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**TNS,
AN IBM 7090 PROGRAM
FOR COMPUTING
THERMAL NEUTRON SPECTRA
AND MULTITHERMAL
GROUP CROSS SECTIONS**

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I N T R O D U C T I O N

This report describes the theory underlying the Thermal Neutron Spectrum (TNS) computer program. Detailed instructions for the use of the program are also included.

TNS calculates the thermal neutron spectrums for an infinite homogeneous medium. It also generates spectrum averaged cross section for up to twenty thermal groups, including transfer coefficients between the groups. The program has been used successfully at WANL. In nuclear reactors in which the thermal neutron spectrum varies rapidly as a function of position, the use of one thermal neutron group in diffusion or transport calculations has frequently given poor results. The output from TNS, when used with standard diffusion and transport theory programs, has led to considerable improvement.

Segments of the computer program are taken directly from Reference (1). However, many changes and additions were made to incorporate these into the TNS program.

T H E O R Y -

The thermal neutron spectrum in an infinite homogeneous medium, with a slowing down source, may be obtained as the solution of the equation

$$\begin{aligned} \sum_i N_i \sigma_{ai}(E) \phi(E) + \sum_i C_i \sigma_{oi} \int_0^{E_c} \sigma_i(E \rightarrow E') \phi(E) dE' \\ = \sum_i C_i \sigma_{oi} \int_0^{E_c} \sigma_i(E' \rightarrow E) \phi(E') dE' + \sum_i C_i \sigma_{oi} Q_i(E) \end{aligned} \quad (1)$$

where

- $\phi(E)$ = neutron spectrum,
- N_1 = atom density of absorber 1,
- C_1 = atom density of moderator 1,
- $\sigma_{a1}(E)$ = microscopic absorption cross section of absorber 1,
- $\sigma_1(E' \rightarrow E)$ = normalized microscopic scattering kernel of moderator 1,
- E_c = thermal cut-off energy,
- $Q_1(E)$ = energy distribution of neutrons scattered by moderator 1 into the interval $0 \leq E \leq E_c$ from above E_c ,
- σ_{oi} = free stationary atom microscopic scattering cross section for moderator 1.

In addition to Equation (1), two conditions must be satisfied.

These are:

1. Detailed balance
2. Conservation of neutrons

Condition 1 requires:

$$\sigma_i(E' \rightarrow E) E' e^{-\frac{E'}{kT}} = \sigma_i(E \rightarrow E') E e^{-\frac{E}{kT}} \quad (2)$$

Thus if the scattering kernels for $E' \geq E$ are known, those for $E' < E$ are fixed by Equation (2). The details for computing the kernels will not be discussed here. Suffice it to say that computer codes which compute these according to various physical models are available^{(1), (2)}. Condition 2 requires

$$\int_0^{E_c} \sum_i N_i \sigma_{ai}(E) \phi(E) dE = \int_0^{E_c} \sum_i C_i \sigma_{oi} Q_i(E) dE \quad (3)$$

For conciseness of notation define

$$\gamma(E) = \sum_i N_i \sigma_{ai}(E) \quad (4)$$

$$P(E' \rightarrow E) = \sum_i C_i \sigma_{oi}(E' \rightarrow E) \quad (5)$$

$$S(E) = \sum_i C_i \sigma_{oi} Q_i(E) \quad (6)$$

Equations (1), (2), and (3) now become

$$\gamma(E)\phi(E) + \int_0^{E_c} P(E \rightarrow E')\phi(E)dE = \int_0^{E_c} P(E' \rightarrow E)\phi(E')dE' + S(E) \quad (7)$$

$$P(E' \rightarrow E)E'e^{-E'/RT} = P(E \rightarrow E')Ee^{-E/RT} \quad (8)$$

and

$$\int_0^{E_c} \gamma(E)\phi(E)dE = \int_0^{E_c} S(E)dE \quad (9)$$

The method used to solve Equation (7) is similar to that used in Reference (1).

