod Fuel Element Composition

The fuel composition for the individual control rod assembly are in a separate folder labeled “Benchmark CSV”.

3.1.3.7 High Worth Control Rod Assembly

High Worth Control Rod Fuel Element

The high worth control rod fuel elements were identical to the driver fuel elements.

High Worth Control Rod Poison Element

The high worth control rod poison elements contained B,C slugs, whose compositions are listed in Table 3.1.36. The poison slug was contained in a stainless-steel 316 cladding (Table 3.1.25). The stainless-steel shield blocks were a homogenization of stainless-steel 304L and sodium, whose composition can be found in Table 3.1.37.

Table 3.1.36. Composition of Poison Slug

<table>
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<th>Isotope</th>
<th>Atomic Density (a/b-cm)</th>
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<tr>
<td>C</td>
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</table>

Table 3.1.37 Composition of B4C Shield Block

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Atomic Density (a/b-cm)</th>
</tr>
</thead>
<tbody>
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<td>C</td>
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<td>Na</td>
<td>3.807E-03</td>
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<td>Si</td>
<td>8.133E-04</td>
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<td>P</td>
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<td>S</td>
<td>8.548E-06</td>
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<td>Cr</td>
<td>1.639E-02</td>
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<td>Mn</td>
<td>6.320E-04</td>
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<td>Fe</td>
<td>5.812E-02</td>
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<tr>
<td>Ni</td>
<td>6.996E-03</td>
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</tbody>
</table>
High Worth Control Rod Inner Assembly

The control rod inner assembly composition was identical to the safety rod assembly, with the upper extension region being replaced by the poison elements.

High Worth Control Rod Outer Assembly

The control rod outer assembly composition was identical to the safety rod assembly.

High Worth Control Rod Fuel Element Composition

The fuel composition for the individual high worth control rod assemblies are in a separate folder labeled “Benchmark CSV”.

3.1.3.8 C2776A

C2776A was modeled with the same material composition as a driver assembly. The fuel element composition for C2776A is in a separate folder labeled “Benchmark CSV”.

3.1.3.9 X320C

X320C was modeled with the same material composition as a dummy assembly.

3.1.3.10 X412

X412 was modeled with the same material composition as a driver assembly. The fuel element composition for X412 is in a separate folder labeled “Benchmark CSV”.

3.1.3.11 XX10

XX10 Elements

The stainless-steel dummy elements and the hollow element both consisted of stainless-steel 316 (Table 3.1.25).

XX10 Inner Assembly

The inner assembly was identical to that of a safety rod assembly, with the upper extension and lower adapter containing the same homogenization of stainless-steel and sodium (Table 3.1.34 and Table 3.1.35).

XX10 Outer Assembly

The XX10 outer hexagonal duct composition was identical to the safety rod assembly.
3.1.3.12 XX09

XX09 Elements

XX09 had fuel elements identical to the MK-II fuel elements. The fuel element composition for XX09 is in a separate folder labeled “Benchmark CSV”.

XX09 Inner Assembly

The inner assembly was identical to that of a safety rod assembly, with the upper extension and lower adapter containing the same homogenization of stainless-steel and sodium (Table 3.1.34 and Table 3.1.35).

XX09 Outer Assembly

The XX09 outer hexagonal duct composition was identical to the safety rod assembly.

3.1.3.13 XY-16

XY-16 Elements

XY-16 had dummy elements identical to the dummy assembly (Table 3.1.25).

XY-16 Inner Assembly

The inner assembly was identical to that of a safety rod assembly, with the upper extension and lower adapter containing the same homogenization of stainless-steel and sodium (Table 3.1.34 and Table 3.1.35).

XY-16 Outer Assembly

The XY-16 outer hexagonal duct composition was identical to the safety rod assembly.

3.1.3.14 X402A

X402A Elements

X402A had MK-II fuel elements (Table 3.1.9) and one stainless-steel 316 (Table 3.1.25) hollow MK-II element.

X402A Assembly

The X402A outer hexagonal duct composition was identical to a driver assembly. The fuel element composition for X402A is in a separate folder labeled “Benchmark CSV”.

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Date: December 28, 2017
3.1.3.15 Reflector Assembly

Reflector Hex Block

The reflector hexagonal blocks consisted of a homogenization of either stainless-steel 304L or 316 and sodium. Their compositions can be found in Table 3.1.38 and Table 3.1.39.

Table 3.1.38 Composition Stainless-Steel 304L Reflector Hex Block

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Table 3.1.39 Composition of Stainless-Steel 316 Reflector Hex Block

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**Reflector Assembly**

The reflector hexagonal ducts consisted of either stainless-steel 316 (Table 3.1.25) or 304L (Table 3.1.28) dependent on location in the core. The lower adapter consisted of homogenized stainless-steel 304L and sodium (Table 3.1.31).

**3.1.3.16 Blanket Assembly**

**Blanket Assembly**

The blanket hexagonal ducts consisted of stainless-steel 316 (Table 3.1.28). The lower adapter consisted of homogenized stainless-steel 304L and sodium (Table 3.1.31).

