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Experiments Past for Problems Present

More than a hundred zero power reactor (ZPR) critical assemblies were constructed, over a period of about three decades, at the Argonne National Laboratory ZPR-3, ZPR-6, ZPR-9 and ZPPR fast critical assembly facilities. To be sure, the original reason for performing these critical experiments was to support fast reactor development. Nevertheless, data from some of the assemblies are well suited to form the basis for valuable, new criticality safety benchmarks. The purpose of this paper is to describe the ZPR data that would be of benefit to the criticality safety community and to explain how these data could be developed into practical criticality safety benchmarks.

Of the three classes of ZPR assemblies, engineering mockups, engineering benchmarks and physics benchmarks, the physics benchmarks tend to be most useful for criticality safety. Because physics benchmarks were designed to test fast reactor physics data and methods, they were as simple as possible in geometry and composition. The principal fissile species was ^{235}U and/or ^{239}Pu. Fuel enrichments ranged from 9% to 95%. Often there were only one or two main core diluent materials, such as aluminum, graphite, iron, sodium or stainless steel. The cores were reflected (and totally insulated from room return effects) by one or two layers of materials such as depleted uranium, lead or stainless steel. Despite their more complex nature, a small number of assemblies from the other two classes would make useful criticality safety benchmarks because they have features related to criticality safety issues, such as reflection by soil-like material.

How It Was Done

Criticality, the simplest and most direct integral measurement, was always measured with high precision, [1]. Essentially, it consisted of specifying the contents and conditions of the "as-built" configuration. The inverse count rate was monitored in the approach to critical. The excess reactivity of slightly supercritical configurations was determined by the positive period technique or using calibrated control rods. The reactivity of slightly subcritical configurations was determined by rod drop or source jerk inverse kinetics methods. Near-critical configurations were generally within 0.2% Δk

of unity. Measurements were made for such things as temperature and matrix interface gap adjustments to criticality. All the uncertainty contributions are small. The largest source of uncertainty generally was the mass and compositions of the plate materials making up the assembly. The total criticality measurement uncertainty typically is less than 0.1% Δk.

In a few instances, a configuration of particular interest may only be available in a loading that was subcritical by as much as a few dollars. High precision subcritical source multiplication measurements were made on these configurations, [2]. Typically, between 16 and 64 in-core fission chambers were used, and corrections were made for changes in detector efficiency and source importance. The measurements were calibrated using a slightly subcritical reference configuration. The total uncertainty is at most 2% for any level of subcriticality.

In addition to criticality, an experimental campaign also typically included measurements of numerous other integral quantities. The quantities measured often included reaction rate ratios, reaction rate distributions, kinetics parameters, neutron spectrum, small-sample worth distributions, control rod worths, coolant voiding worth, and ^{238}U Doppler worth. At least some of these data would have diagnostic value in a criticality assessment; they could help identify root causes of criticality mispredictions or they could help in an assessment of whether good accuracy of a criticality prediction was fortuitous. These supplemental data can be applied using a data adjustment formalism, as described below.

The Making of a Benchmark

The as-built ZPR critical assemblies are much too complicated to serve directly as criticality safety benchmarks. Even the simplest ZPR assembly had far more geometric detail than well known Los Alamos benchmark fast critical assemblies such as Godiva, [3]. An XY (radial) slice through a simple assembly is depicted in Fig. 1. Each box represents a 5.5-cm square matrix tube containing a plate-loaded drawer. A drawer is loaded in each half of the matrix, which is split at the axial midplane. An axial segment of a matrix tube with its loaded drawer constitutes a unit cell. The XY cross section of such a cell is shown in Fig. 2. The columns in Fig. 2 are 5.1-cm-tall plates of the various materials that comprise a reactor region. There were always complications introduced by in-core instrumentation and operational control rods, no matter how basic the assembly loading.

Standard analysis of critical experiments employed a sophisticated deterministic calculational scheme developed over many years to deal with plate cell heterogeneity, neutron streaming and three-dimensional issues, [4]. A version of this analysis scheme was used to derive simple benchmarks for the Cross Section Evaluation Working Group (CSEWG), [5]. These benchmarks were composed of a few homogeneous regions with smooth boundaries, eliminating the difficult analysis issues associated with plate critical assemblies. However, if a realistic uncertainty is assigned to the calculated conversion between the as-built assembly and the simple benchmark, the total uncertainty in the criticality of the benchmark is much larger than the uncertainty in the original criticality measurement.

