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A DESCRIPTION OF INTEGRAL PHYSICS DATA
FOR FAST REACTOR DESIGN

by

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PREFACE

This survey is intended as an orientation for persons who are unfamiliar with the detailed data in the field of fast reactor design. Required integral physics data are described.

The major emphasis in the description centers about experimental data. Comparisons between theory and experiment are also described. The latter are limited to "trends" observed by many analysts. The experimental data are referenced. In addition, a selected list of references pertaining to calculational and theoretical interpretation is given.

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I. INTRODUCTION

Integral physics data for reactor design refer to measurements on reactor systems, critical or otherwise, of the various reactor physics quantities of practical and/or theoretical importance. These characterize and lead to an understanding of the system. The measurements needed include those of critical mass, shape factor, detector ratios, neutron spectra, material replacement experiments, reflector savings, neutron lifetime, Rossi- α , and similar quantities. These data are useful toward understanding the various reactor systems.

Calculational procedures and cross-section parameters may be tested by comparison of calculated integral quantities with corresponding experimental quantities. From the practical viewpoint, the reliability of similar calculations for predicting properties of projected systems may be estimated. Integral comparisons between theory and experiment often point out inadequacies in cross-section data and/or in calculational procedures. Such comparisons tend to point out those areas requiring further experimental or analytical investigation.

Recent compilation of the section on fast reactor physics for the forthcoming Second Edition of Reactor Physics Constants⁽¹⁾ has necessitated a survey of the available experimental integral data. The choice of information in fast reactor physics integral data to be included in the compilation was, beside availability, based upon two criteria:

1. The data arise from relatively simple systems which lend themselves to simple theoretical analyses.
2. Complicated systems may be represented by prototypes or mockups having general interest in terms of fast power reactors.

The first criterion was decided upon so as to list integral data for those systems of most general utility for the verification of cross-section parameters and calculational procedures. The second criterion is based upon presentation of current data on actual fast power breeder reactor systems. These are too complicated for simple theoretical analysis. They demonstrate the complexity of the actual reactor versus the more idealized and easily analyzed clean geometry critical experiment.

Experimental information about fast neutron systems is inadequate for a complete empirical understanding of fast reactor physics. Such experimental information is not even adequate for predicting empirically the criticality of the many types of fast neutron systems currently being studied for various applications. This shortage of all-inclusive information has placed a premium on analytical techniques. Neutron cross sections of pure materials as a function of neutron energy have been extensively investigated. These are then used in a multigroup transport or diffusion theory formalism for comparison with measured integral reactor observables. To date, the agreement between theory and experiment is such that the analyst is quite cautious about predicting the neutronics of fast neutron systems which have not been experimentally investigated. "Experimental investigation" here does not imply a mockup of the conceptual system, but does require an experimental investigation of a system "similar" to that of interest. "Similarity" implies that critical mass, core, reflector, and spectral properties are generally like those of the conceptual system.

The major reason for the limitation on the type and number of critical experiments may be attributed to the limitation on the amounts of fissionable material available for such studies. The largest reported U^{235} critical masses are between 580 and 700 kg. Reported critical masses utilizing Pu in any form have not exceeded 50 kg, whereas those utilizing U^{233} have not yet gone critical without the addition of appreciable amounts of U^{235} . This experimental state of affairs is in stark contrast with the critical-mass requirements of the large central-station fast power breeder reactor systems requiring up to 1000 kg of Pu or 1500 kg of U^{235} . Extrapolation of information from the known, relatively small, fast critical systems to the large conceptual systems leaves considerable uncertainty on the neutronics of the latter. To this end, a large amount of analytical effort is devoted to the means of inferring systematically the characteristics of the large assemblies from experiments with small systems. The latter may contain a region having the composition and spectrum of the conceptual system.

The understanding of detailed reactivity and spectral behavior of systems which have been studied experimentally is also not complete. For example, multigroup techniques generally overpredict (by as much as 20%) the measured $\sigma_c^{U^{238}}/\sigma_f^{U^{235}}$, important for determining the conversion ratio of a U^{235} -fueled system. Similarly, it is difficult properly to infer the temperature and power coefficients of reactor systems from a zero-power critical experiment. Indirect experiments by replacing materials in the reactor core or reflector have given some insight to such problems, but satisfactory precision or agreement between theory and experiment is, in general, not to be found. Agreement can, in all cases, be individually "forced" for a particular system by adjusting multigroup constants. This latter approach loses not only generality, but does introduce uncertainty in predictions for it is not always clear that the experiment is "correct" and/or applicable.

The limitations described, then, form a basis for a review of existing fast neutron system data. Certainly, there is a great deal of information, much of it almost repetitive. There is sufficient general information that one can confidently predict most of the necessary physics parameters of core volumes up to 200 liters. Information becomes more limited in the 200- to 500-liter core size and is virtually nonexistent beyond that size.

II. CRITICAL MASS, CORE, AND REFLECTOR STUDIES

The neutronics of fast neutron systems center about critical assemblies or reactors. The general nature of these are described before citing the detailed measurements performed on them. Most of the systems are relatively simple and thus amenable to calculation in spherical geometry by the use of shape factors* and corrections for heterogeneity and irregular boundaries.

A. Pu- and U²³³-fueled Systems

Plutonium- and U²³³-fueled fast critical assemblies have been studied by both Los Alamos Scientific Laboratory (LASL) and the University of California Radiation Laboratory (UCRL).

High-density δ -phase spherical plutonium cores were considered by LASL.⁽²⁾ The unreflected (Jezebel) and the natural uranium-reflected (Popsy) systems were taken as basic. Criticality, spectrum, and reactivity effects have been studied in detail.

Criticality only has been obtained for some Be-reflected, spherical, high-density, α -phase⁽³⁾ plutonium cores at UCRL. Results obtained with several spherical δ -phase plutonium cores reflected by various thicknesses of carbon and beryllium have been reported by the same group.⁽⁴⁾

Critical reflector thicknesses for spherical, high-density U²³³ and Pu²³⁹ cores were reported by LASL.⁽⁵⁾ Reflectors included enriched (93%) uranium, natural uranium, Be, and tungsten alloy (91.3 w/o W). These are the only reported critical experiments utilizing up to 10 kg U²³³. It is from such integral data, when correlated with calculations, that an unreflected sphere of U²³³ is expected to be critical with about 16 kg of U²³³.

*The shape factor is defined as the ratio of the spherical critical mass of the system with similar core composition and reflector parameters to the critical mass of a given assembly.

Critical masses of a cylindrical, unreflected Pu core and of a series of cylindrical, diluted, unreflected Pu cores having nominal Pu: diluent ratios of 2:1 have been reported,⁽⁶⁾ with depleted uranium, steel, Th, Al, and air as diluents. Similar cylindrical systems with diluted cores but reflected with 19 cm of natural uranium or with 19 cm of thorium are also reported for fuel: diluent ratios of 1:1, 2:1, and 1:2.

These data were reported as measured. Serious analyses of these experiments would require some understanding of the inhomogeneity effects.⁽⁷⁾ The assemblies consisted of stacks of ~0.34-cm-thick Pu plates separated by diluent plates with ~0.32, 0.64 and 1.27-cm thickness. All of the cores had a 15.1-cm diameter. The range of the ratio of core height to diameter (L/D) was fairly large ($0.23 \leq L/D \leq 2.82$), and many of the results were subject to appreciable shape factor correction⁽¹⁾ for simple analysis in spherical geometry. These data do form a basis for the analysis of diluting plutonium with representative coolant, structural, and fertile materials of interest to reactor design. They are very useful for the determination or verification of high-energy constants in a multigroup scheme.

