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SOME ASPECTS OF THERMAL NEUTRON DIFFUSION IN NON-UNIFORM TEMPERATURE MODERATORS

BY

J. J. THOMPSON

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Summary

The effect of non–uniform temperature on the Maxwellian distribution of thermal neutrons in a non–capturing moderator has been studied, using the heavy gaseous moderator approach. The results indicate that for typical temperature gradients in power reactors, the neutron temperature follows the moderator temperature with negligible distortion of the spectrum, and that at the boundary between regions of different temperature, perturbations are restricted to a few centimetres.

1. INTRODUCTION

1.1
Temperature gradients will exist in core and reflector of a power reactor. Because neutron flux spectra in moderators are temperature dependent, the effect of non–uniform temperature distributions should be included in studies of power reactor systems.

1.2
The general problem is very complex, for it is a study of the establishment of an equilibrium neutron spectrum by the combined actions of neutron scattering by moderator atoms in thermal motion, which varies from point to point, and neutron absorption. For neutron kinetics, the unsteady–state problem is also significant. To date much work has been done on neutron thermalization with capture in an isothermal infinite medium, and some work has been done on the isothermal finite region problem.

1.3
Considerable effort would be required to extend this work to include the effects of non–uniform temperature. In the following, attention will be focused only on the steady–state diffusion of thermal neutrons, for several particular cases of non–uniform temperature, without including absorption and slowing down from much higher energies. A rigorous analysis would involve details of scattering by the particular moderator under discussion, but comparatively simple solutions are possible for the heavy gaseous moderator model. This should give a first approximation for moderators like Graphite and Beryllium (1).

1.4
The aim is to obtain some idea of how the Maxwellian spectrum of thermal neutrons is modified when the moderator temperature is a function of position. The first problem is the neutron spectrum in a moderator with a finite temperature gradient, and is of interest in connection with the temperature gradient in a power reactor core. The second problem is the spectrum of neutrons in a moderator the two halves of which are maintained at different temperatures. This problem is of interest in connection with the conditions that must exist at the boundary between a core and reflector at different temperatures.

2. THE EFFECT OF A FINITE TEMPERATURE GRADIENT

Using the heavy gaseous moderator model, the diffusion approximation leads to the equations

$$\frac{1}{\Sigma_s}\frac{\partial \phi_0}{\partial X} + \phi_1 = 0 \qquad (1)$$

$$\frac{1}{\xi\Sigma_s}\frac{\partial \phi_1}{\partial X} = \frac{\partial}{\partial E}\left[(E-T)\,\phi_0 + ET\,\frac{\partial \phi_0}{\partial E}\right] \qquad (2)$$

These refer to systems with flux and temperature variations only in the X direction with Σ_s independent of X. $\phi_0(E)$ and $\phi_1(E)$ are the first two terms in the spherical harmonics expansion of the vector flux, and are related to the scalar flux and the neutron current as follows.

$$\Phi = \int_0^\infty \phi_0(E)\,dE \qquad (3)$$

$$J = \int_0^\infty \phi_1(E)\,dE \qquad (4)$$

Integrating (1) and (2) with respect to E, using the fact that ϕ_0 vanishes at the two limits, shows that J must be constant, and Φ must be a linear function of X. In terms of the new variable $\epsilon = E/T$ a possible solution is

$$\phi_0 = \frac{X}{T}\,\Omega(\epsilon) + \frac{1}{T}\,g(\epsilon) \qquad (5)$$

$$J = -\frac{1}{3\Sigma_s}\int_0^\infty \Omega(\epsilon)\, d\epsilon \tag{6}$$

From (1) and (2), writing $\beta^2 = 1/3\,\xi\,\Sigma_s^2$

$$\beta^2 \frac{\partial^2 \phi_o}{\partial \chi^2} + \frac{\partial}{\partial \epsilon}\left[(\epsilon - 1)\phi_o + \epsilon \frac{\partial \phi_o}{\partial \epsilon}\right] = 0 \tag{7}$$

Remembering that T is a function of χ, substitution of (5) into (7) shows that an equation in terms of ϵ only will be obtained if $T = T_o \exp(\lambda\chi)$. This equation is

$$\beta^2 \left[\chi\lambda^2(\Omega + 3\epsilon\Omega' + \epsilon^2\Omega'') + \lambda^2(g + 3\epsilon g' + \epsilon^2 g'') - \lambda(\Omega + \epsilon\Omega')\right]$$

$$+ \frac{\partial}{\partial \epsilon}\left[(\epsilon - 1)(\chi\Omega + g) + \epsilon(\chi\Omega' + g')\right] = 0 \tag{8}$$