Equation (7) is rearranged to give

$$\phi(E) = \frac{S(E) + \int_0^{E_c} P(E' \rightarrow E)\phi(E')dE'}{\gamma(E) + \int_0^{E_c} P(E \rightarrow E')dE'} \quad (10)$$

For the moment, let us assume that $S(E)$ is known. Then the following iterative procedure is used to solve Equation (10).

$$\hat{\phi}^{(k)}(E) = \phi^{(k)}(E) \frac{\int_0^{E_c} S(E)dE}{\int_0^{E_c} \gamma(E)\phi^{(k)}(E)dE} \quad (11)$$

$$\phi^{(k+1)}(E) = \frac{S(E) + \int_0^{E_c} P(E' \rightarrow E)\hat{\phi}^{(k)}(E')dE'}{\gamma(E) + \int_0^{E_c} P(E \rightarrow E')dE'} \quad (12)$$

One begins with an initial flux guess $\phi^0(E)$ and applies Equations (11) and (12) until

$$\left| \frac{\phi^{(k+1)}(E)}{\phi^{(k)}(E)} - 1 \right| < \epsilon \quad \text{for } 0 < E \leq E_c \quad (13)$$

where ϵ is the convergence criterion. Equation (11) is used as part of the iterative procedure in order to satisfy Equation (9) after each iteration.

For purposes of numerical calculations, the continuous variable E is approximated by discrete energy points E_1 and the integrations required in Equations (11) and (12) are carried out by Simpson's rule. The energy intervals may be chosen arbitrarily, but there must be an odd number of energy points (even number of intervals).

Specifically, Equations (11), (12) and (13) are approximated by

$$\hat{\phi}_i^{(k)} = \phi_i^{(k)} \frac{\sum_{j=1}^N S_j \delta_j}{\sum_{j=1}^N \gamma_j \phi_j^{(k)} \delta_j} \quad i=1, \dots, N \quad (14)$$

$$\phi_i^{(k+1)} = \frac{S_i + \sum_{j=1}^N P_{ji} \hat{\phi}_j^{(k)} \delta_j}{\gamma_i + \sum_{j=1}^N P_{ij} \delta_j} \quad i=1, \dots, N \quad (15)$$

and

$$\left| \frac{\phi_i^{(k+1)}}{\phi_i^{(k)}} - 1 \right| < \epsilon \quad i = 1, \dots, N \quad (16)$$

where N represents the number of energy points, and δ_i is defined by

$$\delta_1 = \frac{1}{6} \left[E_3 + E_2 - 2E_1 - \frac{(E_3 - E_2)^2}{E_2 - E_1} \right] + \frac{E_1}{2}, \quad (17)$$

$$\delta_i = \frac{(E_{i+1} - E_{i-1})^3}{6(E_{i+1} - E_i)(E_i - E_{i-1})} \quad \text{for } 1 < i < E_{N-2} \text{ and even } i, \quad (18)$$

$$\delta_i = \frac{1}{6} \left[E_{i+2} + E_{i+1} - E_{i-1} - E_{i-2} - \frac{(E_{i-1} - E_{i-2})^2}{E_{i-1} - E_{i-2}} \right] \quad (19)$$

$$\left[- \frac{(E_{i+2} - E_{i+1})^2}{E_{i+1} - E_i} \right] \quad \text{for } 1 < i < E_{N-2} \text{ and odd } i,$$

$$\delta_i = \frac{V - W(E_{N-1} + E_N) + E_{N-1}E_N}{(E_{N-1} - E_{N-2})(E_N - E_{N-2})} (E_m - E_{N-2}) \quad (20)$$

$$+ \frac{1}{6} \left[E_{N-3} - E_{N-4} + 2(E_{N-2} - E_{N-3}) - \frac{(E_{N-3} - E_{N-4})^2}{E_{N-2} - E_{N-3}} \right]$$

$$\delta_{N-1} = \frac{V - W(E_{N-2} + E_N) + E_{N-2} E_N}{(E_{N-1} - E_{N-2})(E_{N-1} - E_N)} (E_m - E_{N-2}) \quad (21)$$

$$\delta_N = \frac{V - W(E_{N-2} + E_{N-1}) + E_{N-2} E_{N-1}}{(E_N - E_{N-2})(E_N - E_{N-1})} (E_m - E_{N-2}) \quad (22)$$

where

$$E_m = E_N + \frac{E_N - E_{N-1}}{2}, \quad (23)$$

$$V = \frac{1}{3} (E_m^2 + E_m E_{N-2} + E_{N-2}^2), \quad (24)$$

and

$$W = \frac{1}{2} (E_m + E_{N-2}) \quad (25)$$

Although the appropriate δ_i 's for trapezoidal integration are much simpler, the i 's need be computed only once. For this reason, the use of Simpson's integration does not add significantly to the computing time. Equations (17) to (25) define δ_i appropriate for integration over E from $E = 0$ to $E = E_m$, where E_m is given by Equation (23). To compute integrals from zero to E_N , the appropriate δ_i are given in Equations (17) to (19), which are applicable for

$i = N-2$ and $i = N-1$, and with

$$\delta_N = \frac{1}{6} \left[2E_N - E_{N-1} - E_{N-2} - \frac{(E_{N-1} - E_{N-2})^2}{E_N - E_{N-1}} \right] \quad (26)$$

In the TNS computer program the integrations required for the computation of the ϕ_i are carried out over the interval $[0, E_m]$.