**Blanket Rod Fuel Element Composition**

The fuel composition for the individual blanket assemblies are in a separate folder labeled “Benchmark CSV”. Within that folder, the general types of assemblies are further broken down into drivers MK-IIA, drivers MKIIAI, safeties, controls, experimentals, and blankets. Each folder has a set of “.csv” files which are titled by the assembly position in the core. Figure 1.1.3 shows the manner in which EBR-II assemblies positions were referenced. The separate folder system was included due to the excessive length of the materials used for the depleted core. Using the Argonne National Laboratory depletion analysis results produced in the early 1990s, each blanket assembly has an individual data set associated with it, and each uniquely depleted assembly also has three unique axial fueled regions, each with their own material composition. Table 3.1.40 shows an example of one blanket assembly fuel composition.
Table 3.1.40 Composition of Blanket Subassembly 11A01

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<th>Isotope</th>
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<td>1.620E-09</td>
<td>2.170E-10</td>
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<td>1.530E-04</td>
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</table>
3.1.3.17 Core Shield Block

The core shield block contained borated graphite as described in section 1.1.2.1. Due to the extremely low importance of the core shield block it was determined that replacing the block with a mixture of stainless-steel and sodium produced identical results. Due to this, the core shield block was modeled with the same material as the homogenized lower extension from Table 3.1.30.

3.1.4 Temperature Data

The benchmark model temperature was 616 K, for the entirety of the core. A temperature distribution was not performed in the model, and thus each component in the reactor was set at this standard temperature.

3.1.5 Experimental and Benchmark-Model $k_{\text{eff}}$ and/or Subcritical Parameters

The experimental $k_{\text{eff}}$ was assumed to be 1.0000. There was no calculated $k_{\text{eff}}$ in the logbook or elsewhere. The only data that was recorded for critical was rod position and a stamp in the logbook that indicated critical.

<table>
<thead>
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<th>Table 3.1.41. Analytical Results of EBR-II Run 138B Benchmark Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental $k_{\text{eff}}$</td>
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<tr>
<td>Bias $\Delta k_{\text{eff}}$</td>
</tr>
<tr>
<td>Benchmark</td>
</tr>
</tbody>
</table>

3.2 Benchmark-Model Specifications for Buckling and Extrapolation-Length Measurements

Buckling and extrapolation length measurements were not evaluated.

3.3 Benchmark-Model Specifications for Spectral Characteristics Measurements

Buckling and extrapolation length measurements were not evaluated.

3.4 Benchmark-Model Specifications for Reactivity Effects Measurements

Buckling and extrapolation length measurements were not evaluated.

3.5 Benchmark-Model Specifications for Reactivity Coefficient Measurements

Buckling and extrapolation length measurements were not evaluated.

3.6 Benchmark-Model Specifications for Kinetics Measurements

Buckling and extrapolation length measurements were not evaluated.
3.7 **Benchmark-Model Specifications for Reaction-Rate Distribution Measurements**

Buckling and extrapolation length measurements were not evaluated.

3.8 **Benchmark-Model Specifications for Power Distribution Measurements**

Buckling and extrapolation length measurements were not evaluated.

3.9 **Benchmark-Model Specifications for Isotopic Measurements**

Buckling and extrapolation length measurements were not evaluated.

3.10 **Benchmark-Model Specifications for Other Miscellaneous Types of Measurements**

Buckling and extrapolation length measurements were not evaluated.
4.0 RESULTS OF SAMPLE CALCULATIONS

All models were run using cross-sections from the ENDF/B-VII.0 library and then temperature corrected to 616 K.

4.1 Results of Calculations’ of the Critical or Subcritical Configurations’

Table 4.1.1 is the effective multiplication factor determined for EBR-II Run 138B.

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<th>Benchmark</th>
<th>(C-E)/E (%)</th>
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</thead>
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<td>$1.00927 \pm 0.00458$</td>
<td>0.23948 $\pm$ 0.458</td>
</tr>
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</table>

4.2 Results of Buckling and Extrapolation Length Calculations

Buckling and extrapolation length measurements were not made.

4.3 Results of Spectral-Characteristics Calculations

Spectral-Characteristics Calculations were not made.

4.4 Results of Reactivity-Effects Calculations

Reactivity-Effects Calculations were not made.

4.5 Results of Reactivity Coefficient Calculations

Reactivity Coefficient Calculations were not made.

4.6 Results of Kinetics Parameter Calculations

Kinetics measurements were not made.

4.7 Results of Reaction-Rate Distribution Calculations

Reaction-Rate Distribution Calculations were not made.

4.8 Results of Power Distribution Calculations

Power distribution measurements were not made.
4.9 **Results of Isotopic Calculations**

Isotopic measurements were not made.

4.10 **Results of Calculations for Other Miscellaneous Types of Measurements**

Other Miscellaneous Types of Measurements were not made.
5.0 REFERENCES


15. XX-09 - EX-193 Quality Assurance Documentation, Argonne National Laboratory.

16. XX402 Quality Assurance Documentation, Argonne National Laboratory.

Revision: 0  Page 141 of 200

Date: December 28, 2017
A.1. Critical/Subcritical Configurations

A.1.1. Name(s) of code system(s) used.

1. Monte Carlo n-Particle, version 6.1.1-Beta
2. NJOY-99.296.

A.1.2. Bibliographic references for the codes used.


A.1.3. Origin of Cross-section data.

The Evaluated Neutron Data File library, ENDF/B-VII.0 processed by NJOY to 480 K.

A.1.4. Spectral calculations and data reduction methods used.

Not applicable

A.1.5. Number of energy groups or if continuous-energy cross-sections are used in the different phases of the calculation.

Continuous-energy cross sections

A.1.6. Component calculations.

- Type of cell calculation – Not Applicable
- Geometry – HEX-Z homogenous with heterogeneous fuel and absorber elements
- Theory used – Not applicable
- Method used – Monte Carlo
- Calculation characteristics – histories/cycles/cycles skipped = 150,000/1,030/30 continuous-energy cross sections

A.1.7. Other assumptions and characteristics.

