AI-AEC-13024

U3R
A CODE TO CALCULATE UNRESOLVED RESONANCE CROSS SECTION PROBABILITY TABLES

AEC Research and Development Report

Atomics International
North American Rockwell

P.O. Box 309
Canoga Park, California 91304

DISCLAIMER

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy $3.00; Microfiche $0.95

AI-AEC-13024

U3R
A CODE TO CALCULATE UNRESOLVED RESONANCE CROSS SECTION PROBABILITY TABLES

BY

J. M. OTTER
R. C. LEWIS
L. B. LEVITT

Atomics International
North American Rockwell

P.O. Box 309
Canoga Park, California 91304

CONTRACT: AT(04-3)-824
ISSUED: JULY 31, 1972

THIS PAGE

WAS INTENTIONALLY

LEFT BLANK

CONTENTS

TABLES

FIGURES

ABSTRACT

The U3R code is described in detail. This code generates probability tables for the representation of unresolved neutron resonance cross sections in calculations using pointwise data. Methods using the tables have greatly reduced computer storage and/or running time in Monte Carlo calculations.

The theory is summarized, input and output formats described, and a sample case included. Results of tests in an integral transport theory slowing down calculation are shown.

THIS PAGE

WAS INTENTIONALLY

LEFT BLANK

I. INTRODUCTION AND SUMMARY OF THEORY

The representation of neutron cross sections in the unresolved resonance energy range for continuous energy calculations is severely limited by the high-speed memory size and/or speed of even the most advanced computers. A new approach, the Probability Table Method, has been developed.[1] This method represents the neutron cross section at a given energy by a tabulated distribution function. The tables have been used successfully in both Monte Carlo[1] and analytical[2] calculations.

U3R is a FØRTRAN code which generates the cross section probability tables. U3R numerically constructs a table of the cumulative probability distribution functions of cross sections in a narrow energy range. The procedure is to: (1) generate a ladder of resolved resonances over the energy range using prescribed average values and distribution functions of resonance parameters, (2) calculate Doppler-broadened point cross sections for the ladder, and (3) distribute the point cross sections with their probabilities (fractional energy increments) into a table. Additional ladders are accumulated into the table until the desired accuracy of table entries is obtained. Thus, cross section data which are properties of the individual isotopes only, rather than group-averaged sets, are obtained. For criticality calculations, a few tables, to be used in an energy range about the table energy, may be distributed throughout the unresolved energy range. The theory of the method is described in Reference 3 and is summarized below.

The Probability Table Method assumes that the resonance energies are so close together that the neutron enters a resonance randomly, i.e., its precollision energy plays no role in determining what part of the resonance the neutron sees. This is most nearly valid in heterogeneous assemblies where the neutron is likely to have made its last collision with a different isotope. The severest test of the assumption occurs in large regions containing a single heavy isotope; but, even there, one would expect reasonable results. Figure 1 shows some representative point data obtained from a typical ladder of resonances. One can see that if the probable energy loss is large compared to the width of a resonance, and at the same time is likely to span even a few resonances whose exact locations are not known, that the assumption of no correlation between the cross sections seen by a neutron on successive collisions is easily met. This condition is met reasonably well for unresolved resonances of U^{238}, U^{235}, and Pu^{239}, for example.

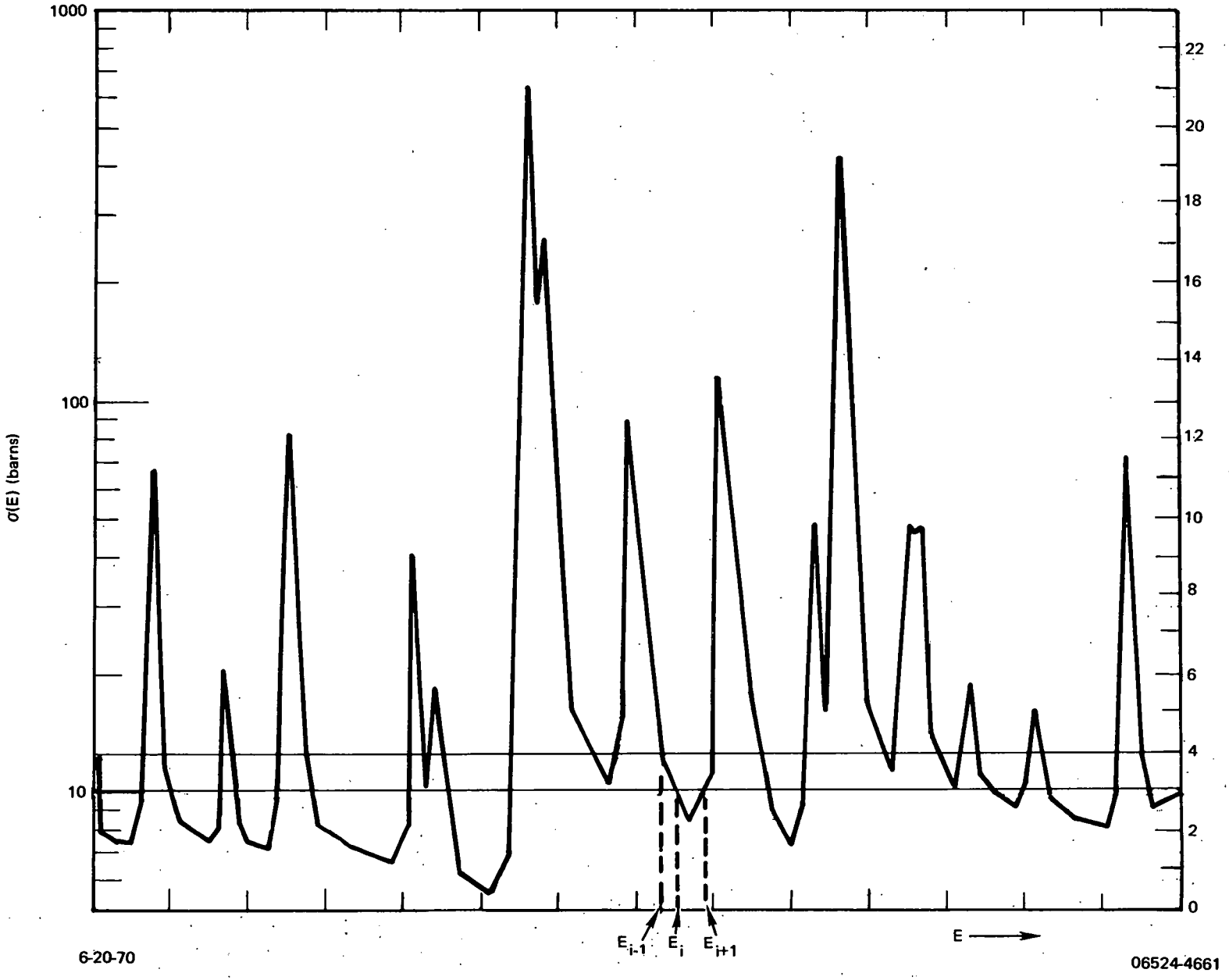

Figure 1. Typical Point Data from Statistically Generated Ladder

The entries to the table ($\overline{\sigma}_J$, P_J) may be defined as follows:

Let there be a set of σ_J's, J=1, N, such that $\sigma_J > \sigma_{J-1}$, $\sigma_1 \geq \sigma_{MIN}$ and $\sigma_N \geq \sigma_{MAX}$. σ_{MIN} is the lowest value of $\sigma(E)$ between E_0 and E_M, and σ_{MAX} is the highest value of $\sigma(E)$ in this range.

Let

$$\int_{E_{MIN}}^{E_{MAX}} \sigma(E)\,dE = \sum_{i=1}^{M} \int_{E_{i-1}}^{E_i} \sigma(E)\,dE = \sum_{i=1}^{M} I_i \quad ,$$

and let each $\sigma(E_i)$, $1 \leq i \leq M-1$, be equal to one of the σ_J's. Figure 1 shows typical point cross section data for a ladder of statistically generated resonances. One can see that I_i would simply to be area under the curve from E_{i-1} to E_i. In the example depicted, $\sigma(E_{i-1}) = \sigma_4$, (J=4), while $\sigma(E_i)$ and $\sigma(E_{i+1}) = \sigma_3$. Then, $\sigma_{J-1} \leq \sigma(E) \leq \sigma_J$ with probability

$$p_J = \frac{\sum_{i=1}^{M} \Delta E_i \, \delta_{iJ}}{E_{MAX} - E_{MIN}}$$

where

$$\Delta E_i = E_i - E_{i-1}$$

and

$$\delta_{iJ} \equiv \begin{cases} 1, & \text{if } \sigma_{J-1} \leq \sigma(E) \leq \sigma_J, \text{for } E_{i-1} \leq E \leq E_i \\ 0, & \text{otherwise .} \end{cases}$$

The probability that the cross section lies below σ_J is then

$$P_J = \sum_{k=1}^{J} p_k \quad ,$$

while

$$\bar{\sigma}_J = \frac{\sum_{i=1}^{M} I_i \delta_{iJ}}{\sum_{i=1}^{M} \Delta E_i \delta_{iJ}}$$

represents the mean value of the cross section between σ_{J-1} and σ_J. (For efficiency, the details of the procedure used in U3R are somewhat different, as described in Section II-F.)

One process, which in U3R is the total cross section, is chosen as the basis for constructing the table. Values of its magnitude serve as the band limits, the σ_J's above. For each interval in the point data set, I_i is entered in the sum in the numerator of σ_J for the appropriate J, and the energy interval is entered in the denominator sum. At the same time, the corresponding values of other processes are entered in appropriate sums with the same band number. Thus, all average reaction cross sections in each band are the conditional averages corresponding to the average total cross section of that band.

When, in a Monte Carlo calculation, the cross section of an isotope in its unresolved range is needed, it is obtained by a random selection from the appropriate probability table as follows:

Select a random number, $0 < r < 1$, and set $\sigma(E) = \bar{\sigma}_J$, where

$$P_{J-1} < r \leq P_J \ .$$

All reaction cross sections are selected from the same band, that is, with the same random number, to make use of the conditional correlations of the table.

Coding is done in FORTRAN for the IBM 360. Double precision arithmetic is used. About 470K bytes of storage are required. The coding is designed for ease of use with the resonance parameter data of ENDF/B3. A single precision version of the code for the CDC 7600 was also produced.

II. DESCRIPTIONS AND FORMULAS

A. SUBROUTINE STRUCTURE AND CODE LIMITS

Each of the four principal steps in the calculation is controlled by a subroutine called by the main program (U3R). These subroutines in the order called are:

LADDER	Generates a ladder of resolved resonances
UNEK	Calculates point cross sections at 0°K
DOPCRS	Doppler-broadens point cross sections
PROTAB	Forms cross section probability tables.

In addition, 5 other subroutines are employed.