B. Highly Enriched U^{235} Systems in Optimum Geometry

Among the most extensively studied fast-neutron critical systems are the bare (Godiva)⁽⁸⁾ and natural uranium-reflected (Topsy) assemblies from LASL.⁽⁸⁻¹¹⁾ The spherical cores consist of high-density, highly enriched (~93.5%) uranium. These, like the Jezebel and Popsy assemblies cited above Sect. (II-A), have yielded much information on criticality, spectrum and material replacement (reactivity effects) characteristics of extremely hard fast-neutron spectra. The Godiva assembly has also been subjected to a series of superprompt critical bursts.⁽¹²⁾

High-density, enriched uranium (~93.5%) cores have been studied at LASL with a multitude of reflectors of various thicknesses.^(11,13) Although some of these experiments were performed in cylindrical geometry, all are reported in spherical geometry after suitable corrections for shape are applied. Reflectors included natural uranium, graphite, water, heavy water, paraffin, beryllium, beryllium oxide, tungsten, tungsten carbide, copper, nickel, aluminum, aluminum oxide, iron, zinc, thorium, titanium, and magnesium.

The data obtained in such experiments are basic to analyses pertinent to considerations of nuclear safety. They can be helpful toward determination of high-energy cross-section parameters for the reflector materials as used in multigroup analyses.

C. Uranium Cores of Various Enrichments and Dilutions

A variety of data on critical mass for cores of various enrichments of U^{235} in uranium and cores with diluents of structural, moderator, and coolant materials have been reported by LASL and Argonne National Laboratory (ANL). The LASL Jemima^(8,14,15) assemblies are stacks of interspersed plates of high-density highly enriched and natural uranium. Three bare Jemima assemblies have volume fractions of U^{235} of about 53%, 37%, and 29% with corresponding L/D ratios of 0.58, 1.0, and 1.8, respectively. The single reflected Jemima assembly has about 16% U^{235} by volume and is reflected by 7.62 cm of natural uranium. The data from these assemblies require corrections for inhomogeneity if they are to be compared with data from homogeneous reactors. The thicknesses of constituent plates in these assemblies are 0.6 cm and 0.8 cm for natural and enriched uranium, respectively. For example, the approximately 29% enriched uranium assembly consists of stacks, each containing one enriched and three natural uranium plates. The distance between successive enriched uranium plates is 1.8 cm. The effect of inhomogeneity may be quite pronounced, since it extends across the diameter of the core.

The ZPR-III assemblies⁽⁷⁾ consist of thin rectangular plates of the basic constituent materials placed into core drawers of a two-half honeycomb machine. The assemblies are generally cylindrical cores, with L/D ratios chosen to require the least correction for shape. There are two spherical systems. The assemblies are reflected by thick, high-density reflectors containing about 83.4 vol-% depleted uranium and 9 vol-% stainless steel. The ZPR-III assemblies include the following core compositions:

1. U^{235} , U^{238} , stainless steel, and aluminum containing 5 to 14 vol-% U^{235} , 1 to 38% U^{238} , 12 to 28% stainless steel, and 19 to 43% aluminum.^(7,16,17)

2. U^{235} highly diluted with U^{238} , including nominal U^{238}/U^{235} ratios from 5 to 10.^(16,17)

3. U^{235} diluted with graphite representing nominal graphite/ U^{235} volume ratios from 2 to 7.^(7,16,17)

4. An assembly containing 43 vol-% aluminum and 9% stainless steel as diluent and an assembly containing 80 vol-% stainless steel as diluent, both fueled with about 9.3 vol-% of U^{235} .^(16,17)

5. Two oxide assemblies, fueled with 5 to 6% U^{235} and 9 to 10% U^{238} , having sufficient oxygen content in Al_2O_3 to provide O/U atomic ratios of about 2 and 1. Structural material is represented by about 25% stainless steel and coolant by about 24% total aluminum content.⁽¹⁶⁾

6. A sodium-containing assembly fueled with ~9 vol-% U^{235} , 64% stainless steel and 16% sodium.⁽¹⁶⁾

7. A core which mocks up the composition of a carbide-fueled fast reactor (~5 vol-% U^{235} , 10% C, 25% aluminum).⁽¹⁶⁾

A wide variety of core size, composition, neutron spectrum, and critical mass is represented by these particular assemblies. They pose a real test for analytical techniques and successful use of multigroup constants. The data obtained from these assemblies must also be corrected for inhomogeneity when desiring a precision comparison between theory and experiment. Some of these systems approach compositions of idealized fast reactors designed to operate with a heat-removal system. Experiments to give critical mass, spectral properties, neutron lifetime (by Rossi α), and selected material replacement have been reported for each system.

Some systems have been subject to more intensive experimental investigation. This variation of effort generally represents the type and number of material-replacement experiments performed with the system. Some assemblies stimulated only material-replacement experiments at the center of the core, whereas in others material-replacement experiments were performed throughout the core and reflector. In addition, a number of EBR-II-size systems⁽⁷⁾ containing about 14 vol-% U^{235} , 16% U^{238} , 31.5% Al, and 12% stainless steel were investigated with ZPR-III to determine the effect of low-density radial, axial, and central blankets.

D. Extreme Geometry Critical Experiments

A number of critical configurations with high and low ratios of core height to core diameter were investigated at LASL and ANL. The latter (ANL) included rectangular core geometry.⁽⁷⁾ These assemblies have been used with two core compositions, one similar to that of EBR-II, whereas the other was a fairly dense core with $N^{U^{238}}/N^{U^{235}} \approx 3$. Both core systems were reflected with a high-density (~83 vol-%) depleted uranium reflector. The data obtained from these are basic to construction of shape factor curves.⁽¹⁾ The ratio of core height to diameter (L/D) varied from 0.2 to 2.2 for the EBR-II-sized systems.

Another series of experiments basic to the construction of shape-factor curves are the LASL assemblies of highly enriched high-density uranium cores reflected by various thicknesses of natural uranium, graphite and water.^(10,11,18) The ratios of core height to diameter investigated were from 0.3 to 1.9, 0.2 to 3.0 and 0.2 to 3.5 for the water, graphite, and natural uranium reflectors, respectively.

Special critical experiments in extreme geometry (very high or very low L/D) were reported by LASL with highly enriched high-density uranium and plutonium cores with various thicknesses of natural uranium, graphite, H_2O , Be, and polyethylene reflectors.⁽¹⁹⁾ Critical mass studies

using 46% enriched uranium and having low L/D ratios have been carried out at Aldermaston⁽²⁰⁾ for unreflected and reflected flat cylinders. Reflectors of natural uranium, graphite, graphite and borated graphite, aluminum, and steel were studied to obtain experimental information about the consequences of fast reactor core meltdown.

A series of critical experiments were reported from LASL⁽¹¹⁾ which show the influence of both internal and external reflectors for annular, high-density, highly enriched uranium cores. The reflectors were natural uranium, polyethylene, graphite, and natural uranium in polyethylene. An assembly without inner reflector was also reported. Core heights were from 12.7 to 17.8 cm, and inner and outer core diameters were 15 and 31 cm, respectively.

E. Specific Reactor Systems

A number of fast-reactor critical experiments have been performed which do not readily lend themselves to criticality calculations in simple geometry. In most cases these have been performed to obtain design information for a specific reactor system. Others were investigated to obtain the effect of perturbing the idealized simple system by introducing structural plenum regions, etc., such as may be required for actual reactor design.

