
COVER PAGE**Nuclear Energy University Program
Final Scientific/Technical Project Report**

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INTRODCUTION:

PROTEUS was a zero-power nuclear research reactor in operation from February 1968 to April 2011. The facility is located at the Paul Scherrer Institute in Villigen, Switzerland. PROTEUS featured a cylindrical central cavity that is driven critical by a surrounding graphite region fueled with 5 wt.% UO_2 fuel pins. The central cavity had the capability of being filled with different sub-critical fuel arrangements and made critical to study different reactor concepts. It was used to carry out experimental reactor physics investigations for a wide range of advanced reactor concepts, like the gas-cooled fast reactor (GCFR); the tight-pitch, high conversion, light water reactor (HCLWR); and the modular high temperature reactor (HTR).

The GCFR-PROTEUS core configuration which serves as the foundation of this benchmark was a coupled fast-thermal reactor. Its purpose was to replicate at its center, a flux profile similar to that of a typical fast reactor while using approximately one-tenth the volume of fuel a pure fast reactor would need to achieve criticality. GCFR-PROTEUS achieved this by using UO_2 fuel in the graphite and D_2O regions in tandem with the MOX fuel at the center of the cavity to drive the entire system critical. To reduce leakage of thermal neutrons from the D_2O zone to the fast zone, the MOX test region was bounded radially by a buffer zone containing depleted Uranium metal pins and axially by an upper and bottom blanket containing depleted UO_2 pins. Generic cross-sections of the GCFR-PROTEUS reactor are shown in Figure 1 and Figure 2. A central test column (6, in Figure 3) could be moved in and out of the test zone and served as a means of easy access to measurement positions at the center of the test zone.

The GCFR-PROTEUS experimental program was carried out between April 1972 and April 1979. Different core loading configurations were assembled, including mixed oxide (uranium, plutonium, and thorium) cores with and without breeding blankets. Measurements taken included: criticality measurements, integral reactivity, spectral indices, and reaction-rate measurements. Further experiments explored steam ingress. The measurements were used to determine the adequacy of the calculation methods and related nuclear data libraries used in the design of gas-cooled fast breeder reactors.

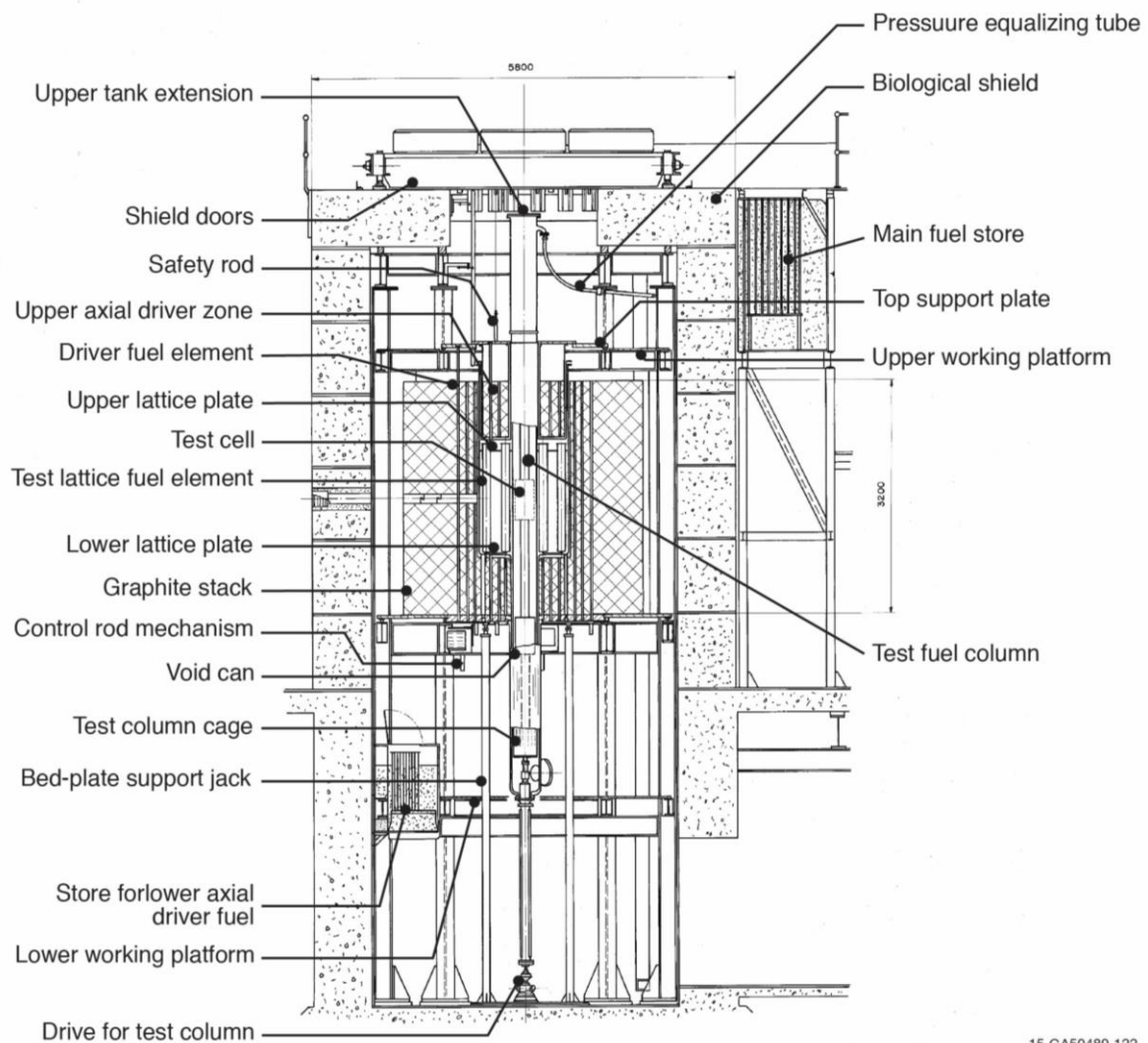
The GCFR-PROTEUS program primarily focused on configurations providing characteristic fast neutron spectra of central lattice configurations containing unmoderated (U-Pu) O_2 fuel and characterizing breeding ratios and neutron spectrum through the measurement of reaction rates (i.e. C8/F9, F8/F9, and C2/F9). However, part of the program was devoted to the evaluation of the $^{232}\text{Th}/^{233}\text{U}$ fuel cycle, which is the main focus of upcoming benchmarks. A summary of the cores that were evaluated as benchmarks follows:

- Core 11, [PROTEUS-GCFR-EXP-001](#), serves as the reference configuration in which the test-zone of the PROTEUS reactor is filled with a homogeneous unmoderated arrangement of (U-Pu) O_2 pins without thorium fuel. It served to check the reproducibility of the results obtained in earlier phases of the program and investigated the infinitely diluted cross-section of ^{232}Th , ^{233}U and ^{237}Np . The fuel contained 15 wt.% plutonium (80% fissile) and was clad in stainless steel. Fuel pellets had a diameter of 6.7 mm and a density of 10.6 g/cm^3 and were sandwiched between a top and a bottom blanket of depleted uranium oxide (0.42 wt.%, 10.5 g/cm^3), making up a total fuel length of 1.4 m. It is distributed in a hexagonal lattice with a pitch of 1 cm.
- Core 12, [PROTEUS-GCFR-EXP-002](#), featured a homogeneous mixed arrangement of 2 (U-Pu) O_2 for 1 ThO_2 pins with similar axial blankets of depleted uranium. The thorium oxide fuel is in the form of sintered particles with densities of 9.9 g/cm^3 and diameters of $\sim 400 \text{ }\mu\text{m}$. The particles are packed in 18/8 steel cigars and the apparent ThO_2 fuel density is only 6.08 g/cm^3 because of the packing factor. The driver region of the core was adjusted to make the reactor critical. Although the density is low as compared to the theoretical density of ThO_2 , the first effect of self-shielding could be investigated with ^{232}Th spectral indices measurements in ThO_2 pins. The other spectral indices were reproduced in the (U-Pu) O_2 pins to check the flux spectrum change.

- Core 15, **the focus of this benchmark**, featured a heterogeneous test zone containing metallic thorium in the center of the standard GCFR (U-Pu)O₂ lattice. Measurements were carried out in this Th-metal region and its interface with the (U-Pu)O₂ rod lattice. The Th-metal rods were 19 mm in diameter, had a density of 11.3 g/cm³ and were distributed on a hexagonal lattice pitch of 21 mm. The increase in the fuel density and in the packing of the Th-metal rods resulted in an averaged cell density increase of almost a factor 4. This provided a more stringent test for ²³²Th data than did the corresponding measurements in Core 13. The strong coupling between the Th-metal blanket and the MOX lattice was studied with the same radial reaction rate traverses as in Core 13 and compared to that obtained in the homogeneous Core 11.

Additionally, the original project proposal mentions the following cores that do not have complete benchmarks:

- Core 13 featured a heterogeneous thorium blanket zone in the center of the test zone made of 169 ThO₂ pins of the same type as those in Core 12. Apart from spectral indices measurements made in the center of the ThO₂ zone, reaction rate traverses were measured across the blanket-core interface since these provided a sensitive test for the calculation of the breeding ratio in a heterogeneous core. The radial traverses feature neutron capture ²³⁸U, ²³²Th and fissions in ²³⁹Pu, ²³³U and ²³²Th and were compared with the results obtained in the homogeneous Core 11.
- Core 14 featured an upper blanket of thorium oxide (355 mm) above the (U-Pu)O₂ fuel in the test zone. A steel shield was introduced above to obtain clean and well-defined axial boundary conditions. Axial reaction rate traverses across the core blanket interface were of principal interest in the Core 14 measurements, and these were determined along the central axis. The neutron spectrum at the center of the ThO₂ blanket was also determined.
- Core 16 layout is similar to that of Core 14, but for the ThO₂ rods in the axial blanket that were replaced with Th-metal rods similar to those of Core 15. The same axial traverses as in Core 4 were performed along the core's central axis. The spectrum in the middle of the metal blanket was characterized with spectral indices measurements.