Not applicable

---

A.1.8. Typical input listings for each code system type.

A.1.8.1. As-built Model

[DUE TO THE SIZE, THE SAMPLE INPUT FILE HAS BEEN REMOVED AND PLACED IN A SEPARATE DOCUMENT LABELED “EBRII138BAsBuilt.i”]

A.1.8.2. Benchmark Model

[DUE TO THE SIZE, THE SAMPLE INPUT FILE HAS BEEN REMOVED AND PLACED IN A SEPARATE DOCUMENTS LABELED “EBRII138BBenchmark.i”]
A.2. **Buckling and Extrapolation Length**

Buckling and Extrapolation Length measurements were not made.

A.3. **Spectral Characteristics Configurations**

Spectral Characteristics Configuration measurements were not made.

A.4. **Reactivity-Effects Configurations**

Reactivity-Effects Configuration measurements were not made.

A.5. **Reactivity Coefficient Configurations**

Reactivity Coefficient measurements were not made.

A.6. **Kinetics Parameter Configurations**

Kinetics Parameter measurements were not made.

A.7. **Reaction Rate Configurations**

Reaction Rate measurements were not made.

A.8. **Isotopic Configurations**

Isotopic measurements were not made.

A.9. **Configurations of Other Miscellaneous Types of Measurements**

Configurations of Other Miscellaneous Types of Measurements were not made.
ADDITIONAL ILLUSTRATION OF INTEREST

B.1. Engineering Drawings

The following figures are all of the engineering drawings available and used for the benchmark evaluation. They are broken down into assembly types. All of the drawings are scans of the original engineering drawings. They have been cropped down to just the drawing, but no attempt was made to correct the rotation of the images.

B.1.1. Drivers

B.1.1.1. MK-II

Figure. B.1.1. MK-II Assembly
B.1.1.2. MK-IIA

![MK-IIA Assembly Diagram]

Figure. B.1.2. MK-IIA Assembly
B.1.1.3. Upper Extension

Figure B.1.3. Driver Assembly Upper Extension
B.1.2. Half Worth Drivers

Figure. B.1.4. Half-Worth Driver Assembly
B.1.3. Safeties

B.1.3.1. Assembly

Figure. B.1.5. Safety Assembly
B.1.3.2. Upper Extension

The upper extension for the safety rod was called the shield block. The design for the shield block was identical to the shield block used in the blanket assemblies. Reference B.1.8.2 for the engineering drawing.

B.1.4. High Worth Control Rods

![High Worth Control Rod Assembly Diagram]

Figure. B.1.6. High Worth Control Rod Assembly
B.1.5. Control Rod

Figure. B.1.7. Control Rod Assembly
B.1.6. Dummies

Figure B.1.8. Dummy Assembly
B.1.7. Reflectors

Figure. B.1.9. Reflector Assembly
B.1.8. Blankets

B.1.8.1. Assembly

Figure. B.1.1. Blanket Assembly
B.1.8.2. Shield Block

Figure. B.1.2. Blanket Shield Block
B.1.9. Experiments

Figure. B.1.3. Control Rod Position Locking Type
B.1.10. Fuel Elements

B.1.10.1. MK-II Fuel Element

Figure. B.1.4. MK-II Fuel Element
B.1.10.2. MK-IIA Fuel Element

![Diagram of MK-IIA Fuel Element]

Figure. B.1.1. MK-IIA Fuel Element
B.1.10.3. MK-II Dummy Element

Figure. B.1.2. MK-IIA Dummy Element
B.1.10.4. MK-II Fuel Slug

Figure. B.1.3. MK-II Fuel Slug
B.1.10.5. MK-II Element Spade

Figure. B.1.4. MK-II Element Spade
B.1.10.6. MK-II Top Plug

Figure B.1.5. MK-II Element Top Plug
B.1.11. Poison Elements

B.1.11.1. $\text{B}_4\text{C}$ Element

Figure. B.1.6. $\text{B}_4\text{C}$ Element
B.1.11.2.  B₄C Element Shield

Figure. B.1.7. B₄C Element Shield
B.1.11.3.  B₄C Slug Stack

Figure. B.1.8. B₄C Slug Stack
B.1.12. Blanket Element

Figure. B.1.9. Blanket Element
B.2. Assembly Positions

Figure B.2.1 shows numbers associated with assembly position. Table B.2.1. shows a list of assembly position and type.\textsuperscript{a}

### Table B.2.1. Assembly Position Reference

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<td>626</td>
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</tr>
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<td>627</td>
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<td>641</td>
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<td>670</td>
<td>16E09</td>
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<td>16F08</td>
<td>Blanket</td>
</tr>
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<td>699</td>
<td>16A08</td>
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</tr>
<tr>
<td>700</td>
<td>16A09</td>
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</tr>
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<td>701</td>
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<tr>
<td>714</td>
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</table>
DISCUSSION OF MODEL HOMOGENIZATION

C.1. Simplified Model

C.1.1. Simplified Model Description

Multiple simplified models of EBR-II Run 138B were developed to simplify the geometric and material composition of the core while trying to maintain a neutronically accurate representation. The simplified model took two approaches to simplifications, the removal of the lower adaptor and the homogenization of different components. These simplifications were dependent on perceived impact to the calculated eigenvalue, and convenience of implementation. The calculated eigenvalue was found to be most sensitive to the homogenization technique and less sensitive to the lower adaptor removal. Due to this, it was determined that the EBR-II core during Run 138B most resembled a heterogeneous core, and the heterogeneity was required to account for the underlying physics occurring.