RNRG	Initializes the random number generator and establishes an energy range
RAND	Generates random numbers
BP	Calculates nuclear angular momentum barrier penetration factors
PT	Calculates an optimized energy grid by which to represent a resonance
LWSD	Selects equally probably samples from level width statistical distributions.

Detailed descriptions of the main program and each subroutine are given in sections II-B through II-K below. The calling structure is shown in Figure 2. The size limits of the code per case are:

Number of unresolved resonance (ℓ, J) series	= 20
Number of temperatures	= 4
Number of ladders	= 100
Number of energies	Unlimited
Table length	= 99.

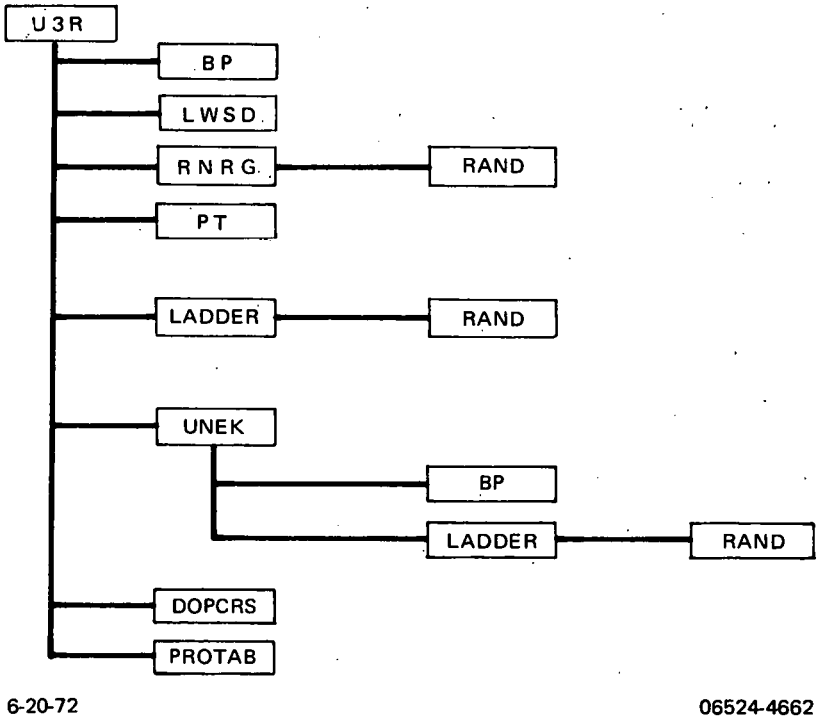

Figure 2. U3R Subroutine Structure

B. U3R

The main program (U3R) reads and prints the input data and calculates or sets several parameters. It contains the loops on the number of energy ranges and the number of ladders.

The input data quantities are:

NCASE	The number of cases
ITAPUN	Option to punch tables or also store tables on an auxiliary storage device
AN	A title
ATW	The atomic weight
SPIN	The target nucleus total angular momentum quantum number
PSM	The ℓ=0 potential scattering cross section at E=0 in barns

SDC	A convergence criterion for the standard deviation of the average cross sections of the table (see below)
STRN	Random number initialization parameter
NEB	The number of energies at which tables are to be formed
MSER	The number of unresolved resonance (ℓ,J) series for which resonance parameter data is input
NTMP	The number of temperatures at which tables are to be formed
NPRINT	The output print option (see Section V)
LD	Option to use an input number of ladders, rather than the SDC criterion
NPROB	The table length (see Section II-F)
TMP (I), I=1, NTMP	The temperatures at which tables are to be formed
(LSER (I),	ℓ = neutron orbital angular momentum quantum number
QSER (I),	J = compound nucleus total angular momentum quantum number
NU (K,I), K=1,4) I=1, MSER	ν = number of degrees of freedom in the χ^2 distribution of level widths for each process (K), (see below)
(E,	The energy
DBAR (I),	The average level spacing
GBAR (K,I), K=1,4) I=1, MSER	The average level widths for each process (K).

Four resonance processes are considered. In conformance with the ENDF/B3 format, the processes are a competitive reaction ('other'), coherent scattering, radiative capture, and fission. The competitive reaction is assumed

to be noncoherent scattering. It is accounted for separately at 0°K (UNEK) and is added to the coherent scattering before Doppler broadening (DOPCRS).

MSER is the maximum number of (ℓ, J) series which may be used at any energy. The order of entering the (ℓ, J) series should be with increasing ℓ values. At each energy, the code uses only the series with values of ℓ for which the sum of all series with a given ℓ contributes at least 1% to the total scattering, capture, or fission average cross sections, based on an analytic calculation. The number of series used is named NSER. With this arrangement, the ℓ, J, and ν_i values are entered only once per case. The formulas used to determine the contributions of each state are:

$$\overline{\sigma}_{x\ell} = \frac{\pi C}{2E} \sum_J \frac{g_J}{\langle D_{\ell J}\rangle \prod_x N_{x\ell J}} \sum_{i(n)}^{N_{n\ell J}} \sum_{i(\gamma)}^{N_{\gamma\ell J}} \sum_{i(f)}^{N_{f\ell J}} \sum_{i(o)}^{N_{o\ell J}} \frac{G_{xi(x)} \langle \Gamma^o_{n\ell J}\rangle \nu_{n\ell J} p_\ell z_{n\ell Ji(x)}}{\sum_x \langle \Gamma_{x\ell J}\rangle z_{n\ell Ji(x)}}$$

where

$$G_{xi(x)} = \langle \Gamma_{x\ell J}\rangle z_{x\ell Ji(x)} \quad , \quad x = \gamma, f, o$$

$$G_{ni(n)} = \langle \Gamma^o_{n\ell J}\rangle \nu_{n\ell J} p_\ell z_{n\ell Ji(n)} - 2\sum_x \langle \Gamma_{x\ell J}\rangle z_{n\ell Ji(x)} \sin^2\left(\frac{\sigma_{pot\ell} E}{C}\right)^{1/2}$$

where

$$C = 2.6038 \times 10^6 \left(1 + \frac{1.008665}{ATW}\right)^2$$

$$\sigma_{pot\ell} = \begin{cases} PSM & \ell = 0 \\ 0 & \ell \neq 0 \end{cases}$$

p_ℓ = angular momentum barrier penetration factor (see Subroutine BP, Section II-I).

N and z are the number of equally probable samples from the level width statistical distributions and their values, respectively (see Subroutine LWSD, Section II-K). These calculated averages are accurate to within a few percent and the sum for each process provides a normalization for the average of the final table.

The energy range of the ladder is set small enough so that several ladders are needed, but large enough to adequately represent overlap and interference

effects. The energy spread for the range from which cross sections are taken to form tables is set initially to the smaller of the range limited by the number of points accommodated (4000), or the range which assures enough ladders to obtain meaningful convergence statistics, This range is then subjected successively to a lower limit of 1.5 *MR* $\langle D \rangle$ and an upper limit of 20% of the input energy. Allowance is made so that it is highly improbable that the dimensions will be exceeded (see Section II-D). The formula used is

$$2.0*\min\left[\frac{200*\langle D\rangle}{\log_{10}(\mathrm{HLWL})+1}\ ,\ \frac{L1}{4}\left(\frac{100}{\mathrm{SDC}}\right)^2\frac{\langle D_T\rangle}{\min(\mathrm{LD},30)}\right]$$

where

$\langle D \rangle$ = the average level spacing

$$\langle D_T \rangle = \left(\frac{\sum_{\ell,J}\langle D\rangle_{\ell,J}^{1/2}\langle\sigma_t\rangle_{\ell,J}}{\sum_{\ell,J}\langle\sigma_t\rangle_{\ell,J}}\right)^2$$

$\langle \sigma_t \rangle$ = the average total resonance cross section

L1 = 2 nonfissile isotope

= 3 fissile isotope.

The parameters which determine the number of points used to represent a resonance are initialized to PNTPR=27 and HLWL=10 if $\langle D \rangle < 1$ and HLWL=100, if $\langle D \rangle \geq 1$. Two considerations enter these selections: the accuracy of integrated cross sections given by the point values, and the accuracy of Doppler-broadening. The dimensioning for the number of resonances is set so the number of points will be the limiting dimension.

The nuclear radius for use in calculating the penetration of the angular momentum barrier of the nucleus is coded according to the formula adopted for ENDF/B3, namely,

$$R_p = 1.23\left(\frac{\mathrm{ATW}}{1.008665}\right)^{1/3} + 0.8 \text{ fermis.}$$

The number of resonances summed in the calculation of pointwise cross sections, MR, is set to

$$10\left[1 + \frac{1}{0.75 + (\text{SPIN} - 0.5)^2}\right]\text{NSER}$$

(see Section II-D). The formula is designed to place roughly 10 resonances of the least dense series in the summation.

SDC and NPROB are made input quantities because different applications may require different accuracies. Default values of 10% for SDC and 10 for NPROB are set. The printing frequency for the accumulated tables is set to 5, and the maximum number of ladders is set to 100.

C. LADDER

LADDER constructs a ladder of resolved resonances from prescribed average values and distribution functions of resonance parameters. All (ℓ,J) series called out are accounted for in a single pass.

LADDER first generates the resonance energies using random sampling from the Wigner level spacing distribution. A lowest energy resonance for each series is established below the lower limit of the extended energy range (Section II-G) by an amount equal to $\langle D \rangle_{\ell,J} R$, where R is a random number between 0 and 1. In this way, enough resonances are generated beyond the energy range used for the table to give good accuracy at the energy limits. Successively higher resonance energies are obtained by adding level spacings found from random samplings of the Wigner distribution, including one energy in excess of the upper limit of the extended range. The formula is

$$E_{\ell J, i+1} = E_{\ell J, i} + 1.128379 \langle D \rangle_{\ell, J} (\log R)^{1/2} .$$

Level width distributions are taken to be χ^2 distributions with the number of degrees of freedom, ν, input. LADDER randomly samples χ^2 distributions with $\nu = 1, 2, 3$. Also $\nu = \infty (\Gamma_i = \text{constant})$ is accommodated. For $\nu = 1$ and 3, random samples are found using rejection techniques. The formulas are

$\nu = 1$:

$$\frac{\Gamma_i}{\langle \Gamma_i \rangle} = R_1^2$$

where $(R_1 - 1)^2 \leq 2R_2$;

$\nu = 2$: $$\frac{\Gamma_i}{\langle \Gamma_i \rangle} = -\log R$$

$\nu = 3$: $$\frac{\Gamma_i}{\langle \Gamma_i \rangle} = \frac{20}{3} R_1$$

where $(20R_1)^{1/2} \exp(-10R_1 + 0.5) > R_2$.

D. UNEK

The UNEK subroutine is based on the UNICORN code.[4] It calculates point cross sections for Breit-Wigner resonances including multilevel scattering interference. For resonances with $\ell > 0$, the single level Breit-Wigner formula is used and potential scattering is assumed to be negligible.