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Figure 1. Vertical Cross Section of General PROTEUS Facility.

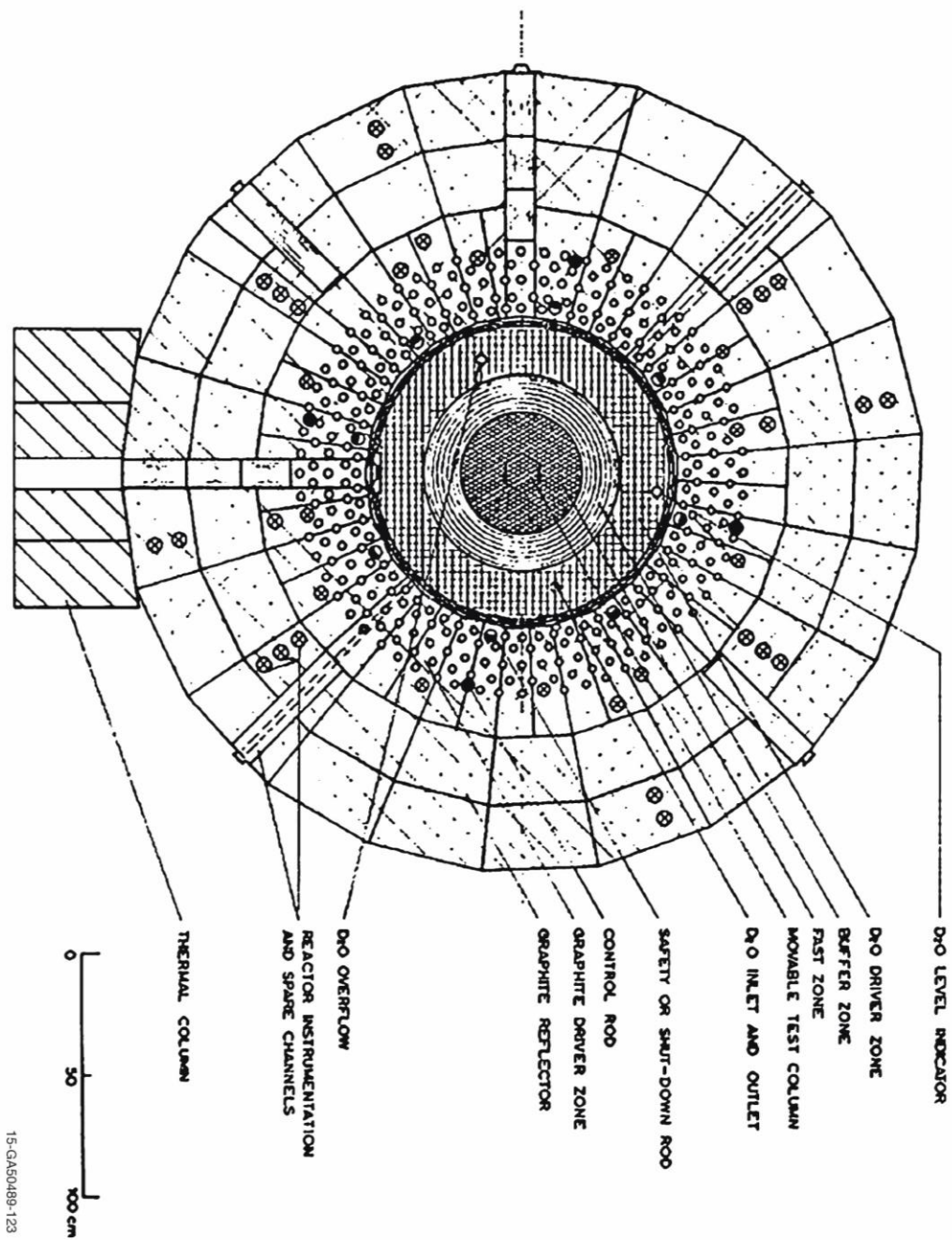
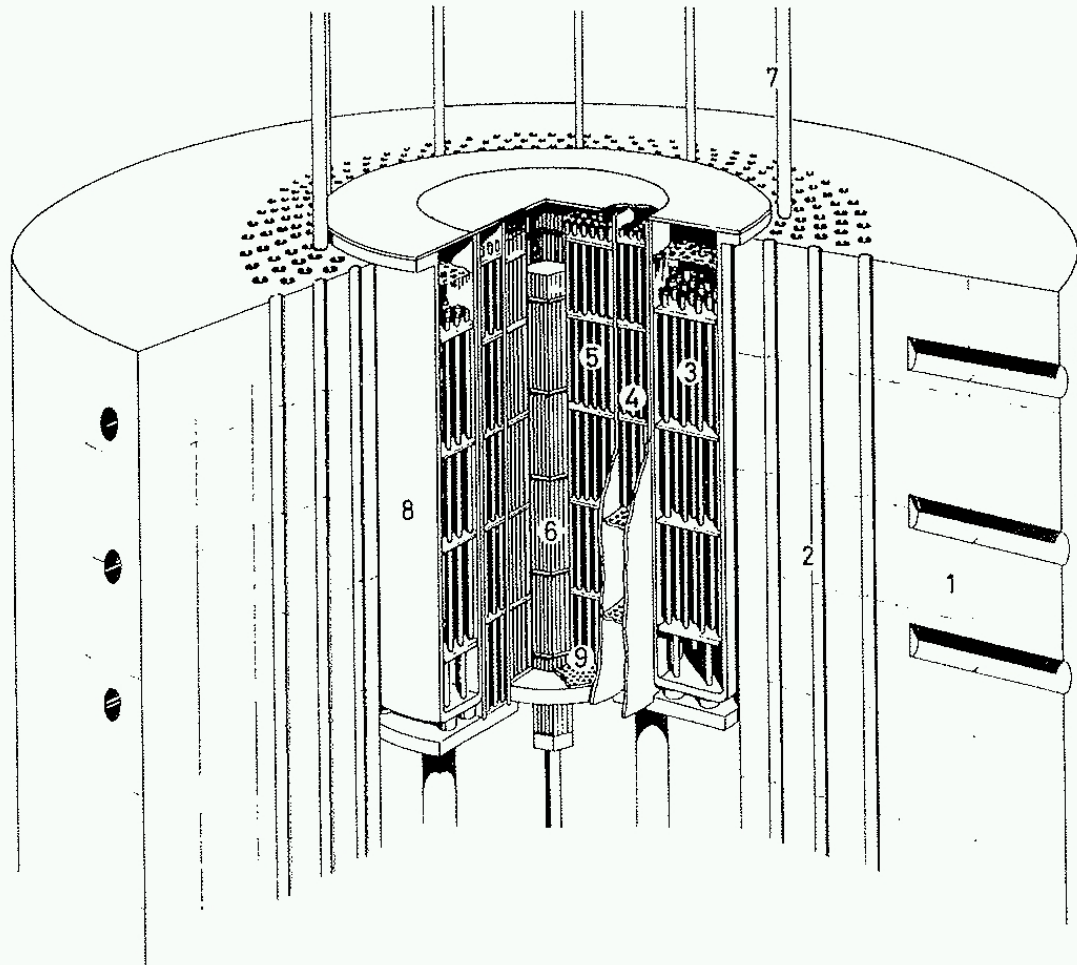


Figure 2. Horizontal Cross Section of GCFR PROTEUS.



- | | |
|--|------------------------|
| 1 GRAPHITE REFLECTOR | 6 TEST COLUMN |
| 2 GRAPHITE DRIVER | 7 CONTROL ROD |
| 3 D ₂ O-DRIVER | 8 MODERATOR TANK |
| 4 BUFFER (U-METAL) | 9 REMOVABLE GRID PLATE |
| 5 FAST ZONE (PuO ₂ /UO ₂) | |

Figure 3. Vertical Cross Section of GCFR-PROTEUS.

FURTHER TECHNICAL DESCRIPTION OF PROTEUS

For completeness of the description of benchmarks and the PROTEUS reactor in particular a somewhat lengthy description of the configuration of PROTEUS and its control and operating mechanisms(rods), in the configuration of experiment 2 (Core 12):

Overview of the Experiment

The neutron physics of a fast reactor lattice is inherently more complex than its thermal counterpart. This is due to the neutron interactions with a larger number of nuclides as well as a significant number of

neutrons being absorbed over an energy range spanning several decades. Despite the considerable amount of time and effort put into the procurement of the methods and data sets needed to predict the fast lattice reactor properties prior to the 1970s, the available methods yielded results with subpar accuracy. This was judged to be primarily due to inadequacies in the nuclear data sets available at the time. The basic aim of Core 12 in the GCFR PROTEUS campaign was to measure the neutron spectrum and relative neutron reaction rates of important isotopes and complement previous measurements in similar configurations. This was done through the use of foils made up of desired isotopes of uranium, plutonium, thorium, and neptunium as well as fission chambers with the corresponding deposits. PROTEUS personnel between October and December of 1977 performed the experiments.

The measured and evaluated spectral indices are considered acceptable as benchmark data by the author.