The simplification via the removal of the lower adapters and the homogenization of the core took place in five steps. These steps were first performed individually and then integrated such that each new step contained the steps previous. The steps in the simplification process were as such:

Step 1: Blanket Assemblies
Step 2: Reflector Assemblies
Step 3: Dummy Assemblies
Step 4: Half-Worth Assemblies
Step 5: Driver Assemblies

There were two main sections of the EBR-II core that were not homogenized, the experimental assemblies and the control/safety/high worth control rods. It was determined the experimental assemblies were not characterized well enough to warrant investigation into the effects of homogenization. Due to the extreme complexity in the creation of the control rods, homogenizing the control rods was not feasible. Along with this, the control rods were determined to have a similar effect to homogenizing a driver assembly.

C.1.2. Simplified Model: Removal of the Lower Adapters

C.1.2.1. Lower Adapter Removal: Results

The removal of the lower adaptor took place in five steps beginning with the blanket assemblies. This process involved removing the entire lower adaptor from each blanket assembly. The same process was followed for steps two through five, where the results of the lower cylinder removal can be seen in Table. C.1.1 and Table. C.1.2.
### Table. C.1.1. Calculated Eigenvalue for the Individual Lower Adapter Removal

<table>
<thead>
<tr>
<th>Step</th>
<th>$k_{\text{eff}}$</th>
<th>Uncertainty</th>
<th>$k_{\text{eff}}$ Difference (pcm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1</td>
<td>1.00596</td>
<td>0.00006</td>
<td>-1.789</td>
</tr>
<tr>
<td>Step 2</td>
<td>1.00605</td>
<td>0.00007</td>
<td>-0.895</td>
</tr>
<tr>
<td>Step 3</td>
<td>1.00607</td>
<td>0.00006</td>
<td>-0.696</td>
</tr>
<tr>
<td>Step 4</td>
<td>1.00302</td>
<td>0.00006</td>
<td>-1.192</td>
</tr>
<tr>
<td>Step 5</td>
<td>1.00604</td>
<td>0.00006</td>
<td>-0.993</td>
</tr>
</tbody>
</table>

### Table. C.1.2. Calculated Eigenvalue for the Integral Lower Adapter Removal

<table>
<thead>
<tr>
<th>Step</th>
<th>$k_{\text{eff}}$</th>
<th>Uncertainty</th>
<th>$k_{\text{eff}}$ difference (pcm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1</td>
<td>1.00596</td>
<td>0.00006</td>
<td>-1.789</td>
</tr>
<tr>
<td>Step 2</td>
<td>1.00599</td>
<td>0.00006</td>
<td>-1.093</td>
</tr>
<tr>
<td>Step 3</td>
<td>1.00603</td>
<td>0.00007</td>
<td>-1.093</td>
</tr>
<tr>
<td>Step 4</td>
<td>1.00603</td>
<td>0.00007</td>
<td>-1.093</td>
</tr>
<tr>
<td>Step 5</td>
<td>1.00594</td>
<td>0.00006</td>
<td>-1.988</td>
</tr>
</tbody>
</table>

### C.1.3. Simplified Model: Homogenization of the EBR-II Core

### C.1.4. Homogenization: Process

The homogenization process left out the lower adapter and focused on homogenizing the central region of the assemblies of interest. The first step was to determine the appropriate volumes for each homogenized portion. The engineering drawings were utilized to find dimensions for each contributing volume at room temperature. These individual volumes were then used to find a volume fraction which could be used to homogenize the material section.

#### C.1.4.1. Blanket Assembly Homogenization

The first step of the homogenization process involved homogenizing the individual assemblies in the blanket region. This process removed the lower adapter and homogenized the fuel, sodium bonded region, plenum, fuel cladding, sodium coolant, and hexagonal duct. The total volume for a blanket assembly was 4806cm³, where the volume fraction for each component can be seen in Table. C.1.3.
Table. C.1.3. Volume Fraction for a Blanket Assembly

<table>
<thead>
<tr>
<th>Component</th>
<th>Volume Fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Slug</td>
<td>52.47</td>
</tr>
<tr>
<td>Sodium Bonding</td>
<td>7.26</td>
</tr>
<tr>
<td>Plenum</td>
<td>5.33</td>
</tr>
<tr>
<td>Fuel Cladding</td>
<td>10.70</td>
</tr>
<tr>
<td>Sodium Coolant</td>
<td>17.32</td>
</tr>
<tr>
<td>Hex duct</td>
<td>6.92</td>
</tr>
</tbody>
</table>

The volumes fractions found in Table. C.1.3 were then applied to their respective material compositions and the new material atom densities were used to create a new material for the homogenized region. The material composition of a representative blanket assembly can be found in Table. C.1.4. The final blanket assembly had the dimensions of the outer hexagonal duct and was filled with the homogenized material from Table. C.1.4.
### Table. C.1.4. Composition of Blanket Assembly

