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General Electric Company
KNOLLS ATOMIC POWER LABORATORY
Schenectady, New York

**EXPERIMENTAL DETERMINATION OF THE SPECTRA
IN SEVERAL COLD WATER MODERATED ASSEMBLIES**

By

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ABSTRACT

This memo is a preliminary report on the cold water spectrum experiments which have been carried on in the thermal column of the TTR during the first half of 1956. Using the experimental techniques outlined in KAPL 1499, neutron spectra have been obtained for a series of subcritical fuel loaded matrices with light water as a moderator. One concludes from the experimental results that the observed spectra are in reasonable agreement with the Wigner-Wilkins thermal neutron spectra calculations.

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INTRODUCTION

The spectrum measuring techniques discussed in KAPL-1499¹ have been used to study the spectrum of four water moderated subcritical matrices located in the thermal column of the Thermal Test Reactor. The experimentally observed spectra were obtained by deriving a neutron beam from the center of the matrices and measuring the spectral distribution of this beam with a neutron velocity spectrometer.

An energy dependent correction is applied to the observed beam spectrum to correlate it with the neutron energy spectrum in the matrix. This correction is necessary, since the spectral distribution of the beam depends not only on the spectrum at the source point, but also on the flux gradients and material cross sections in the neighborhood of the source point. A detailed discussion of this correction is given in the experimental method section of this report.

The formalism outlined in the Theoretical Section of this report relates the observed spectral hardening to the theoretical spectral hardening calculated on the basis of a Wigner-Wilkins model.² This relationship is given by

$$\beta\gamma = \frac{\Sigma_a(E_0)}{\Sigma_s(E_0)} = \frac{\left\{1 + \frac{1}{\Sigma_s(E_0)} (\Sigma_a(E_0) + DB^2_{eff})\right\} E_0 \Phi(E_0)}{\int_0^{E_0} \left(\frac{E_{th}}{E}\right)^{1/2} \Phi(E) dE + \frac{1}{\Sigma_a(E_{th})} \int_0^{E_0} DB^2 \Phi(E) dE} \quad (1)$$

¹KAPL-1499 Reactor Spectrum Measurements Using a Neutron Time of Flight Spectrometer, R. S. Stone and R. E. Slovacek, March, 1956.

²AECD-2275 Effects of the Temperature of the Moderator on the Velocity Distribution of Neutrons with Numerical Calculations for H as a moderator, E. P. Wigner and J. E. Wilkins, Jr., Sept. 14, 1944.

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The quantity on the left side of this equation is the theoretical spectrum hardening and is a function of the matrix materials only. The quantity on the right is experimentally determined from the observed spectrum, the measured thermal and epi-thermal leakage in the source area, and a knowledge of the material cross sections. Agreement between the theoretical and experimental result is a check on the validity of the Wigner-Wilkins calculation.

CONCLUSIONS

In the types of reactor cores studied, the experimentally observed spectra are consistent with the spectra calculated for H as a moderator, using a Wigner-Wilkins formalism in which the macroscopic absorption is assumed to have a $1/E^2$ dependence, the scattering cross section is assumed to be independent of energy, and the moderator is assumed to be a monoatomic gas. Previous experiments using this experimental technique on a graphite matrix yielded a Maxwellian distribution of neutron energies with the most probable energy at kT . This result establishes the validity of the experimental method. One, therefore, concludes that this present series of experiments is an experimental verification of the Wigner-Wilkins calculations over the range of hardening parameter investigated.

The comparison between matrices two and three in which the matrix composition is the same is somewhat tenuous, since a good energy calibration was not obtained for the third matrix. The close agreement of the most probable energies and the ratio of thermal to epi-thermal flux lead one to conclude that reorientation of a two-inch unit cell at the source region does not materially affect the observed spectra.