Geometry of the Experiment Configuration and Measurement Procedure

As can be expected with an experiment performed over three decades prior to the commencement of the benchmarking process, there has been attrition in the form of lost intellectual expertise and document loss. As such, some data described below was gleaned from experimental reports and facility documentation completed as recently as the early 2000s. This is appropriate since the significant components (i.e. graphite reflector region) of the PROTEUS facility remained largely unchanged or were reused throughout the facility lifetime. This is noted in the report when appropriate.

Reactor Block

Concrete shielding surrounds the reactor system entirely and made up the reactor block. The reactor is surrounded by 800 mm of concrete shielding. The concrete shielding has no appreciable effects on spectral measurements at the center of the core.

Reactor Plates

There are three reactor plates; the plate supporting the graphite block, the plate supporting the D₂O driver zone, the buffer and central test zone, and the upper reactor plate above the graphite driver zone (Figure 1).

Upper Reactor Plate

The upper reactor plate is a rectangular (2270 mm × 2570 mm) stainless steel (St-37) plate having a thickness of 55 mm and a central aperture (Ø1314 mm).¹² The upper surface of the upper plate is located 505 mm above the upper surface of the graphite block.

D₂O, Buffer, and Test Zone Support Plate

The plate supporting the D₂O, buffer and test zone has the shape of a drilled cylinder made of St-37 and contains some boron shield plastics in its inside, and below it.³ It is a cylindrical annulus with an inner and outer diameter of 400 mm and 1210 mm, respectively, and a height of 50 mm. Its upper surface is located 1730 mm above the lower surface of the graphite block. A 6 mm thick layer of boron shield plastic, having the same radial dimension, is located just below the support plate. An additional cylindrical layer of boron plastic (Ø 400 mm, H 17 mm, thickness 12 mm) is located in the middle of the

¹ Plan 0-154270

² Plan 2-155530

³ Plan 0-171188

inner cavity of the plate supporting the D₂O, buffer and test zone and around the plate supporting the central column of the test zone.

Graphite Support Plate

The graphite support plate is a 75 mm thick plate with an inner and outer diameter of 440 mm and 3260 mm respectively. The plate is located at the base of the graphite zone.

Steel Shielding

Above the upper reactor plates, a 600 mm thick St-37 cylinder of diameter 1250 mm was placed to act as an outer shield as well as neutron reflector. Also a St-37 cylindrical lid of diameter 450 mm and thickness of 225 mm covered the D₂O tanks, with a 3 mm boron plastic layer at the bottom of the lid.

Graphite Zone and Components

The height of the graphite zone is 3180 mm (10 blocks of 318 mm) and the core mid-plane is located 698 mm below the upper limit of the graphite zone.⁴ All graphite blocks are made of Reactor Grade A, made by British Achesons Electrodes Ltd. and E.I.R. (former PSI) [1].

The graphite zone is made of 22 columns of graphite blocks arranged as a cylindrical format. The inner limit is not circular, but rather made of a 22-sided polygon as described in [2] and shown in Figure 4.⁵ The inner radial limit of the graphite zone is the same as for the LWR-PROTEUS program [1] with an inner average diameter of 1250 mm. The external limit is also a 22-sided polygon with an average diameter of 3260 mm. This gave an average radial thickness of 1005 mm that is divided into two zones. The inner zone is a 350 mm thick driver region where the vertical penetrations into the graphite were located. The outer zone is the 655 mm thick reflector region.

⁴ PH-1-155402

⁵ AA 551/5/9601-Sheet 3

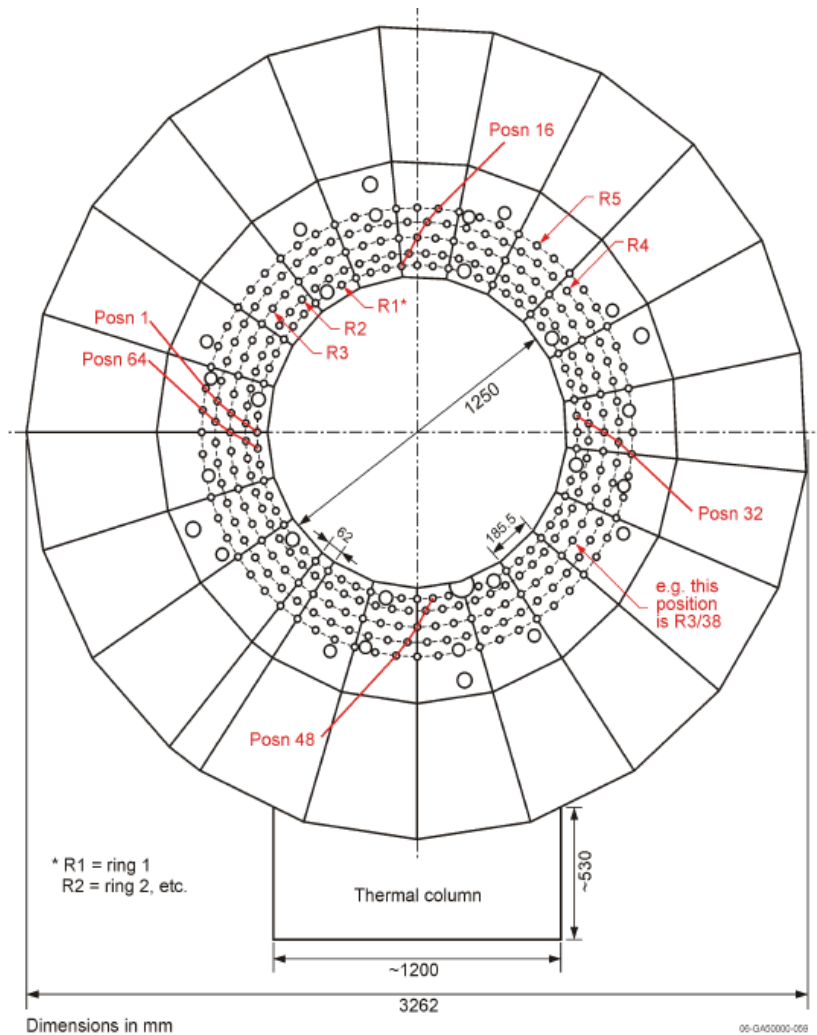


Figure 4. Cross Section View of Radial Reflector [3].

The graphite blocks are drilled vertically with holes for driver fuel pins ($\varnothing$ 27.3 mm), for four control rods ($\varnothing$ 45.5 mm) and for eight shutdown/safety rods $\varnothing$ 45.4 mm) [2].⁶ Radial positions of the shutdown/safety rods, control rods and fuel pins are illustrated in Figure . However, four of the control rods channels have been filled with graphite plugs during the GCFR experiments. In addition, there are just eight safety/shutdown rods instead of sixteen as during the LWR-PROTEUS program (the eight additional positions being standard driver fuel positions during the GCFR experiments). The diameters of the holes for the driver fuels and shutdown/safety and control rods vary slightly. They are 27.3 mm and 45 mm, respectively.

⁶ Plan PH-1-155401

Attached to one side of the radial reflector was a reactor thermal column, which was a quasi-rectangular structure with a height and width of 1200 mm and a depth of ~500 mm. Its top surface was situated 1120 mm from the upper surface of the radial reflector [2].

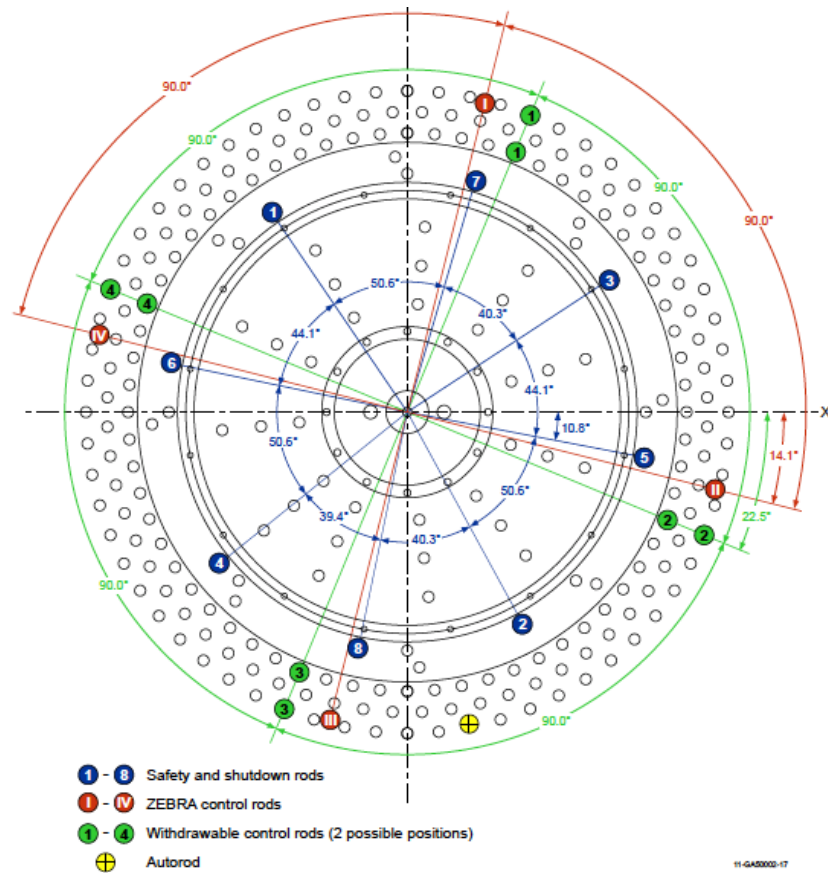


Figure 5. Bore Hole Locations and Control Rod Positions.

Note, for the GCFR campaign, the withdrawable control rod positions were filled with graphite plugs [3].