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Atom Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{242}$Cm</td>
<td>4.75E-14</td>
</tr>
<tr>
<td>$^{243}$Cm</td>
<td>2.39E-17</td>
</tr>
<tr>
<td>$^{244}$Cm</td>
<td>5.61E-18</td>
</tr>
<tr>
<td>$^{245}$Cm</td>
<td>3.79E-21</td>
</tr>
<tr>
<td>$^{246}$Cm</td>
<td>1.72E-25</td>
</tr>
<tr>
<td>$^{241}$Am</td>
<td>7.78E-10</td>
</tr>
<tr>
<td>$^{242}$Am</td>
<td>1.78E-14</td>
</tr>
<tr>
<td>$^{243}$Am</td>
<td>1.77E-15</td>
</tr>
<tr>
<td>$^{238}$Pu</td>
<td>7.20E-16</td>
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<td>$^{239}$Pu</td>
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<td>$^{240}$Pu</td>
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<td>$^{241}$Pu</td>
<td>1.85E-07</td>
</tr>
<tr>
<td>$^{242}$Pu</td>
<td>7.90E-10</td>
</tr>
<tr>
<td>$^{243}$Pu</td>
<td>1.16E-12</td>
</tr>
<tr>
<td>$^{237}$Np</td>
<td>3.02E-08</td>
</tr>
<tr>
<td>$^{235}$U</td>
<td>3.34E-11</td>
</tr>
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<td>$^{235}$U</td>
<td>5.57E-05</td>
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<td>0.025485</td>
</tr>
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<td>1.47E-07</td>
</tr>
<tr>
<td>$^{144}$Nd</td>
<td>1.29E-07</td>
</tr>
<tr>
<td>$^{145}$Nd</td>
<td>1.17E-07</td>
</tr>
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<td>$^{146}$Nd</td>
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<td>$^{148}$Nd</td>
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<td>$^{141}$Pr</td>
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<td>$^{142}$Ce</td>
<td>1.48E-07</td>
</tr>
<tr>
<td>$^{139}$La</td>
<td>1.79E-07</td>
</tr>
<tr>
<td>$^{133}$Cs</td>
<td>2.10E-07</td>
</tr>
<tr>
<td>$^{135}$Cs</td>
<td>2.15E-07</td>
</tr>
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<td>$^{137}$Cs</td>
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<td>$^{132}$Xe</td>
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<td>6.34E-08</td>
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<tr>
<td>$^{105}$Pd</td>
<td>1.18E-07</td>
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<tr>
<td>$^{106}$Pd</td>
<td>6.43E-08</td>
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<tr>
<td>$^{101}$Rh</td>
<td>1.80E-07</td>
</tr>
<tr>
<td>$^{101}$Ru</td>
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</tr>
<tr>
<td>$^{102}$Ru</td>
<td>1.90E-07</td>
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<tr>
<td>$^{104}$Ru</td>
<td>1.46E-07</td>
</tr>
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<td>$^{91}$Zr</td>
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<tr>
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</tr>
<tr>
<td>$^{88}$Sr</td>
<td>6.80E-08</td>
</tr>
</tbody>
</table>
C.1.4.2. Reflector Assembly Homogenization

The second step of the homogenization process involved homogenizing the individual assemblies in the reflector region. This process removed the lower adapter and homogenized the inner hex duct region and the hex duct. The total volume for the reflector assembly was 1653cm³, where the volume fraction for each component can be seen in Table. C.1.5.

<table>
<thead>
<tr>
<th>Component</th>
<th>Volume Fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner Hex Region</td>
<td>96.38</td>
</tr>
<tr>
<td>Hex duct</td>
<td>3.62</td>
</tr>
</tbody>
</table>

The volumes fractions found in Table. C.1.5 where then applied to their respective material compositions and the new material atom densities were used to create a new material for the homogenized region. The material composition of a representative reflector assembly can be found in Table. C.1.6. The final reflector assembly had the dimensions of the outer hexagonal duct and was filled with the homogenized material from Table. C.1.6.
Table. C.1.6. Composition of a Reflector Assembly

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Weight %</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>1.29E-05</td>
</tr>
<tr>
<td>( ^{28}\text{Si} )</td>
<td>0.000197</td>
</tr>
<tr>
<td>( ^{29}\text{Si} )</td>
<td>1.08E-05</td>
</tr>
<tr>
<td>( ^{30}\text{Si} )</td>
<td>7.59E-06</td>
</tr>
<tr>
<td>( ^{31}\text{P} )</td>
<td>5.24E-06</td>
</tr>
<tr>
<td>( ^{32}\text{S} )</td>
<td>2.79E-06</td>
</tr>
<tr>
<td>( ^{33}\text{S} )</td>
<td>2.38E-08</td>
</tr>
<tr>
<td>( ^{34}\text{S} )</td>
<td>1.42E-07</td>
</tr>
<tr>
<td>( ^{36}\text{S} )</td>
<td>7.44E-10</td>
</tr>
<tr>
<td>( ^{50}\text{Cr} )</td>
<td>0.000597</td>
</tr>
<tr>
<td>( ^{52}\text{Cr} )</td>
<td>0.012458</td>
</tr>
<tr>
<td>( ^{53}\text{Cr} )</td>
<td>0.001468</td>
</tr>
<tr>
<td>( ^{54}\text{Cr} )</td>
<td>0.000379</td>
</tr>
<tr>
<td>( ^{55}\text{Mn} )</td>
<td>0.000642</td>
</tr>
<tr>
<td>( ^{54}\text{Fe} )</td>
<td>0.003325</td>
</tr>
<tr>
<td>( ^{56}\text{Fe} )</td>
<td>0.056122</td>
</tr>
<tr>
<td>( ^{57}\text{Fe} )</td>
<td>0.001343</td>
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<tr>
<td>( ^{58}\text{Fe} )</td>
<td>0.000185</td>
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<tr>
<td>( ^{58}\text{Ni} )</td>
<td>0.005354</td>
</tr>
<tr>
<td>( ^{60}\text{Ni} )</td>
<td>0.002207</td>
</tr>
<tr>
<td>( ^{61}\text{Ni} )</td>
<td>9.91E-05</td>
</tr>
<tr>
<td>( ^{62}\text{Ni} )</td>
<td>0.000327</td>
</tr>
<tr>
<td>( ^{64}\text{Ni} )</td>
<td>8.86E-05</td>
</tr>
<tr>
<td>( ^{23}\text{Na} )</td>
<td>0.000277</td>
</tr>
</tbody>
</table>

C.1.4.3. Dummy Assembly Homogenization

The third step of the homogenization process involved homogenizing the individual dummy assemblies. This process removed the lower adapter and homogenized the stainless-steel dummy elements, sodium coolant, and
the hex duct. The total volume for the reflector assembly was 4819 cm³, where the volume fraction for each component can be seen in Table. C.1.7.

