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DOPPLER AND RELATED
MEASUREMENTS IN A
SOFT FAST-REACTOR SPECTRUM

AEC Research and Development Report

ATOMICS INTERNATIONAL

A DIVISION OF NORTH AMERICAN ROCKWELL CORPORATION

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Printed in the United States of America
Available from

Clearinghouse for Federal Scientific and Technical Information
National Bureau of Standards, U.S. Department of Commerce
Springfield, Virginia 22151

Price: Printed Copy \$3.00; Microfiche \$0.65

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MEASUREMENTS IN A
SOFT FAST-REACTOR SPECTRUM

By

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ACKNOWLEDGMENT

The authors wish to express their appreciation to Mr. P. J. Campbell and Mr. G. Schumann who provided much of the detailed design and development of the heated "blanket" apparatus, to Mr. M. E. Rogers who prepared and installed the various Doppler experiments, to Dr. S. G. Carpenter who provided a great amount of technical guidance in this work, and to various other individuals on the staff who spent time operating the reactor and collecting experimental data.

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ABSTRACT

This report deals with a group of both theoretical and experimental investigations which have been carried out, utilizing Core 15, one in a series of critical assemblies that have been constructed at Atomics International's Epithermal Critical Experiments Laboratory (ECEL). Core 15 contains a U^{235} - U^{239} fueled, fast-spectrum test region, characterized by a median fission energy (mfe) of 18 kev. The investigations included studies of the neutron energy spectrum, the reactivity worths, and the Doppler coefficients of various candidate liquid metal, fast breeder reactor (LMFBR) materials. The latter two studies were performed on small heated samples, not only in the unperturbed core but also in an environment in which the samples were surrounded by "blankets" of fertile materials which could be heated to 400°C. The heated blanket technique permitted detailed experimental investigation of the so-called "hot sample - cold reactor" problem.

These experiments show that, as a result of flux depressions at the resonances, large decreases in the Doppler coefficients of Th and U^{238} occur when a blanket of the same material as the sample is introduced in the immediate environment. When the surrounding blanket of the same material is heated to 400°C, a further decrease in the Doppler coefficient is observed. The implication is that a similar reduction in the Doppler effect of a particular isotope would occur in a LMFBR in which that isotope exists in large quantities.

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I. INTRODUCTION

A. JUSTIFICATION AND SCOPE

One of the dominant factors in the prompt temperature coefficient of a fast reactor is the Doppler broadening of the fuel material resonance cross sections resulting from thermal agitation of target nuclei; the other dominant factor is the thermal expansion of the fuel element. A detailed understanding of both of these phenomena is required, in order to predict adequately, under all circumstances, the kinetic behavior of a fast reactor, as well as to achieve safe, inherently stable operation. Since the Doppler and expansion coefficients of reactivity are both dependent upon the energy distribution of the neutrons in the reactor, it has been necessary to study these factors in various environments, covering the complete range of spectra that would encompass nearly all fast power reactor concepts. In general, as the spectrum becomes softer, the Doppler coefficients of the fertile elements (in particular, U^{238} , the material which contributes by far the largest effect in a commercial fast reactor) become substantially more negative; consequently, some fast reactor concepts have included the addition of moderators, such as beryllium, in order to take advantage of this more negative coefficient. The interest exhibited in such schemes indicates that a knowledge of the prompt temperature coefficient of reactor fuel, structural, and cladding materials, over a large range of realistic neutron energy distributions, is desirable, in order to evaluate adequately the various economic factors involved in the development of a reliable, safe, and economical fast power reactor.

This report deals with a short series of studies in a U^{235} - U^{238} fueled critical assembly, designated Core 15, characterized by a U^{235} median fission energy (mfe) of 18 kev. These studies included both theoretical and experimental investigations of the neutron energy spectrum, and the reactivity and Doppler coefficients of various samples of liquid metal, fast breeder reactor (LMFBR) materials, both in the unperturbed core and in an environment in which the sample was surrounded with blankets of fertile materials. Some studies pertaining to a determination of the capture-to-fission ratio in Pu^{239} and U^{235} in Core 15 were also carried out, but will be reported separately.

Figure 1. ECEL Critical Assembly

Figure 2. Pseudospherical Configuration of the Multi-Region Critical Assembly

B. CRITICAL ASSEMBLY DESCRIPTION

The Epithermal Critical Experiments Laboratory (ECEL) reactor, a split-table critical assembly, has been described in detail elsewhere;⁽¹⁾ it consists, in brief, of a spherical, fast-spectrum test region surrounded by a spherical shell of Th metal which serves to decouple the test region from a polyethylene-moderated, U^{235} fueled, thermal energy "driver." The spherical shell of Th metal, in turn, is surrounded by a polyethylene reflector region. The overall diameter of this arrangement of spherical shells is roughly 4 ft, with the fast-spectrum test region being about 2 ft in diameter. The detailed structure of the reactor consists of a collection of 2 in. by 2 in. by 3-ft long square aluminum matrix tubes, stacked on each of two tables in such a way that two 5 ft by 5 ft by 3 ft rectangular parallelepipeds are formed in the manner shown in Figure 1. Aluminum drawers, containing the appropriate reactor materials, usually in the form of plates 2 in. by 2 in. by 1/8-in. thick, are inserted into the matrix to form a hemisphere on each table, in the manner shown in Figure 2. Thus, when the tables are closed, a spherical assembly of the type shown is formed.

The spherical test region is made up of selected materials (such as U^{235} , U^{238} , stainless steel, sodium, aluminum, and graphite) which simulate or duplicate the materials constituting the core of a hypothetical fast reactor of interest. By varying the material composition, the neutron energy distribution can be readily changed, thereby simulating the neutron spectrum that one might expect to achieve in an actual fast reactor.

Studies of the Doppler coefficient of a large variety of samples have been made in numerous ECEL cores, with neutron spectra extending from median fission energies as high as 200 kev to as low as 4 kev.

C. EXPERIMENTAL TECHNIQUES

Studies of reactivity effects are carried out by oscillating a sample of the material of interest into and out of the center of the test region on a 1-min cycle, using a pneumatic piston with a stroke of 3 ft.⁽²⁾ Two "pockets," located 3 ft apart in an oscillator bar, hold the samples of interest. During oscillation, first one sample and then another (a so-called reference sample) is placed in the center of the fast spectrum test region. The ensuing reactor power variation is detected by a BF_3 chamber located in the thermal driver region. The

signal from the BF_3 chamber is converted to a voltage in the 0- to 1-v range by a vibrating reed electrometer whose output is fed into a voltage-to-frequency converter that generates a 100-kc signal with 1 v input. The latter frequency, which is proportional to the reactor power, is "counted" in a 200-channel analyzer operating in the time mode. The firing of the bar and the starting of the analyzer are synchronized in such a way that multiple oscillations can be stored for periods commonly of the order of 20 min. The uncertainty on a reactivity value, determined by this technique, is of the order of $\pm 0.0003\%$ when data are taken for 40 min at a reactor power of 150 w.