Analytical resonance and cross section integrals are calculated for the first ladder. By comparing the printed average cross sections derived from 1/E weighted integration (resonance integrals) with those from an unweighted integration (cross section integrals) the effect of the finite energy range can be seen. This is normally very small. The capture and fission cross section integrals provide a check on integrated point cross sections. Scattering cross sections may not be an accurate comparison because the analytic formulas do not account for scattering interference.

The analytic integrals are given by:

$$I_i = \sum_m \left[6.5095 \times 10^5 \left(1 + \frac{1.008665}{ATW} \right)^2 g_m \frac{\Gamma_{nm} \Gamma_{im}}{E_{rm}^{1/2}} \cdot \sum_{k=1}^{3} a_{km} P_{km} \right]$$

where

$$P_{1m} = \frac{1}{y_1} - \frac{1}{y_2}$$

$$P_{2m} = \ell n \left\{ \frac{\left[G_1^2(y_2) + 1 \right] \left[G_2^2(y_1) + 1 \right]}{\left[G_2^2(y_2) + 1 \right] \left[G_1^2(y_1) + 1 \right]} \right\}$$

$$P_{3m} = \tan^{-1}\left[G_{1m}(y_2)\right] + \tan^{-1}\left[G_{2m}(y_2)\right] - \tan^{-1}\left[G_{1m}(y_1)\right] - \tan^{-1}\left[G_{2m}(y_1)\right]$$

$$G_{1m}(x) = \frac{x + \frac{\beta_m}{2}}{\gamma_m}$$

$$G_{2m}(x) = \frac{x - \frac{\beta_m}{2}}{\gamma_m}$$

$$y_1 = \check{E}^{1/2}$$

$$y_2 = \hat{E}^{1/2} .$$

$\check{E}$ and $\hat{E}$ are the lower and upper limits of the energy range from which the table is formed

	$\frac{1}{E}$ weighting	no weighting
a_{1m}	$-\frac{2}{\alpha_m^2}$	0
a_{2m}	$\frac{2\left(\beta_m^2 - \alpha_m\right)}{4\alpha_m^3 \beta_m}$	$\frac{1}{2\beta_m}$
a_{3m}	$\frac{2\left(\beta_m^2 - 3\alpha_m\right)}{4\alpha_m^3 \gamma_m}$	$\frac{1}{2\gamma_m}$

where $\alpha_m^2 = E_{rm}^2 + \frac{\Gamma_m^2}{4}$

$$\gamma_m = \left[\frac{1}{2}(\alpha_m - E_{rm})\right]^{1/2}$$

$$\beta_m = \frac{\Gamma_m}{2\gamma_m}$$

The average cross sections are

$$\overline{\sigma}_i = I_i/(\hat{E} - \check{E}), \text{ no weighting}$$

$$\overline{\sigma}_i = I_i/\log(\hat{E}/\check{E}), \text{ 1/E weighting.}$$

The only energy dependencies which have been suppressed in the above formulas are in Γ, σ_p, and Γ_n when it occurs as Γ_i. The 1/E weighted formula is taken with correction from Reference 7.

An energy grid is formed by calculating energy points for each resonance based on a level-width relative grid (Section II-J), and then sorting. The energy range limits are included. If the number of energy points in the ladder exceeds 4000 despite the precautions taken, a message is printed and that ladder is ignored. At each energy point the cross sections are summed over up to MR/2 resonances from lower energies, if available, plus up to MR resonances from higher energies, if available, but not over more than MR total resonances. More resonances at higher energies are allowed because scattering interference effects remain significant further below resonances than above.

The point cross section formulas are

$$\sigma_i = \sum_m \sum_J 4\pi g_J \lambda\!\!\!^{-2} Y_{Jm} \frac{\Gamma_{iJm}}{\Gamma_{Jm}} \quad , \qquad \begin{array}{l} i = \text{all processes except} \\ \ell = 0 \text{ coherent scattering} \end{array}$$

$$\ell=0 \ , \ \sigma_s = \sum_J 4\pi g_J \lambda\!\!\!^{-2} \left[\left(\sum_m Y_{Jm} \right)^2 + \left(\sum_m x_{Jm} Y_{Jm} \right)^2 - 2\sin^2(kR) \cdot \left(\sum_m Y_{Jm} \right) + \sin(2kR) \cdot \left(\sum_m x_{Jm} Y_{Jm} \right) + \sin^2(kR) \right]$$

where

$$Y_{Jm} = \frac{\frac{\Gamma_{nJ}}{\Gamma_J}}{1 + x_J^2} \quad , \qquad x_J = \frac{2(E - E_r)}{\Gamma_J}$$

$$g_J = \frac{1}{2}\left(\frac{2J+1}{2I+1}\right) \qquad = \text{statistical weight factor}$$

$$\Gamma_{Jm} = \sum_i \Gamma_{iJm} \qquad = \text{total level width}$$

$$k = \frac{1}{\lambda\!\!\!^{-}} \qquad = \text{neutron wave number}$$

R = potential scattering radius, assumed to be independent of J. At E=0, $\sigma_{pot} = 4\pi R^2$.

$$4\pi\lambda\!\!\!^{-2} = \frac{2.6038 \times 10^6}{E}\left(1 + \frac{1.008665}{ATW}\right)^2 \qquad \text{(laboratory system parameters)}$$

As usual, Γ_n is given by $\Gamma_n^o \sqrt{E}\, p_\ell \nu_n$, where p is the angular momentum barrier penetration factor (Section II-I). The value of p_ℓ at the resonance energy is used at all energies.

Integrals for point cross sections are found assuming that the log of the cross sections is linear in energy between neighboring points of the energy grid. The energy grid is generated based on the same energy dependence of the cross section (Section II-J), so this assumption is better than others for the integration. The formulas in the form which minimizes exponents in the computer are:

$$\int_{E_L}^{E_U} \sigma dE = \frac{\sigma_{i-1}\left[B^{C(E_U - E_{i-1})} - B^{C(E_L - E_{i-1})}\right]}{C * \log B}$$

where

$$B = \frac{\sigma_i}{\sigma_{i-1}}$$

$$C = \frac{1.0}{E_i - E_{i-1}} \; .$$

If $E_U = E_i$ and $E_L = E_{i-1}$,

$$\int_{E_i}^{E_{i-1}} \sigma\, dE = \frac{\sigma_i - \sigma_{i-1}}{C * \log B}$$

If $\sigma_i = \sigma_{i-1}$, $\quad \int_{E_L}^{E_U} \sigma\, dE = \sigma_i (E_U - E_L)$

The "other" cross section is added to the coherent scattering to form a total scattering cross section before Doppler broadening.

E. DOPCRS

Doppler-broadened point cross sections are calculated in DOPCRS by a numerical solution of the one-dimensional, time-dependent, heat equation, using the techniques of Dunford and Bramblett.[5] Their technique makes no approximations nor assumptions as to the form of the cross section line shape, and will broaden data at any temperature to any higher temperature.

A fairly fine energy mesh is needed. A minimum of about 17 points per resonance is used (Section II-J). The technique leaves the cross sections at the boundaries of the energy range invariant; so, the energy range was extended (Section II-G) for this as well as other reasons (Section II-C). A parameter which specified the temperature step size in the integration has been set to 5*NT(°K) where NT is the temperature order number.

DOPCRS is called inside a loop on temperature, so that the data at each temperature are obtained from the data at the preceding temperature. Thus, the temperatures entered should be ordered with increasing values.

F. PROTAB

For each temperature at each input energy, PROTAB accumulates table entries over sufficient ladders to meet the convergence criterion for average cross sections, or, optionally, for a fixed number of ladders.

The first time PROTAB is entered for every energy, it establishes values of the total cross section to be used as limits of table bands into which cross sections are assigned. Except for the lowest magnitude band, these are a double geometric series. The lowest magnitude band extends from 0.0 to SIGPRB(1) = 0.3 x L1 x σ_{pot}, where L1 is 2 for nonfissionable isotopes and 3 for fissionable isotopes.

$$SIGPRB(I) = SIGPRB(I-1)*TINC^{I-1} \quad ,$$

where

$$TINC = \left(\frac{SXXX}{0.3*L1*\sigma_{pot}}\right)^{\frac{2}{NPR\emptyset B*(NPR\emptyset B - 1)}}$$

NPROB = Table length

$$SXXX = 0.2*L1*\sum \sigma_{2\ell J} + \sigma_{pot}$$

and σ_2 = Average cross section when $\Gamma_n = 2\langle\Gamma_n\rangle$.

This breakdown yields more closely spaced probabilities for the high and low cross section magnitudes, which facilitates accurate calculations of self-shielded cross sections, cross section windows, and variances.

The bands are established for the first (lowest) temperature. For higher temperatures, the average cross sections in each incremental energy range are placed in the same band as for the first temperature. Thus, the probability in each band is forced to be the same for all temperatures. For a given cumulative probability, this provides a convenient correlation between average cross sections at different temperatures. Such correlations are highly desirable when two or more spatial regions having different temperatures contain the same isotope.

The integrated cross sections between each two energy grid points are calculated assuming the log of the cross section is linear in energy as described in Section II-E. The average total cross section is calculated, and the probability, i.e., the energy width, and the cross section integrals for other processes placed in the same table band. Thus, the natural correlation of the total cross section with other processes is accounted for. Variance and covariance statistics for scattering, capture, and fission processes are calculated from the pointwise cross sections and accumulated over the ladders.

The average cross sections for the table formed from a single ladder are calculated and, optionally, the table is printed. The table entries from the individual ladders are added to a table accumulated over entries of all previous ladders and the average cross sections of the accumulated table calculated. The accumulated table is printed after every 5 ladders. Starting with the tenth ladder, the percentage standard deviations of the average cross sections of the individual ladders are calculated assuming normally distributed means. Also, the variance and covariances of scattering, capture, and fission are calculated for the ladder and printed along with values from the pointwise data. These are provided because they may be of interest to persons wishing to investigate the limits of accuracy of the probability table representation. They may be disregarded by others. If LD<5, the accumulated table and final edits are printed after LD ladders.

The convergence criterion option operates as follows: If the deviation of any average cross section exceeds the criterion input (SDC), another ladder is called for. A maximum of 100 ladders per energy is set in the code. The assumption of normal distributions represents an approximation, of course, particularly for small numbers of ladders. Since a finite probability exists for an unrepresentatively close bunching of the first few ladder results, the number of ladders and average cross sections should be checked to make sure they are reasonable. If not, a different random number initialization can be tried or the option to use a fixed number of ladders used.

The final accumulated table is normalized to the analytic average cross sections. Then it is optionally punched and/or placed on an auxiliary storage device.