It follows that this equation will be satisfied if

$$\Omega'(\gamma\epsilon^2 + \epsilon) + \Omega(\gamma\epsilon + \epsilon - 1) = 0 \tag{9}$$

$$\text{and } g'(\gamma\epsilon^2 + \epsilon) + g(\gamma\epsilon + \epsilon - 1) = \frac{\gamma}{\lambda}\epsilon\Omega \tag{10}$$

where $\gamma = \beta^2\lambda^2 = \lambda^2 / 3\,\xi\,\Sigma_s^2$

$$\text{Hence } \Omega = C\epsilon / (1 + \gamma\epsilon)^{2 + \frac{1}{\gamma}} \tag{11}$$

$$g = C\gamma\epsilon \log(1 + \gamma\epsilon) / \lambda(1 + \gamma\epsilon)^{2 + \frac{1}{\gamma}}$$

$$+ D\epsilon / (1 + \gamma\epsilon)^{2 + \frac{1}{\gamma}} \tag{12}$$

As the temperature gradient tends to zero

$$\phi(\epsilon)\, d\epsilon \rightarrow \lim_{\gamma \rightarrow 0} (C\chi + D)\,\epsilon / (1 + \gamma\epsilon)^{2 + \frac{1}{\gamma}}$$

$$\rightarrow (C\chi + D)\,\epsilon\, e^{-\epsilon}$$

and this is simply the Maxwellian distribution.

Equations (11) and (12) together with (5) represent the solution of the problem. Of particular interest is the case when the neutron current is zero. Then

$$\phi(\epsilon)\, d\epsilon \propto \epsilon\, d\epsilon / (1 + \gamma\epsilon)^{2 + \frac{1}{\gamma}}$$

In terms of neutron velocity ($v = 2\,E/m$, $v_o = 2\,T/m$) the neutron density distribution will therefore be

$$n(v)\,dv = A\,v^2\,dv \;/\; \left(1 + \frac{\gamma v^2}{v_o^2}\right)^{2 + \frac{1}{\gamma}}$$

Let $N = \int_o^{\infty} n(v)\,dv$ be the total neutron density. Then

$$N = A\sqrt{\pi}\,v_o^3\;\Gamma\left(\frac{1}{2} + \frac{1}{\gamma}\right) \;/\; 4\,\gamma^{\frac{3}{2}}\;\Gamma\left(2 + \frac{1}{\gamma}\right)$$

and the neutron density distribution is

$$\frac{4N}{\sqrt{\pi}}\;\frac{v^2}{v_o^3\left(1 + \frac{\gamma v^2}{v_o^2}\right)^{2+\frac{1}{\gamma}}}\;\frac{\gamma^{\frac{3}{2}}\,\Gamma\left(2 + \frac{1}{\gamma}\right)}{\Gamma\left(\frac{1}{2} + \frac{1}{\gamma}\right)} \tag{13}$$

Because Limit $(m \to \infty)\;\Gamma(m)\,m^{\gamma} / \Gamma(m + \gamma) = 1$ this expression reduces to the Maxwellian distribution for $\gamma \to o$

The mean velocity $\bar{v}$ is obtained from

$$\bar{v} = \frac{1}{N}\int_o^{\infty} n(v)\,v\,dv$$

$$= \frac{2v_o}{\sqrt{\pi}}\;\frac{\Gamma\left(\frac{1}{\gamma}\right)}{\gamma^{1/2}\,\Gamma\left(\frac{1}{2} + \frac{1}{\gamma}\right)} \tag{14}$$

Since $v_o(\chi)$ is known, from $T = T_o \exp(\lambda\chi)$, the variation of $N(\chi)$ follows from the condition that

$$\frac{\partial}{\partial\chi}(N\bar{v}) = 0$$

For Graphite and Beryllium, the following values will be assumed

	ξ	$\xi\Sigma_s$
C	.158	.064
Be	.209	.176

An effective λ can be defined as $(dT/d\chi)/T$. For the rather severe conditions of a temperature gradient of 3^{o} C per cm., these values give

γ (Be) = 1/20,000

γ (C) = 1/3,400

From (13) and (14) it follows that the deviations from Maxwellian distributions at the temperatures of the moderator are negligible.

