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FOREWORD

In recent years there has been growing interest in transient, as opposed to static, techniques of neutron and reactor physics investigation. Perhaps the most notable example of the newer transient techniques is the pulsed neutron source method which has been applied to various studies of the detailed interaction of neutrons with non-multiplying as well as multiplying media.

More than 230 scientists from 22 countries and 3 international organizations participated in this IAEA Symposium held at the Kernforschungszentrum Karlsruhe, at the invitation of the Government of the Federal Republic of Germany. Although there have been previous meetings concerned with pulsed neutron measurements (notably at Berkeley in 1958 and at Brookhaven in 1962), this was the first international meeting on pulsed neutron research in which working scientists from all parts of the world participated.

This Symposium has provided not only new and significant pulsed neutron data, but also, what is equally important, fresh viewpoints of interpretation pointing toward useful directions for future pulsed neutron investigation. The general opinion of participants at Karlsruhe was that the potential value of pulsed neutron studies, on fast systems particularly, has scarcely been tapped and that much greater effort in this direction can be expected in the coming years.

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R. Comte

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THERMAL MULTIPLYING SYSTEMS

(Session IV)

SURVEY OF PULSED NEUTRON SOURCE METHODS FOR MULTIPLYING MEDIA

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Abstract — Résumé — Аннотация — Resumen

SURVEY OF PULSED NEUTRON SOURCE METHODS FOR MULTIPLYING MEDIA. In recent years there have existed two schools of thought on the most effective manner of obtaining measurements of the shutdown reactivity using pulsed neutron generators; these are (i) the conventional pulsed neutron source measurements with a repetitively pulsed source and (ii) methods based on a pseudo-random impulse response technique using cross-correlation between input and output. In both techniques the pertinent information obtained is identical, i.e. ideally both methods serve to determine the response function.

The development of pulsed neutron source techniques on thermal systems for the purpose of reactivity measurements is traced from the early efforts of Sjöstrand to the recent ($k\beta/\ell$) method. In the usual pulsed neutron source method, the Green's function of the subcritical assembly, the reactor response to a delta function source of neutrons, is the sought-after property. The exponential decay, $\exp(-\alpha t)$, of the Green's function yields a spatially independent prompt neutron decay constant. The methods by which the reactivity is derived from the α-measurement, e.g. the α-delayed critical measurement and the recent ($k\beta/\ell$) method, are discussed. The fundamental modal treatments are examined in the light of the theory of the pulsed neutron source techniques as developed for the ($k\beta/\ell$) model.

The implications of the pulsed neutron source theory to obtain precise decay constants and suitable data for the analysis of pulsed systems are considered. Experimental work is reviewed that shows the advantages as well as the limitations of the ($k\beta/\ell$) technique.

The use of pseudo-random impulse response methods with cross-correlation between the input and output for the determination of the Green's function of a multiplying assembly is also discussed. It is shown that the information obtained by the pseudo-random method is identical to that obtained from the repetitively pulsed method. Thus, this makes it possible to apply the methods developed for the repetitive to that of the pseudo-random technique.

MÉTHODES DES NEUTRONS PULSÉS POUR L'ÉTUDE DES MILIEUX MULTIPLICATEURS. Depuis quelques années, il existe deux opinions sur la manière la plus efficace de mesurer la réactivité d'arrêt au moyen de générateurs de neutrons pulsés, savoir: a) les mesures classiques au moyen d'une source pulsée à répétition; b) des méthodes qui sont fondées sur la réponse à des impulsions pseudo-aléatoires et utilisent une corrélation entre l'entrée et la sortie. Dans les deux cas, les renseignements pertinents que l'on obtient sont identiques, en d'autres termes, idéalement les deux méthodes servent à déterminer la fonction de réponse.

L'auteur retrace l'évolution des méthodes de mesure de la réactivité fondées sur les sources pulsées dans les systèmes à neutrons thermiques, depuis les premières tentatives de Sjöstrand jusqu'à la récente méthode de ($k\beta/\ell$). Dans la méthode habituelle, la fonction de Green relative à l'assemblage sous-critique - la réponse du réacteur à une source de neutrons à fonction delta - constitue la propriété recherchée. La décroissance exponentielle, $\exp(-\alpha t)$, de la fonction de Green donne une constante de décroissance des neutrons instantanés indépendante du lieu. L'auteur examine les méthodes permettant de déduire la réactivité de la mesure de α, par exemple, la mesure de α à l'état critique retardé et la récente méthode de ($k\beta/\ell$). Il étudie notamment les traitements du mode fondamental à la lumière de la théorie des méthodes des neutrons pulsés, telles qu'elle a été mise au point pour le modèle ($k\beta/\ell$).

L'auteur examine les incidences de la théorie des neutrons pulsés en vue d'obtenir des constantes de décroissance précises et les données voulues pour l'analyse des systèmes pulsés. Il passe en revue les travaux expérimentaux qui font ressortir à la fois les avantages et les limitations de la technique de ($k\beta/\ell$).