A more accurate approach is now available to define the criticality safety benchmarks from ZPR experiments. Benchmarks can be derived from as-built critical configurations using continuous energy Monte Carlo. Monte Carlo models of the as-built configuration and the simplified benchmark configuration would be generated. The measured eigenvalue would be adjusted by the difference between the eigenvalues of the two models. The fully detailed models would be created using the BLDVIM code, which was developed in the last years of ZPPR operation. BLDVIM reads the assembly description on the ZPPR computer database and prepares the model input to the VIM continuous energy Monte Carlo code. BLDVIM yields a high fidelity, quality assured model, and makes quite tractable a task that would take months of effort to do by hand for even a single loading. The VIM code has a geometry option designed to be computationally efficient for plate critical assemblies. VIM accuracy has been proven through many years of use in conjunction with the analysis of ZPR critical experiments and with British and Los Alamos benchmarks. The features that are difficult to deal with deterministically (e.g., plate heterogeneity) are no problem for continuous energy Monte Carlo. Thus, the adjusted eigenvalue of the benchmark model would be very accurate; a total uncertainty on the order of 0.2% Δk is expected with this approach, which is much better than the ≈0.5% Δk accuracy of the ZPR CSEWG benchmarks. To minimize the Monte Carlo extrapolation of the experimental data, the benchmark model should deviate as little as practical from the exact model and, at the same time, be easily calculable by a variety of standard criticality safety codes. The viability of this approach has already been demonstrated by its application to ZPPR Assembly 21, [6], the last of the plate critical assemblies and the only one dedicated specifically to criticality safety.

Meet the Candidates

Many of the assemblies that would add significantly to the criticality safety database are listed in Table I. The assemblies are identified by facility and assembly number, e.g., ZPR-9/34 is Assembly 34 at the ZPR-9 facility. Brief sketches of some features of each assembly are included in Table I. In general, complicated assemblies were excluded unless they had some important and unusual characteristic. Three characteristics were used in the selection of assemblies: 1) a simple core composition that could help identify problems with neutron cross section data, 2) a variation of reflector material, again with concern about cross section data problems, and 3) a geometric feature related to difficulties in criticality safety calculations. Many of the candidates came from two series of diagnostic benchmark cores, the ZPR-3 plutonium-fueled benchmark series, [7], and the ZPR-6 and 9 Diagnostic Cores Program, [8].

Figures 3 shows plots of core neutron spectrum from three of the assemblies. It can be seen that there is a wide variation in energy range and emphasis.

Features of interest include the following:

- ZPR-9/35, also known as the U9 benchmark, had a simple geometry and the simplest composition of any ZPR assembly. Except for the stainless steel (SS) matrix tubes and drawers, it consisted entirely of uranium - 9% homogenized enrichment in the core and depleted uranium metal (DU) reflectors.
- The alternating rings of blanket and core in ZPPR/13A bear some resemblance to a storage configuration with rows of fissile material separated by nonfissile material. The fuel composition was Pu-^{238}U oxide and the spectrum was moderately hard. ZPPR/12 had a core with a similar composition to that of ZPPR/13A but the core geometry was a simple cylinder, which should make a comparison between these two assemblies useful.
- ZPPR/8 is the only ZPR assembly that contained thorium. Some configurations of this engineering benchmark differed only by depleted uranium replacing thorium in some blanket regions.
- The ZPPR/15 configurations provide a comparison between ^{235}U and ^{239}Pu metal fuels in very similar critical configurations. The enrichment was 15-20% and the spectrum was moderately hard. The effect of replacing steel with zirconium can be deduced by comparing two of the configurations.
- Highly enriched U and ^{239}Pu can be compared using ZPR-3/14 and ZPR-3/58. Both of the cores had graphite as the principal diluent and had DU reflectors.

- Different diluents used with ^{239}Pu can be compared using ZPR-3/58, ZPR-3/54 and ZPR-6/10. Similarly, different simple diluent mixes used with highly enriched U can be compared using ZPR-9/34, ZPR-9/35, ZPR-3/14 and ZPR-3/23.
- ZPPR/21 was constructed specifically to address criticality safety for Argonne's Fuel Conditioning Facility. Both ^{235}U and ^{239}Pu metal fuels were mocked up. The enrichment was 50-60% and the spectrum was hard.
- The effects of different reflector material can be evaluated using several of these cases. ZPR-3/53 and ZPR-3/54 were the same except for DU and SS reflection, respectively. Similarly, ZPR-3/58 and ZPR-3/59 differed only by DU vs. Pb reflection. Variants of ZPPR/12 differed by use of DU vs. depleted uranium oxide for the reflectors. ZPPR/20 had variants with different reflecting materials including sand (SiO_2), which could be of particular interest for waste burial.