Shutdown/Safety Rods

There were eight, identical, borated-steel safety/shutdown rods located adjacent to the core in the radial reflector (see Figure). These rods were separated into two groups of four rods (rods 1-4 and rods 5-8). One of these groups was selected as the “safety rod” group and the other as the “shutdown rod” group.

Rods 1- 4 are the shutdown rods and rods 5-8 are the safety rods. The safety/shutdown rods consisted of four 35 mm diameter borated steel rod sections and one B₄C section enclosed in 18/8 stainless steel tubes with an inside diameter of 36 mm and outside diameter of 40 mm. The rods were located in 45 mm inner diameter graphite guide tubes within the graphite zone. The centers of the guide tubes were 675 mm from the center of the core. The azimuthal positions of the eight rods are shown in Figure [2].

Each rod contains four, 35 mm diameter, 350 mm long, cylindrical pieces of borated steel stacked below one cylindrical piece of boron carbide with the same dimensions.⁷ Aluminum and steel shock dampers were located under each of the safety/shutdown rods, as shown in

Figure 7, to prevent damage in case one of the rod cables should fail. A gap of approximately 30 mm separated the bottom of the safety rod from the upper, aluminum part of the shock damper. The steel parts of the shock dampers (end caps, springs, and damper chamber) were affixed to the underside of the lower support plate; only a fraction of the total mass of these components resided within the graphite reflector [2].

A diagram of a safety/shutdown rod is shown in

⁷ 157154a

Figure 7; the rods traveled a total distance of 1770 mm (1400 mm free fall plus 370 mm braking distance) from fully withdrawn to fully inserted positions [4].

The safety rods were always maintained in withdrawn positions, i.e., out of the reflector. Criticality was achieved when the four shutdown rods were also fully withdrawn and only the four control rods and the autorod were partially inserted for fine control.

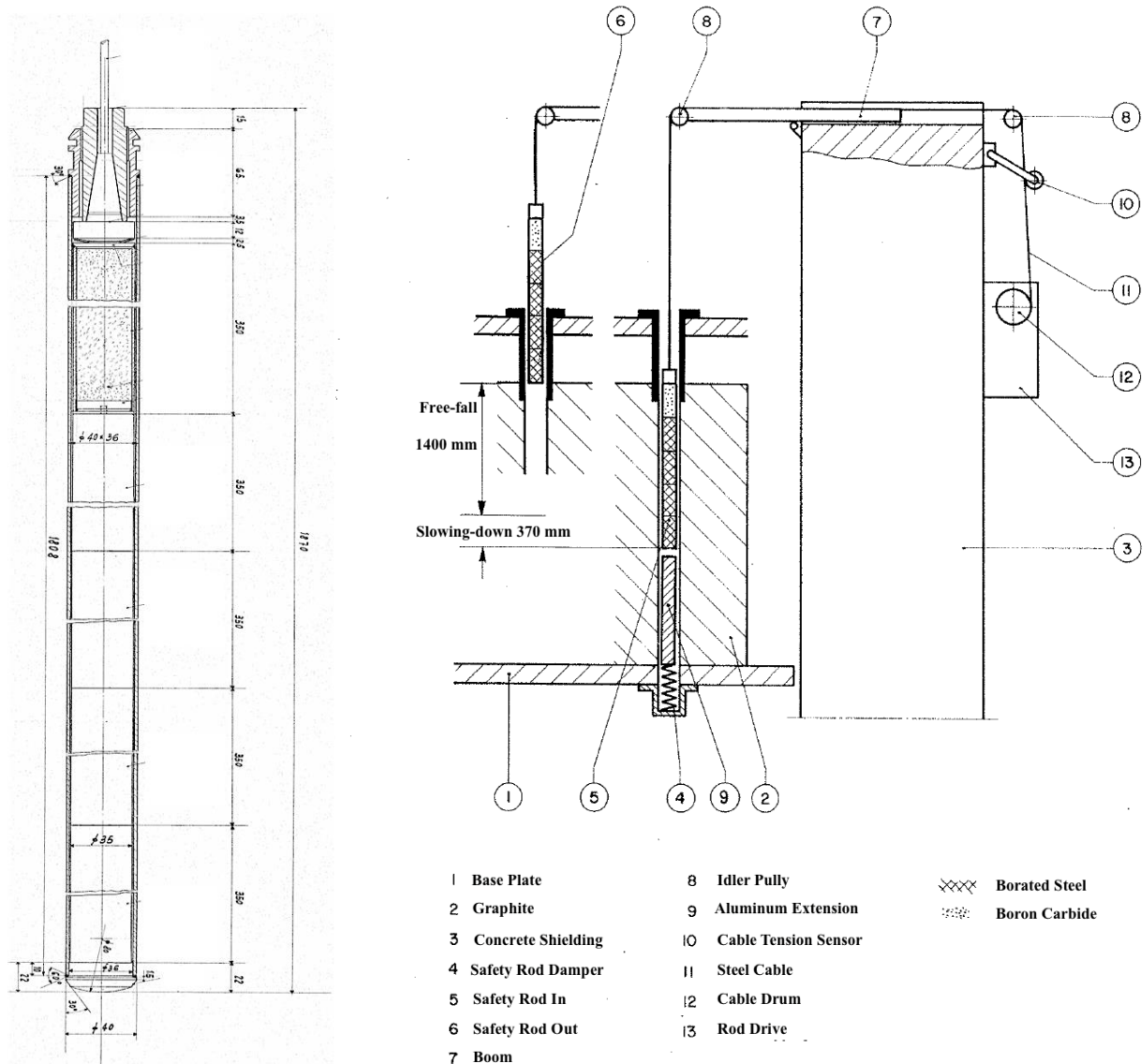


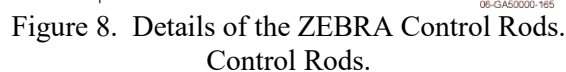
Figure 6 (left). Details of Safety/shutdown Rods. Units are in millimeters.

Figure 7(right). Safety/shutdown Rod Movement [4].

ZEBRA Control Rods

There are four ZEBRA type control rods in the graphite block. They are made of two concentric aluminum tubes, whose diameter, thickness and composition have been taken from [1] in the absence of other information. The ZEBRA control rod configurations, consisted of two concentric Peraluman R-257 tubes. The inner tube had an inner diameter of 30 mm and an outer diameter of 35 mm; the outer tube had

The outer aluminum tubes were fixed onto lower and upper steel support plates while the inner tubes were driven from below. The four assemblies were situated symmetrically in 45 mm diameter channels in the radial reflector at a radius of 896 mm, as shown in Figure 4. The configuration of ZEBRA rods 1-4 is depicted in **Error! Reference source not found.** and **Error! Reference source not found.**.



Auto Rod

A single, fine control rod (Figure Error! No text of specified style in document.) was utilized to automatically maintain reactor criticality at a nominal required power. It responded to signals from a single ionization chamber (deviation channel) located in the radial reflector 810 mm above the cavity floor and ~500 mm from the outer radial boundary of the core. The rod itself is located in a vertical channel with an inside diameter of 55 mm situated 890 mm from the radial center of the system; it was located azimuthally ~80° from the x-direction in a clockwise direction Figure . The rod was comprised of a wedge shaped copper plate supported within an aluminum tube with an outer diameter of 44 mm. The copper plate was 3 mm thick, 2300 mm long, and 39 mm at its wide end with a reduction in width along its length of 17 mm per meter. The rod was fully inserted when the position display showed 0 mm and the pointed end of the copper plate was flush with the underside of the steel plate upon which the reactor stands. The complete withdrawal of the autorod was indicated by a display of 1000 mm when the pointed end of the copper plate was ~200 mm above the base of the core cavity and the blunt end was 79 mm below the top of the radial reflector graphite.

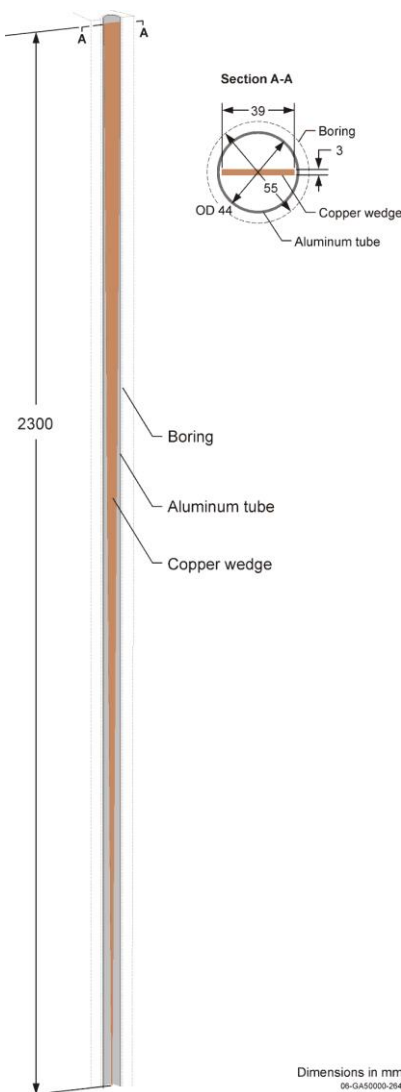


Figure Error! No text of specified style in document.. Automatic Control Rod.

Fuel in Graphite Driver Zone

There are five concentric rings of fuel channels distributed in the graphite zone. Rings have 64 azimuthal positions or arcs, some of which are used for the safety/shutdown rods or the autorods. There are therefore 55 available positions in the first (inner most) ring, 64 in the second, third and fourth rings and 61 in the fifth. The channels have a diameter of 27.3 mm and their positions are shown in Figure Error!