G. RNRG

The input random number initialization parameter, STRN, is used to form the starting random number each time RNRG is entered. If STRN is zero, a built-in number, 1123456789AB, is used for STRN. This resetting procedure correlates random numbers for different energies. The sequences for different temperatures are implicitly correlated as the identical ladders are used. One hundred random numbers are generated initially but not used in order to avoid any unusual effects that might be caused by the starting random number.

The limits of the energy range from which the table will be formed are set as the input energy plus or minus half the energy spread (see Sections II-B and II-D). Limits extended by the level spacing of the first (ℓ, J) series, normally the largest of any series, are also set. The expanded range is used in UNEK where it results in points being calculated outside the energy range used to form the table so that end effects in the Doppler broadening numerical integration will be unimportant (see Section II-E). It is also used in LADDER where it results in resonances being generated with energies outside the range used to form the table, in order to better calculate cross sections near the limits of the table energy range.

H. RAND

The random number generator[6] is a symbolic machine language subroutine. It has a built-in starting number, the first 2 bytes of which are used as such. The input random number initialization parameter, STRN (6 bytes), completes the starting random number. The last digit of STRN should be odd. The starting random number is located in the first 8 bytes of named COMMON block /RNDOM/. The next 8 bytes are the double precision random number generated. RAND also uses the next 4 bytes of /RNDOM/ and the first 16 bytes of blank COMMON, but they are not called elsewhere in the code.

I. BP

BP calculates the nuclear angular momentum barrier penetration factor, p, for $\ell>0$ neutrons. p is defined by

$$p(0) = 1$$

$$p(1) = \rho/(\rho+1)$$

$$p(2) = \rho^2/(\rho^2 + 3\rho + 9)$$

$$p(3) = \rho^3/(\rho^3 + 6\rho^2 + 45\rho + 225),$$

where

$$\rho = (kR_p)^2 = 4.826166 \times 10^{-8}\, E\left[R_p \Big/ \left(1 + \frac{1.008665}{ATW}\right)\right]^2$$

for E in electron volts and R_p in fermis. k and R_p are defined in Section II-B.

Clearly, below sufficiently low energies (depending on ℓ), $\ell>1$ contributions to cross sections become negligible. It is highly advisable to delete all such (ℓ,J) series where appropriate to lower computations times. This is done automatically in U3R using a 1% contribution criterion (see Section II-B).

J. PT

A grid in $x=2(E-E_o)/\Gamma$ is determined in which the difference between the exact integral for an isolated single-level Breit-Wigner resonance and the integral which assumes that the log of the cross section is linear in energy is the same prescribed value for every two neighboring points. The mathemetical formulation is given in the Appendix of Reference 4.

The prescribed difference between integrals is determined from the parameter PNTPR in the code. The width of the representation in x is set by the parameter HLWL (see Section II-B).

K. LWSD

The calculation of the number of states which contribute significantly to the cross sections (Section II-B) is an analytical formulation in which a number of equally probable samples from the level width statistical distributions are used. LWSD selects the number of samples and the values of $z_{x,i} = \Gamma_{x,i}/\langle\Gamma_x\rangle$ to be employed.

The level width distributions are assumed to be χ^2 distributions with the number of degrees of freedom input. If $\nu_x>4$, the mean value only is used (z=1). Otherwise, the distributions are divided by boundaries B^i into N equally likely intervals, and the average value of z in each is used to represent that interval. N=10, 5, 4, and 3 for ν=1, 2, 3, and 4, respectively. Fewer points are needed for a given accuracy for distributions with the larger number of degrees of freedom because they are more peaked around the mean value.

$$z_x^i = N\int_{B^{i-1}}^{B^i}\Gamma_x P(z_x,\nu_x)dz_x \quad ,$$

where

$$P(z,2\nu) = \frac{(z\nu)^{\nu-1}}{\Gamma(\nu)}\,\nu\, e^{-z\nu}$$

$\Gamma(\nu)$ = the gamma function.

The values used in the code are listed in Table 1.

L. BUILT-IN PARAMETERS

Because U3R may use fairly substantial amounts of computing time, the accuracy of the calculation has been limited by built-in parameters in the interests of economy. The chosen accuracy is believed to be sufficient for anticipated uses of the results. For the user who wishes to vary the parameters for newly developed uses or for greater economy, they are explained below.

TABLE 1

SAMPLE POINTS z^i FOR χ^2 DISTRIBUTIONS OF LEVEL WIDTHS

	$\nu = 1$	$\nu = 2$	$\nu = 3$	$\nu = 4$	$\nu > 4$
1	0.005252519	0.10744	0.2253591	0.3543	1.0
2	0.03717225	0.36007	0.5888224	0.8490	
3	0.1031289	0.69991	1.051297	1.7967	
4	0.2078424	1.22314	2.137087		
5	0.3598630	2.60944			
6	0.5743032				
7	0.8793668				
8	1.334867				
9	2.105343				
10	4.392704				

PNTPR (Sections II-B and II-J) is the number of points in the representation of a resonance out to x = ±10,000. HLWL is the x limit actually used. The combination of PNTPR=27, HLWL=10 ($\langle D \rangle < 1$) gives 17 points in the grid; PNTPR=27, HLWL=100 ($\langle D \rangle \geq 1$) gives 23 points. Further information should be obtained from the authors before these values are changed. Other point spacing schemes could be tried.

L1 (Sections II-B and II-F) is a parameter used to distinguish different approximations for fissile and nonfissile isotopes. A fissile index is obtained by a nonzero number of degrees of freedom for fission in the first (ℓ, J) state. L1 is used in the determination of the probability table band limits, the energy spread (sometimes), and as a DØ loop index limit.

MR (Sections II-B and II-D) sets the number of resonances in the cross section sum, subject to the limitation of the number of resonances in the ladder. MR can be varied by changing the constant of proportionality in the formula in the main program.

The penetration factor, PF, (Sections II-B, II-D, and II-I) for resonances with $\ell > 0$ could be made energy dependent in UNEK as a sophisticated refinement. When not using data from the ENDF/B3 file, a different formula for the nuclear radius, contained in PFC (Section II-B) may well be better.

The temperature step DELTA for Doppler broadening, described in Section E, may be varied. The accuracy of Doppler broadening is also a function of the number of points describing the line shape and their spacings, which are described above.

The choice of band limits for the probability table, described in Section II-F, could be varied. These are the array SIGPRB. The formulas which obtain the average cross section to which the final table is normalized are believed to be accurate to within about 3% (sections II-B and II-K).

The analytic formulas for the average cross sections for the first ladder are believed to be essentially exact for capture and fission in these applications.

III. INPUT FORMATS AND EXAMPLES

A. FORMATS

The input quantities are described in former sections, particularly Section II-B. All input data must be repeated for multiple cases. Size limitations per case are given in Section II-A.

Card Type	Columns	Variables	Format	Description
1	1-12	NCASE	I12	Number of cases
	13-24	ITAPUN	I12	= 0 not used; =1, punch table; = 2, punch and store on auxiliary device
2	1-72	AN	18A4	Alphanumeric title
3	1-12	ATW	E12.8	Atomic weight
	13-24	SPIN	E12.8	I
	25-36	PSM	E12.8	Potential scattering cross section
	37-48	SDC	E12.8	Convergence criterion, default =10.0 (not used if LD>0)
	49-60	STRN	3Z4	Random number initialization parameter, default = 1123456789AB
4	1-12	NEB	I12	Number of energies, no limit
	13-24	MSER	I12	Number of (ℓ,J) series, ≤20
	25-36	NTMP	I12	Number of temperatures, ≤4
	37-48	NPRINT	I12	= 0, short print; =1, long print
	49-60	LD	I12	= 0, use SDC; =N, use N ladders
	61-72	NPROB	I12	Table length, ≤99
5	1-12	TEMP (1)	E12.8	Temperatures (°K), NTMP increasing values
	13-24	TEMP (2)	E12.8	
	25-36	TEMP (3)	E12.8	
	37-48	TEMP (4)	E12.8	
6	The format of the first 12 columns is repeated in successive 12 column fields for MSER total fields. Multiple cards are used if needed. Order with increasing ℓ values.			
	1	LSER	I1	ℓ
	2-8	QSER	F7.3	J
	9	NU (4)	I1	ν for other
	10	NU (1)	I1	ν for coherent scattering
	11	NU (2)	I1	ν for radiative capture
	12	NU (3)	I1	ν for fission
7	MSER cards, one for each (ℓ,J) series. The ENDF/B3 format is used.			
	1-11	E	E11.4	E
	12-22	DBAR	E11.4	$\langle D \rangle$
	23-33	GBAR (4)	E11.4	$\langle \Gamma_{other} \rangle$
	34-44	GBAR (1)	E11.4	$\langle \Gamma_n^o \rangle$
	45-55	GBAR (2)	E11.4	$\langle \Gamma_\gamma \rangle$
	56-66	GBAR (3)	E11.4	$\langle \Gamma_f \rangle$

Repeat Card Type 7 for successive energies.

B. EXAMPLE

FORTRAN FIXED 10 DIGIT DECIMAL DATA

DECK NO. _____ PROGRAMMER _____ DATE _____ PAGE 1 of 3 JOB NO. _____

NUMBER	IDENTIFICATION	DESCRIPTION DO NOT KEY PUNCH
1		NCASE
0		ITAPUN, =0, not used; =1, punch; =2 punch and store
	73 80	
	10	
TA-181. ENER		TITLE
GY DEPENDENT		
PARAMETERS		
FRØM ENDF/B3		
ANALYSIS.	73 80	
J.ØTTER 5-72	20	
180.95		ATW , Atomic Weight
3.5		SPIN , I
8.3		PSM , σ_{pot}
10.0		SDC , Convergence Criterion
1 123456789AB	73 80	STRN , Random Number Initialization Parameter
	30	
1		NEB , No. of energies
6		MSER , Max. no. of (I,J) series
2		NTEMP , No. of temperatures
0		NPRINT, =0, short print; =1, long print
0	73 80	LD , =0, use SDC; >0, use LD ladders
10	40	NPRØB , Table Length

FORTRAN FIXED 10 DIGIT DECIMAL DATA

DECK NO. _____ PROGRAMMER _____ DATE _____ PAGE 2 of 3 JOB NO. _____

NUMBER	IDENTIFICATION	DESCRIPTION DO NOT KEY PUNCH
300.0		TMP (1) , first temperature
700.0		TMP (2) , second temperature
	73 80	
	50	
0 4.0 21		LSER, QSER, (NU(I), I=1, 4). (I1, F7.3, 4I1)
0 3.0 11		I , J , ν_{other}, ν_{scat}, ν_{cap}, ν_{fis}
1 5.0 11		
1 4.0 12		MSER sets
1 3.0 22	73 80	
1 2.0 11	60	
300.0		E Energy
7.4097		DBAR (1) , $\langle D \rangle$ first (I,J) series
0.0		GBAR (4, 1) , $\langle \Gamma_{other} \rangle$
1 .1516-3		GBAR (1, 1) , $\langle \Gamma_n^o \rangle$ (6E11.4)
6 .5152	73 80	GBAR (2, 1) , $\langle \Gamma_\gamma \rangle$ MSER cards
	70	GBAR (3, 1) ; $\langle \Gamma_f \rangle$
300.0		E
8.3727		DBAR (2) second (I,J) series
0.0		GBAR (4,2)
1 .3013-3		GBAR (1,2)
6 .5152	73 80	GBAR (2,2)
	80	

FORTRAN FIXED 10 DIGIT DECIMAL DATA

DECK NO. _____ PROGRAMMER _____ DATE _____ PAGE 3 of 3 JOB NO. _____

	NUMBER	IDENTIFICATION	DESCRIPTION DO NOT KEY PUNCH
1	300.0		
13	7.1244		
25	0.0		
37	5.1334-4		
49	6.515-2	73 80	
61		90	
1	300.0		
13	7.4097		
25	0.0		
37	5.3390-4		
49	6.515-2	73 80	
61		100	
1	300.0		
13	8.3727		
25	0.0		
37	6.0329-4		
49	6.515-2	73 80	
61		110	
1	300.0		
13	10.640		
25	0.0		
37	7.6665-4		
49	6.515-2	73 80	
61		120	

IV. OUTPUT

A. OPTIONS

If NPRINT = 0, the following printing is done:

Most input data and internally set parameters.