Typical of the critical experiments yielding design data for reactor construction are the results from ZEUS⁽²¹⁾ which yielded detailed physics parameters for the design of the UKAEA Fast Reactor. Four distinct U^{235} -fueled core assemblies were investigated. The cylindrical ZEUS cores had a radial reflector different from that in the axial direction. The various assemblies ranged in critical mass from 190 kg to 210 kg of U^{235} . One of the assemblies was designed to yield information on the behavior of systems containing ceramic fuel elements. The natural uranium pieces in the core were largely replaced by graphite. In this way, a U:C atomic ratio of 2:3 was achieved, which contains sufficient moderator to enable estimates of an actual ceramic fuel.

Engineering mockups of the Experimental Breeder Reactor-II (EBR-II) with ZPR-III have included a detailed mockup with all the geometric and compositional asymmetries due to the presence of control and safety rods, as well as of the structural plena and nonuniform reflectors.⁽⁷⁾ Many of the reactivity experiments were performed on a "clean core" mockup which had a uniform core composition by eliminating detailed representation of control and safety mechanisms. The uniform core containing about 14 vol-% U^{235} , 16% U^{238} , 26.5% Al, and 19% steel had a 36-cm height and ~23-cm radius. The radial reflector consisted of three similar annular regions. Axially, the core was reflected by structural gaps containing aluminum and stainless steel together with void, and in

turn was reflected by a mixture of aluminum, stainless steel, depleted uranium, and void. Partial substitution of sodium for aluminum in both core and inner portions of the reflector region enabled an estimate of both incremental and total sodium worth in the actual EBR-II. The inhomogeneity effects were found to be quite small in this mockup on ZPR-III.

An interesting experiment determined the attenuation of neutron flux through core, breeder blanket, and into the neutron shield.⁽²²⁾ This experiment served to determine the instrument response of neutron flux-monitoring equipment located in the neutron shield. Several neutron-shield configurations were investigated for optimum instrument response. A similar effort determined the required strength of an Sb-Be neutron source to insure adequate count rates during reactor startup. A series of detailed material-replacement experiments with U^{235} , U^{238} , Na, and stainless steel were performed throughout the reactor core and reflector; the results are being used to obtain an understanding of the power kinetics of the system. Experiments were performed to determine the reactivity worth of various control mechanisms, including motion of fuel, poison ($B_4^{10}C$), or both. These studies also yielded a calibrated oscillator rod.⁽²²⁾

Engineering mockups of the Enrico Fermi Fast Breeder Reactor (EFFBR) have also been carried out on ZPR-III.^(16,23) The "clean" core mockup was a system with core radius of 40 cm and height of 76 cm and containing approximately 6 vol-% U^{235} , 19% U^{238} , 25% Al, 14% SS, 5% Mo, and 4% Zr, surrounded by axial and radial blanket regions of U^{238} , which contained various volume fractions of aluminum and stainless steel to simulate coolant and structural materials. The general experimental program was similar to that with the EBR-II mockup. Some experiments were of a more limited nature, principally because limited amounts of material were available for macroscopic material-replacement experiments. An actual engineering mockup including channels for the B_4C control and safety mechanisms served to evaluate the reactivity worth of control, safety, and oscillator subassemblies.

The LAMPRE (Los Alamos Molten Plutonium Reactor) mockup experiments were conducted at LASL⁽²⁴⁾ to yield design information similar to that described for the EBR-II and Fermi reactors. The LAMPRE critical mass is about 22 kg Pu. LAMPRE is primarily a facility to test the feasibility of molten Pu as a reactor fuel.

Tests with two EBR-I mockups (the EBR-I Mark-II and Mark-III core mockups) were conducted with ZPR-III.⁽⁷⁾ Because of the small core size and geometric asymmetries in reflecting regions, these mockups were of doubtful general utility other than in a qualitative sense.

The USSR has reported experiments with several reactors.⁽²⁵⁾ The BR-1 zero-power reactor has a small Pu core with either a depleted uranium or a copper reflector. Reported investigations with this facility were confined to criticality, cross sections, and flux-distribution phenomena.

The UKAEA ZEPHYR^(21,26) facility, also fueled with a small Pu core, was used for basic reactor cross section and reactivity studies. The attenuations of neutrons in both a thorium and natural uranium reflector were investigated.

In addition to the zero-power fast reactor mockups, there is some physics information available from actual fast reactor operation at power and/or temperature. Such results are currently limited to those obtained from:

1. The LASL fast reactor (Clementine).. This is a mercury-cooled and Pu-fueled system.⁽²⁷⁾

2. The ANL EBR-I. Three cores (Mark I, II, and III) have yielded physics information on the basic reactor statics as well as an extended amount of data pertaining to reactor kinetics.^(28,29,30)

3. The USSR BR-2 reactor⁽²⁵⁾ is a mercury-cooled, plutonium-fueled fast reactor similar in size to the BR-1 experiment with a uranium reflector.

4. The USSR BR-5 reactor⁽³¹⁾ is fueled with plutonium oxide near the center of a small core surrounded by uranium-molybdenum alloy elements at the core periphery. This reactor is reported to have operated at about 5 Mw.

5. The UKAEA Fast Reactor (Dounreay)⁽³²⁾ has gone critical and been subjected to some low-power operation. Temperature effects upon reactivity have been measured.

6. Both the EBR-II⁽³³⁾ and the Fermi⁽³⁴⁾ reactors are expected to be placed into preliminary operational stages during 1961.

Critical experiments of interest because they involve coupling of fast and thermal fissioning regions to form a composite system are exemplified by the coupled fast-thermal power breeder critical experiment⁽³⁵⁾ with ZPR-III and the ZPR-V critical assembly.⁽³⁶⁾ In the former, an internal fast core is surrounded radially by an inner natural uranium blanket and axially by a depleted low-density uranium blanket. The radial blanket is then surrounded by a Be moderator, followed by a high-density depleted uranium blanket surrounding the entire system. The ZPR-V reactor consisted of a central fast core separated from an outer annular water-moderated, U^{235} -fueled region, by a blanket of

natural uranium. Of special interest are the integral data on the detector responses through the different regions and on the division of reactivity. Similar experiments have been reported by the UKAEA with the ZEPHYR reactor.⁽²¹⁾ In these, the main reflector was replaced by graphite to provide a limited amount of neutron moderation for low-energy reactions in the inner uranium reflector surrounding the small Pu core. The USSR BR-3 experiment⁽²⁵⁾ is also a small coupled system. Thermalization is accomplished by use of a closely spaced uranium-water lattice surrounding a solid uranium region which reflects a small plutonium-fueled core. The core is essentially that of the BR-1 reactor.

III. INTEGRAL DATA ON CORE MOCKUP INHOMOGENEITIES

A series of experiments to estimate the effect of using finite fuel-plate thicknesses upon reactivity have been performed with various ZPR-III fast assemblies.^(7,16) These experiments determine the sensitivity of a given composition system to various fuel-plate thicknesses. In general, changes in reactivity have been determined due to use of highly enriched U^{235} fuel plates of either 0.64-cm, 0.32-cm or 0.16-cm thickness. With increased heterogeneity (i.e., thicker fuel plates) an increase in reactivity was observed for the fast systems studied. These inhomogeneity studies suggest that corrections for this effect must be applied to either calculated or measured results for precise comparison between theory and experiment.