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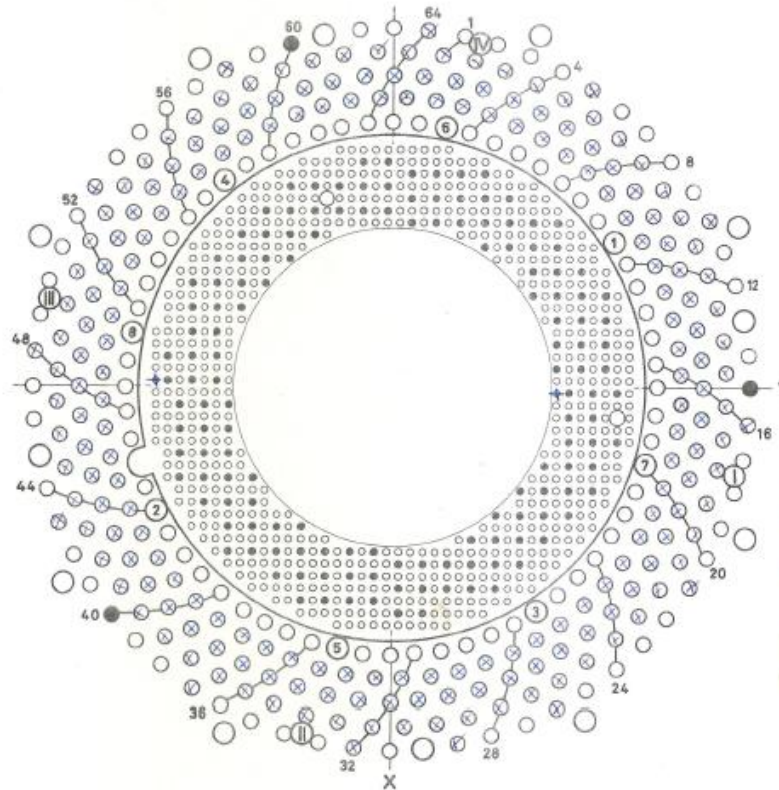


Figure Error! No text of specified style in document.. Graphite and D₂O Driver Zone Fuel Placement for Core 12 [5]. “⊗” denotes graphite driver zone fuel placement. “•” denotes D₂O zone fuel placement.

The fuel pins consist of 5% enriched UO₂ pellets of total height 930 mm and a diameter of 10.18 mm. The fuel was clad in 15 separate aluminium cigars each with an out diameter of 11.0 mm and a length of 61.3 mm. The cigars were surrounded by a Peraluman (Pe25) hull with an outer diameter of 12.2 mm and were capped on both ends (Pe25) for a total length of 1026 mm (Figure Error! No text of specified style in document.). Depending on the core, the loading of this section varies to make the reactor critical. For Core 12, there were 205 fuel pins in the C-driver, arranged in the different rings shown in Figure Error! No text of specified style in document..

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¹⁰ AA 551/5/9601-Sheet 3

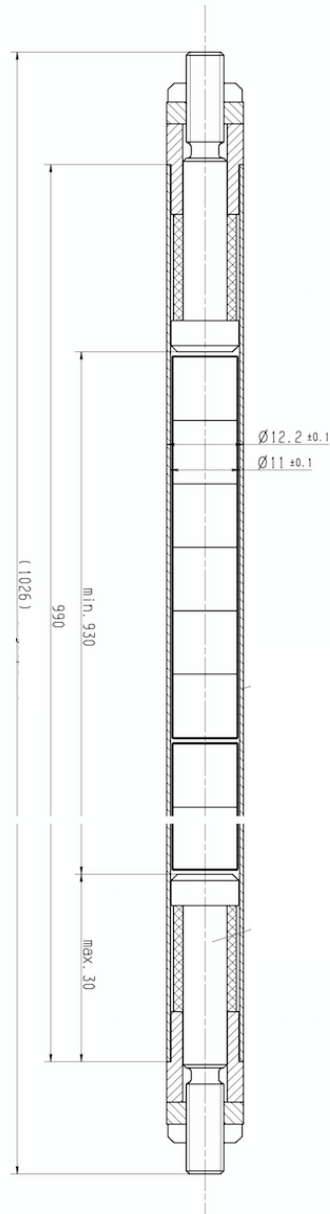


Figure **Error! No text of specified style in document.** D₂O and graphite driver zone fuel.

The accomplished central fast zone was achieved through the geometric configuration shown in figure 13 (as used in GCFR-PROTEUS Core 11 configuration).

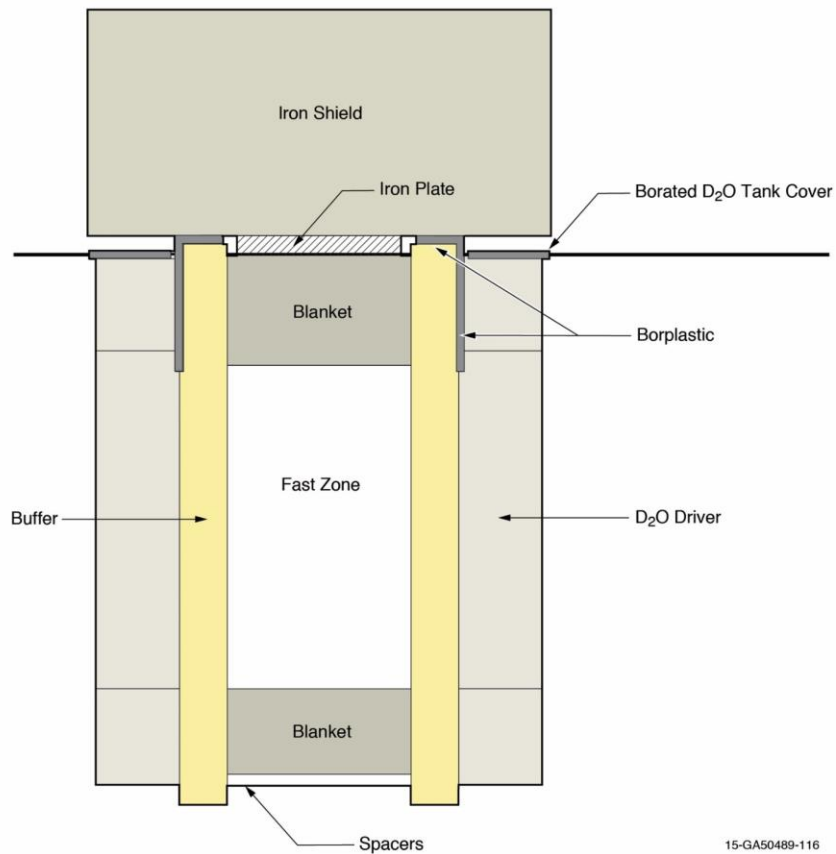


Figure 4. Rudimentary Diagram of Main Components inside Central Annulus of GCFR-PROTEUS Core 11.

ACCOMPLISHMENTS:

Sample works will be shown below from various benchmark cores to highlight some of the accomplishments.

GCFR-PROTEUS Core 11:

The PROTEUS GCFR Core 11 was modeled and evaluated using the MCNP6 code package in conjunction with the ENDF/B-VII.0 cross section library [3]. Upon discussion with G. Perret at PSI; it became apparent that this would be too limited a scope for creating a valid benchmark. Comparisons with other cross-section libraries would be needed. Therefore, Core 11 was evaluated using ENDF-7.0, ENDF-7.1, JEFF-3.1, JEFF-

3.1.1, JEFF-3.2, and JENDL-4.0. By using the JEFF-3.1 library, a direct comparison was able to be made to previous Core 11 results. This was important since, every cross-section library is maintained through different methods depending on the institution/country that developed them. For instance, Table I displays the results for the six cross section libraries used in the evaluation of reaction rate ratios. The difference between the MCNP derived results and the experimentally derived results for the (n, 2n) reaction of ^{232}Th differs from 8.3% (ENDF-7.0) and 22% (JEFF-3.1.1) Once the standard deviation for each process is taken into account, the cross-section libraries can be used to back check each other.

Table I: Core 11 reaction rate ratios for multiple cross-section libraries (difference between computed and experimental results is in percent)

	ENDF-7.0		ENDF-7.1		JEFF-3.1		JEFF-3.1.1		JEFF-3.2		JENDL-4.0	
	Value	C/E-1	Value	C/E-1	Value	C/E-1	Value	C/E-1	Value	C/E-1	Value	C/E-1
C238/F239	1.32×10^{-1}	-1	1.32×10^{-1}	-0.5	1.31×10^{-1}	-1.3	1.31×10^{-1}	-1.4	1.32×10^{-1}	-0.4	1.30×10^{-1}	-2.6
F238/F239	3.13×10^{-2}	0.5	3.15×10^{-2}	1.4	3.07×10^{-2}	-1.2	3.11×10^{-2}	-0.1	3.20×10^{-2}	2.9	3.16×10^{-2}	1.6
F235/F239	$1.02 \times 10^{+0}$	1.3	$1.02 \times 10^{+0}$	1.2	$1.02 \times 10^{+0}$	1.2	$1.02 \times 10^{+0}$	1	$1.04 \times 10^{+0}$	3	$1.00 \times 10^{+0}$	-0.9
C232/F239	2.01×10^{-1}	0.4	2.06×10^{-1}	2.9	1.93×10^{-1}	-3.6	1.98×10^{-1}	-1.2	2.07×10^{-1}	3.3	2.00×10^{-1}	0.1
F232/F239	7.33×10^{-3}	-9	7.59×10^{-3}	-5.9	7.76×10^{-3}	-3.8	7.84×10^{-3}	-2.7	7.53×10^{-3}	-6.6	8.05×10^{-3}	-0.1
F233/F239	$1.50 \times 10^{+0}$	-1.2	$1.50 \times 10^{+0}$	-1.2	$1.51 \times 10^{+0}$	-1	$1.51 \times 10^{+0}$	-0.8	$1.51 \times 10^{+0}$	-0.7	$1.49 \times 10^{+0}$	-1.7
(n,2n)232/C232	7.41×10^{-3}	8.3	7.64×10^{-3}	11.7	7.68×10^{-3}	12.3	8.35×10^{-3}	22	7.23×10^{-3}	5.8	7.73×10^{-3}	13
C237/F239	8.26×10^{-1}	0	8.26×10^{-1}	-0.1	7.88×10^{-1}	-4.6	7.96×10^{-1}	-3.7	8.11×10^{-1}	-1.8	7.97×10^{-1}	-3.6
F237/F239	2.27×10^{-1}	0.1	2.28×10^{-1}	0.6	2.29×10^{-1}	0.7	2.20×10^{-1}	-2.9	2.20×10^{-1}	-3	2.29×10^{-1}	0.7