The reactivity worths of various materials are determined by placing a sample of the material of interest in one of the oscillator bar pockets, leaving the other pocket empty, and oscillating the bar for some specified period of time, determined by the statistical accuracy desired. By performing an identical run with both pockets empty, the absolute worth of the sample is achieved, the calibration of the oscillator having already been well established.

Measurements of the Doppler coefficients are made in a similar way, with the two pockets now occupied by identical samples, each surrounded by small compact heaters, as shown in Figure 3. First, the bar is oscillated for some number of cycles with both samples at room temperature, and a reactivity value is established (both pockets need not be "balanced" exactly). Then one of the samples is raised to some prescribed elevated temperature (by means of the resistance heaters), and a new series of oscillations is then begun, a procedure which produces a new reactivity value. The difference between the above two reactivity values is a measure of the temperature coefficient of the sample, so long as there is no significant reactivity effect arising from the heat energy expended or from a temperature rise in the surrounding heater materials. The latter effects are, in fact, generally small, but are routinely measured and incorporated in a correction factor.

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Figure 3. Doppler Oscillator Bar

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II. NEUTRONIC CHARACTERISTICS OF CORE 15

A. THEORETICAL METHODS

The fast-spectrum test region of Core 15 is composed of U^{235} , U^{238} , carbon, aluminum, iron, chromium, and nickel (the latter three combined in stainless steel) in atom ratios of 1.00:3.27:35.22:21.56:11.19:2.72:1.21; it is characterized by median fission, median flux, and median absorption energies of 18, 11, and 125 kev, respectively; and it has a central, calculated, coarse (35) group spectrum as given in Figure 4. Core characteristics were calculated by means of the one-dimensional diffusion theory code, CAESAR.⁽³⁾ A 35-group cross-section library was prepared, in several steps, for these calculations; and, because of the very different moderating and absorbing properties of the various core regions, and the different spectra therein, these effective group cross sections were calculated separately for each region.

These cross sections were calculated, using GRISM,⁽⁴⁾ a code which:

- 1) Provides for flux depression at resonance energies
- 2) Computes the scattering transfer matrix
- 3) Averages each cross section according to an input spectrum.

Figure 4. Core 15 Flux Spectrum

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The particular library used had been prepared for Core 14, which differed from Core 15 only in a small change in the quantities of carbon and aluminum present in the test region. Because of the large amount of computer time required by GRISM at the time these calculations were done, a new library was not prepared for Core 15. In addition, since the predicted reactivity change between Core 14 and Core 15 (-10.3¢) agreed well with the observed change (-11.3¢), it was decided to continue the use of the Core 14 library for calculations of Core 15. Part of the averaging spectrum used in GRISM was calculated, using AILMOE⁽⁵⁾ (The Atomics International version of ELMOE, the fast slowing-down code that accounts for scattering resonances of the lighter elements). This program provides ultra-fine-group scattering cross sections and coarse-group absorption cross sections. The coarse-group cross sections (22 groups in the energy range covered by 603 AILMOE groups) that provide absorption and heavy-element scattering information were prepared by F. Fillmore.⁽⁶⁾

Because of the small size of the plates used in the test region, and their nearly-random distribution, the test-region material was treated as homogeneous in the GRISM calculation, and no spatial self-shielding was applied.

Averaging by GRISM was based on a fission spectrum above 3.68 Mev, the AILMOE spectrum from 3.68 Mev to 101 ev, a spectrum proportional to the energy between 101 and 22 ev, a constant spectrum from 22 to 0.41 ev, and a Maxwellian spectrum below 0.41 ev.

Cross sections for the decoupler region that had been prepared by H. Hennies⁽⁷⁾ were used in these calculations.

Because the decoupler is a thin spherical shell, an equilibrium spectrum is not established. Thus, Hennies prepared cross sections for the inner part, using a test-region spectrum (that of Core 5 of the AETR Program);^(1,7) while cross sections for the outer part were prepared, using a spectrum calculated for the driver region that surrounds the decoupler.

The cross sections used for the driver and reflector regions had also been prepared by Hennies. The averaging spectrum for GRISM was calculated by means of FORM,⁽⁸⁾ a fast slowing-down code accounting for moderation by hydrogen, and by means of TEMPEST II,⁽⁹⁾ a thermal spectrum code.

Initial calculations for Core 14, using this cross-section library, produced somewhat poorer agreement between the calculated and observed criticality constant (k_{eff}) than had been obtained with the older 18-group library previously used. This phenomenon had also been noted by Hennies in his analysis of the AETR critical experiments.⁽⁷⁾

Since the decoupler is relatively thin, the location of the boundary between the two cross-section sets used for the decoupler is rather arbitrary. Hennies had chosen the midpoint of the decoupler for this boundary, and this was also used for the initial calculations for Core 14. The criticality constant is very sensitive to this division; and moving the boundary inward 1.23 cm, to a position 38% from the inner boundary of the decoupler, produced excellent agreement with experiment. This location was therefore used for the calculations for Core 15. However, subsequent calculations have shown that, in spite of the dependence of k_{eff} on the location of the boundary between cross-section sets, the central spectrum is not significantly affected.

The AILMOE calculation, which was carried out for the Core 15 test region, provided the basic data for the fine-structure spectrum of Figure 5a, as well as the smoothed spectrum of Figure 5b. In Figure 5a, the lower-energy resonance-structure is due to iron and aluminum, while most of the structure at higher energy is due to carbon.

The importance, or adjoint flux spectrum, is shown in Figure 6. This spectrum has been normalized to a flux-weighted average value of unity.

B. COMPARISON OF THEORETICAL SPECTRA WITH EXPERIMENTS

Some experimental information on the actual neutron energy distribution in the center of Core 15 has been obtained by the use of a proton-recoil spectrometer (see Appendix) and the results^{*} are included in Figure 5b. The measured results are absolute for 1 w of reactor power, and seem to verify a considerable amount of the calculated resonance structure. The calculated spectrum, which was referenced previously, has been smoothed by applying a 20% resolution

*The proton-recoil energy pulses collected by the spectrometer are analyzed by means of a computer code⁽¹⁰⁾ which derives a spectrum corresponding to the distribution of neutron energies in the reactor.

a. AILMOE Calculated Spectrum

b. Proton-Recoil Experimental Spectrum

Figure 5. Core 15 Spectrum

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Figure 6. Core 15 Importance Spectrum

factor, roughly corresponding to the energy resolution achieved by the proton-recoil counter. In addition, a rather arbitrary normalization factor of 0.8 has been applied, indicating that, in magnitude, the directly calculated spectrum is somewhat too high. Some of this difference may be attributable to errors in the calibration of the reactor power monitor, although there are other indications, such as reactivity worth data, which tend to show that the calculated spectrum is systematically too high in this energy range, by a factor of some 20 to 30%.