The number of resonances, analytic resonance integrals, cross section integrals, and the average cross sections derived from each, for the first ladder at each energy.

The number of energy points in each ladder.

Integrated pointwise cross sections at 0°K for the first ladder at each energy.

The total cross section break points in the table at each energy.

The average cross sections for each ladder at each temperature.

The cumulative table for each temperature after every fifth ladder.

The variances and covariances of point cross sections and cumulative table for the first temperature after every fifth ladder.

The standard deviations of the mean ladder cross sections for the first temperature after each ladder is accumulated starting with the tenth ladder.

The cumulative table and normalized table for each temperature, and standard deviations, variances and covariances for the first temperature after the last ladder.

If NPRINT = 1, the following extra printing is done:

The normalized grid used to represent a resonance.

Analytic resonance integrals and cross section integrals by resonance for the first ladder at each energy.

Cross sections at each energy point at 0°K and specified temperatures for each ladder.

Tables at each temperature for each individual ladder.

NPRINT = 1 yields a very large amount of printing, and consequently is normally used only for detailed checkout.

If ITAPUN = 1, the final tables are punched in the following format. The number of cards is equal to the table length, NPROB.

Column	Variable	Description
1-12	APCUMC	Cumulative probability
13-24	ASCUM (1)	Average scattering cross section Kth row
25-36	ASCUM (2)	Average capture cross section Kth row
37-48	ASCUM (3)	Average fission cross section Kth row
49-72		Blank
73-76	IJKM	Energy order number
77-80	K	Table row number

If ITAPUN=2, the final tables are placed on Unit 8, an auxiliary storage device called out by computer control cards (Section V). The table data are in the following order:

E, NPRØB, (APCUMC (K), (ASCUM (I,K), I=1,3), K=1, NPRØB).

Each table is a separate data record.

The output shown below is that of the input example, which uses the short print. The case required about 30 seconds of central processing unit time for the "execute" step on the IBM 360/165. The cost for execution was about $15.

The last three columns of the tables, headed TØAT, SPRØB, and ALPHA, are $\overline{\sigma}_{tk}/\overline{\sigma}_t$, $\overline{\sigma}_{sk}/\overline{\sigma}_{tk}$, and $\overline{\sigma}_{ck}/\overline{\sigma}_{tk}$, respectively, where k is the table row index.

B. EXAMPLE

TA-181. ENERGY DEPENDENT PARAMETERS FROM ENDF/B ANALYSIS J.OTTER,5-72

INPUT DATA

ATOMIC WEIGHT	=	180.950
SPIN OF TARGET NUCLEUS	=	3.5
POTENTIAL SCATTERING XSEC	=	8.300
CONVERGENCE CRITERION	=	10.0
NO. OF ENERGY BANDS	=	1
NO. OF (L,J) SERIES INPUT	=	6
NO. OF TEMPERATURES	=	2
PRINT OPTION (1=LONG)	=	0
TABLE PUNCH, TAPE OPTION	=	0
FIXED NO OF LADDERS OPTION	=	0
XS PROBABILITY TABLE LENGTH	=	10

CHI-SQUARED DEGREES OF FREEDOM

NO	L	J	NUO	NUN	NUC	NUF
1	0	4.0	2	1	0	0
2	0	3.0	1	1	0	0
3	1	5.0	1	1	0	0
4	1	4.0	1	2	0	0
5	1	3.0	2	2	0	0
6	1	2.0	1	1	0	0

TA-181. ENERGY DEPENDENT PARAMETERS FROM ENDF/B ANALYSIS J.OTTER, 5-72

ENERGY BAND NO. 1

MEAN ENERGY	=	300.00
NUMBER OF LADDERS (MAXIMUM)	=	100
FREQUENCY OF PRINTING ACCUMULATED TABLE	=	5

UNRESOLVED RESONANCE PARAMETERS

NO	L	J	D	OTHER	RED. SCAT	CAPTURE	FISSION	ST. WT.
1	0	4.0	7.410	0.0	1.1516D-03	6.5150D-02	0.0	0.5625
2	0	3.0	8.373	0.0	1.3013D-03	6.5150D-02	0.0	0.4375
3	1	5.0	7.124	0.0	5.1334D-04	6.5150D-02	0.0	0.6875
4	1	4.0	7.410	0.0	5.3390D-04	6.5150D-02	0.0	0.5625
5	1	3.0	8.373	0.0	6.0329D-04	6.5150D-02	0.0	0.4375
6	1	2.0	10.640	0.0	7.6665D-04	6.5150D-02	0.0	0.3125

ANALYTICAL AVERAGE CROSS SECTIONS

L	SCAT	CAP	FIS
0	2.37021D 01	2.16354D 01	0.0
1	1.88502D-05	4.41859D-02	0.0
TOT	2.37021D 01	2.16796D 01	0.0

THE ENERGY RANGE FROM WHICH TABLES ARE FORMED IS 270.00 TO 330.00 EV

NO. OF (L,J) SERIES USED FOR THIS ENERGY	=	2
MAXIMUM NUMBER OF RESONANCES IN XSEC SUM	=	22
NO. OF POINTS IN RESONANCE DESCRIPTION GRID	=	23

TA-181. ENERGY DEPENDENT PARAMETERS FROM ENDF/B ANALYSIS J.OTTER,5-72

LADDER NO. 1

ANALYTICAL INTEGRALS AND AVERAGE CROSS SECTIONS

	1/E WEIGHTING				NO WEIGHTING			
NO	SCAT	CAPTURE	FISSION	OTHER	SCAT	CAPTURE	FISSION	OTHER
I TOT	4.6795D 00	4.2883D 00	0.0	0.0	1.3768D 03	1.2757D 03	0.0	0.0
AV XS	3.1617D 01	2.1370D 01	0.0	0.0	3.1244D 01	2.1262D 01	0.0	0.0

NO. OF POINTS = 444
NO. OF RESONANCES = 25

POINTWISE AVERAGE CROSS SECTIONS AT 0 DEG. K

SCATTERING	CAPTURE	FISSION
3.127265D 01	2.136894D 01	0.0

TOTAL CROSS SECTION BREAK POINTS FOR THE PROBABILITY TABLE

I	SIGPRB(I)
1	4.97843D 00
2	5.64184D 00
3	7.24565D 00
4	1.05454D 01
5	1.73930D 01
6	3.25100D 01
7	6.88632D 01
8	1.65305D 02
9	4.49689D 02
10	1.38633D 03

TEMP = 300.00 DEG K

AV XS - SCAT = 31.2726, CAP = 21.30856, FIS = 0.0 , ABS = 21.30856, TOT = 52.5811

TEMP = 700.00 DEG K

AV XS - SCAT = 31.2278, CAP = 21.30088, FIS = 0.0 , ABS = 21.30088, TOT = 52.5287

LADDER NO. 2

NO. OF POINTS = 396

TEMP = 300.00 DEG K

AV XS - SCAT = 23.1137, CAP = 22.07481, FIS = 0.0 , ABS = 22.07481, TOT = 45.1885

TEMP = 700.00 DEG K

AV XS - SCAT = 23.1858, CAP = 22.13263, FIS = 0.0 , ABS = 22.13263, TOT = 45.3184

LADDER NO. 3

NO. OF POINTS = 425

TEMP = 300.00 DEG K

AV XS - SCAT = 13.9498, CAP = 14.77827, FIS = 0.0 , ABS = 14.77827, TOT = 28.7281

TEMP = 700.00 DEG K

AV XS - SCAT = 13.9377, CAP = 14.67237, FIS = 0.0 , ABS = 14.67237, TOT = 28.6101

LADDER NO. 4

NO. OF POINTS = 444

TEMP = 300.00 DEG K

AV XS - SCAT = 17.2137, CAP = 20.28356, FIS = 0.0 , ABS = 20.28356, TOT = 37.4973

TEMP = 700.00 DEG K

AV XS - SCAT = 17.2002, CAP = 20.12446, FIS = 0.0 , ABS = 20.12446, TOT = 37.3247

LADDER NO. 5

NO. OF POINTS = 483

TEMP = 300.00 DEG K

AV XS - SCAT = 17.8903, CAP = 21.15049, FIS = 0.0 , ABS = 21.15049, TOT = 39.0408

AVERAGE VALUES, 5 LADDERS

K	P	PCUM	SCAT	CAP	FIS	ABS	TOT	TOAT	SPROB	ALPHA
1	0.007967	0.00797	4.151	0.7270	0.0	0.727	4.878	0.12012	0.85095	0.0
2	0.007977	0.01594	4.857	0.6494	0.0	0.649	5.507	0.13561	0.88207	0.0
3	0.099023	0.11497	6.182	0.5159	0.0	0.516	6.698	0.16494	0.92298	0.0
4	0.345325	0.46029	8.147	0.9299	0.0	0.930	9.077	0.22354	0.89756	0.0
5	0.225673	0.68596	10.083	2.8152	0.0	2.815	12.898	0.31763	0.78173	0.0
6	0.101839	0.78780	13.165	9.7832	0.0	9.783	22.948	0.56513	0.57369	0.0
7	0.087372	0.87518	18.996	28.7348	0.0	28.735	47.731	1.17543	0.39798	0.0
8	0.063385	0.93856	39.322	73.1261	0.0	73.126	112.448	2.76917	0.34969	0.0
9	0.051403	0.98996	115.132	157.3242	0.0	157.324	272.456	6.70956	0.42257	0.0
10	0.010036	1.00000	349.164	266.2100	0.0	266.210	615.374	15.15433	0.56740	0.0