Further information of Core 11 was obtained, including data on the reaction rates along the center axis of Core 11 in both the fast region and blanket regions. Radial reaction rates measurements were also obtained. These measurements are highly valuable. Since the PROTEUS reactor is a coupled fast/thermal reactor, these measurements verify that the center of the core is an ideal fast region.

The measurements involved simultaneous irradiation of foils and fission chambers located in both the test lattice and in the PROTEUS thermal column [8]. A given reaction rate ratio in the core was thus obtained relative to its known value in a standard thermal spectrum. The absolute calibration of foils, deposits and counting-system efficiencies was unnecessary. Clearly, the thermal comparison approach could not be applied to the measurement of threshold reactions such as ^{232}Th and ^{238}U fission.

Reference Core (11) Analysis Progression

In accordance with the experiments, Core 11 served as the reference core. Variations from Core 11 in later experiments consisted of deliberate modifications of the test lattice and minor elements in the surrounding regions. Main sections such as the steel shielding and the graphite in the driver zone were not modified.

Results for Core 11 indicate an agreement with experimental data with the exception of ^{232}Th fission and the (n, 2n) reaction of ^{232}Th . The standard deviations from MCNP6 were less than 1% for all actinides except for the (n, 2n) reaction of ^{232}Th which had a standard deviation of 3.3%. The experimental values had a calculated standard deviation between 1% and 2.5% with the (n, 2n) reaction of ^{232}Th being the highest as well.

Experimental data has been collected on the reaction rates along the center axis of the core. This was done using foils placed at predetermined points in both the fast zone and the blanket zone. MCNP6 results using JEFF-31. are shown in Figures below which indicate a strong match between the MCNP model and the experimental results. Each of the plotted values are with one standard deviation of each other.

Data processing for Core 11 was finalized and the benchmark was compiled. All data indicates a strong

ability to reproduce the experimental results with an MCNP model. The experience gained from modeling Core 11 aided in modeling Core 12 and future cores which have increasing complexity.

Due to certain ambiguities in elements located in the periphery of both Core 11 and Core 12, approximations have been made to obtain a $K_{\text{eff}} \approx 1$. These approximations are not expected to have an effect on the neutron spectrum or reaction rates at the core center. However, if more definitive data is not found in core blueprints, the computed values for criticality measurements will be unsuitable for benchmarking due to large inherent error.

The most important features to evaluate next are the effects the geometric and material uncertainties that the Core 11 design has on the spectral indices and reaction rate distributions. The evaluation will involve inducing perturbations in the material size and composition. These perturbations include changing the fuel meat density, fuel rod diameter, and graphite composition.

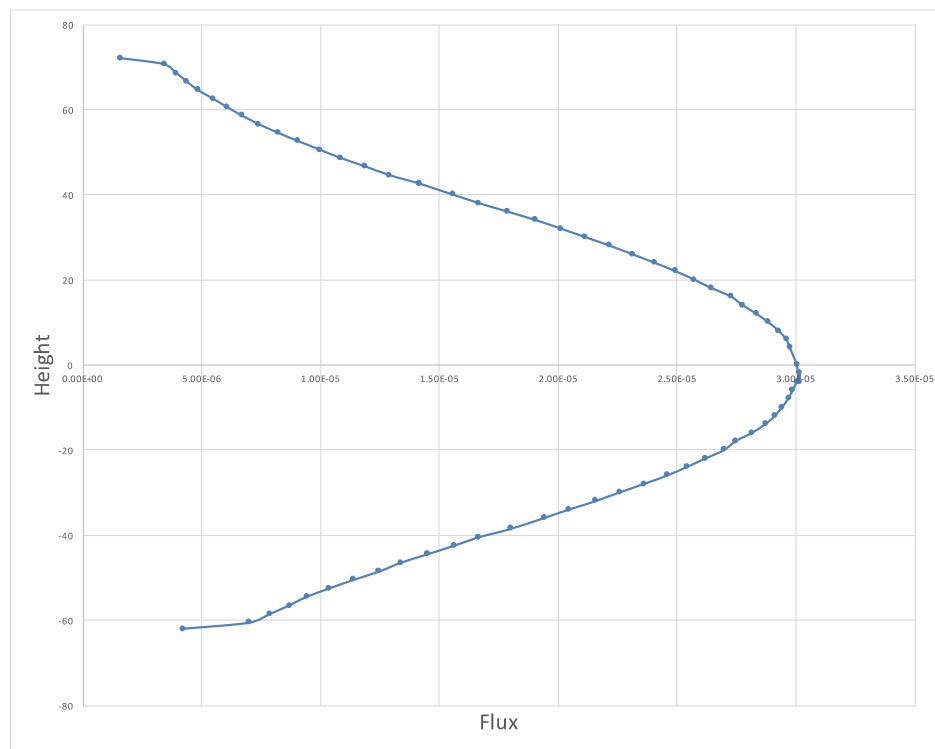


Figure 14. Axial profile of Core 11.

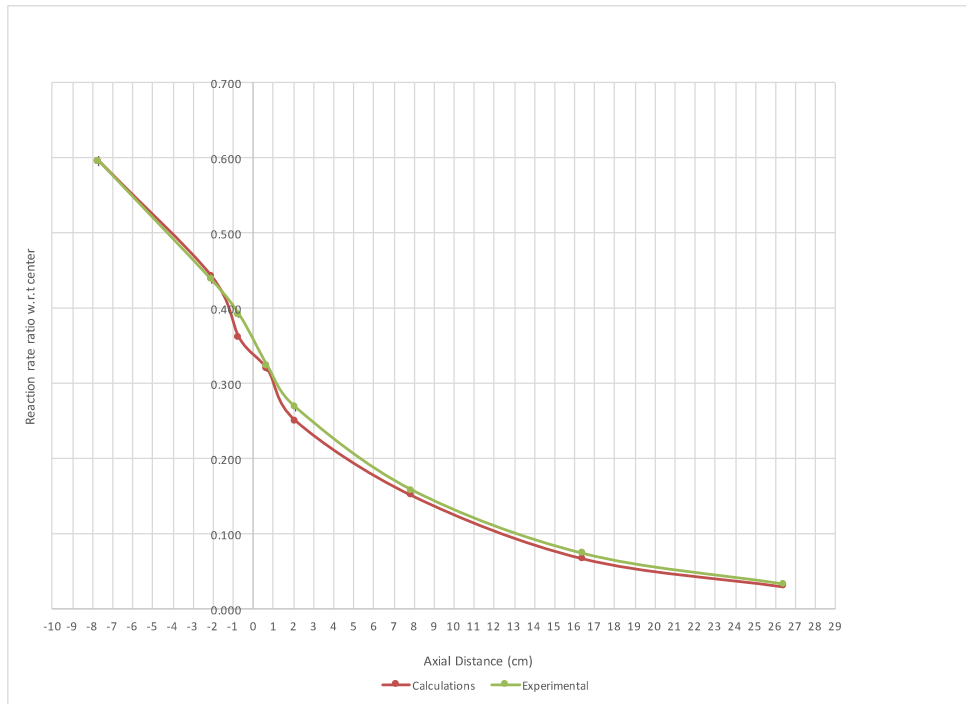


Figure 15. Fission of U^{238} along center axis.

GCFR-PROTEUS Core 12:

Error Analysis:

Error Analysis for core 12 was completed and evaluated for relevant reaction ratios.

Summaries for the typical PROTEUS-GCFR campaign systematic and statistical errors for the $(n,2n)2/c2$, $f2/f9$, $c2/f9$, and $f8/f9$ ratios are listed in 2 through

Table 5. A specific break down for the typical systematic/statistical components of the $(n,2n)_2/f_9$ ratio could not be found. Based on the error value ranges summarized in the previous sections and for other ratios, the error values listed in Table 6 were considered reasonable. Further information on the PROTEUS-GCFR measurement campaign can be found in references, [7], [6], [8], [9], and [10]. In Core 12, the uranium and plutonium reaction rates were measured in the central MOX fuel rod at the test zone center. The thorium reaction rates were measured in a thorium rod directly adjacent to the MOX rod at the center.

Table 2. Estimated Errors in Measurement of $(n,2n)_2/c_2$ ratio.