IV. SPECTRAL STUDIES AND DETECTOR RATIOS

Currently, there is little experimental information on the characteristic neutron spectra of individual fast neutron systems. Direct measurements of leakage spectra from the unreflected high-density, highly enriched uranium and plutonium cores of Godiva and Jezebel,⁽³⁷⁾ have been reported. A beam of neutrons was extracted from the EBR-I core for spectral studies.⁽³⁰⁾ In all three of these experiments the nuclear-emulsion technique was used, whereas low-energy neutrons from the EBR-I spectrum were detected with a cloud chamber. Proton-recoil emulsions were exposed in ZPR-V⁽³⁶⁾ as well as some ZPR-III assemblies. The results from these latter experiments have not been reported, mainly because data analysis is not complete.

Most of the experimental spectral data for fast neutron systems must be inferred from measured detector ratios, activation cross sections, and neutron lifetimes.

For instance, a measurement of $\bar{\sigma}_f^{U^{238}} / \bar{\sigma}_f^{U^{235}}$ allows an estimate of the fraction of the neutron flux above the U^{238} fission threshold (~ 1.4 Mev).

Similarly, a measurement of $\sigma_f^{U^{234}}/\sigma_f^{U^{235}}$ can be used to determine the fraction of neutrons above the fission threshold of U^{234} (~ 0.5 Mev). Also $\sigma_{n,\gamma}^{U^{238}}/\sigma_f^{U^{235}}$ is important for determination of the conversion ratio of a system fueled with enriched uranium. Comparison of measured with predicted detector ratios from multigroup theory gives a measure of the adequacy of a set of cross-section parameters. Such comparison may suggest improvements or point out possible inconsistencies in the set. Detector ratio data from the central cores of systems whose spectral properties may be readily calculated are generally the basis for such comparisons.

Detector ratios for high-density uranium and plutonium systems (the LASL Godiva, Jezebel, and Jemimas)(2,8,14,38) include $\sigma_f^{U^{235}}/\sigma_f^{U^{238}}$, $\sigma_f^{Np^{237}}/\sigma_f^{U^{238}}$, $\sigma_f^{Pu^{239}}/\sigma_f^{U^{235}}$, $\sigma_f^{U^{234}}/\sigma_f^{U^{235}}$, $\sigma_f^{U^{233}}/\sigma_f^{U^{235}}$ and $\sigma_{n,\gamma}^{U^{238}}/\sigma_f^{U^{238}}$. The reported values, particularly for $\sigma_f^{U^{235}}/\sigma_f^{U^{238}}$, were obtained by a variety of experimental techniques, which did not always give the same quantity. In most cases, the experimental differences were about the same as the difference between theory and average experimental values.

Detector ratios at the core centers for essentially all of the ZPR-III assemblies(7,16,17) have been obtained. In most cases these include: $\sigma_f^{U^{238}}/\sigma_f^{U^{235}}$, $\sigma_f^{U^{234}}/\sigma_f^{U^{235}}$, $\sigma_f^{Pu^{239}}/\sigma_f^{U^{235}}$, $\sigma_f^{U^{233}}/\sigma_f^{U^{235}}$, $\sigma_f^{Pu^{240}}/\sigma_f^{U^{235}}$, and $\sigma_{n,\gamma}^{U^{238}}/\sigma_f^{U^{235}}$.

Such data have been extensively studied by comparing them with predictions by multigroup diffusion theory and SNG calculations.(8,15,39,40) In general, it is possible to obtain fair agreement between measured and predicted values. Certain disturbing trends are observed when the required precision of comparison between theory and experiment is narrowed.

Predicted values for $\sigma_{n,\gamma}^{U^{238}}/\sigma_f^{U^{235}}$ always appear to exceed measured values, often by as much as 20%. The predicted values of $\sigma_f^{U^{238}}/\sigma_f^{U^{235}}$ tend to be less than measured for the LASL-Godiva, Jezebel, Popsy, Topsy, and Jemima systems. The predicted values of the same quantity always tend to exceed measured ANL APR-III results. A consistent trend appears in comparing predicted with measured values for $\sigma_f^{Np^{237}}/\sigma_f^{U^{238}}$ or $\sigma_f^{U^{234}}/\sigma_f^{U^{235}}$. The former are usually underpredicted, whereas the latter are overpredicted (by as much as 15%). In general, it appears that the predicted neutron spectra from multigroup theory tend to be more energetic than measured spectra. This conclusion is even more firmly established when comparing predicted with measured neutron lifetime (by the Rossi- α technique).

Integral out-of-pile measurements of threshold detector responses, with and without a spherical shell of the material to be studied separating the neutron source from the detector, permit the determination of the effective cross sections averaged over the energy region above the detector threshold.^(41,42,43) The experimental arrangement consists of a neutron source placed some distance from the shell, and the detector is placed at the center of the shell. Averaged cross sections for fission spectrum neutrons above the fission threshold of U^{238} (~ 1.4 Mev) and above the fission threshold of Np^{237} (~ 0.5 Mev) for uranium and various nonfissionable materials are available. The averaged cross sections are $\bar{\sigma}_f$, $\bar{\sigma}_{tr}$, and $\bar{\sigma}_{in}$, where $\bar{\sigma}_{in}$ includes all processes other than fission for removal of neutrons from energies above the threshold. The average cross section for fission of U^{238} has been determined by Leachman and Schmitt.⁽⁴⁴⁾

Activation cross sections have also been measured in fission,⁽⁴⁵⁾ Godiva,⁽⁴⁶⁾ Jezebel,⁽⁴⁶⁾ ZEUS,⁽²¹⁾ ZEPHYR,⁽²¹⁾ and BR-1⁽²⁵⁾ spectra for a large number of elements.

Integral measurements of the capture-to-fission ratio (α) for both U^{235} and Pu^{239} have been reported as a function of position in EBR-I.⁽⁴⁷⁾ The measurements were made through the core, and inner and outer blankets by mass spectrometric techniques.

V. URANIUM EQUILIBRIUM SPECTRUM DATA

The degradation of neutron energies in a fast reactor is largely due to inelastic scattering. In a dilute fast system (large atomic ratio of U^{238} to U^{235}) the neutron spectrum is then primarily determined by a fission spectrum distribution modified by inelastic scattering in U^{238} . Measurements of average cross sections and of diffusion length in the equilibrium spectrum of natural uranium are thus very useful for a comparison with corresponding calculated values to test the group cross-section parameters for U^{238} , especially the inelastic scattering matrix. The experiments generally consist of measuring the energy dependence and spatial dependence of various detectors at positions within a large block of natural uranium. Into one face of the block neutrons diffuse from a neutron source, such as a reactor. The neutrons diffusing into the block cause fission and give rise to a fast neutron source at a short distance into the block.

In addition, the presence of natural uranium blankets in numerous reactor systems has enabled measurements of spectra and detector responses at positions, within the blankets, at which an equilibrium spectrum is approached.

Early experiments were performed at Oak Ridge National Laboratory (ORNL). Recently, measurements have been performed in France, at ANL,⁽⁴⁸⁾ and at LASL.⁽⁴⁹⁾ In addition, measurements with depleted uranium have been made in the USSR.⁽²⁵⁾ The various reported values of diffusion length and detector responses have recently been summarized by Chezem.⁽⁴⁹⁾

VI. MATERIAL-REPLACEMENT MEASUREMENTS

A variety of material-replacement experiments in various fast neutron systems have been reported. Significant systematic investigations include replacement data for the high-density Jezebel, Godiva, and Topsy, and for a nickel-reflected Godiva assembly.⁽⁵⁰⁾ Small samples of materials were substituted throughout core and reflector, where appropriate, to give fairly complete reactivity information as a function of radial position. About sixty distinct isotopes or materials were used in these investigations, some on all four assemblies.