A good example of the relevance of these assemblies to the criticality safety community is ZPR-9/34, the Uranium/Iron Benchmark. An article in a recent issue of the Criticality Safety Quarterly[1] describes an investigation of large discrepancies among criticality predictions for simple metal/^{235}U systems. The article states, incorrectly, "there are no experiments that adequately represent the characteristics of these metal/^{235}U systems, and so the ability to predict the 'correct' critical configuration is not known." In fact, the Uranium/Iron Benchmark, which was built in 1980, is closely related to the iron/^{235}U system described in the article, since it was a critical assembly composed predominantly of iron and 93% enriched uranium. Furthermore, the problems with treatment of resonance cross section behavior in the neutron cross sections of iron and other structural materials uncovered in the investigation were discovered previously, in connection with analysis of the Uranium/Iron Benchmark.[2] There is other information from ZPR experiments that is relevant to this investigation, including the aluminum/uranium critical assembly ZPR-3/23, and code comparisons for model problems inspired by ZPR critical assemblies.

Putting It All Together - Data Adjustment

In addition to physics measurements directly relevant to criticality safety, there exists an extensive database of supporting measurements and calculations resulting from decades of fast reactor research conducted at the ZPRs, as well as independent data from Los Alamos National Laboratory and the United Kingdom. This database currently contains over 250 integral measurements of parameters such as k-eff, control rod worths, boron worths, and reaction rate ratios. The supplementary database contains a wealth of information that can be used to validate and extrapolate measurements of primary concern.

The full potential of the database is realized through the use of formal data fitting procedures incorporated in the GMADJ (Gauss-Markov Adjustment) code, [9]. GMADJ employs a generalized least-squares fitting procedure that combines information contained in the integral measurements with the pre-evaluated data library via sensitivity coefficients. The system is overdetermined and a best (minimum variance, unbiased) estimate of any integral parameter is obtained. The procedure also makes use of covariances associated with both integral and differential data.

Use of the supplementary database by way of the GMADJ procedure provides several powerful capabilities. This procedure has proven effective, [10], as a consistency check for experimental data as well as a means of validating experimental techniques. For example, performing the least-squares fit using independent data immediately points to measurements or calculations that are inconsistent with the rest of the database, therefore providing an effective layer of quality control. GMADJ also supplies biases and uncertainties of parameters not directly measurable (for both supplementary data and data of primary concern), thus effectively extending the knowledge from a given experiment. One aspect of the data fitting procedure which may be particularly useful for criticality analyses is the ability to predict biases and uncertainties relating to systems for which no measurements exist. This is accomplished by extrapolating the existing database via sensitivity coefficients. GMADJ also produces a set of correlation coefficients after fitting which provides information on the relevance of a measurement in one system to a measurement in another system, making GMADJ a useful tool for correlation analyses. The ability to use all available physics information via the GMADJ least-squares fitting procedure compliments the directly relevant measurements and enhances any criticality data analysis.

Making it Happen

Some effort would be needed to confirm that all the selected experiments are free from significant flaws. In the last 20 years of operation, care was taken to make sure that room return effects were totally negligible. However, this could be an issue for two of the older assemblies, ZPR-3/54 and ZPR-3/59. Since all the ZPR-3 experiments are quite old, the data from them would have to be scrutinized carefully.

Many of the selected assemblies are not on the ZPPR computer database but their descriptions could be entered from hard-copy archival records. This would involve transcribing drawer master and matrix loading documents. The plate description library currently covers most of the materials but a few plate types would have to be added. Once the computer database is expanded, all the cases could be processed using the proposed modeling scheme.

The capability to process the data cannot be assured far into the future. The last Argonne critical facility, ZPPR, ceased operation several years ago. Its personnel have dispersed throughout the laboratory and beyond. The only computer on which the ZPPR relational database can be used is increasingly subject to breakdowns. Moreover, the programmatic funding source (IFR Program) that provided the funds to maintain ZPPR in a non-operational standby state has been terminated.