Source of error	Error ($\pm\%$)
<i>Systematic</i>	
1) Uncertainties in decay constants	0.3
2) Impurity corrections in α -counting of deposits	0.9
3) Relative self-absorption correction in γ -counting	1.5
4) Background subtraction in γ -counting	0.5
5) Foil self-shielding effects	0.2
Net systematic error	1.9
<i>Statistical</i>	
1) α -counting of deposits	0.4
2) γ -counting of deposits	0.9
3) γ -counting of foil	0.2
Net statistical error	1.6
Total Error	2.5

Table 3. Estimated Errors in Measurement of c_2/f_9 .

Source of error	Error ($\pm\%$)
<i>Systematic</i>	
1) Thermal Spectrum, Cross sections	1.2
2) Discriminator bias	0.5
3) Foil self-shielding effects	0.4
Net systematic error	1.4
Net statistical error	1.0
Total Error	1.7

Table 4. Estimated Error in Measurement of f_2/f_9 .

Source of error	Error ($\pm\%$)
<i>Systematic</i>	
1) Calibration of Th-deposits	0.7
2) Discriminator correction for ThF ₄ deposit	0.5
3) Selfabsorption	0.7
4) Neutron spectrum perturbations	0.5

5) Calibration of Pu-deposits	0.4
6) Discriminator correction for Pu deposit	0.4
Net systematic error	1.4
Net statistical error	1.0
Total Error	1.7

Table 5. Estimated Errors in Measurement of f_8/f_9 Ratio.

Source of error	Error ($\pm\%$)
<u>Systematic</u>	
1) Thermal cross sections	0.45
2) Thermal spectrum	1.00
3) Fission chamber calibration experiments:	
---discriminator bias	0.35
---non-escape of fission products	0.20
Presence of impurities	0.06
4) Fission product gamma counting	
---flux perturbation in lattice	0.18
---decay during a counting cycle	0.30
Net systematic error	1.22
<u>Statistical</u>	
1) Fission chamber experiment	
---Lattice	0.16
---Thermal column	0.24
2) Fission product γ -counting	
---Lattice	0.20
---Thermal column	0.38
---Background subtraction	0.12
Net statistical error	0.79
Total Error	1.4

It is important to note that the summaries of error sources in the measurements (Table 2 through

Table) were obtained from measurements performed at different time periods throughout the Core 12 series and is provided in this document to serve as an example for Core 12. They are complete to the fullest extent of the available documentation. The specific uncertainties obtained for the specific measurement results used in this benchmark are listed in Table .

Table 6. Experimental Results at the Center of Core 12.

Ratio	Experiment	Error
c8/f9	1.420E-01	1.420E-03(1.0%)
f8/f9	2.524E-02	4.291E-04(1.7%)
c2/f9	1.802E-01	3.063E-03(1.7%)
f2/f9	6.271E-03	1.066E-04(1.7%)
(n,2n)2/f9	9.660E-04	4.830E-05(5.0%)
(n,2n)2/c2	5.360E-03	2.787E-04(5.2%)

Spectral Data Library Influences:

Monte Carlo calculations were previously performed with 3030 generations with 500,000 neutrons per generation. The spectral indices estimations were based on 30 skipped generations and a total of 1,500,000,000 neutron histories. The data was evaluated for various evaluated data libraries.

The neutron capture rates were measured in ²³⁸U (c8) and ²³²Th (c2). The fission rates were obtained in ²³⁸U (f8), ²³²Th (f2), and ²³⁹Pu (f9). Finally, the (n,2n) reaction in ²³²Th ((n,2n)2) was measured. All experimental values were reported as ratios with the f9 (i.e. c8/f9) being the denominator for all ratios except the ((n,2n)2) ratio which featured the c2 reaction rate in the denominator ((n,2n)2/c2).

Comparing the MCNP results to the measured values, the difference was found to be within 1 σ uncertainty for c8/f9. The ratios c8/f9, f2/f9 and (n, 2n)2/c2 were within 2 σ . Assuming that the model reasonably represents the flux in the PROTEUS system – which is confirmed by the very good agreement of the typical spectral indices like c8/f9 and f8/f9, attention must be turned to the cross-section library to help identify why the ratios c2/f9 and (n,2n)2/c2 are almost 3 σ different from the experimental values. To do so, the Core 12 input deck was rerun with 5 additional libraries including: ENDF/B-VII.0, JEFF-3.1, JEFF-3.1.1, JEFF-3.2, and JENDL-4.0. All spectral indices were derived, allowing to also check the more typical spectral indices like c8/f9 and f8/f9, and the results are displayed in Figure 1 for easier comparison.

With regards to spectral indices, perturbations in the fuel should yield the most significant change in the model values at the center of the core. It was shown that materials outside the test zone had relatively little effect. Besides the fuel, only a strong absorber or reflector would achieve a significant change in the spectral indices in the center of the core. Neither of which is present in the test lattice. Therefore, it is assumed that simplifications in the model would induce no statistically significant bias in the results.

Since, the Core 12 configuration was primarily focused on spectral indices, simplifications were made to parts of the model (i.e. simplified geometry or material compositions). If evaluations of reaction rates or spectral indices outside of the core center were desired, a higher degree of scrutiny would be needed for the components in the periphery of the test zone.

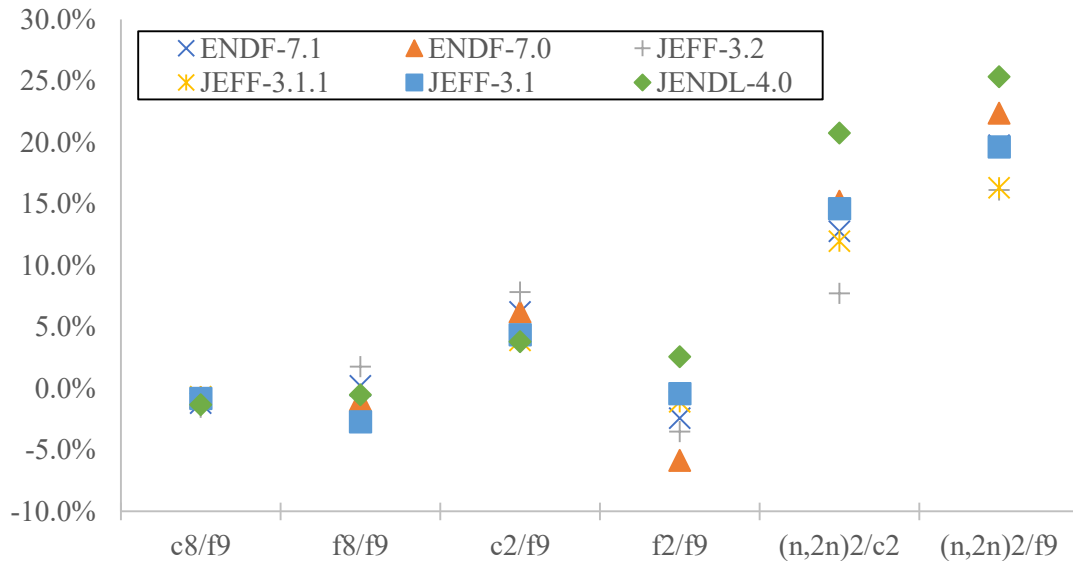


Figure 16. Comparison of Spectral Indices for all Cross-Section Libraries to Benchmark Values.

GCFR-PROTEUS Core 15:

MOX Fuel Isotopes

A lot of analysis was dedicated to the MOX fuel characteristics, this was motivated by a lack of reported uncertainty of MOX fuel isotope concentrations. A double-sided perturbation was performed in which the isotope concentrations of ^{235}U , ^{240}Pu , ^{241}Pu , and ^{242}Pu in the MOX fuel in all 1984 fuel rods was perturbed individually in order to estimate the uncertainty in all spectral indices ratios due to the uncertainty in the MOX fuel isotope concentration. When the ^{235}U concentration was perturbed, the ^{238}U was inversely changed. The concentration of ^{239}Pu was also changed to accommodate the perturbations in the other plutonium isotopes. For each isotope perturbation, half the difference between the calculated upper and lower perturbation values was determined to be the 1σ uncertainty. The perturbation amounts and their associated results are reported in Table Error! No text of specified style in document..

Table Error! No text of specified style in document.. Effect of Uncertainty in MOX Fuel Isotope Composition.

The U-235 was varied by ~0.17 wt.% and was scaled by a factor of 1/10 (~0.017 wt.%). The wt.% of U-238 was change to accommodate the change in U-235	Ratio	Δ (Δ/MEAN)	1σ (σ/Δ)
	c8/f9	1.343E-04 (0.085%)	2.624E-04 (195.4%)
	f8/f9	8.207E-06 (0.043%)	6.086E-06 (74.1%)
	c2/f9	1.370E-05 (0.009%)	2.665E-05 (194.6%)
	f2/f9	2.117E-06 (0.046%)	1.523E-06 (72.0%)
	(n,2n)2/c2	2.238E-06 (0.037%)	1.288E-05 (575.8%)
	f3/f9	1.061E-03 (0.069%)	3.980E-04 (37.5%)
	c8/f9	3.173E-04 (0.201%)	3.413E-04 (107.5%)

