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Usefulness of k_{eff} Measurements in Validating Nuclear Cross Section Sets

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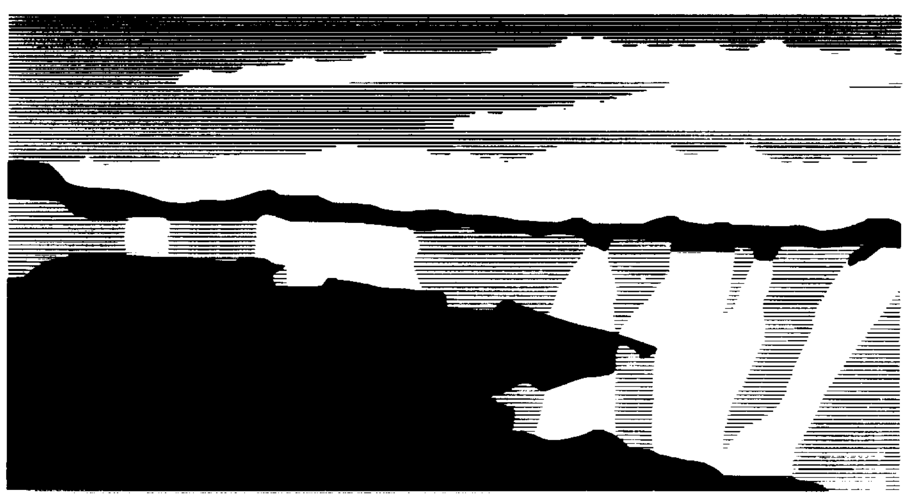

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USEFULNESS OF k_{eff} MEASUREMENTS IN VALIDATING NUCLEAR CROSS-SECTION SETS

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ABSTRACT

A k_{eff} measurement is a necessary and vital measurement, but by itself it is not sufficient to validate any cross-section set; to validate all aspects of a cross-section set, numerous integral and differential quantities such as k_{eff}, neutron lifetime, fission ratios, central reactivity worth, neutron and gamma-ray spectra, effective delayed neutron fraction, and others should also be measured.

For the last 50 or so years, the nuclear industry has been trying to validate nuclear cross-section sets largely by using k_{eff} measurements obtained from a wide variety of benchmark critical-mass experiments. However, benchmarking against k_{eff} is not as beneficial as one might hope because k_{eff} is merely the ratio of the neutron production rate to the neutron loss rate. That is,

$$k_{eff} = \frac{\int \Psi \chi_f \bar{\nu}_t \Sigma'_f \Phi' \; d\Omega' dE' d\Omega dE d\mathbf{r}}{\int \Psi \Omega \cdot \nabla \Phi \; d\Omega dE d\mathbf{r} + \int \Psi \Sigma_a \Phi \; d\Omega dE d\mathbf{r}} \quad .$$

As such, the absolute value of the cross-sections in any given library may be significantly in error and still yield reasonably accurate estimates of k_{eff} if the ratio of $\nu\Sigma_f/\Sigma_a$ is correct. Although a k_{eff} measurement is a necessary and vital measurement, by itself it is not sufficient to validate any cross-section set; a favorable comparison between a measured and calculated k_{eff} only tests one aspect of that cross-section set—namely, the ratio of $\nu\Sigma_f/\Sigma_a$.

Furthermore, when one compares calculated k_{eff} with measured values obtained from various critical mass experiments, it is often difficult to ascertain whether observed differences are attributable to the cross-section set or merely the inability of the experimenter to adequately characterize the experiment (i.e., define the exact geometry, the isotopic composition of the fuel, or the impurity level) As an example of an inadequate characterization, consider a series of critical mass experiments performed several years ago using plutonium nitrate solutions of various concentrations in spherical containers. Although the dimensions of the spherical containers were well characterized, the hydrogen content in the plutonium solution was not. The ability to measure a precise and accurate hydrogen content using wet chemistry is known to be somewhat limited; unfortunately, k_{eff} is strongly dependent on the ratio of hydrogen-to-plutonium; therefore, the comparison between the measured and calculated k_{eff} for this particular series of measurements showed considerable scatter (see Figure 1). In all likelihood, this scatter is the result of an inadequate characterization of the experiments rather than a fundamental problem with the nuclear cross-sections.