Additional spectrum studies, using standard U^{235} , Np^{237} , and Pu^{239} fission counters, were carried out in this core, and the results are delineated in Table 1. Since the response functions for these materials are broad, only gross spectrum checks, by way of a comparison of the calculated and measured ratios of fissions in Np^{237} and Pu^{239} to the fission in U^{235} , are practical. These values are listed in the table as a function of the radial position, where the center of the core is designated as zero. Although the Pu/U ratio appears to be reasonably well calculated, that for Np/U is not; consequently, the neutron population may, in fact, be somewhat higher at the high energies than the calculations would indicate.

TABLE 1
FISSION COUNTER MEASUREMENTS

Core Position (cm)	Pu/U Fission Ratio		Np/U Fission Ratio		Relative Fission Rate in U ²³⁵	
	Measured	Calculated	Measured	Calculated	Measured	Calculated
0	0.734 ± 0.010	0.770	0.105 ± 0.001	0.134	1	1
5.08	-	-	0.107 ± 0.002	0.131	1.002	1.006
10.16	-	-	0.091 ± 0.002	0.137	0.830	1.013
17.78	-	-	0.110 ± 0.002	-	0.945	0.999
25.24	-	-	-	-	0.463	0.868
33.17	-	-	-	-	0.116	0.117
39.12	1.253 ± 0.039	1.317	0.006 ± 0.001	0.045	0.026	0.031

III. MEASUREMENTS AND CALCULATIONS OF REACTIVITY WORTHS

A. MEASUREMENTS OF ABSOLUTE REACTIVITY WORTHS

The absolute reactivity worths of a variety of samples of interest to the LMFBR Development Program have been determined in the Core 15 spectrum, and are listed in Table 2. Most of these samples represent materials that are used to clad other samples, or are promising LMFBR cladding or structural materials. Other samples, such as Th, W, and C, serve as spectrum indices, in the sense that one might be able to calculate their reactivity worths with some degree of confidence, for comparison with the experiment. As gross spectrum indices, their worths are routinely determined in all the cores which are constructed in the ECEL reactor. The two uranium isotopes and Pu are, of course, of paramount importance in any fast reactor studies. Certain other reactivity values, such as those for polyethylene and Teflon, are included for information as to their scattering properties, their values from a practical standpoint being minimal. Polyethylene is used extensively in the driver and exclusively in the reflector of this particular critical assembly. Tantalum, on the other hand, is being considered for use as a control rod material in commercial fast breeder reactors, since it has a rather large absorption cross section in the high energy region. The samples designated Physicum I and II are fission product mockup samples containing the materials discussed in Reference 11.

An additional interest in the absolute reactivity worth of various samples lies in the fact that Doppler effects can be expressed in terms of the energy distribution of the neutron spectrum in which the measurement is made (i. e., the Doppler coefficient, as defined here, is given by $|1/\rho| d\rho/dT$, where ρ is the reactivity and T is the temperature). This quantity does not depend upon the reactor itself or its configuration, and it is characteristic of the sample and the spectrum (both real and adjoint).

B. MEASUREMENTS AND CALCULATIONS OF REACTIVITY EFFECTS ARISING FROM EXPANSION OF SAMPLES

When a sample is heated for the purpose of measuring the ensuing reactivity changes, a change in the physical size of the material occurs as a result of thermal expansion. The extent of this expansion is, of course, a property of

TABLE 2
REACTIVITY WORTHS OF SELECTED MATERIALS

Sample	Size (in.)		Mass (gm)	Worth/Unit Mass (measured) (¢/gm)
	Diameter	Length		
Stainless Steel	0.438	4.00	77.8551	$-3.035 \times 10^{-4} \pm 8.86 \times 10^{-6}$
Aluminum	0.500	2.00	16.8323	$-1.616 \times 10^{-4} \pm 4.34 \times 10^{-5}$
Zirconium	0.500	2.00	41.8072	$-3.320 \times 10^{-4} \pm 1.75 \times 10^{-5}$
Graphite	0.500	2.00	11.2435	$+8.721 \times 10^{-4} \pm 6.49 \times 10^{-5}$
Polyethylene	0.500 OD ~0.480 ID	1.75	0.9719	$+0.04994 \pm 0.00072$
Polyethylene	0.500	2.00	6.2734	$+0.05468 \pm 0.00012$
Teflon	0.500 OD ~0.460 ID	1.75	4.0639	$+5.0272 \times 10^{-4} \pm 1.796 \times 10^{-4}$
Inconel	0.500	1.89	47.1463	$-4.206 \times 10^{-4} \pm 1.55 \times 10^{-5}$
Physicum I	0.480	2.03	11.989 (metal + oxygen)	$-4.923 \times 10^{-3} \pm 6.59 \times 10^{-5}$
Physicum II	0.480	2.03	10.768 (metal + oxygen)	$-4.365 \times 10^{-3} \pm 7.34 \times 10^{-5}$
Tantalum	0.438	4.00	163.2689	$-5.0218 \times 10^{-3} \pm 4.23 \times 10^{-6}$
Tungsten	0.438	4.00	188.4561	$-1.791 \times 10^{-3} \pm 3.66 \times 10^{-6}$
U ²³⁸ *	0.438	4.00	184.7387	$-1.0408 \times 10^{-3} \pm 3.14 \times 10^{-6}$
U ²³⁸ †	0.438 OD 0.250 ID	4.00	117.8490	$-1.0787 \times 10^{-3} \pm 5.43 \times 10^{-6}$
Thorium	0.438	4.00	114.0419	$-1.867 \times 10^{-3} \pm 5.09 \times 10^{-6}$
U ²³⁵ (1/8 in.)§	0.125	4.00	13.7821	$+1.1125 \times 10^{-2} \pm 4.44 \times 10^{-5}$
U ²³⁵ (1/4 in.)	0.250	4.00	59.1139	$+1.1787 \times 10^{-2} \pm 1.053 \times 10^{-5}$
U ²³⁵ (annular)	0.438 OD 0.250 ID	4.00	117.7661	$+1.0733 \times 10^{-2} \pm 5.28 \times 10^{-6}$
U ²³⁵ (annular + 1/4 in.)	0.438	4.00	176.8800	$+1.0615 \times 10^{-2} \pm 3.46 \times 10^{-6}$
U ²³⁵ (full size)	0.438	4.00	183.3159	$+1.0635 \times 10^{-2} \pm 3.39 \times 10^{-6}$
PuO ₂ (No. 2)	0.3675	3.6391	66.1960	$+1.4459 \times 10^{-2} \pm 8.81 \times 10^{-6}$
PuO ₂ (No. 4)	0.3745	3.7904	66.1916	$+1.4493 \times 10^{-2} \pm 8.81 \times 10^{-6}$