Results of material-replacement experiments at the core center and core boundary for numerous ZPR-III assemblies have been obtained^(7,16,17) with a large assortment of materials, including the fission product mockup materials Physicum I and II.⁽⁷⁾

Results of experiments with material replacement uniformly distributed throughout the core of the EBR-II and Fermi mockups, as well as of other systems in ZPR-III, have also been obtained.

Material-replacement data are often reported in either cents/mole or inhours/kilogram. (A cent is 1/100 of a dollar, the dollar being the amount of reactivity required to bring a system from delayed to prompt critical. An inhour is the amount of reactivity which will give a stable period of 3600 sec.) Generally, material-replacement data become useful upon conversion of the relative reactivity measurements in terms of reactor period or control-mechanism movement to absolute reactivity. This can be accomplished by assigning a conversion, based largely on theory, between reactor period and absolute reactivity, for example, the number of inhours per $\% \Delta k/k$. Most fast systems have a non-negligible number of U^{238} fissions. Since the delayed neutron fraction of U^{238} is greater than either that of U^{235} or Pu^{239} , the specification of this conversion, depending also on the importance of delayed versus prompt neutrons, becomes an important calculated quantity. Such calculated or estimated values are required to interpret experimental period measurements in terms of the absolute reactivity used by the reactor analyst.

The method of conversion described above is by no means unique. Since the conversion requires at least some analytical results, it is possible to choose almost any reactor parameter that may be predicted with a minimum uncertainty. Results obtained by UKAEA are usually

normalized with respect to the reactivity worth of a sample of Pu at the center of the core.

Material-replacement data, including those from small-sample and macroscopic regional substitution experiments, are extremely useful for certain analytical techniques. Small-sample substitution can be used to generate spectrum-averaged perturbation cross sections. Large- and small-sample substitutions can be used to obtain information about the effect of perturbing a critical reactor. The most interesting of such perturbations are either power or temperature induced. In a qualitative, as well as semiquantitative, sense, such experiments can do much to give confidence in theoretical predictions of conceptual systems.

VII. INTEGRAL DATA FOR FAST REACTOR DYNAMICS

The kinetics of zero- or low-power fast reactors below prompt critical are principally determined by the delayed neutrons. Kinetic behavior above prompt critical is principally determined by the prompt-neutron lifetime.

The influence of fertile fissions on the zero-power kinetics is generally important in a fast power-breeder reactor because of the large quantities of U^{238} , Th, or Pu^{240} , both in the core and breeder blanket reflector. The evaluation of the effective delayed-neutron fraction of the system considers both the spatial distribution of the U^{238} or fertile fissions,^(7,8) which differs from that of the fuel (U^{233} , U^{235} , or Pu^{239}) fissions, as well as the different delayed-neutron characteristics of the fuel and fertile materials. Because of the importance of relating the measurements in inhours or cents/mole to reactivity in terms of $\Delta k/k$, the evaluated and/or estimated inhours per percent reactivity values for various ZPR-III assemblies have been reported.⁽⁷⁾ Similar conversion formulae have been obtained for most of the LASL elementary critical experiments.⁽⁸⁾

The importance of relating inhours to reactor period has stimulated investigation of the variation of this relationship as a function of fast neutron spectrum or reactor system. This analytical investigation showed that the "inhour curve" is relatively invariant in the range of periods used for making measurements (30-200 sec).

The prompt-neutron lifetime has been measured in many systems by various methods. The frequently used Rossi- α method gives the ratio of the overall lifetime of the system and the effective delayed-neutron fraction. The $1/v$ poison method is based upon a determination of the loss of reactivity associated with the uniform distribution of a $1/v$ -absorber in the system. A review paper⁽⁵¹⁾ describes and compares the various

methods.^(52,53) Rossi- α values for the LASL high-density, high enrichment Pu and U systems and for the Jemima assemblies have been reported.^(8,52) Rossi- α values have been measured for a large number of ZPR-III fast assemblies.^(7,53) The experimental values together with calculated and/or estimated values of delayed neutron fraction then allow prompt-neutron lifetimes to be determined. The prompt-neutron lifetime is a fairly sensitive "spectral index" to the low-energy tail of the neutron spectrum in a reactor.

Experimental information pertaining to the power kinetics of fast neutron systems is limited to those reactors which have operated on nuclear heat over a large power range. Systematic experimental investigations have been reported for neutron pulses in Godiva⁽¹²⁾ and for extended periods of operation with EBR-I.⁽²⁸⁾ The Godiva-I assembly is one of the simplest and most thoroughly investigated spherical critical systems. Godiva-II, the successor to Godiva-I, is a cylindrical reactor, but has most of the Godiva-I properties and behavior. Godiva-I was subjected to a series of self-limiting bursts, each initiated by a step change in reactivity. Following the retirement of Godiva-I, after an accidental burst which damaged the reactor, Godiva-II was designed specifically for the reliable production of super-prompt-critical fission bursts. By empirical analysis of a series of Godiva-I bursts, various relationships related to the period of the initial excess reactivity have been reported, such as: total number of fissions in burst, maximum fission rate, temperature rise, and burst width as a function of excess reactivity above prompt critical. The relations were based on experiments ranging from 1 to 30 cents above prompt critical. (A cent = 0.01 dollar $\approx 6.6 \times 10^{-3} \% \Delta k/k$.) Initial reactor periods before shutdown coefficients became operative ranged from 3.8×10^{-2} sec to 1.2×10^{-5} sec^(54,55,56,57)

Extended periods of power operation with EBR-I, Mark-I, II, and III cores, have yielded experimental information on fast power reactor kinetics and stability.^(28,30) The appearance of a large resonance in the power transfer function and the occurrence of spontaneous oscillations under certain operating conditions with the Mark-II core have stimulated a large analytical effort on the EBR-I core loadings. A summary of recent experimental and analytical work is given in References 28 and 29. Some analytical models for EBR-I, Mark-II and Mark-III cores, are described in References 29, 58, 59, 60 and 61. The nonlinear aspects of such studies are treated in Reference 62.

The knowledge of the prompt temperature coefficient of reactivity for fast reactors is important because of its role in the safety of these systems. One component of the prompt temperature coefficient is due to the Doppler effect, which arises from a change in the relative velocity distribution of the neutrons and nuclei following a change in temperature. Doppler broadening of the cross-section resonances leads to a lessening

of flux depletion at these same resonances, with a consequent increase in interaction rate. The positive component of a change in the reactivity is due to an increase in the fission rate of U^{233} , U^{235} , Pu^{239} , and Pu^{241} as a result of the Doppler effect. The negative component of a change in reactivity is primarily due to the increase in the neutron capture rate of Th, U^{238} , and Pu^{240} , as well as of the thermally fissile isotopes just mentioned. The magnitude and sign of the net Doppler coefficient of reactivity is a function of the relative densities of fissionable and fertile materials, the neutron spectrum, and the operating temperature of the reactor.