When attempting to validate other aspects of a nuclear cross section library, it is imperative that other integral and differential quantities—such as neutron lifetimes, fission ratios, central-worth reactivity measurements, neutron and gamma-ray spectra, effective delayed neutron fraction, etc.— be compared as well. For example, to validate the total absorption cross-section (i.e., $\Sigma_a = \Sigma_t - \Sigma_s$) for a given cross-section library, a neutron lifetime measurement is particularly useful. In both multiplying and nonmultiplying systems, the neutron lifetime varies approximately as $1/\Sigma_a$,

$$\tau = \frac{\int \frac{\Psi\Phi}{v}\, d\Omega dE d\mathbf{r}}{\int \Psi\Omega \cdot \nabla\Phi \; d\Omega dE d\mathbf{r} + \int \Psi\Sigma_a\Phi \; d\Omega dE d\mathbf{r}} ,$$

and can be easily and accurately measured using standard die-away techniques. A favorable comparison between a measured and calculated neutron lifetime is particularly important in reactor dynamics, particularly above prompt critical. The behavior of a nuclear reactor above prompt critical is highly dependent on the characteristic time constant, ω, of the system which is related to k_{eff} and τ as

$$\omega = \frac{k_{eff}(1-\beta) - 1}{\tau}$$

Obviously, to calculate the correct value of ω, both k_{eff} and τ must be correct! However, experimental data taken from numerous benchmark critical-mass systems indicate that the absorption cross sections in some of our most trusted cross section libraries are somewhat biased. For example, in 1964, Davey (for reference, see Fig. 2 caption) compared the prompt-neutron lifetimes measured in fifty different fast, unreflected, critical-mass assemblies in ZPR-III and compared those lifetimes with calculated values using the 16-group Yiftah, Okrent, and Moldauer (YOM) fast reactor cross section set. As shown in Figure 2, the calculated lifetimes were consistently lower than the measured lifetimes by an average of 34% even though the measured and calculated k_{eff} for those systems showed excellent agreement. Because the calculated lifetimes were lower than the measured lifetimes, we conclude that the absorption cross sections *in that particular cross section library* must be too high. This bias, however, is not atypical; several other cross section libraries, such as the 16-group Hansen-Roach set and 16-group ANL set, show similar biases.

In conclusion, a k_{eff} measurement is a necessary and vital measurement, but by itself it is not sufficient to validate any cross-section set; to validate all aspects of a cross-section set, numerous integral and differential quantities such as k_{eff}, neutron lifetime, fission ratios, central reactivity worth, neutron and gamma-ray spectra, effective delayed neutron fraction, and others should also be measured.