Table. C.1.7. Volume Fraction for a Reflector Assembly

<table>
<thead>
<tr>
<th>Component</th>
<th>Volume Fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dummy Elements</td>
<td>69.29</td>
</tr>
<tr>
<td>Sodium Coolant</td>
<td>23.79</td>
</tr>
<tr>
<td>Hex Duct</td>
<td>6.92</td>
</tr>
</tbody>
</table>

The volumes fractions found in Table. C.1.7 were then applied to their respective material compositions and the new material atom densities were used to create a new material for the homogenized region. The material composition of a representative dummy assembly can be found in Table. C.1.8. The final dummy assembly had the dimensions of the outer hexagonal duct and was filled with the homogenized material from Table. C.1.8.
Table. C.1.8. Composition of a Dummy Assembly

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Weight %</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>1.11E-05</td>
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<tr>
<td>$^{28}\text{Si}$</td>
<td>0.000298</td>
</tr>
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<td>$^{29}\text{Si}$</td>
<td>1.62E-05</td>
</tr>
<tr>
<td>$^{30}\text{Si}$</td>
<td>1.14E-05</td>
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<tr>
<td>$^{50}\text{Cr}$</td>
<td>0.000411</td>
</tr>
<tr>
<td>$^{52}\text{Cr}$</td>
<td>0.008561</td>
</tr>
<tr>
<td>$^{53}\text{Cr}$</td>
<td>0.001009</td>
</tr>
<tr>
<td>$^{54}\text{Cr}$</td>
<td>0.000261</td>
</tr>
<tr>
<td>$^{55}\text{Mn}$</td>
<td>0.001273</td>
</tr>
<tr>
<td>$^{54}\text{Fe}$</td>
<td>0.002308</td>
</tr>
<tr>
<td>$^{58}\text{Fe}$</td>
<td>0.038957</td>
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<tr>
<td>$^{57}\text{Fe}$</td>
<td>0.000932</td>
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<tr>
<td>$^{58}\text{Fe}$</td>
<td>0.000128</td>
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<tr>
<td>$^{59}\text{Ni}$</td>
<td>0.005412</td>
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<tr>
<td>$^{60}\text{Ni}$</td>
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<tr>
<td>$^{61}\text{Ni}$</td>
<td>0.0001</td>
</tr>
<tr>
<td>$^{62}\text{Ni}$</td>
<td>0.00033</td>
</tr>
<tr>
<td>$^{64}\text{Ni}$</td>
<td>8.96E-05</td>
</tr>
<tr>
<td>$^{92}\text{Mo}$</td>
<td>0.000378</td>
</tr>
<tr>
<td>$^{94}\text{Mo}$</td>
<td>0.000246</td>
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<tr>
<td>$^{95}\text{Mo}$</td>
<td>0.000433</td>
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<tr>
<td>$^{96}\text{Mo}$</td>
<td>0.000463</td>
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<tr>
<td>$^{97}\text{Mo}$</td>
<td>0.000271</td>
</tr>
<tr>
<td>$^{98}\text{Mo}$</td>
<td>0.000698</td>
</tr>
<tr>
<td>$^{100}\text{Mo}$</td>
<td>0.00029</td>
</tr>
<tr>
<td>$^{23}\text{Na}$</td>
<td>0.078461</td>
</tr>
</tbody>
</table>
C.1.4.4. Half-Worth Driver Assembly Homogenization

The fourth step of the homogenization process involved homogenizing the individual half-worth driver assemblies. This process removed the lower adapter and homogenized the stainless-steel dummy elements, fuel elements, and sodium coolant. The hexagonal duct was not homogenized with this step to prevent the artificial increase of stainless-steel in the fueled region. The homogenization split the central region into two regions, a plenum region and a fueled region. The plenum region homogenized the plenum, fuel cladding, fuel wire wrap, dummy elements, dummy element wire wrap, and the coolant. The fuel region homogenized the three fuel slug regions, sodium bond, fuel cladding, fuel wire wrap, dummy element, dummy element wire wrap, and coolant. The total volumes for the plenum region and fuel region assembly were 924 cm$^3$ and 1118 cm$^3$, where the volume fraction for each component for the plenum region and fueled region can be seen in Table. C.1.9 and Table. C.1.10.