Criticality safety benchmarks from ZPR fast neutron critical assembly experiments would significantly broaden the scope of the benchmark database and thus provide a valuable contribution in the increasingly important study of criticality safety. The wealth of criticality data that heretofore has been largely inaccessible to the criticality safety community could be used to test criticality safety tools and cross section data. The data adjustment formalism offers a way to apply the data to unmeasured configurations and estimate the uncertainty in the criticality predictions.

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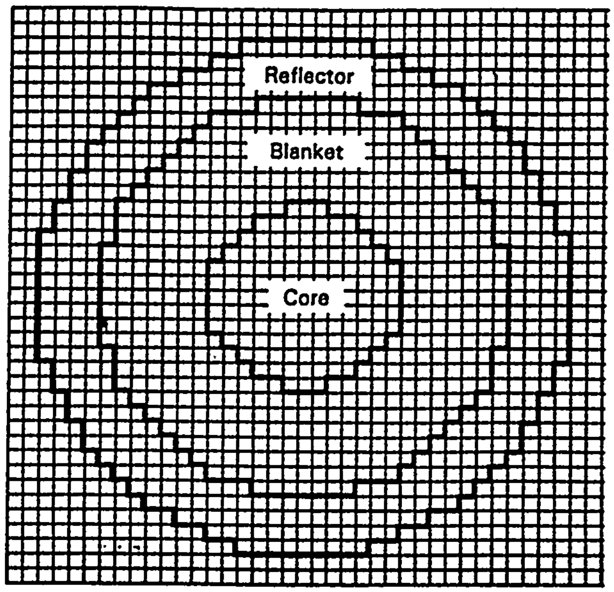