The balance checks, which are discussed later, are also computed over this interval. The calculation of group cross sections, however, are computed by integration over the interval $[0, E_N]$; that is, the largest energy of the highest energy group is E_N .

Until now, it has been assumed that $S(E)$ is known. Actually, $S(E)$ is given by:

$$S(E) = \int_{E_c}^{\infty} P(E' \rightarrow E) \phi(E') dE' - \int_{E_c}^{\infty} P(E \rightarrow E') \phi(E) dE' \quad (27)$$

If $E_c \gg kT$, where k is Boltzmann's constant and T is the moderator temperature, $S(E)$ has a particularly simple form. The up-scattering term may be neglected, the epithermal flux can be taken as $1/E$, and $P(E' \rightarrow E)$ may be taken as the scattering kernel for free atoms at rest. In this case we have:

$$P(E' \rightarrow E) = \sum_i C_i \sigma_{0i} \frac{1}{E'(1-\alpha_i)} f(E - \alpha_i E') \quad (28)$$

where

$$\alpha_i = \left(\frac{A_i - 1}{A_i + 1} \right)^2, \quad (29)$$

A_i being the atomic weight of moderator i ,

$$f(x) = \begin{cases} 1 & \text{for } x > 0 \\ 0 & \text{for } x \leq 0 \end{cases} \quad (30)$$

and

$$S(E) = \sum_i \frac{C_i \sigma_{oi}}{1 - \alpha_i} \left[\frac{1}{E_c} - \frac{\alpha_i}{E} \right] f(E - \alpha_i E_c) \quad (31)$$

It has been found that in many practical applications, the assumptions upon which Equation (31) is based are not well satisfied.

In order to get a better expression for the thermal source, it is necessary to use less drastic assumptions in the evaluation of (27). The scattering kernel used in Equation (8), which in principle is the same as is used in Equation (7), can be approximated by a free gas kernel above E_c as well as at energies slightly below E_c . Of course, in many cases the kernel in Equation (7) will also be chosen to be a gas kernel, thus making a consistent approximation. The epithermal flux distribution, also required in Equation (27) can be obtained from experiment or from some suitable theoretical approach ⁽³⁾.

However, it has been found that the assumption of a $1/E$ epithermal flux gives results which are not significantly different from those obtained by a more sophisticated approach.

In order to evaluate Equation (27) numerically, one proceeds as follows:

Define:

$$\Delta = E_N - E_{N-1}, \quad (32)$$

That is, Δ is the energy spread between the last two energy points. Then, by trapezoidal integration of Equation (27),

$$S_i = \Delta \sum_j \bar{P}(E_N + j\Delta \rightarrow E_i) \phi(E_N + j\Delta) - \Delta \sum_j \bar{P}(E_i \rightarrow E_N + j\Delta) \phi(E_i) \quad (33)$$

where $\bar{P}$ is the scattering kernel for all elements except free monatomic hydrogen,

$$\bar{P} = P - P_H \quad (34)$$

$\bar{P}$ is calculated from a free gas model and $\phi(E)$ is taken as $\frac{1}{E}$.

Equation (33) is first evaluated for $i = N$, then $i = N - 1$, and so on

until $\frac{S}{S_N} < \epsilon_2$ where ϵ_2 is a specified convergence criterion

(10^{-3} in TNS). The required summations on j are carried out until addition of another term does not contribute significantly to the partial sums.