This theory has assumed that Σ_s is independent of position, and therefore independent of temperature. It is believed that qualitatively, the conclusion reached above will be unaltered by including Σ_s as a function of temperature.

As very severe temperature gradients are required to disturb the spectrum, it might be expected that interesting results would be obtained from an analysis of conditions existing at the boundary between two regions maintained at different moderator temperatures.

3. THE EFFECT OF A TEMPERATURE DISCONTINUITY

Consider an infinite region of moderator. For $\chi < o$ the temperature is T_- and for $\chi > o$ the temperature is T_+. Again assuming Σ_s independent of temperature, the equation to be satisfied is of the form

$$\frac{1}{3\xi\Sigma_s^2}\frac{\partial^2\phi_o}{\partial\chi^2} + \frac{\partial}{\partial E}\left[(E-T)\phi_o + ET\frac{\partial\phi_o}{\partial E}\right] \qquad (15)$$

It will be assumed that there is no net current across the boundary. For solution, put $\epsilon = E/T$ and try

$$\phi_o = f(\chi)\,\Omega(\epsilon)\,\epsilon e^{-\epsilon}/T \qquad (16)$$

Thus $f(\chi)\int_o^{\infty}\Omega(\epsilon)\,\epsilon e^{-\epsilon}d\epsilon$ must be independent of χ.

Substituting from (16) into (15) gives

$$\epsilon\Omega'' + (2-\epsilon)\Omega' + \frac{1}{3\xi\Sigma_s^2}\left(\frac{f''}{f}\right)\Omega = 0 \qquad (17)$$

Hence $f = \exp(\lambda\chi)$. Writing $\beta = \lambda^2/3\xi\Sigma_s^2$ equation (17) becomes

$$\epsilon\Omega'' + (2-\epsilon)\Omega' + \beta\Omega = 0$$

and the solution is $\Omega = L_n^1(\epsilon)$ where $n = 1+\beta$ is an integer. The function $L_n^k(\epsilon)$ is an associated Laguerre polynomial of degree $n-k$. The first few functions required here are as follows

$L_1^1(\epsilon) = -1$

$L_2^1(\epsilon) = 2\epsilon - 4$

$L_3^1(\epsilon) = -3\epsilon^2 + 18\epsilon - 18$

$L_4^1(\epsilon) = 4\epsilon^3 - 48\epsilon^2 + 144\epsilon - 96$

Since $\int_o^\infty L_n^1(\epsilon)\,\epsilon\, e^{-\epsilon}\, d\epsilon = \begin{cases} -1 & \text{for } n = 1 \\ 0 & \text{for } n = 1 \end{cases}$

and n = 1 corresponds to $\lambda = 0$, it follows that a solution of equation (15) will be given by a series of terms involving these polynomials which decay exponentially as the distance from the boundary increases. The decay factors λ_n are given by

$$\lambda_n = [\, 3\,\xi\, \Sigma_s^2 (n-1)\,]^{1/2} \quad n = 1, 2, 3 \text{ etc} \tag{18}$$

Writing, for the problem under discussion, $\epsilon = E/T_-$ and $\bar{\epsilon} = E/T_+$ the required solutions are

$$\phi^+ = \frac{1}{T_+}[\,\bar{\epsilon}e^{-\bar{\epsilon}} + \sum_2^\infty A_n e^{-\lambda_n x}\, \bar{\epsilon}\, e^{-\bar{\epsilon}} L_n^1(\bar{\epsilon})\,] \tag{19a}$$

$$\phi^- = \frac{1}{T_-}[\,\epsilon e^{-\epsilon} + \sum_2^\infty B_n e^{\lambda_n x}\, \epsilon\, e^{-\epsilon} L_n^1(\epsilon)\,] \tag{19b}$$

It is now convenient to define $\gamma = T_- / T_+$. The solutions can be written

$$\phi^+ = \frac{1}{T_+}[\,\gamma\epsilon e^{-\gamma\epsilon} + \sum_2^\infty A_n e^{-\lambda_n x}\gamma\, \epsilon\, e^{-\gamma\epsilon} L_n^1(\gamma\epsilon)\,] \tag{20a}$$

$$\phi^- = \frac{1}{\gamma T_+}[\,\epsilon e^{-\epsilon} + \sum_2^\infty B_n e^{\lambda_n x}\epsilon\, e^{-\epsilon} L_n^1(\epsilon)\,] \tag{20b}$$