Fig. 1. ZPPR/12 Assembly Interface Diagram

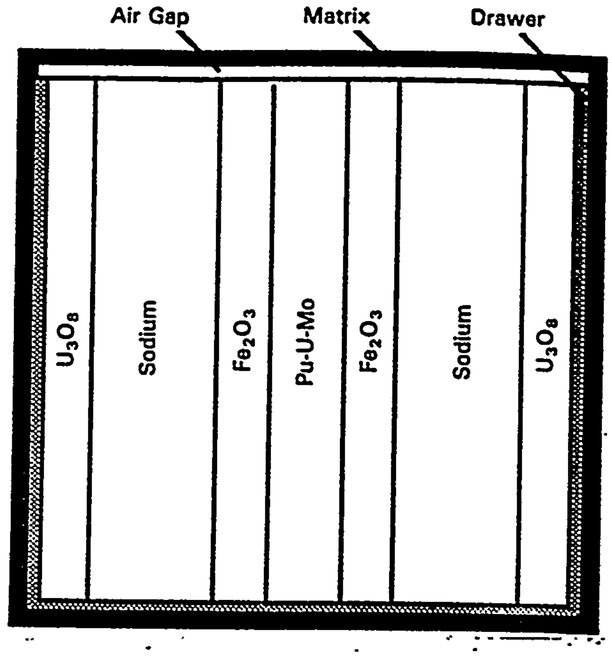

Fig. 2. Typical Core Unit Cell

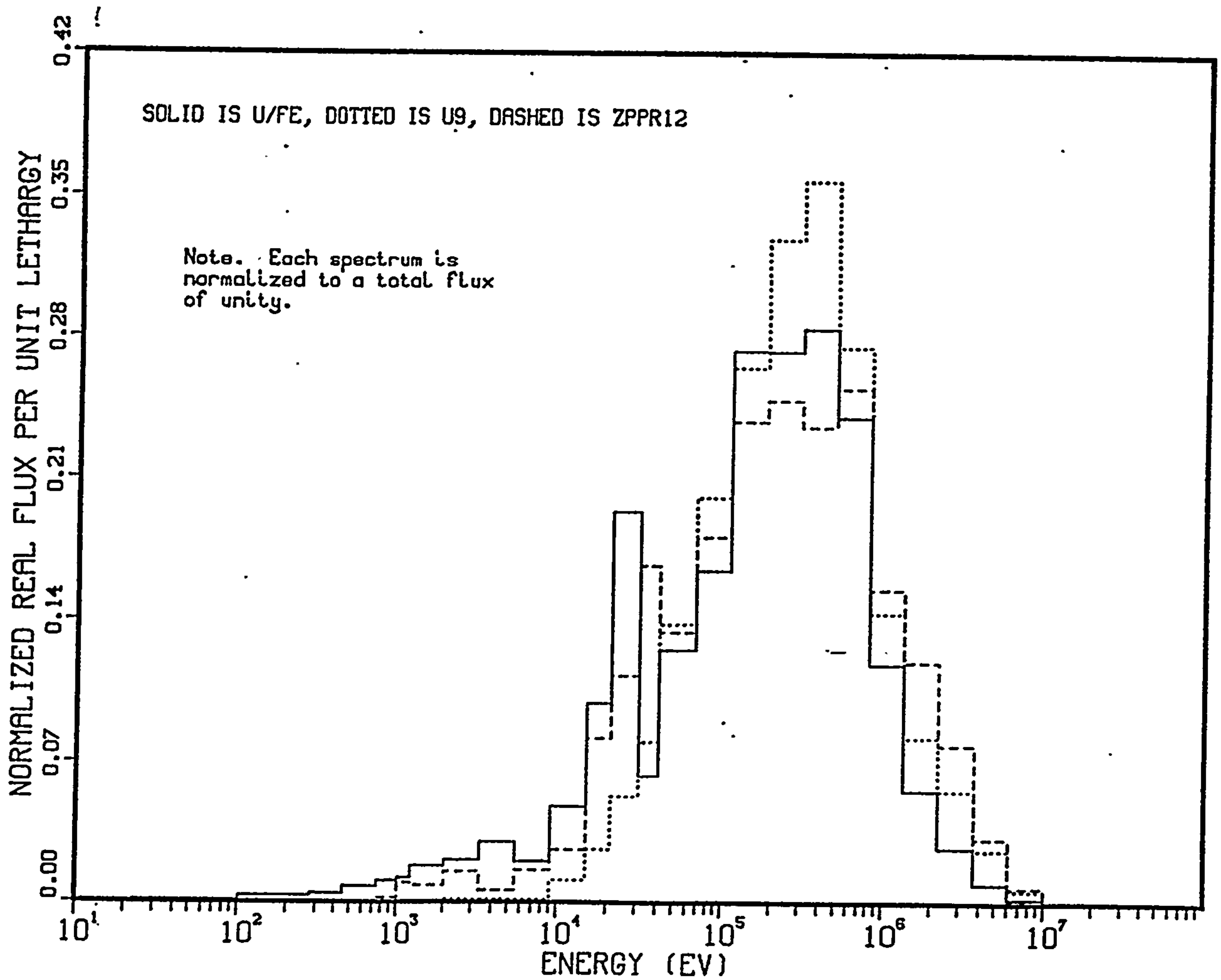

Fig. 3. Comparison of Core Neutron Spectra From Three ZPR Assemblies

Table I. ZPR Assemblies Useful For Criticality Safety

Assembly	Attributes
ZPR-9/35	All-U core and reflectors; 9% enriched core; hard, narrow spectrum.
ZPR-9/34	Core: 93% enriched U, Fe diluent; SS reflectors; broad spectrum.
ZPR-3/23	Core: 93% enriched U, Al diluent; DU reflectors.
ZPR-3/14	Core: 93% enriched U, C diluent; DU reflectors.
ZPR-6/10	Core: ^{239}Pu, C and SS diluents; SS reflectors. Soft, broad spectrum.
ZPR-3/53	Core: ^{239}Pu, C and DU diluents; DU reflectors.
ZPR-3/54	Core: ^{239}Pu, C and DU diluents; SS reflectors.
ZPR-3/58	Core: ^{239}Pu, C diluent; DU reflectors.
ZPR-3/59	Core: ^{239}Pu, C diluent; Pb reflectors.
ZPPR/8	Radially heterogeneous Pu oxide LMFBR; U vs. Th in blankets.
ZPPR/12	Pu oxide LMFBR comp. but simple geometry core; DU vs U_3O_8 blankets.
ZPPR/13A	Core comp. similar to ZPPR/12 but alternating annular rings of core and blanket.
ZPPR/15	Metal-fuel LMFBR comp.; ^{239}Pu vs. ^{235}U fissile; Zr vs. SS in a zone.
ZPPR/20	Core: ^{235}U with Li, Nb, Re; compare reflection by BeO, CH_2, SiO_2.
ZPPR/21	Compare ^{235}U vs. ^{239}Pu fissile; Zr, SS & DU diluents; C reflectors.