*0.22 wt % U²³⁵

†0.49 wt % U²³⁵

§93.19 wt % U²³⁵ for all samples designated "U²³⁵,"

the chemical and physical state of the sample. (For example, U^{235} might be present as metal, oxide, or carbide, and in the α or β phase.) It has been shown, in numerous experiments,⁽¹²⁻¹⁵⁾ that this expansion produces, in many cases, a measurable and significant reactivity change that is independent of the temperature change, per se. This so-called expansion coefficient of reactivity is both prompt and inherent — prompt, in the sense that the sample expansion rapidly follows a temperature rise, and inherent, in the sense that it occurs in a spatially flat flux and adjoint spectrum. The expansion phenomenon in fissionable materials is most pronounced in rather hard spectra where two competing reactivity effects occur.

1. Self-Multiplication Effects*

The first reactivity effect, known as self-multiplication, is a measure of the probability that a fast neutron that is born in the sample will undergo another collision there before leaving. To illustrate this phenomenon, consider an infinitely long, cylindrical, fissile sample of radius (r), in which fast neutrons are being born by fission. The probability(P_c) that one of these neutrons will collide within the sample is given approximately, and within certain size restrictions, by the quantity ($kN\sigma r$), where k is a constant, N is the number of fissionable atoms per cubic centimeter, and σ is the microscopic cross section. When the sample expands, r increases, but N decreases and does so more rapidly; consequently, P_c becomes smaller. Fewer total neutrons are therefore generated in the sample; and its reactivity worth, from this standpoint alone, is seen to be less, thus giving a negative temperature coefficient.

2. Self-Shielding Effects

A second reactivity phenomenon, the more familiar self-shielding factor, offsets, to some extent, the former trend, however, and tends to increase the worth of the fissile sample, thus producing a positive reactivity effect. This effect occurs because the expanded sample is more dilute, and there is therefore an increase in the effective absorption cross section of the sample.

*The significance of these effects, with regard to current techniques for measuring the Doppler coefficient, was first pointed out to us by G. E. Hansen of LASL.

These effects are included in the usual first-order perturbation equation, as correction terms to the fission and absorption cross sections in the following way:

$$\rho \approx \frac{N_a M}{DA} \sum_{i=1}^g \left[\nu \phi_i^* \phi_i \sigma_{f_i} (1 - P_{c_i}) \left(\frac{1 - P_{c_F}}{1 - \eta_F P_{c_F}} \right) - \phi_i^* \phi_i \sigma_{a_i} (1 - P_{c_i}) \right] \dots (1)$$

In this explicit escape-probability formulation, which has been simplified to exclude the transfer and diffusion terms,

$1 - P_{c_i}$ = self-shielding term (also called the escape probability, P_o)

$\frac{1 - P_{c_F}}{1 - \eta_F P_{c_F}}$ = self-multiplication term

M = mass of the sample

A = atomic weight

D = normal denominator expression.

All other symbols have their usual connotations. The term (P_c) is the collision probability, and has been calculated for numerous shapes by several investigators.^(16,17) The subscript (F) refers to fission-spectrum-averaged quantities; thus, the self-multiplication factor involves the fission-spectrum-averaged collision probability (i. e., $P_{c_F} = \chi_i P_{c_i}$) and the fission-spectrum-averaged number of neutrons produced per fission (η_F). For practical cases, it can be shown that $(1 - P_{c_F})/(1 - \eta_F P_{c_F})$ is somewhat greater than unity, whereas $(1 - P_{c_i})$ varies from values slightly less than unity (for the high-energy cross sections) to values approaching zero (for large samples and low-energy cross sections). Which factor dominates the overall reactivity worth depends upon the spectrum, since P_c is a property not only of the physical shape of the sample but also of the cross section. P_c is therefore energy dependent. In

neutron spectra characteristic of metal-fueled, unmoderated, fast breeder reactors, the self-multiplication term overrides the self-shielding term; and a net negative expansion coefficient ensues, as has been demonstrated previously.⁽¹²⁻¹⁵⁾ In softer spectra, such as the one under investigation here, the reverse is true, and the expansion of the sample increases its worth.

3. Direct Measurement

There are numerous ways in which the expansion coefficient of reactivity can be conveniently measured for a particular fissile isotope, and all involve some change in either or both of the terms (N) and (r) as they appear at the beginning of the previous section for the case of the infinite cylinders, or, for the case of any physical shapes, some change in either or both of the terms (N) and (ℓ) , where ℓ , a more fundamental term, is the mean chord length. Since ℓ is equal to $4(V/S)$, where V is the volume and S is the surface area of the sample, the mean chord length for an infinite cylinder is just equal to $2r$. A change in the product $(N\ell)$ yields a change in P_c ; and, according to Equation 1, a new reactivity value will occur. One of the most direct methods of measuring this expansion coefficient is to determine, at room temperature, the reactivity difference between two samples, A and B, which have virtually the same mass but differ in dimensions in such a way that Sample B, at room temperature, corresponds to the size that Sample A would have if the latter were at some elevated temperature (e.g., 1000°C). The thermal expansion, which changes both N and ℓ in Sample A, is thereby simulated without a corresponding rise in temperature.

4. Indirect Methods

Another technique involves the measurement of the reactivity change in a fissile material across a phase change in which, in certain materials, a nearly isothermal dimensional alteration can take place. However, probably the simplest method of establishing the expansion coefficient of reactivity requires only the measurement of a group of samples in which the value of ℓ differs from one sample to the next. The latter technique has been employed for U^{235} in this core; and the results, which are derived from data in Table 2, are plotted in Figure 7 as a function of $N\ell$, where a polynomial fit of order 2 has been applied to the data by the least squares method. Since the change in $N\ell$ that a

Figure 7. Specific Worth of U^{235} vs Nl for Core 15-6

Figure 8. Specific Worth of Pu^{239} vs Nl for Core 15-6

TABLE 3
DOPPLER, EXPANSION, AND TEMPERATURE
REACTIVITY EFFECTS - CORE 15

Sample	Mass (gm)	γ	20 to 600°C			$\left \frac{1}{\beta} \left(\frac{\Delta \rho}{\Delta T} \right)_D \right $ (/°C)
			$(\Delta \rho)_T$ (ϵ)	$(\Delta \rho)_E$ (ϵ)	$(\Delta \rho)_D$ (ϵ)	
U^{235}	181.7202	1.40*	+0.0097	+0.00084	+0.0078	$+7.38 \times 10^{-6}$
$U^{235}O_2$	101.3604	0	+0.0026	+0.00038	+0.0022	$+4.28 \times 10^{-6}$
PuO_2 (No. 1)	66.82	0	-0.0051	+0.00036†	-0.0056	-1.25×10^{-5}
PuO_2 (No. 6)	61.85	0	-0.0055	-	-0.0055	§
PuO_2 (No. 9)	62.07	0.90	-0.0077	-	-0.0077	§
Th	114.0172	1.20	-0.0216	-	-0.0221	-1.79×10^{-4}
U^{238}	179.1275	1.10	-0.0214	-	-0.0219	-1.97×10^{-4}