AV XS - SCAT = 20.6880, CAP = 19.91914, FIS = 0.0 , ABS = 19.91914, TOT = 40.6072

VARIANCES AND COVARIANCES

		SCAT	CAP
SCAT	POINT	1.98245D 03	
SCAT	TABLE	1.67406D 03	
CAP	POINT	1.73588D 03	2.14451D 03
CAP	TABLE	1.70428D 03	2.00968D 03

TEMP = 700.00 DEG K

AV XS - SCAT = 17.9198, CAP = 21.11266, FIS = 0.0 , ABS = 21.11266, TOT = 39.0324

AVERAGE VALUES, 5 LADDERS

K	P	PCUM	SCAT	CAP	FIS	ABS	TOT	TOAT	SPROB	ALPHA
1	0.007967	0.00797	4.165	0.7973	0.0	0.797	4.962	0.12234	0.83933	0.0
2	0.007977	0.01594	4.997	0.9057	0.0	0.906	5.903	0.14552	0.84657	0.0
3	0.099023	0.11497	6.251	0.7662	0.0	0.766	7.017	0.17300	0.89082	0.0
4	0.345325	0.46029	8.391	1.6569	0.0	1.657	10.048	0.24772	0.83510	0.0
5	0.225673	0.68596	10.988	5.0752	0.0	5.075	16.063	0.39600	0.68404	0.0
6	0.101839	0.78780	16.288	14.1138	0.0	14.114	30.402	0.74950	0.53576	0.0

7	0.087372	0.87518	25.786	38.6154	0.0	38.615	64.402	1.58770	0.40040	0.0
8	0.063385	0.93856	46.448	73.6035	0.0	73.603	120.051	2.95964	0.38690	0.0
9	0.051403	0.98996	99.140	127.9001	0.0	127.900	227.040	5.59723	0.43666	0.0
10	0.010036	1.00000	266.337	200.3377	0.0	200.338	466.674	11.50497	0.57071	0.0

AV XS - SCAT = 20.6942, CAP = 19.86860, FIS = 0.0 , ABS = 19.86860, TOT = 40.5628

LADDER NO. 6

NO. OF POINTS = 464

TEMP = 300.00 DEG K

AV XS - SCAT = 19.5960, CAP = 16.53085, FIS = 0.0 , ABS = 16.53085, TOT = 36.1268

TEMP = 700.00 DEG K

AV XS - SCAT = 19.6497, CAP = 16.55339, FIS = 0.0 , ABS = 16.55339, TOT = 36.2031

LADDER NO. 7

NO. OF POINTS = 467

TEMP = 300.00 DEG K

AV XS - SCAT = 9.3177, CAP = 5.93115, FIS = 0.0 , ABS = 5.93115, TOT = 15.2488

TEMP = 700.00 DEG K

AV XS - SCAT = 9.3193, CAP = 5.89819, FIS = 0.0 , ABS = 5.89819, TOT = 15.2175

LADDER NO. 8

NO. OF POINTS = 507

TEMP = 300.00 DEG K

AV XS - SCAT = 41.8597, CAP = 32.06584, FIS = 0.0 , ABS = 32.06584, TOT = 73.9256

TEMP = 700.00 DEG K

AV XS - SCAT = 41.7598, CAP = 32.17341, FIS = 0.0 , ABS = 32.17341, TOT = 73.9333

LADDER NO. 9

NO. OF POINTS = 457

TEMP = 300.00 DEG K

AV XS - SCAT = 49.6506, CAP = 25.27100, FIS = 0.0 , ABS = 25.27100, TOT = 74.9216

TEMP = 700.00 DEG K

AV XS - SCAT = 49.5536, CAP = 25.17538, FIS = 0.0 , ABS = 25.17538, TOT = 74.7290

LADDER NO. 10

NO. OF POINTS = 419

TEMP = 300.00 DEG K

AV XS - SCAT = 20.3809, CAP = 21.56294, FIS = 0.0 , ABS = 21.56294, TOT = 41.9438

PERCENTAGE STANDARD DEVIATIONS OF MEAN CROSS SECTIONS

SCATTERING	CAPTURE	FISSION
16.497	10.755	0.0

AVERAGE VALUES, 10 LADDERS

K	P	PCUM	SCAT	CAP	FIS	ABS	TOT	TOAT	SPROB	ALPHA
1	0.003983	0.00398	4.151	0.7270	0.0	0.727	4.878	0.10957	0.85095	0.0
2	0.008883	0.01287	4.736	0.7796	0.0	0.780	5.515	0.12388	0.85864	0.0
3	0.083599	0.09647	6.075	0.6394	0.0	0.639	6.714	0.15082	0.90477	0.0
4	0.353563	0.45003	8.084	0.8569	0.0	0.857	8.941	0.20083	0.90416	0.0
5	0.224171	0.67420	10.217	2.8115	0.0	2.812	13.028	0.29264	0.78420	0.0
6	0.107910	0.78211	13.774	9.4196	0.0	9.420	23.194	0.52097	0.59387	0.0
7	0.087953	0.87006	19.805	27.6447	0.0	27.645	47.450	1.06581	0.41740	0.0
8	0.069523	0.93959	38.912	70.4511	0.0	70.451	109.363	2.45647	0.35580	0.0
9	0.044095	0.98368	125.858	148.5674	0.0	148.567	274.425	6.16406	0.45862	0.0
10	0.016319	1.00000	442.799	257.5021	0.0	257.502	700.301	15.72996	0.63230	0.0

AV XS - SCAT = 24.4245, CAP = 20.09574, FIS = 0.0 , ABS = 20.09574, TOT = 44.5202

VARIANCES AND COVARIANCES

		SCAT	CAP
SCAT	POINT	4.24901D 03	
SCAT	TABLE	3.51173D 03	
CAP	POINT	2.43159D 03	2.21003D 03
CAP	TABLE	2.45642D 03	2.07545D 03

TEMP = 700.00 DEG K

AV XS - SCAT = 20.3527, CAP = 21.51451, FIS = 0.0 , ABS = 21.51451, TOT = 41.8672

AVERAGE VALUES, 10 LADDERS

K	P	PCUM	SCAT	CAP	FIS	ABS	TOT	TOAT	SPROB	ALPHA
1	0.003983	0.00398	4.165	0.7973	0.0	0.797	4.962	0.11157	0.83933	0.0
2	0.008883	0.01287	4.829	0.9610	0.0	0.961	5.790	0.13018	0.83403	0.0
3	0.083599	0.09647	6.148	0.8990	0.0	0.899	7.047	0.15845	0.87243	0.0
4	0.353563	0.45003	8.307	1.5182	0.0	1.518	9.825	0.22091	0.84548	0.0
5	0.224171	0.67420	11.026	4.9746	0.0	4.975	16.000	0.35975	0.68910	0.0
6	0.107910	0.78211	16.980	13.7798	0.0	13.780	30.760	0.69159	0.55202	0.0
7	0.087953	0.87006	26.838	36.1935	0.0	36.193	63.031	1.41718	0.42578	0.0
8	0.069523	0.93959	46.506	69.0068	0.0	69.007	115.513	2.59717	0.40260	0.0
9	0.044095	0.98368	119.366	126.9864	0.0	126.986	246.353	5.53895	0.48453	0.0
10	0.016319	1.00000	351.669	199.7412	0.0	199.741	551.410	12.39782	0.63776	0.0

AV XS - SCAT = 24.4106, CAP = 20.06578, FIS = 0.0 , ABS = 20.06578, TOT = 44.4764

LADDER NO. 11

NO. OF POINTS = 436

TEMP = 300.00 DEG K

AV XS - SCAT = 19.7102, CAP = 15.12794, FIS = 0.0 , ABS = 15.12794, TOT = 34.8381

PERCENTAGE STANDARD DEVIATIONS OF MEAN CROSS SECTIONS

SCATTERING	CAPTURE	FISSION
15.294	10.214	0.0

TEMP = 700.00 DEG K

AV XS - SCAT = 19.7226, CAP = 15.09014, FIS = 0.0 , ABS = 15.09014, TOT = 34.8128

LADDER NO. 12

NO. OF POINTS = 414

TEMP = 300.00 DEG K

AV XS - SCAT = 11.0594, CAP = 8.00948, FIS = 0.0 , ABS = 8.00948, TOT = 19.0688

PERCENTAGE STANDARD DEVIATIONS OF MEAN CROSS SECTIONS

SCATTERING	CAPTURE	FISSION
15.356	11.097	0.0

TEMP = 700.00 DEG K

AV XS - SCAT = 11.0587, CAP = 7.98391, FIS = 0.0 , ABS = 7.98391, TOT = 19.0426

LADDER NO. 13

NO. OF POINTS = 401

TEMP = 300.00 DEG K

AV XS - SCAT = 19.9532, CAP = 19.94635, FIS = 0.0 , ABS = 19.94635, TOT = 39.8995

PERCENTAGE STANDARD DEVIATIONS OF MEAN CROSS SECTIONS

SCATTERING	CAPTURE	FISSION
14.303	10.168	0.0

TEMP = 700.00 DEG K

AV XS - SCAT = 19.9464, CAP = 19.88958, FIS = 0.0 , ABS = 19.88958, TOT = 39.8360

LADDER NO. 14

NO. OF POINTS = 483

TEMP = 300.00 DEG K

AV XS - SCAT = 13.7973, CAP = 14.55117, FIS = 0.0 , ABS = 14.55117, TOT = 28.3485

PERCENTAGE STANDARD DEVIATIONS OF MEAN CROSS SECTIONS

SCATTERING	CAPTURE	FISSION
13.924	9.706	0.0

TEMP = 700.00 DEG K

AV XS - SCAT = 13.8003, CAP = 14.47482, FIS = 0.0 , ABS = 14.47482, TOT = 28.2751

LADDER NO. 15

NO. OF POINTS = 410

TEMP = 300.00 DEG K

AV XS - SCAT = 25.3563, CAP = 23.35739, FIS = 0.0 , ABS = 23.35739, TOT = 48.7137

PERCENTAGE STANDARD DEVIATIONS OF MEAN CROSS SECTIONS

SCATTERING	CAPTURE	FISSION
12.873	9.047	0.0

AVERAGE VALUES, 15 LADDERS

K	P	PCUM	SCAT	CAP	FIS	ABS	TOT	TOAT	SPROB	ALPHA
1	0.002656	0.00266	4.151	0.7270	0.0	0.727	4.878	0.11877	0.85095	0.0
2	0.008607	0.01126	4.700	0.7968	0.0	0.797	5.497	0.13383	0.85504	0.0
3	0.074981	0.08624	6.071	0.6708	0.0	0.671	6.742	0.16416	0.90050	0.0
4	0.386865	0.47311	8.073	0.8320	0.0	0.832	8.905	0.21682	0.90657	0.0
5	0.220078	0.69319	10.168	2.7474	0.0	2.747	12.916	0.31447	0.78728	0.0
6	0.101970	0.79516	13.516	9.7005	0.0	9.701	23.217	0.56527	0.58217	0.0
7	0.084111	0.87927	19.166	28.2253	0.0	28.225	47.391	1.15387	0.40442	0.0
8	0.065441	0.94471	38.419	71.1824	0.0	71.182	109.602	2.66856	0.35054	0.0
9	0.041523	0.98623	123.178	150.8736	0.0	150.874	274.052	6.67257	0.44947	0.0
10	0.013769	1.00000	420.359	256.0045	0.0	256.005	676.363	16.46798	0.62150	0.0