At the boundary ϕ and $\frac{\partial \phi}{\partial x}$ must be continuous. These conditions are

$$\gamma^2 \epsilon e^{-\gamma\epsilon} + \sum_2^\infty A_n \gamma^2 \epsilon e^{-\gamma\epsilon} L_n^1(\gamma\epsilon) = \epsilon e^{-\epsilon} + \sum_2^\infty B_n\, \epsilon e^{-\epsilon} L_n^1(\epsilon) \tag{21}$$

$$\sum_2^\infty (n-1)^{1/2} \{\, A_n \gamma^2\, \epsilon\, e^{-\gamma\epsilon} L_n^1(\gamma\epsilon) + B_n\, \epsilon e^{-\epsilon} L_n^1(\epsilon)\,\} = 0 \tag{22}$$

To solve (21) and (22) use can be made of the properties of the associated Laguerre polynomials.

Let $\epsilon e^{-\gamma\epsilon} L_n^1(\gamma\epsilon) = \sum_1^\infty a_{nm}\, \epsilon e^{-\epsilon} L_m^1(\epsilon)$ (23)

Then $\int_o^\infty \epsilon e^{-\gamma\epsilon} L_n^1(\gamma\epsilon) L_m^1(\epsilon)\, d\epsilon = \frac{(m!)^3}{(m-1)!} a_{nm}$ (24)

It can be shown, by a standard procedure, that

$$\sum_1^\infty \sum_1^\infty \frac{\gamma_1^n\, \gamma_2^m}{m!\, n!} \int_o^\infty \epsilon e^{-\gamma\epsilon} L_n^1(\gamma\epsilon) L_m^1(\epsilon)\, d\epsilon = \frac{\gamma_1\, \gamma_2}{[\gamma(1-\gamma_2) + \gamma_2(1-\gamma_1)]^2} \tag{25}$$

The required coefficients, from (24), therefore follow from equating coefficients of $\mathfrak{z}_1^n \; \mathfrak{z}_2^m$ in the expansion of (25). Put $\gamma = 1 - \delta$ Then

$$\frac{\mathfrak{z}_1 \, \mathfrak{z}_2}{(1-\delta(1-\mathfrak{z}_2)-\mathfrak{z}_1 \, \mathfrak{z}_2)^2} = \sum_{\lambda=0}^{\infty} (\mathfrak{z}_1 \, \mathfrak{z}_2)^{1+\lambda} \left[\frac{(1+\lambda)!}{\lambda!} + 2\,\delta(1-\mathfrak{z}_2)\frac{(2+\lambda)!}{2!\,\lambda!} + 3\,\delta^2(1-\mathfrak{z}_2)^2 \frac{(3+\lambda)!}{3!\,\lambda!} + \dots \right]$$

$$= \sum_{\lambda=0}^{\infty} \Bigg\{ \mathfrak{z}_1^{1+\lambda} \, \mathfrak{z}_2^{1+\lambda} \left[\frac{(1+\lambda)!}{\lambda!} + \frac{2\,\delta\,(2+\lambda)!}{2!\,\lambda!} + \frac{3\,\delta^2(3+\lambda)!}{3!\,\lambda!} + \frac{4\,\delta^3(4+\lambda)!}{4!\,\lambda!} + \dots \right]$$

$$- \mathfrak{z}_1^{1+\lambda} \, \mathfrak{z}_2^{2+\lambda} \left[\frac{2\,\delta\,(2+\lambda)!}{2!\,\lambda!} + \frac{3.2.\,\delta^2\,(3+\lambda)!}{3!\,\lambda!} + \frac{4.3.\,\delta^3(4+\lambda)!}{4!\,\lambda!} + \dots \right]$$

$$+ \mathfrak{z}_1^{1+\lambda} \, \mathfrak{z}_2^{3+\lambda} \left[\frac{3\,\delta^2(3+\lambda)!}{3!\,\lambda!} + \frac{4.3.\,\delta^3(4+\lambda)!}{4!\,\lambda!} + \dots \right]$$