* $\gamma = 1.40$ applies to temperature coefficient. The best fit for the Doppler coefficient occurs for $\gamma = 1.50$

†Based on experimental data

§Absolute reactivity worths were not determined

Doppler sample undergoes over some arbitrary temperature interval (such as 20 to 600°C) can be calculated from its linear coefficient of thermal expansion, the change in reactivity resulting from expansion alone $[(\Delta\rho)_E]$ can readily be derived from the graph. Furthermore, since the change in Nl caused by thermal expansion is usually small, compared to changes represented by practical samples, a constant slope corresponding to the derivative at the Nl value of the cold sample is usually used as a matter of convenience. The reactivity changes derived in this manner are given in Column 5 of Table 3 for the arbitrary temperature interval of 20 to 600°C.

Due to a paucity of samples, only two data points applying to expansion in PuO_2 have been obtained, and these are given in Figure 8. The two samples employed here have nearly identical mass, but differ in length and diameter in such a way that PuO_2 Sample No. 4 simulates the size that PuO_2 Sample No. 2 would have if the latter were at some fictitious temperature of several thousand degrees. Thus, in these samples, both N and l change, the density of one being 92% of theoretical and of the other 84%. A straight line has been drawn between experimental points, and is used to establish the value of $(\Delta\rho)_E$ for the PuO_2 Sample No. 1, as given in Column 5 of Table 3. Inasmuch as the quantity of Pu^{239} in Samples 6 and 9 of Table 3 is considerably reduced, no expansion correction for the latter samples has been applied.

5. Comparison of Theory and Experiment

Also included in Figures 7 and 8 are the dashed lines which represent analytical calculations of the variation of ρ_m , the worth per unit mass, as a function of Nl . The calculation consists of two parts; the first is a determination of P_c values for a series of samples, and the second is a standard perturbation calculation, using calculated fluxes and adjoints as well as "infinitely dilute" cross sections, which are modified by the P_c values in the manner indicated in Equation 1. In order to carry out the first part of the calculation, the ESCAPE code has been written to calculate $(1 - P_c)$ and $(1 - P_{cF})/(1 - \eta_F P_{cF})$, using formulas and tables essentially identical to those given by Case, de Hoffman, and Placzek for infinite cylinders, slabs, and spheres,⁽¹⁶⁾ and by M. E. Gubbins for finite cylinders.⁽¹⁷⁾ The code further provides punched card output which contains the σ_c values (which were input data to the code) multiplied by $(1 - P_{c_i})$

by group and $\nu\sigma_f$ values (which were also input) multiplied by $(1 - P_{c_i})[(1 - P_{c_F}) / (1 - \eta_F P_{c_F})]$ by group. The latter deck is then combined with a point perturbation code^F(CTRWORTH)⁽¹⁸⁾ to produce reactivity worths. The so-called "infinitely dilute" 35-group cross sections for σ_a and $\nu\sigma_f$ used in these calculations are an AI set, weighted by the 4-kev mfe Core 14 spectrum. The calculated curves have been arbitrarily adjusted by an additive constant, in order to force agreement with the measurement at the largest $N\ell$ value for each isotope. An additive adjustment is used, since a direct comparison of measured and calculated slopes is made possible. The agreement is seen to be very good for U^{235} ; but, for Pu^{239} , the signs of the slopes are different, and this occurrence is as yet unexplained. Fortunately, in this particular spectrum, the expansion reactivity effect is not large.

IV. TEMPERATURE COEFFICIENTS OF REACTIVITY

A. MEASUREMENTS

The measured reactivity change which accompanies a change in the temperature of a sample, an effect which we call the temperature coefficient of reactivity and which obviously includes the expansion effect, has been measured for a selected group of materials by the technique described in Section I-C (i. e., the sample of interest is placed in a small heater and oscillated in and out of the reactor core, in order to ascertain net temperature-dependent reactivity changes). The results are given in Figures 9 through 15, and the data pertaining to the physical composition and size of the samples involved are listed in Table 4. A code, DOPFIT, has been written to perform a least squares fit of the form $\rho = A + BT^{(1-\gamma)}$ to the experimental points for a range of values of γ from 0 to 1.5, in increments of 0.1. When $\gamma = 1.0$, the code is programmed to fit the equation $\rho = A + B(\log T)$. The value of γ (to the nearest 0.1) which yields the best fit in the range is given in Table 3, and is used, along with the constants $A + B$, to form the solid line drawn in each figure. Although the expansion reactivity effect described previously can be represented adequately by a constant slope over the changes in Nl which are produced by the normal temperature ranges in which experiments are conducted, it can be seen from the figures that, for most substances, fertile and fissionable materials included, the temperature coefficient is usually not linear with the temperature. It therefore follows that no single parameter suffices to describe the temperature coefficient exactly. As a matter of convenience, however, the reactivity change over the particular temperature interval of 20 to 600°C is frequently used as an indication of the relative sizes of the various phenomena which combine to produce the total observed temperature reactivity effect. Thus, over the previously mentioned temperature interval, values of $(\Delta\rho)_T$ [where the subscript (T) refers to the temperature effect] are derived from the data in Figures 9 through 15 and are listed in Column 4 of Table 3, along with the previously described values for $(\Delta\rho)_E$. Assuming that the only reactivity effects which take place when a sample is heated are expansion and Doppler, a simple algebraic subtraction of $(\Delta\rho)_E$ from $(\Delta\rho)_T$ is made, in order to yield the Doppler effect $[(\Delta\rho)_D]$ as shown in Column 6. The actual Doppler coefficient $[1/\rho](\Delta\rho/\Delta T)_D$

Figure 9. Doppler Effect in U238 Metal, Core 15

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Figure 10. Doppler Effect in Th Metal, Core 15

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Figure 11. Doppler and Temperature Coefficients, U238 Metal

Figure 12. Doppler and Temperature Coefficients, U235O₂

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Figure 13. Doppler and Temperature Coefficients, PuO₂ No. 1

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Figure 14. Doppler Effect in PuO₂ No. 6, Core 15

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Figure 15. Doppler Effect in
PuO₂ No. 9, Core 15