Table. C.1.9. Volume Fraction for a Half-Worth Driver Assembly – Plenum Region

<table>
<thead>
<tr>
<th>Component</th>
<th>Volume Fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plenum</td>
<td>16.73</td>
</tr>
<tr>
<td>Fuel Cladding</td>
<td>5.82</td>
</tr>
<tr>
<td>Fuel Wire Wrap</td>
<td>1.58</td>
</tr>
<tr>
<td>Dummy Slug</td>
<td>22.07</td>
</tr>
<tr>
<td>Dummy Wire Wrap</td>
<td>1.55</td>
</tr>
<tr>
<td>Coolant</td>
<td>52.26</td>
</tr>
</tbody>
</table>

Date: December 28, 2017
Table. C.1.10. Volume Fraction for a Half-Worth Driver Assembly - Fuel Region

<table>
<thead>
<tr>
<th>Component</th>
<th>Volume Fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slug 1</td>
<td>5.67</td>
</tr>
<tr>
<td>Slug 2</td>
<td>5.67</td>
</tr>
<tr>
<td>Slug 3</td>
<td>5.67</td>
</tr>
<tr>
<td>Na Bond</td>
<td>1.85</td>
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<tr>
<td>Fuel Clad</td>
<td>6.54</td>
</tr>
<tr>
<td>Fuel Wire Wrap</td>
<td>1.78</td>
</tr>
<tr>
<td>Dummy Slug</td>
<td>24.85</td>
</tr>
<tr>
<td>Dummy Wire Wrap</td>
<td>1.74</td>
</tr>
<tr>
<td>Coolant</td>
<td>46.22</td>
</tr>
</tbody>
</table>

The volumes fractions found in Table. C.1.9 and Table. C.1.10 were then applied to their respective material compositions, and the new material atom densities were used to create a new material for the plenum and fuel homogenized regions. The material compositions of a representative half-worth driver assembly can be found in Table. C.1.11 and Table. C.1.12. The final half-worth driver assembly had the dimensions of the outer hexagonal duct and was filled with the homogenized materials from Table. C.1.11 and Table. C.1.12.
Table. C.1.11. Composition of a Half-Worth Driver Assembly – Plenum Region

<table>
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<tr>
<th>Isotope</th>
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<tr>
<td>$^{38}\text{Ar}$</td>
<td>4.96E-09</td>
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<tr>
<td>$^{40}\text{Ar}$</td>
<td>8.67E-06</td>
</tr>
<tr>
<td>$\text{C}$</td>
<td>3.49E-05</td>
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<tr>
<td>$^{28}\text{Si}$</td>
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<tr>
<td>$^{29}\text{Si}$</td>
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<tr>
<td>$^{30}\text{Si}$</td>
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<tr>
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<tr>
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<td>$^{57}\text{Fe}$</td>
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<tr>
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Table. C.1.12. Composition of a Half-Worth Driver Assembly - Fuel Region

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<td>(^{245}\text{Cm})</td>
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<tr>
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<td>(^{242\text{Am}})</td>
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<tr>
<td>(^{243}\text{Am})</td>
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<td>(^{238}\text{Pu})</td>
<td>6.61E-10</td>
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<tr>
<td>(^{239}\text{Pu})</td>
<td>4.31E-06</td>
</tr>
<tr>
<td>(^{240}\text{Pu})</td>
<td>7.20E-09</td>
</tr>
<tr>
<td>(^{237}\text{Np})</td>
<td>1.03E-11</td>
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<tr>
<td>(^{234}\text{U})</td>
<td>1.17E-07</td>
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<tr>
<td>(^{233}\text{U})</td>
<td>7.81E-08</td>
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<tr>
<td>(^{232}\text{U})</td>
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<tr>
<td>(^{149}\text{Ce})</td>
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<tr>
<td>(^{139}\text{La})</td>
<td>3.66E-06</td>
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<tr>
<td>(^{137}\text{Cs})</td>
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<tr>
<td>(^{138}\text{Cs})</td>
<td>1.38E-05</td>
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<tr>
<td>(^{133}\text{Cs})</td>
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<td>1.41E-05</td>
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<tr>
<td>(^{137}\text{Cs})</td>
<td>1.33E-05</td>
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<tr>
<td>(^{134}\text{Xe})</td>
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<td>(^{103}\text{Rh})</td>
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<td>(^{96}\text{Ru})</td>
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<tr>
<td>(^{99}\text{Ru})</td>
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<tr>
<td>(^{104}\text{Ru})</td>
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<td>(^{99}\text{Tc})</td>
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<tr>
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</tr>
<tr>
<td>(^{52}\text{Cr})</td>
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C.1.4.5. Half-Worth Driver Assembly Homogenization

The fifth step of the homogenization process involved homogenizing the individual driver assemblies. This process removed the lower adapter and homogenized the stainless-steel dummy elements, fuel elements, and sodium coolant. Again, the hexagonal duct was not homogenized with this step to prevent the artificial increase of stainless-steel in the fueled region. The homogenization split the central region into two regions, a plenum region and a fueled region. The plenum region homogenized the plenum, fuel cladding, fuel wire wrap, stainless-steel dummy elements, stainless-steel dummy element wire wrap and the coolant. The fuel region homogenized the three fuel slug regions, sodium bond, fuel cladding, fuel wire wrap, dummy element, dummy element wire wrap and coolant. The total volumes for the plenum region and fuel region assembly were 1028 cm$^3$ and 1204 cm$^3$, where the volume fraction for each component for the plenum region and fueled region can be seen in Table. C.1.13 and Table. C.1.14.

