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MEASUREMENTS IN LOS ALAMOS BENCHMARK CRITICALS AND THE CENTRAL REACTIVITY DISCREPANCY

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ABSTRACT

Measurements in seven Los Alamos fast critical facilities are described; all are related to elucidating the causes of the central reactivity discrepancy in fast reactors. Specific capabilities of these specialized assemblies permit measurements well-above delayed critical and these confirm the validity of the delayed neutron data used for calibration; there is therefore no reactivity-scale error. Reactivity measurements in these homogeneous assemblies exhibit no discrepancy. It is concluded that nuclear data should not be adjusted to eliminate the discrepancy found in other, heterogeneous assemblies.

1. Nature and Significance of the Reactivity Discrepancy

"Central reactivity discrepancy" is the term used for the inability to calculate the reactivity worth of fissile, (^{233}U, ^{235}U, ^{239}Pu), fertile (^{238}U, ^{232}Th), control rod (^{10}B, Ta), and other materials in fast critical assemblies constructed of these materials when the same nuclear data give good predictions of critical mass. For a wide range of critical assemblies the calculated reactivities are systematically larger than measured and the average discrepancy is commonly in the range of 10% to 30%. This phenomenon was probably first noted by Codd[1] in the UKAEA but did not receive wide recognition until the work of Little and Hardie[2] in the U.S.A. A more recent, extensive, study which describes the situation well is that of Bohn et al.[3] They found an average ratio of calculated to measured worth of 1.14 (with σ = 0.19) for ^{235}U-fueled systems and 1.22 (with σ = 0.17) in plutonium-fueled systems.

The great significance of the discrepancy from a reactor designer's viewpoint is the conservatism, and therefore penalty, that he must consequently introduce in a power reactor design. To illustrate, if in a hypothetical accident a negative reactivity change due to the Doppler effect in ^{238}U will compensate for a positive change due to sodium voiding there are strong incentives to assume the largest positive and the smallest negative change whether these are based on experiment or calculation.

2. Possible Causes

2.1 Reactivity Scale and Delayed Neutron Fraction

The approximately constant nature of the discrepancy immediately suggested the possibility of a systematic error in the reactivity scale of the measurements as the principal cause. This is because essentially all reactivities are determined, directly or indirectly, with reference to the same sets of delayed neutron parameters; this involves determining the time-dependence of the reactor flux following a reactivity change and calculating the reactivity using the asymptotic period and the microscopic delayed neutron data. Some limited success has resulted from further study of delayed neutrons, in particular the work of Evans, Thorpe, and Krick[4] at Los Alamos, but the discrepancies were not eliminated.

A much more direct check is to measure not only reactor periods (and relate them to microscopic delayed neutron data) but also the actual mass difference between delayed and prompt criticality; this is directly attributable only to the effective delayed neutron fraction, β_{eff}, and thus the absolute yields are tested as well as the relative yields. For any unambiguous, accurate, measurement, experiments must be carried well above delayed critical and this is only apparently feasible with the remotely-operated, specialized facilities at Los Alamos because of the possible hazards. Typically, defining β_{eff} as one dollar ($1) or 100 cents (100¢), experiments are carried out up to 80¢ above delayed critical by rapid physical assembly and dis-assembly of the critical assemblies.

2.2 Computational Techniques for Heterogeneous Assemblies

Almost all measurements in which the central reactivity discrepancy has been found have been made in assemblies which were necessarily constructed using fissile, fertile, and other materials in the form of discrete plates assembled in a steel, supportive, matrix. This heterogeneous geometry presents considerable, and sometimes extreme, computational difficulties which lessens confidence in the accuracy to which the calculated parameter is truly comparable to the measured value. Furthermore, simple geometrical

core configurations such as cylinders and spheres must be approximated using finite-sized component plates and the boundaries between regions are not only heterogeneous but also irregular.

The ... physically-homogeneous assemblies with regular boundaries i... nomically-feasible only for specialized applications and h... n limited almost entirely to physically-small and hence hard-sp... m systems, mostly at Los Alamos. The applicability of c... sions in hard-spectra to the soft-spectra cases has been quest...ed and recently these measurements have been extended to include a much softer spectrum system, Big 10.