For the case of free monatomic hydrogen gas, it is possible to carry out the integration in (27) exactly. Since the microscopic hydrogen scattering kernel is simply:

$$\sigma_H(E' \rightarrow E) = \begin{cases} \frac{1}{E'} \operatorname{erf} \sqrt{\frac{E}{kT}} & \text{for } E' \geq E \\ \frac{1}{E} \exp\left(\frac{E-E'}{kT}\right) \operatorname{erf} \sqrt{\frac{E}{kT}} & \text{for } E' < E \end{cases} \quad (35)$$

one obtains for the source, due to hydrogen moderation,

$$S_H(E) = C_H \sigma_{oH} \left\{ \sigma_H(E_c \rightarrow E) - \sigma(E \rightarrow E_c) \frac{kT}{E} \right\} \quad (36)$$

To get the total thermal source, one adds $S_H(E)$ to the S_1 obtained from Equation (33).

This method of obtaining the thermal source has proved to be quite satisfactory.

P R I N T E D O U T P U T -

Of particular interest in reactor calculations are certain average cross sections taken over the entire thermal neutron spectrum, as well as over a finite number of subdivisions of the thermal spectrum. The quantities computed by the TNS program are:

The macroscopic absorption, scattering, transport and fission cross sections

- (a) For each group and for each material,
- (b) By groups summed over all materials,
- (c) By materials for the entire thermal spectrum,
- (d) For sum of materials over entire thermal spectrum.

The number of neutrons emitted per fission times the fission cross section, as well as the diffusion coefficient are given for (b) and (d) above.

The microscopic absorption, scattering, transport, and fission cross sections are given for (a) and (c) above.

The TNS program also computes a transfer matrix for use in multithermal group reactor calculations. It does so by evaluating:

$$\sum_{j \rightarrow i} = \frac{\int_{L_i}^{U_i} dE \int_{L_j}^{U_j} P(E' \rightarrow E) \phi(E') dE'}{\int_{L_j}^{U_j} \phi(E) dE} \quad (37)$$

where U_1 and L_1 denote the upper and lower energy limits of group 1,

respectively, and $\phi(E)$ is either a computed spectrum or an arbitrarily input spectrum. In addition the scattering cross section:

$$\Sigma_s(E) = \int_0^{E_c} P(E \rightarrow E') dE' \quad (38)$$

is computed.

In (38), the upper limit should be ∞ . However, for all E except those very close to E_c , Equation (38) is accurate.

In addition, the thermal source is integrated over each thermal group. These quantities are useful for making the thermal transfer matrix consistent with a given set of fast removal cross sections. For instance, let $\bar{S}_i$ be the source integrated over group i;

$$\bar{S}_i = \int_{L_i}^{U_i} S(E) dE \quad (39)$$

Then evaluate

$$f_i = \frac{S_i}{\int_0^{E_c} S(E) dE} \quad (40)$$

for all groups. If one has the removal cross sections from the lowest fast group into the thermal groups, Σ_{Rt} , - as may be obtained from MUFT for example - the transfer cross section from the fast

group into thermal group i may be computed from

$$\sum_{\text{fast} \rightarrow i} = f_i \sum_{\text{Re}} \quad (41)$$

The TNS program prints the quantities f_i under the heading "REMOVAL CROSS SECTION FRACTION".

The integrated group fluxes are printed under the heading "WEIGHT FACTOR".

All integrations in the TNS program, with the exception of Equation (28), are carried out by Simpson integration. Equation (28) is integrated by trapezoidal integration, as indicated by Equation (33).

A balance check is computed by the TNS program. For each thermal group the gains, which consist of the fraction of the thermal source going into the group plus the scattering in from other groups is calculated. Similarly, the loss from each group, due to absorption plus scattering into other groups, is calculated. The agreement between the gain and loss for each group directly reflects the accuracy of the integration procedure.

The balance check indicates whether or not enough energy points are included within a group, as well as the accuracy of the Simpson integration. The balance check is a useful indicator only if the initial flux guess has been iterated upon to give the correct spectrum.

<u>CARD(s)</u>	<u>FORMAT</u>	<u>FORTTRAN NAME</u>	<u>EXPLANATION</u>
1	I1	MCARDS	<p>1 If kernels are to be read from cards. This option is used primarily to test new kernels. If MCARDS = 1, no problem stacking is permitted; NEXT (see Card 20) is automatically set equal to 4.</p> <p>0 If kernels are to come from tape.</p>
2	72H		One arbitrary title card. Column 1 should be left blank.
3	I3	NEVR	Number of energy points desired $7 \leq \text{NEVR} \leq 99$; NEVR must be an odd number.
4	24I3	NALPHA, IA	Number of absorbers; identification number for each absorber. $\text{NALPHA} \leq 15$.
5	24I3	MOD, IM	Number of moderators; identification number for each moderator. $\text{MOD} \leq 15$.
6	7E10.5	PENS	Moderator densities. These must be given in same order as on Card 5. Only relative (not absolute) values are required.
7	E 10.5	T	Effective moderator temperature in ev. If MCARDS = 0, this must correspond to a temperature available from the library tape. Problems must be stacked in ascending order of T.
8	2E10.5	A, SRAT	Atomic weight and free stationary atom scattering cross section of first moderator. If MCARDS = 0, this card is omitted.