The Pu-240 was varied by ~1.7 wt.% and was scaled by a factor of 1/10 (~0.17 wt.%). The wt.% of Pu-239 was change to accommodate the change in Pu-240	f8/f9	1.167E-05 (0.061%)	6.031E-06 (51.7%)
	c2/f9	2.725E-05 (0.018%)	2.575E-05 (94.5%)
	f2/f9	2.358E-06 (0.052%)	1.512E-06 (64.1%)
	(n,2n)2/c2	7.594E-06 (0.126%)	1.323E-05 (174.2%)
	f3/f9	3.375E-04 (0.022%)	3.981E-04 (117.9%)
The Pu-241 was varied by ~0.17 wt.% and was scaled by a factor of 1/10 (~0.017 wt.%). The wt.% of Pu-239 was change to accommodate the change in Pu-241	c8/f9	2.015E-04 (0.128%)	1.912E-04 (94.9%)
	f8/f9	1.022E-05 (0.054%)	5.947E-06 (58.2%)
	c2/f9	1.455E-05 (0.010%)	2.428E-05 (166.9%)
	f2/f9	2.262E-06 (0.050%)	1.490E-06 (65.9%)
	(n,2n)2/c2	1.121E-05 (0.186%)	1.305E-05 (116.5%)
	f3/f9	2.217E-04 (0.014%)	3.932E-04 (177.3%)
The Pu-242 was varied by ~0.17 wt.% and was scaled by a factor of 1/10 (~0.017 wt.%). The wt.% of Pu-239 was change to accommodate the change in Pu-242	c8/f9	3.570E-04 (0.227%)	1.667E-04 (46.7%)
	f8/f9	3.462E-06 (0.018%)	5.901E-06 (170.4%)
	c2/f9	3.221E-05 (0.021%)	2.405E-05 (74.7%)
	f2/f9	1.276E-06 (0.028%)	1.467E-06 (115.0%)
	(n,2n)2/c2	1.943E-05 (0.323%)	1.278E-05 (65.8%)
	f3/f9	3.898E-04 (0.025%)	4.074E-04 (104.5%)

MOX Fuel Stoichiometry

Sintered pellets from 42 main production batches and 25 recycled batches were analyzed for the oxygen to heavy metal ratio. The analysis yielded an average ratio of 2.0 ± 0.01 . A double-sided perturbation was performed in which the ratio of oxygen to heavy metal was perturbed by ± 0.5 in order to estimate the uncertainty in all spectral indices ratios due to the uncertainty in MOX fuel stoichiometry. Half the difference between the calculated upper and lower perturbation values was then scaled to obtain the 1σ uncertainty. The results are reported in Table Error! No text of specified style in document..

Table Error! No text of specified style in document.. Effect of Uncertainty in MOX Fuel Stoichiometry.

	Ratio	Δ (Δ /MEAN)	1σ (σ / Δ)
The ratio of oxygen to heavy metal was varied by ± 0.5 and was scaled by a factor of 1/50 (± 0.01)	c8/f9	3.414E-05 (0.022%)	4.987E-05 (146.1%)
	f8/f9	1.011E-05 (0.053%)	1.218E-06 (12.1%)
	c2/f9	7.216E-05 (0.048%)	5.472E-06 (7.6%)
	f2/f9	2.472E-06 (0.054%)	3.045E-07 (12.3%)
	(n,2n)2/c2	6.830E-06 (0.113%)	2.580E-06 (37.8%)
	f3/f9	1.311E-04 (14.388%)	8.028E-05 (61.2%)

Results of Spectral-Characteristic Calculations

Comparing the MCNP results to the measured values, the difference was found to be within 1σ uncertainty for $c8/f9$, $c2/f9$, $(n,2n)2/c2$, and $f3/f9$. The ratios $f8/f9$ and $f2/f9$ were within 2σ . The Core 15 input deck was rerun with 5 additional libraries including: ENDF/B-VII.0, JEFF-3.1, JEFF-3.1.1, JEFF-3.2, and JENDL-4.0. This was done to allow for the comparison and evaluation of the different cross section libraries. Using the benchmark model with each of these cross section libraries, each of the spectral indices was derived, and a sample result is displayed in **Error! Reference source not found.** Figure 17 graphically depicts the results for easier comparison.

With regards to spectral indices, perturbations in the fuel should yield the most significant change in the model values at the center of the core. It was shown that materials outside the test zone had relatively little effect. Besides the fuel, only a strong absorber or reflector would achieve a significant change in the spectral indices in the center of the core. Neither of which is present in the test lattice. Therefore, it is assumed that simplifications in the model would induce no statistically significant bias in the results.

Since, the Core 15 configuration was primarily focused on spectral indices, simplifications were made to parts of the model (i.e. simplified geometry or material compositions). If evaluations of reaction rates or spectral indices outside of the core center were desired, a higher degree of scrutiny would be needed for the components in the periphery of the test zone.

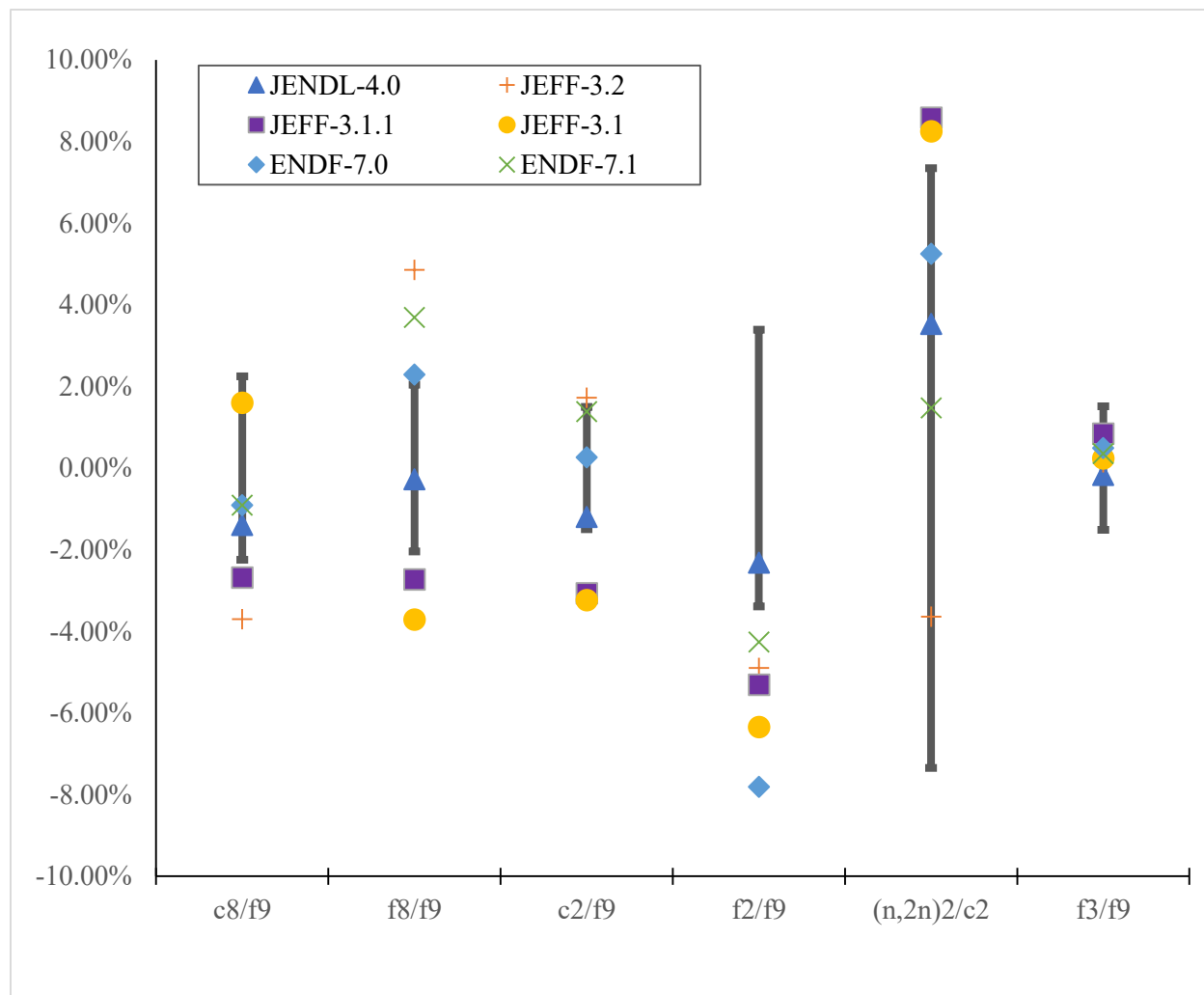


Figure 17. Comparison of Spectral Indices for all Cross-Section Libraries to Benchmark Values. 1 sigma bounds are denoted by the thick bars.

Table 9. Calculated and Benchmark Model Spectral Indices (ENDF-7.1).

Spectral Indices	Calculated (MCNP6) Value	Benchmark Value	(C/E)-1 ^(a)
c8/f9	0.157 ± 0.01610	0.158 ± 0.00355	-0.91% ± 1.65%
f8/f9	0.0191 ± 0.00439	0.018 ± 0.00038	3.69% ± 0.44%
c2/f9	0.152 ± 0.00222	0.150 ± 0.00225	1.38% ± 0.32%
f2/f9	0.00455 ± 0.00466	0.00475 ± 0.00016	-4.26% ± 0.47%
(n,2n)2/c2	0.0057 ± 0.03150	0.00565 ± 0.00042	1.47% ± 3.15%
f3/f9	1.540 ± 0.00358	1.540 ± 0.02330	0.35% ± 2.36%

(a) C= calculated (MCNP6) values and E= benchmark values

PRODUCTS:

Publications:

Thesis:

EVALUATION OF NUCLEAR DATA LIBRARIES THROUGH GCFR-PROTEUS BENCHMARKING,

Ph.D.Thesis in partial fulfillment of Ph.D.

Manuscript in preparation:

VALIDATION OF NUCLEAR DATA LIBRARIES THROUGH GCFR-PROTEUS BENCHMARKING, Gareth Newman, James Totten, et al.

CHANGES/PROBLEMS:

Per recent approval from DOE/NEUP the principal investigator have changed from Dr. Kelly Jordan to Dr. Andreas Enqvist. All other involve personnel have stayed the same.

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