Thermal activation data indicates that, in these cellular matrices, the

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thermal flux cannot be represented by a simple cosine function over the matrix. The major contribution to the thermal leakage is a function which has a periodicity over the individual slugs rather than over the entire matrix. The theoretical treatment discussed in this paper attempts to correct for this effect. However, without detailed leakage data as a function of energy, the discrepancy between the observed spectrum hardening and the hardening calculated on the basis of average slug composition, can be large. One concludes that for a quantitative correlation between theoretical and experimental spectrum hardening, it will be necessary to use multiplying assemblies which are much more homogeneous than those used in this experiment.

An approximate fit may be made to the experimental data by the use of a Maxwellian distribution whose most probable energy $E_m = (1 + \beta\delta) E_{th}$ and a dE/E spectra. The joining energy of these two components of the experimental fit will be given by the solution to the transcendental equation

$$\chi^2 e^{-\frac{\chi}{1+\beta\delta}} = \beta\delta(1+\beta\delta)^{\frac{3}{2}} \frac{\sqrt{\pi}}{2} \quad (2)$$

Where $\chi = E_3/E_{th}$ and E_3 is the energy at which the Maxwellian and dE/E components of the spectra intersect. The maximum error in this approximate fit occurs at the joining energy, and underestimates the flux in this energy region by about twenty-five percent. The error is within the experimental error of the experimentally observed spectra at energies corresponding to half or twice the joining energy.

EXPERIMENTAL RESULTS

The experimentally determined spectra for each of the four matrices are

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shown in Figures 1 through 4. On each of these curves, results of the theoretical calculation³ of the Wigner-Wilkins type thermal spectra for several values of the hardening parameter $\beta\delta$ are also plotted.

The theoretical value of $\beta\delta$ was determined from the composition of the central slug in each matrix. A self-shielding factor of 0.724 was calculated for the 40 mil uranium-aluminum alloy fuel discs. The self-shielding factor for the boron steel strip in the first matrix was calculated to be 0.837. In the case of the fourth matrix, a thinner fuel element was used with a self-shielding factor of 0.812. These calculated theoretical $\beta\delta$ values are tabulated in Table I below. The experimental value of $\beta\delta$ was determined for each case from equation (19), using the observed spectrum and assuming $1/v$ absorption. These experimental values of $\beta\delta$ appear in Table I.

TABLE I
SPECTRUM HARDENING FACTOR $\beta\delta$

<u>Matrix Number</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>
$\beta\delta$ (Theoretical value)	.346	.311	.311	.264
$\beta\delta$ (Experimental value)	.323	.307	.315	.252

The mean absorption energy for a $1/v$ absorber with no self-shielding was calculated from the experimentally determined spectra for the first and fourth matrices. This value was .049 ev in the first matrix and .044 ev in the fourth matrix. The mean absorption energy for two different fuel thicknesses was calculated from the observed spectra in the boron loaded case (matrix 1). This value was .069 ev for a fuel thickness of .144 gr/cm² and .066 ev for a fuel

³MEMO-MSN-5 Wigner-Wilkins Spectra for Hydrogen, D. B. MacMillan and M. S. Nelkin, June 7, 1956.

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thickness of .066 gr/cm².

A cadmium fraction measurement was made along the axis of the second matrix using a .003" fuel strip (.144 gr/cm²). In this measurement, a .032" thick cadmium shield was used. The experimental result is given in Table II. A calculated cadmium fraction was obtained for fuel thicknesses at .144 gr/cm² and .066 gr/cm². These calculations were performed assuming a .62 ev cutoff for the .032" cadmium shield. These calculated values are also given in Table II.

From the data taken in a critical assembly of similar composition,⁴ it is possible to obtain a measurement of the cadmium fraction in the core. For these experiments, .001" fuel (.048 gr/cm²) was used with a .032" cadmium shield. This result is given in Table II.

TABLE II
CADMIUM FRACTIONS

.144 gr/cm ² fuel, measured in matrix 2	0.81	$\frac{f}{-}$	.01
.048 gr/cm ² fuel, measured in critical assembly	0.77	$\frac{f}{-}$	.02
.144 gr/cm ² fuel, calculated from observed spectra			0.75
.066 gr/cm ² fuel, calculated from observed spectra			0.74

EXPERIMENTAL METHOD

Using the experimental technique discussed in detail in KAPL-1499, the neutron energy spectra of several subcritical matrices have been measured. The matrix in each case consisted of a 10" x 10" x 16" assembly of fuel slugs moderated with light water. A table of the composition of the various matrices is given in Table III.