<u>CARD(s)</u>	<u>FORMAT</u>	<u>FORTRAN NAME</u>	<u>EXPLANATION</u>
9	5E12.5	SIG	Scattering kernels for first moderator. If MCARDS = 0 these cards are omitted.
<u>NOTE:</u> If there is more than one moderator, Cards 8 and 9 for the second moderator follow, etc.			
10	72H		One arbitrary title card. Column 1 should be left blank.
11	E10.5	DENS	Atom density of first absorber.
12	7E10.5	ENVR	Absorber densities. These must be given in same order as on Card 4.
13	I1	LANT	= 1 if program computes source = 2 if source is read from cards = 3 if source from previous problem is to be used.
14	5E12.5	S	Source at each energy point, beginning with the lowest energy. These cards are included only if LANT = 2.
15	2I5	LOLA ± LALU	LOLA = 1 Compute a Maxwellian flux guess, 2 Read flux guess, 3 Use flux from previous problem. LALU = 1 No iteration on flux guess. Use guess as actual flux. 2 Iterate on flux guess to obtain converged flux.

<u>CARD(s)</u>	<u>FORMAT</u>	<u>FORTRAN NAME</u>	<u>EXPLANATION</u>
16	5E12.5	PHI	Flux at each energy point, beginning with lowest energy. These cards are inserted only if LOLA = 2.
17	E10.5	EPSI	Covergence criterion for iteration on flux guess. This card is inserted only if LALU = 2.
18	I2	MID	Number of thermal groups MID $\leq$ 20.
19	14I5	NBOUN	Group boundaries. These are odd integers corresponding to the upper energy limits of each group. They must be in ascending order, and the last one must equal NEVR.
20	I1	NEXT	<p>4 If this is last problem. If MCARDS = 1, NEXT automatically assumes this value.</p> <p>2 If data on cards 1 - 9 does not change.</p> <p>3 If data on cards 1 - 17 does not change.</p> <p>5 If data on cards 1 - 9 changes, but data on cards 5, 6, and 7 does not. This option should be used when applicable because it avoids time consuming tape manipulations.</p> <p>6 If data on Cards 1 - 9 changes, but data on Card 4 does not. Considerable tape manipulations are avoided when this option is used.</p> <p>1 If none of the above requirements are fulfilled.</p>

For the next problem, the data can be stacked behind
Card 20 according to the rules below:

If NEXT =

- 1, entire new set of data is required
(Cards 2 - 20)
- 2, only Cards 10 - 20 are needed
- 3, only Cards 18 - 20 are needed
- 5, same as for 1, but Cards 5 - 7 are omitted
- 6, same as for 1, but Card 4 is omitted

LIBRARY TAPES

The pertinent data available on tapes is given in this section of the report. There are two different tapes which are used with TNS. These will be denoted by I and II in this report - the precise tape numbers used may be obtained from the Reactor Physics and Mathematics Section. The principal difference between the two tapes is that the energy mesh differs. Tape I used for moderator temperatures at and below 300°K. Tape II is preferable for higher temperatures.

The energy points and corresponding energies (in ev) on Tape I are:

i	E_i	i	E_i	i	E_i	i	E_i
1	.001	26	.075	51	.30	76	.30
2	.002	27	.080	52	.325	77	.925
3	.003	28	.085	53	.35	78	.950
4	.004	29	.090	54	.375	79	.975
5	.005	30	.095	55	.385	80	1.0
6	.006	31	.10	56	.40	81	1.05
7	.007	32	.11	57	.414	83	1.10
8	.008	33	.12	58	.43	83	1.125
9	.009	34	.13	59	.475	84	1.20
10	.01	35	.14	60	.50	85	1.25
11	.012	36	.15	61	.532	86	1.30
12	.014	37	.16	62	.55	87	1.35
13	.016	38	.17	63	.575	88	1.4
14	.018	39	.18	64	.60	89	1.44
15	.020	40	.19	65	.625	90	1.5
16	.025	41	.20	66	.650	91	1.6
17	.030	42	.21	67	.683	92	1.725
18	.035	43	.22	68	.700	93	1.86
19	.040	44	.23	69	.725	94	1.9
20	.045	45	.24	70	.75	95	2.0
21	.050	46	.25	71	.775	96	2.1
22	.055	47	.26	73	.80	97	2.2
23	.060	48	.27	73	.835	98	2.3
24	.065	49	.28	74	.85	99	2.38
25	.070	50	.29	75	.876		