TABLE 4
SAMPLE SPECIFICATIONS

Sample	Mass (gm)	Diameter (in.)	Length (in.)	Composition (wt %)							
				Pu ²³⁸	Pu ²³⁹	Pu ²⁴⁰	Pu ²⁴¹	Pu ²⁴²	U ²³⁵	U ²³⁸	Th
PuO ₂ (No. 1)	66.8240	0.3678	3.6345	0.013	91.400	7.900	0.657	0.033	-	-	-
PuO ₂ (No. 6)	61.8518	0.3633	3.4909	0.09	57.79	31.63	7.09	3.40	-	-	-
PuO ₂ (No. 9)	62.0718	0.3639	3.4970	0.31	40.66	41.90	10.28	6.85	-	-	-
U ²³⁵	181.7202	0.438	4.00	-	-	-	-	-	93.19	6.81	-
U ²³⁵ O ₂	101.3604	0.436	4.003	-	-	-	-	-	92.5	7.5	-
Th	114.0172	0.438	4.00	-	-	-	-	-	-	-	100
U ²³⁸	178.9909	0.433	4.035	-	-	-	-	-	0.22	99.78	-

can then be calculated, and these values are delineated in the last column of the table. The latter quantities would be expected to be valid in any reactor having the same flux and adjoint spectrum as that existing here. It should be noted further that, although we are seeking to establish the Doppler coefficient, the total temperature effect dictates the prompt reactivity response in the core of actual power reactors; consequently, in this sense, it is the more important parameter.

The expansion coefficient of reactivity has been shown to be quite small (<5% of the total) for most pure absorbers and the fertile elements; thus, the Doppler coefficient is very nearly the same as the temperature coefficient in these instances, and no corrections of this type have been made to the data in Figures 9, 10, 14, and 15. For many U^{235} and Pu^{239} samples, on the other hand, the algebraic subtraction of the expansion must be performed over the entire temperature range, in order to derive a more exact evaluation of the purely Doppler-induced reactivity changes as a function of temperature. A correction factor, based upon the slope of the expansion effect vs temperature curve (Figure 7), has been used by the DOPFIT code to generate a Doppler effect curve, as given by the dashed lines in Figures 11, 12, and 13.

As would be expected, the Doppler coefficients of the fertile elements are negative, and considerably larger in magnitude (by a factor of about 2) than those which were observed previously in the harder spectra that are more characteristic of the unmoderated fast breeder reactors.⁽¹⁹⁾

The fissile isotopes are known to have positive Doppler coefficients at high neutron energies, but, in theory at least, can assume negative values at sufficiently low energies, where broadening of the predominantly absorption resonances can be more important than broadening of the fission resonances. The coefficient for U^{235} is apparently still positive, however, even in this 18-kev mfe region; whereas it is negative for the 91.4% Pu^{239} sample and, as would be expected, negative for the Pu samples containing higher percentages of Pu^{240} .

B. COMPARISON WITH THEORY

A calculation of the Doppler effect in each of the samples listed in Table 4, as well as a calculation of the absolute worths of samples of Th and U^{238} , was performed for this core. For the Doppler effect, temperature-dependent multi group resonance cross sections were calculated with the $TRIX^{(20,21)}$ code,

which analytically integrates isolated, single-level, Breit-Wigner line shapes. Resolved resonance parameters were taken from the library listed in Reference 20. Unresolved resonances were averaged over chi-squared distributions of scattering and fission widths. Above the resonance region, cross sections (σ_a ; σ_f ; $\sigma_{n,2n}$) for Th and U^{238} sample worth calculations were AIENDF/67 cross-section library⁽²²⁾ values, weighted with a fission spectrum by the GRISM code.

The unresolved resonance parameters employed here are given in Table 5. Average fission widths for U^{235} and Pu^{239} were calculated from the channel fission theory model of Hill-Wheeler, using the fission barrier parameters of References 23 and 24. For all isotopes, $\langle \Gamma_n^0 \rangle$ and $\langle D \rangle$ was assumed to be proportional to $(2J + 1)^{-1}$.

The temperature-dependent cross sections thus generated were used in a first-order perturbation theory calculation to obtain the worths in the central spectrum. These calculations were performed by the CTRWORTH code. Doppler effect results are given in Table 6, along with appropriate measured values which were taken from Figures 9 through 15. Absolute reactivity worth values for U^{238} and Th metal samples were calculated to be -0.212 and -0.201¢ respectively. The corresponding experimentally measured values are -0.19227 ± 0.00058 and -0.21295 ± 0.00058 ¢ respectively.

In general, the agreement between calculation and experiment is surprisingly good, considering the economical calculational methods employed. The comparison lends confidence in the use of one-dimensional diffusion theory and isolated, single-level, resonance line shapes. The relatively good agreement for the fissile isotopes is attributable, in a large degree, to use of the fission channel theory treatment of the average fission widths.⁽²⁴⁾

The presence of reasonably large quantities of U^{238} in the test region of the core depresses the flux at the U^{238} resonance energies and reduces the reactivity worth of samples containing this isotope. An upper limit of 15% reduction in the sample worth was estimated by calculating the flux depression at the peak of an average resonance at the median energy point of the $\sigma_{a_i} \phi_i \phi_i^*$ distribution. Since the resonance is highly broadened (the peak is about one-tenth of the 0°K peak), the wings of the resonance make large contributions;

TABLE 5
UNRESOLVED RESONANCE PARAMETERS (ev)

ℓ	J	$10^4 s$	$10^3 \langle \Gamma_n^\circ \rangle$	$\langle D \rangle$	$\langle \Gamma_\gamma \rangle$	$\langle \Gamma_f \rangle$	ν_n	ν_f
U^{238}								
0	1/2	0.874	1.975	22.6	0.025	-	1	-
1	1/2	1.7	3.842	22.6	0.025	-	1	-
1	3/2	1.7	1.92	11.3	0.025	-	1	-
Th								
0	1/2	0.677	1.11	16.4	0.0245	-	1	-
1	1/2	1.1	1.804	16.4	0.0245	-	1	-
1	3/2	1.1	0.902	8.2	0.0245	-	1	-
U^{235}								
0	3	1.0	0.114	1.14	0.042	0.364	1	2
0	4	1.0	0.089	0.89	0.042	0.141	1	1
1	2	1.8	0.288	1.60	0.042	0.255+*	1	2
1	3	1.8	0.206	1.14	0.042	*	2	1
1	4	1.8	0.160	0.89	0.042	0.141+*	2	2
1	5	1.8	0.131	0.73	0.042	*	1	1
Pu^{239}								
0	0	1.0	0.90	9.0	0.040	2.86	1	2
0	1	1.0	0.30	3.0	0.040	†	1	1
1	0	1.5	1.35	9.0	0.040	0	1	-
1	1	1.5	0.45	3.0	0.040	0.955	2	2
1	2	1.5	0.27	1.8	0.040	0.860	1	3
Pu^{240}								
0	1/2	1.3	2.2	17.0	0.018	-	1	-
1	1/2	1.25	2.12	17.0	0.018	-	1	-
1	3/2	1.25	1.06	8.5	0.018	-	1	-
Pu^{242}								
0	1/2	1.13	2.08	18.4	0.0245	-	1	-
1	1/2	1.25	2.3	18.4	0.0245	-	1	-
1	3/2	1.25	1.15	9.2	0.0245	-	1	-

*Two fission channels: $\hbar\omega_1 = 0.5$ Mev, $S_1 = -0.1$ Mev; $\hbar\omega_2 = 0.5$ Mev, $S_2 = 0.2$ Mev

†One fission channel: $\hbar\omega = 0.5$ Mev, $S = 0.1907$ Mev.