Table. C.1.13. Volume Fraction for a Driver Assembly – Plenum Region

<table>
<thead>
<tr>
<th>Component</th>
<th>Volume Fraction (%)</th>
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<tbody>
<tr>
<td>Plenum</td>
<td>26.99</td>
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<tr>
<td>Fuel Cladding</td>
<td>9.38</td>
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<tr>
<td>Fuel Wire Wrap</td>
<td>2.88</td>
</tr>
<tr>
<td>Coolant</td>
<td>60.75</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>Volume Fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
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</tr>
<tr>
<td>$^{54}$Cr</td>
<td>6.82E-05</td>
</tr>
<tr>
<td>$^{55}$Mn</td>
<td>0.000327</td>
</tr>
<tr>
<td>$^{54}$Fe</td>
<td>0.000604</td>
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<tr>
<td>$^{56}$Fe</td>
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<td>$^{57}$Fe</td>
<td>0.000231</td>
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<tr>
<td>$^{60}$Ni</td>
<td>0.000525</td>
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<tr>
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<tr>
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</table>
Table. C.1.14. Volume Fraction for a Driver Assembly - Fuel Region

<table>
<thead>
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</tr>
<tr>
<td>Slug 2</td>
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<tr>
<td>Slug 3</td>
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<td>Na Bond</td>
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<td>Fuel Clad</td>
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<tr>
<td>Fuel Wire Wrap</td>
<td>3.21</td>
</tr>
<tr>
<td>Coolant</td>
<td>56.28</td>
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</table>

The volumes fractions found in Table. C.1.13 and Table. C.1.14 where then applied to their respective material compositions and the new material atom densities were used to create a new material for the plenum and fuel homogenized regions. The material compositions of a representative driver assembly can be found in Table. C.1.15 and Table. C.1.16. The final driver assembly had the dimensions of the outer hexagonal duct and was filled with the homogenized materials from Table. C.1.15 and Table. C.1.16.
Table. C.1.15. Composition of a Driver Assembly – Plenum Region

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<tr>
<th>Isotope</th>
<th>Atom Percent</th>
</tr>
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<tbody>
<tr>
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<tr>
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<td>$^{38}$Ar</td>
<td>8.01E-09</td>
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<tr>
<td>$^{40}$Ar</td>
<td>1.40E-05</td>
</tr>
<tr>
<td>C</td>
<td>1.54E-05</td>
</tr>
<tr>
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</tr>
<tr>
<td>$^{29}$Si</td>
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</tr>
<tr>
<td>$^{30}$Si</td>
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</tr>
<tr>
<td>$^{50}$Cr</td>
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<tr>
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<tr>
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Table. C.1.16. Composition of a Driver Assembly - Fuel Region

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<tr>
<td>$^{243}$Am</td>
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C.1.5. Homogenization: Results

The homogenization process took place in five steps beginning with the blanket assemblies. This process involved homogenizing the step specific assembly. The same process was followed for steps two through five, where the results of the lower cylinder removal can be seen in Table C.1.17 and Table C.1.18.

Table. C.1.17. Calculated Eigenvalue for the Individual Homogenization Steps

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<th>Uncertainty</th>
<th>$k_{eff}$ Difference (pcm)</th>
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</thead>
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<td>0.99880</td>
<td>0.00006</td>
<td>-72.95</td>
</tr>
<tr>
<td>Step 5</td>
<td>0.90986</td>
<td>0.00006</td>
<td>-956.9</td>
</tr>
</tbody>
</table>
Table. C.1.18. Calculated Eigenvalue for the Integral Homogenization Steps

<table>
<thead>
<tr>
<th>Step</th>
<th>( k_{\text{eff}} )</th>
<th>Uncertainty</th>
<th>( k_{\text{eff}} ) Difference (pcm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1</td>
<td>1.00047</td>
<td>0.00006</td>
<td>-56.4</td>
</tr>
<tr>
<td>Step 2</td>
<td>0.98868</td>
<td>0.00006</td>
<td>-173.6</td>
</tr>
<tr>
<td>Step 3</td>
<td>0.99263</td>
<td>0.00007</td>
<td>-134.3</td>
</tr>
<tr>
<td>Step 4</td>
<td>0.98506</td>
<td>0.00007</td>
<td>-209.5</td>
</tr>
<tr>
<td>Step 5</td>
<td>0.88603</td>
<td>0.00006</td>
<td>-1193.8</td>
</tr>
</tbody>
</table>

It should be noted that the as built eigenvalue is different than the eigenvalue found in the benchmark analysis. This difference is due to the homogenized model was analyzed using MCNP6.1.0b, and the benchmark model utilized MCNP6.1.1b. Although there is a slight change in the eigenvalue, the bias values found in Table. C.1.19 show a relative difference for version 6.1.0, which can be used in version 6.1.1. This bias can be used in version 6.1.1 because the change in the eigenvalue from version 6.1.0 to 6.1.1 will cancel when the difference is taken for the bias.

Table. C.1.19. Bias Values for Homogenization

<table>
<thead>
<tr>
<th>Homogenization Step</th>
<th>( k_{\text{eff}} ) Bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1</td>
<td>0.00567</td>
</tr>
<tr>
<td>Step 2</td>
<td>0.01746</td>
</tr>
<tr>
<td>Step 3</td>
<td>0.01351</td>
</tr>
<tr>
<td>Step 4</td>
<td>0.02108</td>
</tr>
<tr>
<td>Step 5</td>
<td>0.12011</td>
</tr>
</tbody>
</table>

It was determined that the bias for steps 1-3 are credible but still provide a large enough difference that applying homogenization may not be appropriate for all models. The bias for step 5 is too large to provide information related to the EBR-II core and should not be utilized. Along with this, step 4 homogenization of the half-worth driver assemblies, should also not be utilized due to the effect homogenization has on fueled assemblies. It is noted that these values were derived from the critical control rod configurations for Run 138B, however, these biases can be applied to any critical configuration and retain accurate results for comparison. If a homogenized model is to be used, the appropriate bias factor as seen in Table. C.1.19 must be applied to accurately resemble the as built model.