⁴ Letter from D. R. Wehner to J. S. King, June 15, 1956

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TABLE III
MATRIX COMPOSITION

Matrix Number	#1	#2	#3 ⁵	#4 ⁶
Cell Materials (gr/cm ²) U ²³⁵	.1027	.1027	.1027	.1218
AL	.4289	.4289	.4289	.2210
Zr	2.833	2.833	2.833	2.399
B	.000387	0	0	0
H ₂ O	.3409	.3476	.3476	.5365
Calc. $\beta\delta$	.346	.311	.311	.264

A sketch of the unit cell construction is shown in Figure 5. The slugs in the body of the matrix each consist of eight unit cells, whereas the central slug consists of five unit cells. This short slug forms a reentrant hole for the beam source.

The validity of the representation of the flux in a full scale reactor by means of a small subcritical matrix depends solely on considerations of neutron conservation, that is

$$q(E, B^2) = \int_0^{E_0} (\Sigma(E) - D \nabla^2(E)) \phi(E) dE \quad (3)$$

⁵ In this matrix, the two-inch unit cell at the bottom of the reentrant hole was rotated so that the channels in the slug were perpendicular to the axis of the matrix.

⁶ In this case, the central slug was replaced by a slug composed of strip-type fuel elements. The quoted matrix composition in the table is that for the central slug only. The composition of the body of the matrix in this case is the same as that for cases two and three.

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If the matrix can be constructed so that $\sum_a(E) \gg DB^2$ for all energies, then the relative flux as a function of energy is a function of matrix composition only. Due to the inhomogeneous nature of the matrix materials, this condition may not be rigorously satisfied experimentally. It is therefore desirable to measure the local leakage in the source region and to make the appropriate corrections to the observed spectra in order to correlate the experimental result with the theoretical spectrum hardening due to the matrix materials. The formalism for making these corrections is derived in the theoretical section of this report. The experimental results on the leakage determination in the source region are given below.

A series of activations were made in order to determine both the longitudinal and transverse flux variation in the source region. The cadmium covered and bare uranium transverse foil data for matrix two are shown in Figures 6 and 7. A summary of the results for the axial activation experiments in this matrix are given in Table IV.

TABLE IV

AXIAL FLUX GRADIENT

$$\gamma \equiv d/dZ \ln \phi \text{ (cm}^{-1}\text{)}$$

<u>Material</u>	<u>Full Slug</u>			<u>Half Slug</u>		
Manganese	.075	$\pm$	.004	.081	$\pm$	.004
Fuel	.070	$\pm$	.004	.071	$\pm$	.004
Fuel Cd Covered	.075	$\pm$	.004	.075	$\pm$	.004
Indium	.066	$\pm$	.003	.073	$\pm$	.003
Indium Cd Covered	.071	$\pm$	.004	.074	$\pm$	.004
Average	.071	$\pm$	.002	.075	$\pm$	.002

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Since both the thermal and epi-thermal flux can be represented by a single eigenfunction in the source region, we can use a buckling concept to measure the average value of the operator $D \nabla^2$ in this region.

On the basis of the activation experiments, the epi-thermal flux within the matrix can be represented by a function of the form.

$$\phi(E) = A \cos \frac{\pi x}{a} \cos \frac{\pi y}{a} \cdot e^{-\delta z} \quad (4)$$