The Doppler temperature coefficient is a difficult quantity to calculate accurately for fast reactors because of the uncertainty of the resonance parameters and level distribution of fissionable and fertile materials in the energy region of tens and hundreds of kilovolts. A number of theoretical estimates of the coefficient for metal-fueled fast reactors have been made by means of nuclear theory and low-energy resonance data.⁽⁶³⁻⁶⁷⁾ Doppler reactivity effects have also been calculated for some large dilute PuO_2 - UO_2 -fueled fast reactors.^(68,69) These analyses indicate that a fast oxide breeder reactor may have a Doppler coefficient of $-1.0 \times 10^{-5} \Delta k/k/^\circ C$ at $900^\circ C$.

Two experiments have been done to measure the Doppler coefficient. The first experiment attempted to measure the Doppler effect of U^{235} in a highly enriched EBR-I mockup in ZPR-III.⁽⁷⁰⁾ A helix made of U^{235} was electrically thermal-cycled between $50^\circ C$ and $170^\circ C$, and the change in reactivity was determined by means of pile oscillator techniques. Because of the uncertainties introduced into the experiment by expansion of the uranium upon heating, an upper limit of $0.83 \times 10^{-8} \Delta k/k/^\circ C$ for the Doppler effect of the 506-gm U^{235} sample at an average temperature of $106^\circ C$ was obtained. Extrapolating this value of the Doppler effect to the entire critical mass of the reactor, the Doppler coefficient was estimated to be no greater than $1.6 \times 10^{-6} \Delta k/k/^\circ C$ at $20^\circ C$ for the EBR-I reactor.

The second measurement of the Doppler effect in a fast reactor was by oscillatory heating of natural uranium and enriched uranium (93% U^{235}) samples in the central channel of ZEUS.⁽⁷¹⁾ The sample was surrounded by material having a U^{238}/U^{235} ratio of 1.63. The accuracy of these experiments was also limited by the corrections necessary for the thermal expansion effect of the sample. A small negative temperature coefficient corresponding to increased capture in U^{238} with increasing temperature was reported.

The Doppler temperature coefficient for the entire ZEUS reactor was reported zero within experimental error. An upper limit for the magnitude of the Doppler coefficient, either positive or negative, was placed at 1×10^{-6} per $^\circ C$ for the ZEUS reactor.

VIII. SUGGESTED FUTURE EXPERIMENTS AND EXPERIMENTAL PROGRAMS

A review of existing experimental information serves to emphasize those areas where information is inadequate either for empirical analysis or for systematic comparison with predicted physics parameters. The inability of theory to predict certain neutronic constants also implies additional experiments, either to verify the reliability of existing data or to extend the current realm of experimental understanding.

In planning an experimental program, it must be recognized that it should, to a large extent, be stimulated by analytical investigations. It is very difficult to recommend a complete outline of experiments and programs which should be pursued without knowing the requirements in the design of future fast reactors. However, certain experimental requirements are self-evident although they are by no means all-inclusive.

Several relatively small fast reactors are to be fueled with plutonium. The amount of plutonium per unit core volume will be sufficient to have some effect on the reactor spectrum. It is clearly necessary that the physics of plutonium-fueled fast reactors might be the subject of a fairly short-range experimental program. Such investigation would certainly have to include some critical experiments dealing with appreciable quantities of Pu^{240} .

The conceptual large, central-station fast power-breeder reactor (core volume >800 liters) is fueled either with plutonium or uranium-233. No direct experimental information pertaining to these systems exists. There is then the question of what experimental information can be obtained for the neutronics of these conceptual systems. The approach may take one or all of several courses:

1. Actually perform some Pu-fueled critical experiments requiring between 500-1000 kg Pu. These could include cores with metal, oxide, or carbide "fuel."

2. Perform U^{235} -fueled critical experiments requiring between 800 and 1500 kg U^{235} . These reactors would be identical to those in 1 except that the ratio of fertile to fissile atoms in the core is smaller than in the Pu-fueled system.

3. Exponential experiments with core compositions described in 1 and/or 2. The experience with fast exponential experiments has not been completely satisfactory. This technique may be made more reliable by increasing the size of the exponential column.

4. "Zoned" critical experiments may determine some of the required physics data of spectrum and criticality. These experiments are essentially critical exponential experiments. The region or composition of interest is assembled and maintains a fraction of the reactivity of the system. Criticality is achieved with either an internal or external "driver" having, at least near the boundary of the region of interest, a spectrum similar to that expected in the composition to be studied. Portions of the driver far removed from the composition to be studied are merely a source of neutrons, and can have a thermal, epithermal, or fast neutron spectrum. The ZPR-V experiments are an approach to this problem. However, insufficient reactivity in the fast system coupled with a problem of neutron transmission through natural uranium made the analysis of these experiments difficult. It may be necessary that facilities of this type operate on none, or very few, thermal neutrons.

The use of either zoned critical experiments or exponential experiments will require analytical verification of the feasibility of such an approach. Further, it is recommended that parallel efforts be carried out: one by use of, say, zoned experiments, and the other through the direct critical experiment. Such experimental verification would suggest the framework of reliability of the indirect and less expensive approach toward measurement of interesting reactor parameters.

The experimental scope and understanding of fast neutron systems can be extended by the performance of a number of elementary critical experiments involving very few, preferably only two or three, materials. For instance, three assemblies have been investigated at ZPR-III, which fall directly into this category. Each core contains about 10 v/o U^{235} , the remaining core volume being occupied by either graphite, stainless steel, or aluminum, respectively. Each system is reflected by high-density depleted uranium. These experiments should be extended to more degraded neutron spectra by systematically reducing the U^{235} content per unit core volume. Such experiments have been performed with U^{238} as core diluent at both ZPR-III and LASL, and are extremely useful for analytical studies with U^{235} and U^{238} . The use of other materials of interest to fast reactor design (such as sodium, molybdenum, niobium, and zirconium) would be of considerable interest for few material critical experiments.

The application of fast reactors in space technology, where weight and size are to be minimized, is the basis for an entirely new area of critical experiments. It is likely that such reactors will not have a thick uranium reflector. A thin, heavy element reflector might be typical. Furthermore, the essentially bare core will contain no fertile materials, whereas most experimentally investigated cores contain sizeable amounts of fertile materials. In certain applications, the core may be quite "leaky" to reactor spectrum neutrons, and there is virtually no experimental information about streaming effects in fast neutron systems.

Existing shape-factor data should be extended to larger systems. Experimental results currently include the small, high-density highly enriched uranium cores reflected by natural uranium, graphite, and water. In addition, there are some shape-factor data for EBR-II-size systems, also in high-density uranium reflectors. Analytical time, effort, and speculation can be reduced by investigating experimentally shape factors for 500-800-liter cores. It will be particularly important to investigate the effect of reflector density and nonuniformity along with the basic shape factor. Furthermore, the optimization of certain reflector regions (axial in current reactor designs) will require experimental verification. Optimum burnup of fuel alloy will determine removal of axial blanket alloy. Analytical and experimental efforts should be devoted to enhancing fertile fissions and plutonium production in the axial reflector.

The problem of fast reactor control should receive considerable attention in the near future. It is apparent that currently designed moving-fuel control mechanisms increase in size, roughly with reactor core size. There is a high penalty in either thermal performance or expense with increasingly larger segments of movable fuel. The use of movable poison ($B_4^{10}C$) in a fast reactor presents some problems of mechanical design. It is appropriate to review this situation both analytically and experimentally. Schemes of moderator or moderator and poison control may offer promise.

The work leading to the development of techniques for measuring fast neutron spectra in a differential way (as a function of neutron energy) should be revitalized. More spectral measurements, perhaps using nuclear emulsions, over an extended neutron energy range are required. As agreement between theory and experiment improves on criticality; the detailed spectral data become important for the next step in calculational improvement.