$$\dots\dots\dots\dots \Bigg\}$$

It will be assumed that δ is small compared with 1. Since $\delta = \Delta t\,(^{\circ}C) / (273 + t + (^{\circ}C))$ a small δ can still represent a substantial temperature difference in $^{\circ}C$. However, the method of solution is applicable to larger values of δ. Retaining only terms up to δ^3 the important coefficients are

$$a_{11} = 1 + 2\delta + 3\,\delta^2 + 4\,\delta^3$$

$$a_{12} = -\tfrac{1}{2}(\delta + 3\,\delta^2 + 6\,\delta^3)$$

$$a_{13} = \tfrac{1}{6}(\delta^2 + 4\,\delta^3)$$

$$a_{22} = 1 + 3\delta + 6\,\delta^2 + 10\,\delta^3$$

$$a_{23} = -\tfrac{2}{3}(\delta + 4\,\delta^2 + 10\,\delta^3)$$

$$a_{33} = 1 + 4\,\delta + 10\,\delta^2 + 20\,\delta^3$$

Using the expansion (23) in (21) and (22) and equating coefficients of $\epsilon\, e^{-\epsilon}\, L_n^1(\epsilon)$ gives

$$-\gamma^2 a_{11} = 1$$

$$-\gamma^2 a_{12} + \gamma^2 A_2 \, a_{22} = B_2$$

$$-\gamma^2 a_{13} + \gamma^2 A_2 \, a_{23} + \gamma^2 A_3 \, a_{33} = B_3 \quad \text{etc.}$$

$$\gamma^2 A_2 \, a_{22} + B_2 = 0$$

$$\gamma^2 A_2 \, a_{23} + \sqrt{2}\,\gamma^2 A_3 \, a_{33} + \sqrt{2}\, B_3 = 0 \quad \text{etc.}$$

Thus $A_2 = a_{12} / 2\, a_{22} \qquad = -\delta/4$

$B_2 = -\gamma^2\, a_{12}/2 \qquad = \frac{\gamma^2}{4}(\delta + 3\delta^2)$

$A_3 = \frac{a_{13}}{2\, a_{33}} - \frac{\sqrt{2}+1}{4\sqrt{2}} \cdot \frac{a_{23}\ a_{12}}{a_{22}\ a_{33}} \qquad = -\delta^2/12\sqrt{2}$

$B_3 = \frac{\gamma^2\, a_{13}}{2} + \frac{\sqrt{2}-1}{4\sqrt{2}} \cdot \gamma^2 \frac{a_{23}\ a_{12}}{a_{22}} \qquad = -\gamma^2(\delta^2 + 4\,\delta^3)/12\sqrt{2}$

In the vicinity of the interface, the variation of the total neutron density is of particular interest. Since there is zero current

$$N_-(\infty)\,v_- = N(x)\,\bar{v}(x) = N_+(\infty)\,v_+$$

where v_- and v_+ are the neutron velocities associated with temperatures T_- and T_+ and $\bar{v}(x)$ is the mean velocity.

$$n_-(v)\,dv = \frac{A_-}{v_-^3}\left[v^2\, e^{-v^2/v_-^2} + \sum_2^\infty B_n\, e^{\lambda_n x} v^2\, e^{-v^2/v_-^2} L_n^1\left(\frac{v^2}{v_-^2}\right)\right]$$

$$n_+(\ )\,dv = \frac{A_+}{v_+^3}\left[v^2\, e^{-v^2/v_+^2} + \sum_2^\infty A_n\, e^{-\lambda_n x}\, v^2\, e^{-v^2/v_+^2} L_n^1\left(\frac{v^2}{v_+^2}\right)\right]$$

Therefore

$$N_-(x) = N_-(\infty)\left[1 + \frac{4}{\sqrt{\pi}}\sum_2^\infty B_n\, e^{\lambda_n x}\int_0^\infty y^2\, L_n^1(y^2)\, e^{-y^2}\, dy\right]$$

$$N_+(x) = N_+(\infty)\left[1 + \frac{4}{\sqrt{\pi}}\sum_2^\infty A_n\, e^{-\lambda_n x}\int_0^\infty y^2\, L_n^1(y^2)\, e^{-y^2}\, dy\right]$$