Then, the epi-thermal buckling is given by

$$B_{epi}^2 = 2\left(\frac{\pi}{a}\right)^2 - \delta^2 \quad (5)$$

From Figure 6, one obtains $\left(\frac{\pi}{a}\right)^2 = .0068$ and using $\delta = .0735$, one obtains $\delta^2 = .0054$, then

$$B_{epi}^2 = .0082 \text{ cm}^{-2}$$

From the thermal activation data, one concludes that the thermal flux in the source region can be represented by a function of the form

$$\phi(E_{th}) = M(1 + Nx^2)(1 + Ny^2) e^{-\delta z} \quad (6)$$

Then, the thermal buckling is given by

$$B_{th}^2 = -4N - \delta^2$$

From Figure 7, one obtains $N = .0116$ and using $\delta = .0735$, then

$$B_{th}^2 = -.0518 \text{ cm}^{-2}$$

For the weak absorption case, the diffusion coefficient can be calculated from a knowledge of the material cross-sections and the mean scattering angle.

$$D = \frac{\lambda_{tr}}{3} = \frac{1}{3 \sum_{Total} (1 - \bar{\mu}_0) \left\{ 1 - \left(\frac{4}{3} - \frac{\bar{\mu}_0}{1 - \bar{\mu}_0} \right) \frac{\sum a}{\sum_{Total}} \right\}} \quad (7)$$

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Assuming that $\bar{\mu}_0 = \frac{2}{3}$ at high energies as in the case for hydrogen and using cross-sections averaged over the matrix materials, one obtains the values of D at high energies, which will be called D_{epi} . At thermal energies, the average diffusion coefficient D_{th} can be calculated from the average transport mean free path obtained by Zweifel and Petrie.⁷

TABLE V

<u>Matrix No.</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>
D_{th} (cm)	.466	.466	.466	.367
D_{epi} (cm)	1.371	1.371	1.371	1.371
DE_{th}^2 (cm ⁻¹)	-.024	-.024	-.024	-.019
DE_{epi}^2 (cm ⁻¹)	.016	.016	.016	.011

The relation between the energy dependence of the neutron beam current and the flux at the source point is given in KAPL-1499 by

$$I(E) = \phi(E, 0) \left\{ 1 + \frac{1}{\Sigma_T} \cdot \frac{1}{\phi} \frac{d\phi}{dz} \Big|_0 + O \left\{ \frac{1}{\Sigma_T^2} \cdot \frac{1}{\phi} \frac{d^2\phi}{dz^2} \Big|_0 \right\} \right\} \quad (8)$$

Equation (8) was derived on the assumption that the perturbation to the flux gradients at the source point due to the presence of the re-entrant hole was small. This assumption is experimentally verified by the data in Table IV. Replacing a 16" central slug by the 10" central slug yields about a five percent increase in the logarithmic flux gradient at the source point. Since the correction factor amounts to 10% at most, this 5% effect is negligible. Terms

⁷ KAPL-1469 Averages of Thermal Cross Sections for Hydrogen-Moderated Assemblies, P. F. Zweifel and C. D. Petrie, January 1, 1956.

containing higher order than the first derivative of the flux are negligible in determining this correction factor.

The measured values of the logarithmic flux gradient, $\frac{1}{\phi} \frac{d\phi}{dz}$, are tabulated in Table IV. Since the average epi-cadmium gradient is approximately equal to the average sub-cadmium gradient, an average value of 0.075 cm^{-1} was used over the entire energy range. However, the total macroscopic cross section, Σ_T , is energy dependent. The correction factor was evaluated over the energy range from 10^{-3} ev to 1 ev for each matrix composition. Since $\Sigma_T \approx \Sigma_S$ above 1 ev , the correction factor is essentially constant above this energy.

The correction is of the order of 2% at 10^{-3} ev and increases to about 10% at the higher energies. Since the relative flux is only of interest here, the relative flux gradient correction factor, f_g , was plotted in Figure 8.

The spectra shown in Figures 1 to 4 were not corrected for this factor; however, the calculations for determining the experimental values of $\beta\delta$ given in Table 1 used this factor.