Experiments on heterogeneity effects for cylindrical fuel rods in coolant and structural matrices will be of interest. Similarly, reactivity effects due to voids, and holes in core and reflector regions have not been systematically investigated.

The analytical predictions of a positive sodium temperature coefficient for large reactors must be experimentally verified. A direct experiment of this effect would require at least 700-800 kg U^{235} in a core with strongly absorbent "structural" material along with either sodium or an aluminum mockup of the coolant material.

The importance of the Doppler coefficient of reactivity for large fast power-breeder reactors cannot be overestimated. Experimental data are needed to verify or reject theoretical predictions. The prompt Doppler coefficient of reactivity in a dilute reactor (large ratio of

$N_{\text{Fertile}}/N_{\text{Fissile}}$) may be sufficiently negative to override the less prompt positive void coefficient of the coolant. Furthermore, in a dilute ceramic-fueled fast reactor, where there is little if any expansion of fuel, the Doppler coefficient of the fertile material may be the only source of prompt negative reactivity feedback.

Importance measurements, by inserting small sources throughout a reactor, will yield useful information both as a function of position and neutron energy.

It is expected that as the number and types of critical experiments grow, there will be increasing attention paid to measurements pertaining to reactor kinetics.

REFERENCES

1. Reactor Physics Constants, ANL-5800 (1958).
2. Jarvis, G. A., et al., Two Plutonium-Metal Critical Assemblies, Nuc. Sci. and Eng., 8 (No. 6) 525 (Dec 1960).
3. Ralston, H. R., Critical Parameters of Spherical Systems of Alpha-phase Plutonium Reflected by Beryllium, UCRL-5349 (Sept 1958).
4. Kloverstrom, F., Spherical and Cylindrical Plutonium Critical Masses, UCRL-4957 (Sept 1957).
5. Plassman, E. A., and Wood, D. P., Critical Reflector Thicknesses for Spherical U^{233} and Pu^{239} Systems, Nuc. Sci. and Eng., 8 (No. 6) 615. (Dec 1960).
6. Wood, D., Beyers, C., and Osborn, L., Critical Masses of Cylinders of Plutonium Diluted with Other Metals, Nuc. Sci. and Eng., 8 (No. 6) 578 (Dec 1960).
7. Long, J. K., et al., Fast Neutron Power Reactor Studies with ZPR-III, Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, Switzerland (1958), 12, 119.
8. Hanson, G. E., "Properties of Elementary Fast Neutron Critical Assemblies," ibid., 12, 84.
9. Josephson, V., Paine, R. W., Jr., and Woodward, L. L., Oralloy Shape Factor Measurements, LA-1155 (Aug 1950).
10. Malary, E. C., Oralloy Cylindrical Shape Factor and Critical Mass Measurements in Graphite, Paraffin, and Water Tamperers, LA-1305 (Oct 1951).
11. Paxton, H. C., Critical Data for Nuclear Safety Guides, LAMS-2415 (Feb 1960).
12. Wimett, T. F., and Orndoff, J. D., Applications of Godiva-II Neutron Pulses, Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, Switzerland (1958), 10, 449.
13. Graves, G. A., and Paxton, H. C., Critical Masses of Oralloy Assemblies, Nucleonics, 15 (No. 6), 90 (June, 1957).
14. Paxton, H. C., et al., Bare Critical Assemblies of Oralloy at Intermediate Concentrations of U^{235} , LA-1671 (May 1954).
15. Roach, W. H., Computational Survey of Idealized Fast Breeder Reactors, Nuc. Sci. and Eng., 8 (No. 6), 621 (Dec 1960).
16. Unpublished ZPR-III Data; private communication.

17. Keeney, W. P., and Long, J. K., Dilute Fast Critical Experiments in ZPR-III, Trans. of Am. Nuc. Soc., 3 (No. 2) 327 (1960).
18. Paxton, H. C., and Graves, G. A., Critical Masses of Fissionable Metals as Basic Nuclear Safety Data, LA-1958 (Sept 1956).
19. Hansen, G., Paxton, H., and Wood, D., Critical Plutonium and Enriched-uranium-Metal Cylinders of Extreme Shape, Nuc. Sci. and Eng., 8 (No. 6) 570 (Dec 1960).
20. Dominey, J. R., Lane, R. C., and Thomas, A. F., Critical Mass Studies with Slabs of 46% Enriched Uranium, NR/A-1/61 (1961).
21. Smith, R. D., and Sanders, J. E., Experimental Work with Zero Energy Fast Reactors, Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, Switzerland (1958), 12, 89.
22. Idaho Division Summary Report (July, Aug, Sept, 1960), ANL-6301.
23. Alexanderson, E. L., Garelis, E., and Nims, J. B., Critical Experiment Calculation for the Enrico Fermi Reactor, Trans. of Am. Nuc. Soc., 1 (No. 2) 98 (1958).
24. Barkmann, H. G., et al., Preliminary Critical Experiments on a Mockup of the Los Alamos Molten Plutonium Reactor, LA-2142 (June 1957).
25. Leipunsky, A. I., et al., Studies in the Physics of Fast Neutron Reactors, Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, Switzerland (1958), 12, 3.
26. Holmes, J. E. R., et al., Experimental Studies on Fast Neutron Reactors at A.E.R.E., Proceedings of the United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, Switzerland (1955), 5, 331.
27. Journey, E. T., et al., The Los Alamos Fast Plutonium Reactor, LA-1679 (1954).
28. Thalgott, F. W., et al., Stability Studies on EBR-I, Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, Switzerland (1958), 12, 242. Smith, R. R., et al., Instability Studies with EBR-I Mark-III, ANL-6266 (Dec 1960).
29. Proceedings of the Conference on Transfer Function Measurement and Reactor Stability Analysis, ANL-6205 (May 1960).
 Smith, R. R., Recent EBR-I Stability Studies, 232.
 Storrer, F., Analysis of the Power Feedback Relations in Fast Reactors, 251.
 Okrent, D., and Hummel, H. H., Kinetics Studies on EBR-I and EBR-II, 269.

30. Lichtenberger, H. V., et al., Operating Experience and Experimental Results Obtained from a NaK Cooled Fast Reactor, Proceedings of the United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, Switzerland, (1955) 3, 345.
31. Leipunsky, A. I., et al., Experimental Fast Reactors, Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, Switzerland (1958), 9, 348.
32. Cartwright, H., and Tatlock, J., The Dounreay Fast Reactor - Basic Problems in Design, Ibid., 9, 316.
33. Koch, L. J., et al., Construction Design of EBR-II: An Integrated Unmoderated Nuclear Power Plant, Ibid., 9, 323.
34. Amorosi, A., and Yevick, G., An Appraisal of the Enrico Fermi Reactor, Ibid., 9, 358.
35. Avery, R., et al., Coupled Fast-Thermal Power Breeder Critical Experiment, Ibid., 12, 151.
36. Hummel, H. H., et al., Experimental and Theoretical Studies of the Coupled Fast-Thermal System ZPR-V, Ibid., 12, 166.
37. Stewart, L., Leakage Neutron Spectrum from a Bare Pu^{239} Critical Assembly, Nuc. Sci. and Eng., 8 (No. 6) 595 (1960).
38. Neuer, J. J., et al., Preliminary Survey of Uranium Metal Exponential Column, LA-2023 (decl. April 2, 1957).
39. Yiftah, S., Okrent, D., and Moldauer, P., Fast Reactor Cross Sections - A Study Leading to a Sixteen Group Set, Pergamon Press, New York (1960).
40. Loewenstein, W. B., and Okrent, D., The Physics of Fast Power Reactors, Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, Switzerland (1958), 12, 16.
41. Bethe, H. A., The Reciprocity Theorem in Neutron Scattering, LA-1428 (June 1952).
42. Bethe, H. A., Beyster, J. R., and Carter, R. E., Inelastic Cross Sections for Fission Spectrum Neutrons, LA-1429 (Dec 1955).
43. Carter, R. E., and Beyster, J. R., Inelastic Collision Cross Sections for Fission Spectrum Neutrons, Phys. Rev., 90, 389 (1953).
44. Leachman, R. B., and Schmitt, H. W., Average Fission Cross Section of U^{238} for Fission Neutrons, LA-1624 (Jan 1953).
45. Hughes, D. J., Garth, R. C., and Levin, J. S., Fast Neutron Cross Sections and Nuclear Level Density, Phys. Rev., 91, 1423 (1953).