But

$$\int_0^\infty y^2\, e^{-y^2}\, L_2^1(y^2)\, dy = \Gamma\left(\tfrac{5}{2}\right) - 2\,\Gamma\left(\tfrac{3}{2}\right) = -\frac{\sqrt{\pi}}{4}$$

$$\int_0^\infty y^2\, e^{-y^2} L_3^1(y^2)\, dy = -\tfrac{3}{2}\,\Gamma\left(\tfrac{7}{2}\right) + 9\,\Gamma\left(\tfrac{5}{2}\right) - 9\,\Gamma\left(\tfrac{3}{2}\right) = \frac{-9}{16}\sqrt{\pi}$$

Thus, retaining only two terms,

$$N_-(x) = N_-(\infty)\left[1 - B_2\, e^{\lambda_2 x} - \tfrac{9}{4}\, B_3\, e^{\lambda_3 x}\right] \qquad (27a)$$

$$N_+ (\chi) = N_+(\infty) \left[1 - A_2 e^{-\lambda_2 \chi} - \frac{9}{4} A_3 e^{-\lambda_3 \chi} \right] \quad (27b)$$

At $\chi = O$, these expressions give

$$N_-(O)/N_+(O) = 1 + O(\delta^3)$$

Substituting values of A_2, A_3, B_2 and B_3 in (27a and b) these solutions can be written as

$$Y_- = 1 - \frac{1}{2} \left[(1 + \frac{3\delta}{4}) e^{\lambda_2 \chi} - \frac{3\delta}{4\sqrt{2}} e^{\lambda_3 \chi} \right] \quad (28a)$$

$$Y_+ = \frac{1}{2} \left[(1 - \frac{3\delta}{4}) e^{-\lambda_2 \chi} + \frac{3\delta}{4\sqrt{2}} e^{-\lambda_3 \chi} \right] \quad (28b)$$

with $Y = N(\chi) - N_+(\infty) / (N_-(\infty) - N_+(\infty))$

Using the values quoted above for ξ and Σ_s for B_e and C the first decay factor λ_2 is

λ_2 (Be) = 0.668

λ_2 (C) = 0.279

It follows that for small δ, the region in which

$0.1 \leqslant Y \leqslant 0.9$ is given by

B_e, -2.41 cm $\leqslant \chi \leqslant + 2.41$ cm

C, -5.77 cm $\leqslant \chi \leqslant + 5.77$ cm

These results give an indication of the extent of the regions close to an interface between regions at different temperatures, in which variations of effective macroscopic cross-sections, due to variations in the effective neutron temperature may be significant. For small highly reflected reactors, the product of neutron flux and neutron importance may be a maximum in the vicinity of the core-reflector interface, and small changes in effective cross-sections may be significant.

It should be noted that this analysis refers only to the steady state. The transient response of a system to a change in temperature over part of the core, is very important for reactor kinetics and will require a separate study.

4. CONCLUSION

On the basis of an analysis of steady-state neutron spectra in a heavy gaseous moderator, two conclusions have been reached.

1. For temperature gradients likely to be encountered in power reactors in the direction of coolant flow, the thermal spectrum can be taken as a Maxwellian distribution at the temperature of the moderator, if effects of absorption and slowing down are neglected.

2. At the boundary between two regions at different temperatures, the effective neutron temperature departs significantly from the asymptotic values equal to the moderator temperature, in a region several centimetres thick. The variation of effective neutron temperature can be calculated.

It would be very interesting to check these results by an experimental program, which would possibl be suitable for a University.

5. REFERENCES

1. Hurwitz, H. and Nelkin, M.S., The Thermal Neutron Spectrum in Diffusing Medium. Nuclear Science and Engineering, 3, 1, Jan. 1958.

6. NOTATION

E		neutron energy $(m v^2/2)$
t		moderator temperature (^{o} C)
T	=	$k(273+t)$, k being Boltzmann's constant
$n(v)\,dv$		neutron density distribution
$N(x)$		total neutron density
v		neutron velocity
$\bar{v}$		mean neutron velocity
x		co-ordinate
m		neutron mass
γ		T_- / T_+
δ		$1-\gamma$
ϵ		E/T
$\phi_0(E)dE$		neutron flux distribution
$\phi_1(E)dE$		neutron current distribution
Σ_s		macroscopic scattering cross section
$\xi\Sigma_s$		slowing down power

SUFFIX

$-$	Refers to $x < 0$
$+$	Refers to $x > 0$