AV XS - SCAT = 22.2748, CAP = 18.79665, FIS = 0.0 , ABS = 18.79665, TOT = 41.0714

VARIANCES AND COVARIANCES

		SCAT	CAP
SCAT	POINT	3.34470D 03	
SCAT	TABLE	2.76391D 03	
CAP	POINT	2.05485D 03	2.01722D 03
CAP	TABLE	2.08163D 03	1.90441D 03

TEMP = 700.00 DEG K

AV XS - SCAT = 25.3254, CAP = 23.29071, FIS = 0.0 , ABS = 23.29071, TOT = 48.6161

AVERAGE VALUES, 15 LADDERS

K	P	PCUM	SCAT	CAP	FIS	ABS	TOT	TCAT	SPROB	ALPHA
1	0.002656	0.00266	4.165	0.7973	0.0	0.797	4.962	0.12097	0.83933	0.0
2	0.008607	0.01126	4.810	0.9747	0.0	0.975	5.785	0.14101	0.83149	0.0
3	0.074981	0.08624	6.144	0.9679	0.0	0.968	7.112	0.17337	0.86391	0.0
4	0.386865	0.47311	8.303	1.4931	0.0	1.493	9.797	0.23881	0.84759	0.0
5	0.220078	0.69319	10.873	4.7277	0.0	4.728	15.601	0.38030	0.69696	0.0
6	0.101970	0.79516	16.644	14.3039	0.0	14.304	30.948	0.75440	0.53781	0.0
7	0.084111	0.87927	25.766	36.1150	0.0	36.115	61.881	1.50843	0.41638	0.0
8	0.065441	0.94471	45.388	69.4682	0.0	69.468	114.857	2.79980	0.39518	0.0
9	0.041523	0.98623	114.416	127.7850	0.0	127.785	242.201	5.90402	0.47240	0.0
10	0.013769	1.00000	331.187	196.7969	0.0	196.797	527.984	12.87039	0.62727	0.0

AV XS - SCAT = 22.2640, CAP = 18.75914, FIS = 0.0 , ABS = 18.75914, TOT = 41.0231

LADDER NO. 16

NO. OF POINTS = 421

TEMP = 300.00 DEG K

AV XS - SCAT = 12.4267, CAP = 16.13184, FIS = 0.0 , ABS = 16.13184, TOT = 28.5585

PERCENTAGE STANDARD DEVIATIONS OF MEAN CROSS SECTIONS

SCATTERING	CAPTURE	FISSION
12.705	8.585	0.0

TEMP = 700.00 DEG K

AV XS - SCAT = 12.4372, CAP = 16.14079, FIS = 0.0 , ABS = 16.14079, TOT = 28.5779

LADDER NO. 17

NO. OF POINTS = 377

TEMP = 300.00 DEG K

AV XS - SCAT = 24.0644, CAP = 23.18420, FIS = 0.0 , ABS = 23.18420, TOT = 47.2486

PERCENTAGE STANDARD DEVIATIONS OF MEAN CROSS SECTIONS

SCATTERING	CAPTURE	FISSION
11.875	8.075	0.0

TEMP = 700.00 DEG K

AV XS - SCAT = 24.0918, CAP = 23.06835, FIS = 0.0 , ABS = 23.06835, TOT = 47.1601

LADDER NO. 18

NO. OF POINTS = 396

TEMP = 300.00 DEG K

AV XS - SCAT = 32.4389, CAP = 20.51712, FIS = 0.0 , ABS = 20.51712, TOT = 52.9561

PERCENTAGE STANDARD DEVIATIONS OF MEAN CROSS SECTIONS

SCATTERING	CAPTURE	FISSION
11.215	7.592	0.0

TEMP = 700.00 DEG K

AV XS - SCAT = 32.4175, CAP = 20.44435, FIS = 0.0 , ABS = 20.44435, TOT = 52.8618

LADDER NO. 19

NO. OF POINTS = 391

TEMP = 300.00 DEG K

AV XS - SCAT = 16.5561, CAP = 14.54141, FIS = 0.0 , ABS = 14.54141, TOT = 31.0975

PERCENTAGE STANDARD DEVIATIONS OF MEAN CROSS SECTIONS

SCATTERING	CAPTURE	FISSION
10.846	7.377	0.0

TEMP = 700.00 DEG K

AV XS - SCAT = 16.5769, CAP = 14.53726, FIS = 0.0 , ABS = 14.53726, TOT = 31.1141

LADDER NO. 20

NO. OF POINTS = 371

TEMP = 300.00 DEG K

AV XS - SCAT = 17.7832, CAP = 16.94378, FIS = 0.0 , ABS = 16.94378, TOT = 34.7270

PERCENTAGE STANDARD DEVIATIONS OF MEAN CROSS SECTIONS

SCATTERING	CAPTURE	FISSION
10.437	7.049	0.0

AVERAGE VALUES, 20 LADDERS

K	P	PCUM	SCAT	CAP	FIS	ABS	TOT	TOAT	SPROB	ALPHA
1	0.003161	0.00316	4.101	0.7899	0.0	0.790	4.891	0.12067	0.83849	0.0
2	0.007630	0.01079	4.708	0.7830	0.0	0.783	5.491	0.13546	0.85738	0.0
3	0.078157	0.08895	6.039	0.6815	0.0	0.682	6.721	0.16582	0.89860	0.0
4	0.388757	0.47770	8.075	0.7923	0.0	0.792	8.868	0.21878	0.91065	0.0
5	0.218882	0.69659	10.198	2.7082	0.0	2.708	12.906	0.31841	0.79016	0.0
6	0.098317	0.79490	13.619	9.5464	0.0	9.546	23.166	0.57153	0.58791	0.0
7	0.085089	0.87999	19.253	28.4109	0.0	28.411	47.664	1.17592	0.40393	0.0
8	0.065401	0.94539	38.025	71.9160	0.0	71.916	109.941	2.71239	0.34587	0.0
9	0.041713	0.98711	121.857	152.4694	0.0	152.469	274.327	6.76800	0.44421	0.0
10	0.012895	1.00000	421.110	254.4905	0.0	254.490	675.601	16.66795	0.62331	0.0

AV XS - SCAT = 21.8695, CAP = 18.66341, FIS = 0.0 , ABS = 18.66341, TOT = 40.5329

VARIANCES AND COVARIANCES

		SCAT	CAP
SCAT	POINT	3.23450D 03	
SCAT	TABLE	2.62332D 03	
CAP	POINT	1.96920D 03	2.00209D 03
CAP	TABLE	1.99582D 03	1.87428D 03

TEMP = 700.00 DEG K

AV XS - SCAT = 17.7829, CAP = 16.90798, FIS = 0.0 , ABS = 16.90798, TOT = 34.6909

AVERAGE VALUES, 20 LADDERS

K	P	PCUM	SCAT	CAP	FIS	ABS	TOT	TOAT	SPROB	ALPHA
1	0.003161	0.00316	4.112	0.9797	0.0	0.980	5.092	0.12577	0.80760	0.0
2	0.007630	0.01079	4.802	0.9426	0.0	0.943	5.745	0.14188	0.83592	0.0

3	0.078157	0.08895	6.113	0.9895	0.0	0.990	7.103	0.17543	0.86069	0.0
4	0.388757	0.47770	8.285	1.3883	0.0	1.388	9.674	0.23893	0.85649	0.0
5	0.218882	0.69659	10.937	4.7700	0.0	4.770	15.707	0.38793	0.69631	0.0
6	0.098317	0.79490	16.651	14.2495	0.0	14.249	30.900	0.76320	0.53885	0.0
7	0.085089	0.87999	25.865	36.5350	0.0	36.535	62.400	1.54120	0.41450	0.0
8	0.065401	0.94539	44.471	69.9711	0.0	69.971	114.442	2.82660	0.38859	0.0
9	0.041713	0.98711	112.144	128.1936	0.0	128.194	240.337	5.93608	0.46661	0.0
10	0.012895	1.00000	333.232	195.4087	0.0	195.409	528.640	13.05685	0.63036	0.0

AV XS - SCAT = 21.8633, CAP = 18.62429, FIS = 0.0 , ABS = 18.62429, TOT = 40.4876

LADDER NO. 21

NO. OF POINTS = 376

TEMP = 300.00 DEG K

AV XS - SCAT = 12.7108, CAP = 16.10416, FIS = 0.0 , ABS = 16.10416, TOT = 28.8150

PERCENTAGE STANDARD DEVIATIONS OF MEAN CROSS SECTIONS

SCATTERING	CAPTURE	FISSION
10.332	6.781	0.0

TEMP = 700.00 DEG K

AV XS - SCAT = 12.7208, CAP = 16.07708, FIS = 0.0 , ABS = 16.07708, TOT = 28.7979

LADDER NO. 22

NO. OF POINTS = 533

TEMP = 300.00 DEG K

AV XS - SCAT = 27.1626, CAP = 24.10389, FIS = 0.0 , ABS = 24.10389, TOT = 51.2665

PERCENTAGE STANDARD DEVIATIONS OF MEAN CROSS SECTIONS

SCATTERING	CAPTURE	FISSION
9.806	6.519	0.0

AVERAGE VALUES, 22 LADDERS

K	P	PCUM	SCAT	CAP	FIS	ABS	TOT	TOAT	SPROB	ALPHA

1	0.002874	0.00287	4.101	0.7899	0.0	0.790	4.891	0.12080	0.83849	0.0
2	0.007089	0.00996	4.689	0.8039	0.0	0.804	5.493	0.13567	0.85366	0.0
3	0.075826	0.08579	5.984	0.7128	0.0	0.713	6.696	0.16539	0.89356	0.0
4	0.385978	0.47177	8.086	0.7825	0.0	0.783	8.868	0.21903	0.91176	0.0
5	0.221351	0.69312	10.177	2.7580	0.0	2.758	12.935	0.31948	0.78679	0.0
6	0.098058	0.79117	13.596	9.7220	0.0	9.722	23.318	0.57592	0.58307	0.0
7	0.087580	0.87876	18.988	28.6581	0.0	28.658	47.646	1.17680	0.39852	0.0
8	0.068455	0.94721	36.877	72.3334	0.0	72.333	109.211	2.69735	0.33767	0.0
9	0.039935	0.98715	121.307	152.4082	0.0	152.408	273.716	6.76038	0.44319	0.0
10	0.012855	1.00000	424.462	258.1627	0.0	258.163	682.625	16.85986	0.62181	0.0