46. Beyers, C. C., Cross Sections of Various Materials in the Godiva and Jezebel Critical Assemblies, Nuc. Sci. and Eng., 8 (No. 6), 608 (Dec 1960).
47. Kafalas, P., Levenson, M., and Stevens, C. M., Determination of the Ratio of Capture to Fission Cross Sections in EBR-I, Nuc. Sci. and Eng., 2 (No. 5) 657 (Sept 1957).
48. Beyer, F. C., et al., The Fast Exponential Experiment, Proceedings of the United Nations International Conference of the Peaceful Uses of Atomic Energy, Geneva, Switzerland, (1955) 5, 342.
49. Chezem, C. G., A Uranium Exponential Experiment, Nuc. Sci. and Eng., 8 (No. 6) 652 (Dec 1960).
50. Engle, L. B., Hanson, G. E., and Paxton, H. C., Reactivity Contributions of Various Materials in Topsy, Godiva and Jezebel, Nuc. Sci. and Eng., 8 (No. 6) 543 (Dec 1960).
51. Bengston, J., Determination of Prompt Neutron Decay Constants of Multiplying Systems, Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, Switzerland (1958), 12, 63.
52. Orndoff, J. D., Prompt Neutron Periods of Metal Critical Assemblies, Nuc. Sci. and Eng., 2 (No. 4) 450 (July 1957).
53. Brunson, G. S., et al., Measuring the Prompt Period of a Reactor, Nucleonics, 15 (11), 132 (Nov 1957).
54. Hansen, G. E., Burst Characteristics Associated with the Slow Assembly of Fissionable Materials, LA-1441 (July 1952).
55. Fuchs, K., Efficiency for Very Slow Assembly, LA-596 (1946).
56. Brittan, R. O., Some Problems in the Safety of Fast Reactors, ANL-5577 (1956).
57. Stratton, W. R., Colvin, T. H., and Lazarus, R. B., Analysis of Prompt Excursions in Simple Systems and Idealized Fast Reactors, Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, Switzerland (1958), 12, 196.
58. Carter, J. C., Sparks, D. W. and Tessier, J. H., The Internal Feedback of EBR-I Mark-III, Nuc. Sci. and Eng., 8 (No. 4) 326 (Oct 1960).

Carter, J. C., Sparks, D. W., and Tessier, J. H., The Internal Feedback of EBR-I Mark-III, ANL-6124 (Feb 1960).
59. Bethe, H. A., Reactor Safety and Oscillator Tests, APDA-117 (Oct 1956).
60. Kinchin, G. H., The Instability of Fast Reactors, AERE RP/M83 (June 1956).

61. Ackroyd, R. T., et al., Stability Considerations in the Design of Fast Reactors, Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, Switzerland, (1958), 12, 230.
62. Sandmeier, H. A., Nonlinear Treatment of Large Perturbation in Power Reactor Stability, Nuc. Sci. and Eng., 6 (No. 2) 85 (Dec 1959).
Sandmeier, H. A., The Kinetics and Stability of Fast Reactors with Special Considerations of Non-linearities, ANL-6014 (June 1959).
63. Goertzel, G., An Estimation of Doppler Effect in Intermediate and Fast Neutron Reactors, Proceedings of the United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, Switzerland, (1955), 5, 472.
64. Feshbach, G., Goertzel, G., and Yamauchi, H., Estimation of Doppler Effect in Fast Reactors, Nuc. Sci. and Eng., 1 (No. 1) 4 (March 1956).
65. Lane, A. M., Lynn, J. E., and Storey, J. S., An Estimation of the Doppler Effect in Fast Reactors, AERE T/M 137 (July 1956).
66. Bethe, H. A., On the Doppler Effect in Fast Reactors, APDA-119 (March 1957).
67. Nicholson, R. B., The Doppler Effect in Fast Neutron Reactors, APDA-139 (June 1960).
68. Greebler, P., Hutchins, B. A., and Sueoka, J. R., Calculation of Doppler Coefficient and Other Safety Parameters for a Large Fast Oxide Reactor, GEAP-3646 (1961).
69. Greebler, P., and Hutchins, B. A., Calculation of Doppler Reactivity Effects in a PuO₂-UO₂ Fueled Fast Reactor, Trans. of Am. Nuc. Soc., 4 (No. 1) (June 1961).
70. Kato, W. Y., and Butler, D. K., Measurement of the Doppler Temperature Effect in an EBR-I Type Assembly, Nuc. Sci. and Eng., 5 (No. 5) 320 (May 1959) ANL-5809 (July 1958).
71. Baker, A. R., and Jaques, T. A. J., A Measurement of the Contribution of the Doppler Effect to the Temperature Coefficient of Reactivity in a Fast Reactor, AERE R/M 168 (June 1958).

SOME CALCULATIONAL AND THEORETICAL REFERENCES FOR INTERPRETING INTEGRAL DATA

72. Hansen, G. E., and Roach, W. H., Sixteen Group Cross Sections, Los Alamos Scientific Laboratory Internal Report, N-2-753, Revision 1 (1960).
73. Carlson, B. G., Solution of the Transport Equation by S_N Approximations, LA-1891 (Feb 1955).

74. Carlson, B. G., Wendroff, B., and Bell, B. I., Solution of the Transport Equation by the S_N Method, Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, Switzerland (1958), 16, 535.
75. Carlson, B. G., et al., The DSN and TDC Neutron Transport Codes, LAMS-2346 (Feb 1960).
76. Carlson, B. G., Solution of the Transport Equation by S_N Approximations, LA-1599 (Oct 1953).
77. Codd, J., Shepherd, L. R., and Tait, J. H., "The Physics of Fast Reactors," Progress in Nuclear Energy, McGraw-Hill Book Co., Inc., New York (1956), Series I: Physics and Mathematics, 264.
78. Frankel, S., and Nelson, E., Methods of Treatment of Displacement Integral Equations, AECD-3497 (Sept 1953).
79. Melvin, H. M., A Method of Calculating the Critical Dimensions of Spherically Symmetrical Reactors: Part II, Systems with a Finite Tamper, AERE T/R-587 (Oct 1950).
80. Davison, B., Neutron Transport Theory, Clarendon Press, Oxford (1957).
81. Okrent, D., Avery, R., and Hummel, H. H., A Survey of the Theoretical and Experimental Aspects of Fast Reactor Physics, Proceedings of the United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, Switzerland (1955), 5, 347.