2.3 Cross Sections

Clearly cross section uncertainties do contribute to deviations of the ratio of calculated and experimental reactivities from unity. This will undoubtedly increase the variation in the ratio but a systematic average deviation from unity must be attributed to one or more common sources of error; this is not impossible since, for example, a given cross section may be used for extensive normalization but is not a likely possibility.

Nevertheless there is a natural inclination by nuclear data measurers and more so by evaluators to favor data which reduce the discrepancy and reactor designers are not reluctant to modify microscopic data in subtle or non-subtle ways. The result is that data files which appear to be based completely upon objective evaluations of basic nuclear data are not necessarily free from prejudice based upon the existence of the central reactivity discrepancy.

3. Los Alamos Measurements

3.1 Description of the Assemblies and Critical Sizes

Extensive measurements have been made in seven assemblies of simple geometry; three unreflected spheres fueled with ^{235}U (Godiva), ^{233}U (Jezebel 23), and ^{239}Pu (Jezebel 49), three similarly fueled, ^{238}U-reflected spheres (Flattop 25, Flattop 23, and Flattop 49), and one ^{238}U reflected cylinder fueled with uranium with a 9/1 $^{238}U/^{235}U$ atom ratio (Big 10). The spherical systems are close to ideal geometry and the cores and reflectors are essentially homogeneous in composition. Big 10 has a homogeneous reflector and a truly homogeneous central cylindrical core region surrounded by a heterogeneous core region composed of plates of enriched and depleted uranium.

The core volumes, critical masses of the principal fissile isotope and calculated multiplication constant, k, for ENDF-IV cross sections are given in Table 1. It can be seen that there is the expected good ability to calculate k to within one-percent of unity with the exception of the ^{233}U cores.

3.2 Tests of the Reactivity Scale

Measurements of reactivity are usually made either by measuring the asymptotic period of the reactor when the sample is inserted or withdrawn or by the equivalent method of using a control rod calibrated by the period method to compensate for the sample movement. The delayed neutron group periods, their relative abundances, and the total delayed neutron fraction, β, must be known and effects of spatial variation of flux and differing delayed neutron worths due to energy differences must be included. If more than one fissioning species is present the separate contributions of delayed neutrons must be included and it is further necessary to know the relative fission rates in the species.

A different method involves the measurement of Rossi-a which

is the ratio of the reactivity of the system measured from prompt critical (Δk_p) and the prompt neutron lifetime (ℓ), $\alpha = \Delta k_p/\ell$. The prompt neutron lifetime is effectively constant with change in reactor reactivity unless this change is produced by such means as introducing a strong neutron absorber whose absorption cross section has an energy dependence differing greatly from that of the core material. This is measured by determining the time dependence of fissions in a single prompt fission chain and must be done at low reactor power to prevent excessive overlap of fission chains and consequent increased errors. An equivalent method is to measure the decay of a short pulse of neutron from an accelerator source. At delayed critical $\alpha = \beta_{eff}/\ell$. At prompt critical $\alpha = 0$.

A plot of α versus fissile mass will therefore extrapolate to the prompt critical mass and thus the actual mass difference corresponding to the delayed neutron fraction may be measured. Extrapolation to prompt criticality is clearly much more accurate if the prompt critical condition is approached and excellent data may be obtained at Los Alamos up to 80¢ above delayed critical because of the capability of rapid assembly and disassembly.

One further very important point is that if the reactivity change can be produced by addition or deletion of core material to a well-defined geometry system in a way which preserves a well-defined geometry, then the absolute reactivity change can be calculated with little ambiguity or uncertainty. For example if the mass increment to an unreflected spherical fast spectrum system is made in the form of a close-fitting spherical shell, the calculated reactivity change is only very slightly dependent upon the cross sections used; this idealized condition is closely approximated in practice by the addition of small "buttons" to the surface of Godiva or Jezebel systems. Equivalent changes can be made, with more difficulty, with cylindrical and reflected systems. It can be seen that such measurements are much more difficult and ambiguous in hetergeneous, ragged-boundary, systems assembled in most split-table machines.