The energy points and corresponding energies (in ev) on Tape II are:

i	E_i	i	E_i	i	E_i	i	E_i
1	.005	26	.16	51	.414	76	.90
2	.01	27	.17	52	.42	77	.925
3	.015	28	.18	53	.43	78	.95
4	.02	29	.19	54	.44	79	.975
5	.025	30	.20	55	.45	80	1.0
6	.03	31	.21	56	.46	81	1.05
7	.035	32	.22	57	.47	82	1.1
8	.04	33	.23	58	.48	83	1.125
9	.045	34	.24	59	.49	84	1.2
10	.05	35	.25	60	.50	85	1.25
11	.055	36	.26	61	.532	86	1.3
12	.06	37	.27	62	.55	87	1.35
13	.065	38	.28	63	.575	88	1.4
14	.07	39	.29	64	.60	89	1.44
15	.075	40	.30	65	.625	90	1.5
16	.08	41	.31	66	.65	91	1.6
17	.085	42	.32	67	.682	92	1.725
18	.09	43	.33	68	.70	93	1.86
19	.095	44	.34	69	.725	94	1.9
20	.10	45	.35	70	.75	95	2.0
21	.11	46	.36	71	.775	96	2.1
22	.12	47	.37	72	.80	97	2.2
23	.13	48	.38	73	.835	98	2.3
24	.15	50	.40	75	.876		

Element Identification Numbers

<u>Absorber</u>	<u>I. D.</u>	<u>Absorber</u>	<u>I. D.</u>
C	4	B ¹⁰	29
Fe	6	Li ⁶	30
Ni	7	Ag	53
Nb	8	Rh	72
Ae	9	Ta	73
Cr	11	Ir	77
Hf	14	Be (300°K)	80
Li	16	Be (100°K)	81
U ²³⁵	18	H Gas	92
U ²³⁸	20	H Para	93

Absorber 81 is only available on Tape I. All others are available on both tapes.

<u>Moderator</u>	<u>I. D.</u>
C	1
H	2
Be	3

The following moderator temperatures are available on Tape I:

<u>T (°K)</u>	<u>T (ev)</u>
50	.004308
75	.006461
100	.008616
125	.010768
150	.01292
175	.015076
200	.01723
225	.019383
250	.02154
275	.02369
293	.02525

At present, the above temperatures are available for Beryllium and Hydrogen. Only 293°K is available for Graphite.

The following moderator temperatures are available on Tape II:

<u>T (°K)</u>	<u>T, °(ev)</u>	<u>T (°K)</u>	<u>T (°K)</u>
50	.004308	1150	.09908
100	.008616	1200	.10340
150	.01292	1500	.12925
200	.01723	1550	.13355
250	.02154	1600	.13786
293	.02525	1700	.14648
350	.03016	2000	.17233
400	.03446	2100	.18094
450	.03877	2200	.18956
500	.04308	2250	.19387
550	.04739	2300	.19818
600	.05170	2350	.20248
650	.05601	2400	.20679
700	.06031	2500	.21541
750	.06462	2600	.22403
800	.06893	2700	.23264
850	.07324	2800	.24126
900	.07754	2900	.24988
950	.08186	3000	.25849
1100	.09478		

At present, Hydrogen is available for all the above temperatures;
 Graphite is available for temperatures from 293°K to 3000°K;
 Beryllium is available for temperatures from 50°K to 500°K.

At present, all kernels on tape are based on a gas model. Efforts to generate kernels based on more sophisticated models are now being made. These will be added to the tapes as they become available.

REFERENCES

1. GAMD-754 (Rev.)
2. Joan Bell, Summit: An IBM 7090 Program for the Computation of Crystalline Scattering Kernels, GA-2492.
3. D. E. Parks, Nuclear Science and Engineering 9, 430 (1961).