TABLE 6
COMPARISON OF CALCULATED AND MEASURED DOPPLER EFFECTS

Sample	Constituent	Doppler Effect (ϵ)			
		300 to 600°K		300 to 1000°K	
		Calculated	Experiment	Calculated	Experiment
Th Metal	Th	-0.0116	-0.0146	-0.0204	-0.0241
U ²³⁸ Metal	U ²³⁸	-0.0150	-0.0141	-0.0274	-0.0239
U ²³⁵ Metal	U ²³⁵	+0.0097		+0.0172	
	U ²³⁸	<u>-0.0006</u>		<u>-0.0011</u>	
	Total	+0.0091	+0.0056	+0.0161	+0.0086
U ²³⁵ O ₂	U ²³⁵	+0.0038		+0.0066	
	U ²³⁸	<u>-0.0010</u>		<u>-0.0018</u>	
	Total	+0.0028	+0.0011	+0.0048	+0.0025
Pu ²³⁹ O ₂ No. 1	Pu ²³⁹	-0.00143		-0.00033	
	Pu ²⁴⁰	<u>-0.00048</u>		<u>-0.00084</u>	
	Total	-0.0019	-0.0028	-0.0012	-0.0065
Pu ²³⁹ O ₂ No. 6	Pu ²³⁹	-0.00102		-0.00016	
	Pu ²⁴⁰	-0.00177		-0.00318	
	Pu ²⁴²	<u>-0.00019</u>		<u>-0.00037</u>	
	Total	-0.0029	-0.0029	-0.0037	-0.0069
Pu ²³⁹ O ₂ No. 9	Pu ²³⁹	-0.00079		-0.00025	
	Pu ²⁴⁰	-0.00229		-0.00414	
	Pu ²⁴²	<u>-0.00035</u>		<u>-0.00065</u>	
	Total	-0.0034	-0.0048	-0.0050	-0.0086

consequently, the reduction in worth is considerably less than the upper limit. It seems unlikely, therefore, that this effect can fully account for the difference between measured and calculated absolute reactivity worths.

The Doppler effect is also influenced by the presence of U^{238} in the test region. This interaction arises primarily from the wings of the resonances; so the effective flux depression is considerably less than for the absolute reactivity worth. However, this occurrence is partially compensated by the fact that the median energy point of the $\delta\sigma_{a_i}\phi_i\phi_i^*$ distribution (where $\delta\sigma_{a_i}$ are Doppler-induced changes) is about a decade lower than the $\sigma_{a_i}\phi_i\phi_i^*$ distribution; and hence the flux depression is greater, because the resonances are larger. The situation is further complicated by the change with temperature in the energy distribution of Doppler-effect contributions in the wings of a resonance. The effective depression is a function of temperature, even though the actual depression is not. As the temperature increases, cross-section contributions move further from the peak, and thus into regions where the depression is less. The Doppler effect is thereby enhanced, and some compensation occurs for the flux depression itself. Again, it seems unlikely that these effects will fully account for the difference between calculation and experiment. Thus, both the calculated Doppler effect and sample worth of U^{238} appear to support the need for lower strength functions and/or a lower capture width. Such a conclusion would agree with a recent determination of lower U^{238} capture cross sections between 1.0 kev and 1.0 Mev.⁽²⁵⁾ On the other hand, both the Doppler effect and sample worth of Th support the need for higher strength functions and/or a higher capture width.

For the Pu samples, since the Doppler effects are composed of significant contributions from two or three isotopes, only tentative conclusions can be drawn about individual components. Nevertheless, it appears that the magnitude of the Pu^{240} contribution is too low. Such a conclusion would agree with recent evaluations of $\langle\Gamma_\gamma\rangle$ for Pu^{240} of 23.2 ± 2.0 mev⁽²⁶⁾ and of $20 < \langle\Gamma_\gamma\rangle < 30$ mev,⁽²⁷⁾ which compare with a value of 18 mev used in these calculations. Also, it appears that the decrease in the magnitude of the Doppler effect for Pu^{239} with increasing temperature is too great. The decrease is a result of competition between different (l, J) series of unresolved resonances, some of which have positive Doppler effects and some negative. Much cancellation occurs; so that it is difficult to pinpoint the source of the discrepancy, from only a few experiments.

Considering the strong overlapping and multilevel effects present in U^{235} , the degree of agreement between calculation and measurement of the Doppler effect for both concentrations is particularly good. The presence of U^{235} and U^{238} in the test region is probably not of great significance for the U^{235} samples; the contributions of U^{238} to the Doppler effect in the 93% U^{235} sample are of secondary importance. Consequently, flux depressions of the size expected are not serious. Since the fission channel parameters of U^{235} are poorly known, refinements in this area may be expected to improve the agreement.

V. DOPPLER MEASUREMENTS IN HEATED BLANKETS

One of the important questions relating to the application of these oscillator-type Doppler measurements to a typical fast breeder reactor system concerns the interpretation of, or solution to, the so-called "hot sample-cold reactor" problem. It is recognized that the measurement of the Doppler coefficient by means of oscillating a small, heated sample within a reactor that is at room temperature may not yield the same results as would occur in the case in which the reactor as a whole is hot. Although direct measurements of the Doppler effect of various samples can be carried out in a fully heated critical assembly, a great amount of information, particularly of a type amenable to analytical studies, can be derived from heating only the small region of the reactor (i. e., a "blanket") that immediately surrounds the sample at the core center. A series of experiments of the latter type has been carried out in this core for the purpose of establishing the change in the Doppler coefficients of Th and U²³⁸ metals when the temperature of the immediate environment is altered.