Il discute en outre l'emploi des méthodes qui sont fondées sur la réponse à des impulsions pseudo-aléatoires et utilisent une corrélation entre l'entrée et la sortie, pour la détermination de la fonction de Green

d'un milieu multiplicateur. Il montre que les renseignements obtenus par ces méthodes sont identiques à ceux fournis par les méthodes de la source pulsée à répétition, ce qui permet d'appliquer aux premières les procédés qui ont été mis au point pour les secondes.

ОБЗОР МЕТОДОВ С ИСПОЛЬЗОВАНИЕМ ИСТОЧНИКОВ ИМПУЛЬСНЫХ НЕЙТРОНОВ ДЛЯ РАЗМНОЖАЮЩЕЙ СРЕДЫ. В последние годы существовали два направления в области эффективных способов получения измерений остаточной реактивности с использованием генераторов импульсных нейтронов: 1) обычные измерения с источником импульсных нейтронов при непрерывном пульсирующем источнике и 2) методы, основанные на псевдослучайном ответе импульса с использованием соотношения между входом и выходом. В обоих случаях получаемая информация идентична, т.е. оба направления идеально служат определению ответной функции.

Разработка методов с источником импульсных нейтронов на тепловых системах в целях измерения реактивности прослеживается от первоначальных попыток Сьестрэнда до недавнего метода ($\kappa\beta/\ell$). При обычном методе с источником импульсных нейтронов функция подкритической сборки Грина, ответ реактора на дельта-функцию источника нейтронов, представляет собой поиск свойств. Экспоненциальный распад, эксп ($-\alpha t$), функции Грина дает пространственно независимую постоянную распада мгновенных нейтронов. Обсуждаются методы, с помощью которых выводится реактивность из альфа-измерения, например измерение запаздывающей критической альфа и последний метод ($\kappa\beta/\ell$). Изучаются основные виды обработки модели в свете теории с источником импульсных нейтронов, которые разработаны для модели ($\kappa\beta/\ell$).

Рассматриваются осложнения, связанные с теорией источника импульсных нейтронов для получения точных постоянных распада и соответствующих данных для анализа импульсных систем. Рассматривается экспериментальная работа, которая показывает преимущества, а также недостатки метода ($\kappa\beta/\ell$).

Обсуждается также использование метода псевдослучайного ответа импульса с корреляцией между входом и выходом для определения функции Грина на размножающей сборке. Показано, что информация, полученная псевдослучайным методом, является идентичной той, которая получена в результате повторного импульсного метода. Таким образом, это делает возможным применять методику, разработанную для повторения метода псевдо-случайности.

ESTUDIO PANORAMICO DE LOS METODOS DE EMPLEO DE FUENTES DE NEUTRONS PULSADOS EN MEDIOS MULTIPLICADORES. En los últimos años ha habido dos tendencias principales acerca de la manera más eficaz de medir la reactividad de parada, empleando fuentes de neutrones pulsados: la primera preconizaba el empleo de métodos tradicionales de medición con fuentes neutrónicas reiteradamente pulsadas, y la segunda propugnaba la aplicación de métodos basados en una técnica seudoaleatoria de respuesta a los impulsos, utilizando una correlación entre los datos de entrada y los de salida. La información obtenida con una y otra técnica es la misma; en teoría, ambos métodos sirven para determinar la función de respuesta.

Se reseña el desarrollo de las técnicas de empleo de fuentes de neutrones pulsados aplicadas a sistemas térmicos con miras a medir la reactividad, desde los primeros intentos de Sjostrand hasta el reciente método ($k\beta/\ell$). Con el método usual de empleo de estas fuentes, la propiedad que se procura determinar es la función de Green del conjunto subcrítico empleado, es decir, la respuesta del reactor a una fuente de neutrones de función delta. El decrecimiento exponencial ($e^{-\alpha t}$) de la función de Green proporciona una constante de decrecimiento de los neutrones instantáneos que es independiente del espacio. El autor examina los métodos para obtener el valor de la reactividad partiendo de la medida de α, como por ejemplo el método de la medición de la criticidad por neutrones retardados α y el reciente método ($k\beta/\ell$). Seguidamente examina el tratamiento del modo fundamental teniendo en cuenta la base teórica de las técnicas de empleo de fuentes de neutrones pulsados que se han perfeccionado para el modelo ($k\beta/\ell$).

Se exponen las repercusiones de la teoría de la fuente de neutrones pulsados en lo que se refiere a la obtención de valores exactos de la constante de decrecimiento y de datos adecuados para el análisis de los sistemas pulsados. También se examina la labor experimental realizada y se ponen de manifiesto tanto las ventajas como las limitaciones de la técnica ($k\beta/\ell$).

El autor estudia también los métodos seudoaleatorios de respuesta a los impulsos, que utilizan una correlación entre los datos de entrada y los de salida para determinar la función de Green de un conjunto multiplicador, y pone de manifiesto que la información obtenida con el método seudoaleatorio es idéntica a la conseguida por el método de la pulsación reiterada. Por consiguiente, los métodos desarrollados para la técnica de la pulsación reiterada se pueden aplicar a la técnica seudoaleatoria.