AV XS - SCAT = 21.6938, CAP = 18.79437, FIS = 0.0 , ABS = 18.79437, TOT = 40.4882

VARIANCES AND COVARIANCES

		SCAT	CAP
SCAT	POINT	3.25392D 03	
SCAT	TABLE	2.62694D 03	
CAP	POINT	1.97647D 03	2.00849D 03
CAP	TABLE	1.99148D 03	1.87247D 03

TA-181. ENERGY DEPENDENT PARAMETERS FROM ENDF/B ANALYSIS J.OTTER,5-72

TABLE NORMALIZED TO ANALYTIC AVERAGE CROSS SECTIONS

K	P	PCUM	SCAT	CAP	FIS	ABS	TOT	TOAT	SPROB	ALPHA
1	0.002874	0.00287	4.481	0.9112	0.0	0.911	5.482	0.12080	0.81733	0.0
2	0.007089	0.00996	5.123	0.9273	0.0	0.927	6.157	0.13567	0.83211	0.0
3	0.075826	0.00579	6.538	0.8222	0.0	0.822	7.506	0.16539	0.87101	0.0
4	0.385978	0.47177	8.834	0.9026	0.0	0.903	9.940	0.21903	0.88875	0.0
5	0.221351	0.69312	11.119	3.1813	0.0	3.181	14.498	0.31948	0.76693	0.0
6	0.098058	0.79117	14.855	11.2145	0.0	11.214	26.136	0.57592	0.56835	0.0
7	0.087580	0.87876	20.746	33.0576	0.0	33.058	53.405	1.17680	0.38847	0.0
8	0.068455	0.94721	40.291	83.4378	0.0	83.438	122.411	2.69735	0.32915	0.0
9	0.039935	0.98715	132.538	175.8054	0.0	175.805	306.798	6.76038	0.43200	0.0
10	0.012855	1.00000	463.757	297.7950	0.0	297.795	765.130	16.85986	0.60612	0.0

TEMP = 700.00 DEG K

AV XS - SCAT = 27.0685, CAP = 23.99044, FIS = 0.0 , ABS = 23.99044, TOT = 51.0589

AVERAGE VALUES, 22 LADDERS

K	P	PCUM	SCAT	CAP	FIS	ABS	TOT	TOAT	SPROB	ALPHA
1	0.002874	0.00287	4.112	0.9797	0.0	0.980	5.092	0.12593	0.80760	0.0
2	0.007089	0.00996	4.784	0.9758	0.0	0.976	5.760	0.14244	0.83058	0.0
3	0.075826	0.08579	6.062	1.0302	0.0	1.030	7.092	0.17539	0.85474	0.0
4	0.385978	0.47177	8.290	1.3712	0.0	1.371	9.661	0.23892	0.85807	0.0
5	0.221351	0.69312	10.920	4.9497	0.0	4.950	15.870	0.39246	0.68811	0.0
6	0.098058	0.79117	16.592	14.4830	0.0	14.483	31.075	0.76849	0.53394	0.0
7	0.087580	0.87876	25.162	36.3697	0.0	36.370	61.531	1.52167	0.40892	0.0
8	0.068455	0.94721	42.563	69.2541	0.0	69.254	111.817	2.76524	0.38065	0.0
9	0.039935	0.98715	112.189	128.4137	0.0	128.414	240.602	5.95009	0.46628	0.0
10	0.012855	1.00000	337.416	199.5578	0.0	199.558	536.974	13.27934	0.62837	0.0

AV XS - SCAT = 21.6843, CAP = 18.75242, FIS = 0.0 , ABS = 18.75242, TOT = 40.4368

TA-181. ENERGY DEPENDENT PARAMETERS FROM ENDF/B ANALYSIS J.OTTER,5-72

TABLE NORMALIZED TO ANALYTIC AVERAGE CROSS SECTIONS

K	P	PCUM	SCAT	CAP	FIS	ABS	TOT	TOAT	SPROB	ALPHA
1	0.002874	0.00287	4.495	1.1327	0.0	1.133	5.715	0.12593	0.78656	0.0
2	0.007089	0.00996	5.229	1.1282	0.0	1.128	6.464	0.14244	0.80894	0.0
3	0.075826	0.08579	6.626	1.1910	0.0	1.191	7.960	0.17539	0.83248	0.0
4	0.385978	0.47177	9.061	1.5852	0.0	1.585	10.843	0.23892	0.83572	0.0
5	0.221351	0.69312	11.936	5.7223	0.0	5.722	17.810	0.39246	0.67018	0.0
6	0.098058	0.79117	18.136	16.7438	0.0	16.744	34.876	0.76849	0.52003	0.0
7	0.087580	0.87876	27.503	42.0469	0.0	42.047	69.056	1.52167	0.39827	0.0
8	0.068455	0.94721	46.524	80.0644	0.0	80.064	125.491	2.76524	0.37073	0.0
9	0.039935	0.98715	122.628	148.4587	0.0	148.459	270.026	5.95009	0.45414	0.0
10	0.012855	1.00000	368.814	230.7082	0.0	230.708	602.640	13.27934	0.61200	0.0

V. COMPUTER CONTROL

The computer control cards needed for use with the IBM 360/165 at the NR Space Division are shown below in the deck setup structure.

1. A /*SETUP card is needed for the auxiliary storage device if ITAPUN=2. Check with the computing department to obtain the current format.
2. //URRR EXEC AFSLINK
   //L.SYSIN DD
3. Compiled (object) Deck
4. /*
5. Control cards for each file placed on the auxiliary device, if ITAPUN=2. Check with the computing department to obtain the current format.
6. //G.SYSIN DD
7. Input data deck
8. /*

U3R requires about 452 bytes of main storage, plus whatever is needed for an auxiliary storage device buffer, if used. See Section IV for an example of running time and cost.

VI. TEST RESULTS

To establish the validity of the method, a test program was set up using the AIRABL code. AIRABL is a modified version of RABBLE[8] which can obtain effective cross sections using probability tables as well as point data. Since a given probability table is based on several ladders generated in the prescribed energy range, the accuracy of the method can be tested by comparing the mean effective cross sections obtained for a given problem using point data sets from each of several ladders with those obtained from several trials using a probability table based on these same point data sets.

Three physical configurations were investigated:

1) A 4.51-cm.-diam tantalum rod in carbon at 300 ev to evaluate mean effective tantalum cross sections.

2) A homogeneous FBR core composition at 5500 ev to evaluate mean effective U^{238} cross sections.

3) A homogeneous FBR core composition at 825 ev to evaluate mean effective Pu^{239} cross sections.

In each case, the U3R code was used to generate probability tables based on 30 ladders of resonances in narrow energy ranges surrounding the test energy. Results were obtained for each of the point data sets corresponding to individual ladders. The mean of these results were then compared with the mean of results using the probability table based on these same point data sets. The means of the results based on the probability table method were obtained from thirty trials each so as to furnish a fair statistical comparison with the ladder results.

NUMERICAL RESULTS

Effective capture and scattering cross sections for three isotopes in problems emphasizing different portions of their unresolved energy ranges are shown in Table 2. The means based on the probability table method were in statistical agreement with their corresponding means from the point data set calculations. The errors shown in Table 2 represent one standard deviation. While most of the calculations were performed using a table size of 45, no appreciable loss in quality was observed using a table size of 10.

TABLE 2

AIRABL EFFECTIVE CROSS SECTIONS COMPUTED WITH PROBABILITY TABLES AND POINT DATA FROM LADDERS

Process	Isotope	Pointwise	Probability Table	Difference	Table Size	Temperature (°K)	Energy (ev)
σ_c	Ta	4.276 ± 0.157	4.204 ± 0.115	-0.072 ± 0.195	45	300	300
σ_c	Ta	5.247 ± 0.201	5.240 ± 0.103	-0.007 ± 0.226	45	700	300
σ_c	Ta	5.247 ± 0.201	5.383 ± 0.098	+0.136 ± 0.224	10	700	300
σ_s	Ta	9.826 ± 0.166	9.639 ± 0.079	-0.187 ± 0.184	45	300	300
σ_s	Ta	10.391 ± 0.199	10.220 ± 0.067	-0.171 ± 0.210	45	700	300
σ_s	Ta	10.391 ± 0.199	10.326 ± 0.062	-0.065 ± 0.208	10	700	300
σ_c	U^{238}	0.817 ± 0.014	0.812 ± 0.009	-0.005 ± 0.017	45	300	5500
σ_c	U^{238}	0.871 ± 0.015	0.863 ± 0.008	-0.008 ± 0.017	45	700	5500
σ_s	U^{238}	13.39 ± 0.18	13.37 ± 0.10	-0.02 ± 0.21	45	300	5500
σ_s	U^{238}	13.80 ± 0.20	13.83 ± 0.09	+0.03 ± 0.22	45	700	5500
σ_c	Pu^{239}	5.007 ± 0.251	5.022 ± 0.064	+0.015 ± 0.259	45	300	825
σ_c	Pu^{239}	5.196 ± 0.270	5.217 ± 0.053	+0.021 ± 0.275	45	700	825
σ_s	Pu^{239}	12.749 ± 0.273	12.723 ± 0.052	-0.026 ± 0.278	45	300	825
σ_s	Pu^{239}	12.886 ± 0.295	12.886 ± 0.044	0.000 ± 0.298	45	700	825

REFERENCES

1. L. B. Levitt, "The Probability Table Method for Treating Unresolved Resonances in Monte Carlo Criticality Calculations," Trans. Am. Nucl. Soc., 14, No. 2, 648, October 1971

2. J. M. Otter, "Application of the Probability Table Method of Treating Unresolved Resonances to an Analytical Calculation," Trans. Am. Nucl. Soc., 14, No. 2, 649, October 1971

3. L. B. Levitt, "The Cross Section Probability Table Method for Treating Unresolved Resonances in Reactor Calculations" (submitted for publication to Nuclear Science and Engineering)

4. J. M. Otter, "UNICORN, A Program to Calculate Point Cross Sections for Resonance Parameters," NAA-SR-11980, Vol. VI, June 30, 1966

5. C. L. Dunford and E. L. Bramblett, "Doppler Broadening of Resonance Data for Monte Carlo Calculations," AI-CE-MEMO-21, June 20, 1966

6. R. A. Blaine, "TYCHE, A Monte Carlo Slowing Down Code," NAA-SR-1357, June 1967

7. G. Doherty, "Some Calculated Infinitely Dilute Resonance Integrals," AAEC/TM-270

8. P. H. Kier and A. A. Robba, "RABBLE, A Program for Computations of Resonance Absorption in Multiregion Reactor Cells," ANL-7326, April 1967

Atomics International
North American Rockwell

P.O. Box 309
Canoga Park, California 91304