There are three important tests that can be made with the above information. First, the absolute reactivity change deduced from the measured mass change between delayed and prompt critical should equal β_{eff}. Second, there should be a linear relationship between the plot of Rossi-α versus the absolute reactivity change (from the mass change). Third, there should be a linear relationship between the reactivity inferred from the delayed neutron data and the absolute reactivity change (or the Rossi-α).

Detailed measurements and analyses of this nature have been made for the spherical Los Alamos systems, both bare and reflected with ^{238}U, and preliminary studies have also been made with Big-10. The resulting measured β_{eff} values are compared with the data calculated from the Keepin and Wimett[5] delayed-neutron data in Table I. It can be seen that there is excellent agreement within the assigned errors of 2%. The accuracies of the assumed individual isotopic β_{eff} values are clearly thus about 2% for ^{233}U, ^{235}U, and ^{239}Pu (from the unreflected assemblies) and that of ^{238}U is confirmed to about 20% accuracy (from bare and ^{238}U reflected systems together).

Regarding the second and third tests, the predicted linearities are confirmed to within about 2% accuracy when using the Keepin and Wimett data.

The Big 10 results are still preliminary but to date the analyses confirm the conclusions reached with the other assemblies.

3.3 Central Reactivity Measurements in Homogeneous Cores

The results of measurements of the worths of the core compo-

sition sample are compared for all seven reactors with calculated values in Table II together with corresponding individual values for some principal isotopes.

The conclusion from Table II is clearly that there is no evidence of a systematic discrepancy such as that found in many other reactors. The major difference from these other reactors appears to be heterogeneity although there are clearly other differences such as the presence of steel in the supporting matrix.

4. Conclusions

First we must state unequivocally that we do not regard these studies as a benediction for any data set, including ENDF/B-IV since it is not likely that all measured and calculated data will be in good agreement. Furthermore, although Big 10 has extended the spectral range of our studies, large power reactors have appreciably softer spectra; they are also fueled with plutonium.

Nevertheless, with these caveats we find that

a) the measured mass difference between delayed and prompt critical is consistent with the Keepin and Wimett delayed neutron yields, including that for ^{238}U,

b) the shape of the Rossi α curve confirms the Keepin and Wimett period and relative abundance data, and

c) using ENDF-B IV cross sections the ratio of calculated and experimental reactivity worths is close to unity.

Although it cannot be regarded as completely proven it seems probable that the central reactivity discrepancy arises from some unknown features of heterogeneous assemblies--experimental, computational, or both.

Most importantly, although it is also not proven conclusively, it is not likely that nuclear data errors are the primary cause and these data should not be adjusted or used selectively in an attempt to resolve the discrepancy.

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TABLE I. Experimental and Calculated Multiplication Factors, k_{eff}, and Effective Delayed Neutron Fractions, β_{eff}.

Assembly	Core Volume (Liters)	Core Mass (kg)	k_{eff} Calculated	$\beta_{eff} \times 10^3$ Experimental	Keepin
Bare					
Godiva	2.79	49.1	1.009	6.63	6.64
Jezebel-23	0.90	16.2	0.967	2.93	2.82
Jezebel-49	1.09	16.0	1.002	1.98	1.95
U-Reflected					
Flattop-25	0.96	16.6	1.016	6.72	6.94
Flattop-23	0.31	5.6	0.985	3.43	3.55
Flattop-49	0.39	5.7	1.008	2.81	2.77
Big Ten	125	236	1.013	7.22	7.09

TABLE II. Ratio of Calculated and Experimental Central Reactivity Coefficients (C/E)

Assembly/Coefficient	^{233}U	^{235}U	^{239}Pu	^{238}U
Bare				
Godiva	not measured	1.00	1.00	0.99
Jezebel-49	0.96	1.04	1.00	0.93
U-Reflected				
Flattop-25	0.93	1.00	0.98	1.00
Big Ten	not measured	1.00	0.98	1.01