1. INTRODUCTION

In the classic paper by SJÖSTRAND [1] on pulsed measurements in subcritical reactors, Sjöstrand indicated that it was Von Dardel who suggested the use of a pulsed neutron source to study reactivities and neutron lifetimes of subcritical assemblies. Sjöstrand derived a relation for the reactivity of a subcritical assembly by considering the prompt and delayed multiplication of a pulsed source; a preliminary account of his work was given at the 1955 Geneva Conference [2]. Also at the same conference, SHAPIRO [3] reported on the prompt decay measurements of Antonov et al. These measurements were made on a uranium-graphite assembly using a pulsed neutron source. In an early review paper BECKURTS [4] gives a summary of the pulsed neutron methods as applied to reactor physics research including thermalization measurements. This paper will concentrate on the pulsed neutron methods for reactivity measurements in thermal systems.

In the usual pulsed neutron experiments for the determination of the subcriticality of an assembly, the assembly is repetitively pulsed with short bursts of neutrons and the resulting time profile of the neutron density is measured with an appropriate detector and recorded with a time analyser. The pulsing is continued until adequate counting statistics are obtained and an accurate representation of the time decay profile can be obtained. The pulse rate R should be small compared to the prompt decay constant to allow the prompt neutron density to decay before the next neutron burst. Since the neutron burst approximates a delta function source, the reactor response is essentially the Green's function for the reactor. A typical response curve is shown in Fig. 1.

The Green's function, the impulse response function, of an assembly is also obtained by a technique using a pseudo-random input with cross correlation between the input and resulting output. These methods were first adopted by communication workers in the field of information transmission; the cross correlation methods are described in detail by LEE [5]. The pseudo-random methods are identical in principle to noise measurement methods. A detailed study comparing the pseudo-random method with noise measurements and allied measurements is given by VALAT and STERN [6].

The exponential decay, $\exp(-\alpha t)$, of the Green's function yields the prompt decay constant of the fundamental spatial mode. This measurement lends itself to a direct comparison to a calculated quantity using multigroup methods, i.e. the prompt eigenvalue calculation. In part, this fact has provided an impetus for the α-measurement. An examination of the usual reactor kinetics equations [7] gives an expression for α, the prompt decay constant. For the case where α is large compared to the decay constants of the delayed neutron precursors, α is given by

$$\alpha = [1 - k(1-\beta)]/\ell \tag{1}$$

where k is the effective multiplication constant, β the delayed fraction and ℓ the effective prompt neutron lifetime.

From a theoretical and experimental point of view, the decay constant of the fundamental mode has an advantage in that it is a unique parameter cf

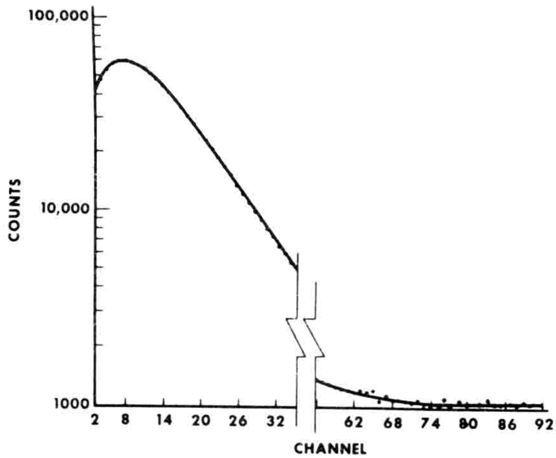

Fig. 1

A typical response curve
(3 wt.% UO_2 stainless steel clad H_2O moderator with 50 ppm B^{10})

$\alpha \sim 1300\ s^{-1} \sim 7$ dollars
R = 50 pulses per second; 45 000 pulses
Channel width = 80 μs; 127 channels

the assembly; however, from a safety point of view, merely knowing the decay constant leaves a great deal unsaid. In particular, it is desirable to have some measure of how far the system is removed from prompt critical, i.e. the reactivity expressed in units of β. Designating α at delayed critical as α_c, then the ratio of (α/α_c) would be a measure of how far the system is removed from prompt critical and hence the quantity

$$(\alpha/\alpha_c) - 1$$

gives a measure from delayed critical. This method of expressing reactivity was introduced by SIMMONS and KING [8]. In general, the determination of α_c is ambiguous since the subcritical reactor with prompt decay constant α can be made critical in many different ways, e.g. changing enrichment, increasing water height, removing control, etc. Each critical configuration will be a different assembly and hence will have a different value of α_c. A thorough discussion of the reactivity concept is given by GOZANI [9].

The recent $(k\beta/\ell)$ technique by GARELIS and RUSSELL [10] for pulsed neutron measurements gives the reactivity directly in units of β as does the method of Sjöstrand. In the $(k\beta/\ell)$ technique, the parameter $(k\beta/\ell)$ is determined using the complete response curve of the pulsed source and the theory is based on a bare monoenergetic diffusion theory model. In the analysis all spatial modes are taken into account as opposed to the fundamental modal treatment of the early method by Sjöstrand. Recent measurements by General Atomic [11, 12] and by the Vallecitos Atomic Laboratory [13] indicate that the $(k\beta/\ell)$ technique gives useful information for bare assemblies