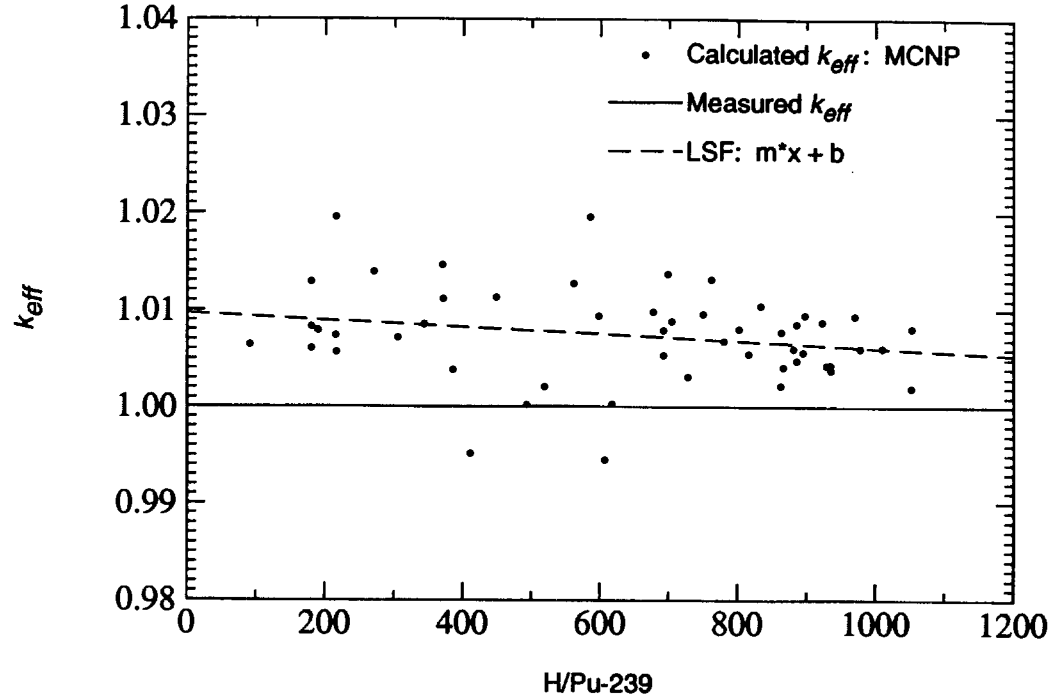

Figure 1. Comparison of measured and calculated k_{eff} for a series of critical mass experiments of plutonium nitrate solutions in spherical containers. (Courtesy of John Miller, University of New Mexico, Master Thesis, 1997).

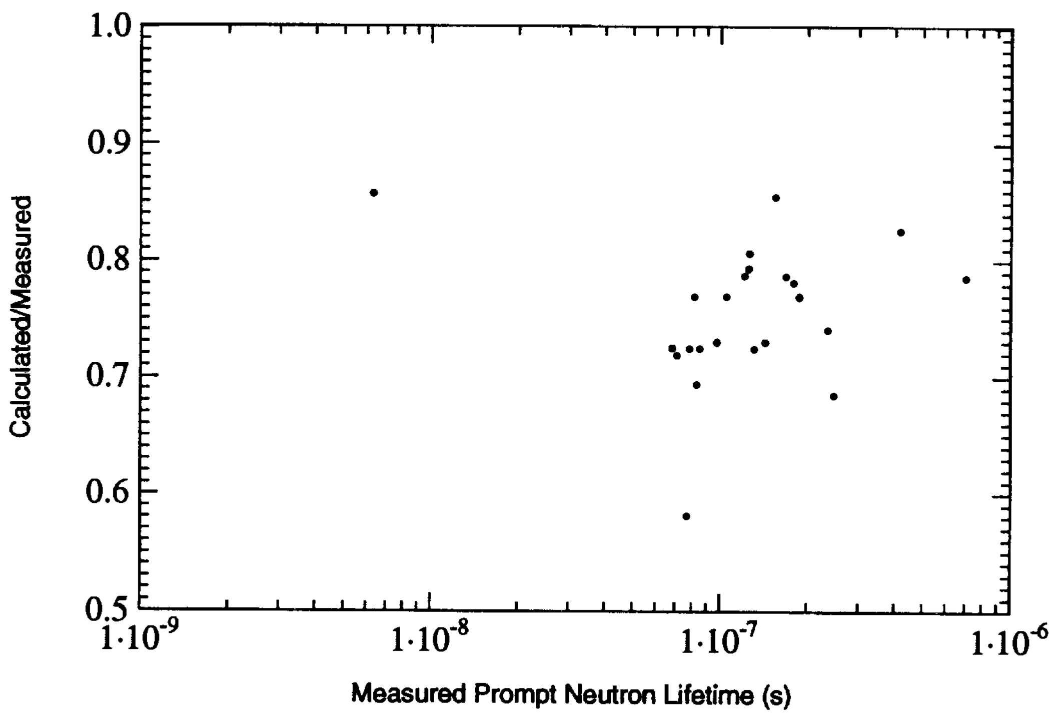

Figure 2. Comparison of measured and calculated neutron lifetimes for a series of critical mass experiments on fast-breeder type systems. [Ref., W. G. Davey, *NS&E*, **19**, 259 (1964).]