In the usual Doppler determination, the square-shaped oscillator bar holding the sample slides inside the 1-in. square oscillator channel that is located along a horizontal diameter of the reactor and traverses the "homogeneous" test region. In this experiment, the 1-in. square hole is surrounded at the core center by a square-shaped, annular, evacuated cartridge containing a heater coil and a blanket of either U²³⁸ or Th metal. In Figure 16a, a partially assembled heater cartridge is shown without the blanket in place. The heater coil, which is wound around the inner 0.005-in. thick molybdenum reflector, consists of commercially available stainless steel-sheathed, MgO-insulated, Chromel-Alumel thermocouple wire, 0.040 in. in diameter, with the Chromel wire being used as the heating element. The blanket material rests directly on the heating coil. A power input of ~70 w produces an average blanket temperature of 400°C, although a spread of as much as 90°C between three distinctly different zones within the blanket has been observed with the three Chromel-Alumel thermocouples. A narrow (~0.040 in.) space between the outer case and the outer reflector, and between the inner oscillator tube (see Figure 16b) and the inner reflector, is evacuated to $\sim 1 \times 10^{-3}$ torr pressure to provide thermal insulation. The blankets are 6 in. long, and have a cross section

a. Partially Assembled

b. Assembled

c. Cross Section

Figure 16. Heated Blanket System
 Heater Cartridge

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as shown in Figure 16c, where a Doppler sample and its heater are also depicted in place. The U^{238} and Th blankets are 0.200 and 0.250 in. thick, respectively.

The results of a series of typical measurements at blanket temperatures of 20 and 400°C are given in Figures 17 and 18 (see Figures 9 and 10 for the no-blanket case) and, in a condensed form, in Table 7. The Doppler measurements are performed in the standard way (i. e., The reactivity difference, if any, is first established between the sample of interest and the reference sample when both are at room temperature. The sample of interest is then heated to some new steady-state temperature, and a new reactivity value is established. When several such measurements are made, the differences between these reactivities can be plotted, as shown in the two figures). Referring to the table, one sees that $(\Delta\rho)_D$ in Th, for example, is significantly reduced by the presence of either blanket, presumably as a result of the general depression of the flux by the absorber.⁽²⁸⁾ The Doppler coefficient is further reduced, although considerably less so, when the Th blanket is heated to 400°C. On the other hand, if a U^{238} blanket is heated, no statistically significant reactivity change is detected. This behavior is ascribed to a resonance interference effect between like materials, and applies as well to a U^{238} sample. The implication is that a similar reduction in the Doppler effect of a particular isotope would occur in a typical fast reactor in which that isotope occurs in reasonably large quantities.

That the change in $(\Delta\rho)_D$ is not due to a change in the absolute reactivity worth $[(\Delta\rho)_W]$ of the sample, as the blanket temperature is changed, is shown in Columns 6 and 7. As in the case of the Doppler effect, however, the reactivity worth is reduced considerably by the presence of the blanket itself. In order to obtain a spectrum-dependent quantity in much the same manner as that previously described, the value of $|1/\rho|(\Delta\rho)_D$ corresponding to the 20 to 600°C temperature interval is given in the last column of the table. Also shown are the values of γ , to the nearest 0.1, which produce the best fit of the form $\rho = A + BT^{(1-\gamma)}$.

Figure 17. Doppler Coefficient of Th Metal in a Th Blanket

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Figure 18. Doppler Coefficient of U²³⁸ in a U²³⁸ Blanket

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TABLE 7
RESULTS OF EXPERIMENTS WITH HEATED BLANKETS
IN CORE 15

Sample	Blanket	Blanket Temperature (°C)	γ^*	$(\Delta\rho)_D$ (20-600°C) (£)	ρ (£)	$(\Delta\rho)_W^\dagger$ (Cold minus hot) (£)	$\frac{\Delta\rho(20-600^\circ\text{C})}{ \rho }$
Th	Th	20	0.9	-0.0167 ±0.0006	-0.16301 ±0.00066	-0.00119 ±0.00089	-0.1024 ±0.0034
		400	0.7	-0.0150 ±0.0006	-0.16182 ±0.00060		-0.0927 ±0.0036
	None	-	1.2	-0.0216 ±0.0003	-0.21254 ±0.00068	-	-0.1016 ±0.0014
	U ²³⁸	20	1.1	-0.0164 ±0.0006	-0.19407 ±0.00066	+0.00136 ±0.00093	-0.0845 ±0.0029
		400	1.1	-0.0169 ±0.0006	-0.19543 ±0.00065		-0.0865 ±0.0030
	U ²³⁸	U ²³⁸	20	0.6	-0.0198 ±0.0014	-0.15283 ±0.00068	-0.00041 ±0.00089
400			1.2	-0.0158 ±0.0016	-0.15242 ±0.00060	-0.1037 ±0.0105	
None		-	1.1	-0.0214 ±0.0003	-0.19186 ±0.00068	-	-0.1115 ±0.0018
Th		20	0.7	-0.0195 ±0.0004	-0.17607 ±0.00066	+0.00057 ±0.00093	-0.1108 ±0.0020
		400	0.8	-0.0189 ±0.0006	-0.17664 ±0.00065		-0.1070 ±0.0028

* $\rho = A + BT^{(1-\gamma)}$

†These values refer to the change in the total worth of the sample within the blanket when the blanket temperature is changed.

APPENDIX

PROTON-RECOIL SPECTROMETER

The proton-recoil spectrometer consists of a hydrogen-filled proportional counter in the center of the core, a preamplifier just outside the core, and electronics in the control room for shaping, counting, and storing the pulses from the detector. The detector is a 4-cm diameter sphere⁽¹⁰⁾ with 0.050-cm thick stainless steel wall and a 0.0022-cm diameter tungsten anode wire along a diameter. Different pressures of H_2 , CH_4 , or a mixture of the two, are used to fill the detectors, depending on the energy range to be measured. For instance, a filling of 1 atm of H_2 is used for measuring neutron spectra between 60 and 300 kev. Below 60 kev, the electrons knocked from the detector walls by gamma rays overwhelm the neutron-induced events. Lower energies are therefore measured by reducing the gas pressure.

The neutron energy is determined by examining the energy of the protons formed by the (n,p) reaction in the hydrogenous gas. Some of the protons strike the detector wall before depositing all their energy in the gas. A theoretical wall effect correction⁽¹⁰⁾ is made to account for this error. Above 300 kev (in the 1-atm H_2 filling), the error in the correction becomes too large to be acceptable; consequently, higher energies are measured by increasing the gas pressure. For the measurements made in Core 15, the detectors were filled with 0.5 atm H_2 (30 to 150 kev), 1 atm H_2 (60 to 300 kev), and 1 atm CH_4 (150 to 400 kev).

A high positive voltage is applied to the anode wire of the detector. When a charged particle ionizes the gas, the electrons are swept to the anode (multiplying as they approach the anode), and give a negative pulse which is proportional to the energy of the particle. The pulse is amplified, shaped, and analyzed for its relative size and stored in a multichannel pulse height analyzer.

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