THEORY

The differential neutron conservation condition at energy E can be written in the diffusion approximation as

$$\left\{ \Sigma_a + \Sigma_s - D \nabla^2 \right\} \phi(E) = \int_0^\infty \phi(E' \rightarrow E) \phi(E') dE' \quad (9)$$

Where Σ_s is defined as

$$\Sigma_s = \int_0^\infty \phi(E \rightarrow E') dE' \quad (10)$$

Selecting an energy E_0 which is sufficiently large so that $b(E \rightarrow E') = 0$ for $E \leq E_0$ and $E' \geq E_0$, then

$$\left\{ \sum_a -D \nabla^2 + \int_0^{E_0} b(E \rightarrow E') dE' \right\} \phi(E) = \int_0^\infty b(E' \rightarrow E) \phi(E') dE' - \phi(E) \int_{E_0}^\infty b(E \rightarrow E') dE' \quad (11)$$

In this preceding expression, the second integral on the right hand side is identically zero due to the choice of E_0 . This expression can now be integrated from 0 to E_0 and the right hand integral may be written in two parts to obtain

$$\int_0^{E_0} \left\{ \sum_a -D \nabla^2 + \int_0^{E_0} b(E \rightarrow E') dE' \right\} \phi(E) dE = \int_0^{E_0} \left\{ \int_0^{E_0} b(E' \rightarrow E) \phi(E') dE' + \int_{E_0}^\infty b(E' \rightarrow E) \phi(E') dE' \right\} dE \quad (12)$$

There now exists a cancellation, since two of the integrals are summed over the same initial and final states. Equation (12) can then be rewritten

$$\int_0^{E_0} \left\{ \sum_a -D \nabla^2 \right\} \phi(E) dE = \int_0^{E_0} dE \int_{E_0}^\infty b(E' \rightarrow E) \phi(E') dE' \quad (13)$$

Since there is no scattering from energies below E_0 to energies above E_0 , the expression on the right hand side of equation (13) is then equal to the slowing down density. Now, under the condition that the slowing down kernel is independent of final energy E at energy E_0 , as it is in the case of hydrogen, the integration over final energy E can be performed in equation (13) to yield

$$\int_0^{E_0} (\sum_a -D \nabla^2) \phi(E) dE = E_0 \int_{E_0}^\infty b(E' \rightarrow E) \phi(E') dE' \quad (14)$$

It now remains to relate the integral on the right hand side of equation (14) to the matrix geometry and material cross sections. If the differential neutron conservation condition, Equation (9), is applied at energy E_0 , one obtains

$$\left\{ \Sigma_a(E_0) + \Sigma_s(E_0) - D\nabla^2(E_0) \right\} \phi(E_0) = \int_0^{E_0} \phi(E' \rightarrow E) \phi(E') dE' + \int_{E_0}^{\infty} \phi(E' \rightarrow E) \phi(E') dE' \quad (15)$$

Again, applying the condition that there is no scattering from energies below E_0 to energy E_0 or greater, the first integral on the right hand side of Equation (15) is identically zero. Therefore,

$$\int_{E_0}^{\infty} \phi(E' \rightarrow E) \phi(E') dE' \left\{ \Sigma_a(E_0) + \Sigma_s(E_0) - D\nabla^2(E_0) \right\} \phi(E_0) \quad (16)$$

Substituting the result of Equation (16) into Equation (14) yields

$$\int_0^{E_0} (\Sigma_a - D\nabla^2) \phi(E) dE = \left\{ \Sigma_a(E_0) + \Sigma_s(E_0) - D\nabla^2(E_0) \right\} E_0 \phi(E_0) \quad (17)$$

Assuming a $1/v$ variation for $\Sigma_a(E)$, and that $D\nabla^2$ can be represented by $-DB^2(E)$ Equation (17) may be rewritten as

$$\Sigma_a(E_0) \int_0^{E_0} \left(\frac{E_0}{E} \right)^{1/2} \phi(E) dE + \int_0^{E_0} DB^2 \phi(E) dE = \left\{ \Sigma_s(E_0) + \Sigma_a(E_0) + DB^2(E_0) \right\} E_0 \phi(E_0) \quad (18)$$

Rearranging terms and defining the quantity $\beta\gamma$ as being equal to

$$\frac{\Sigma_a(E_0)}{\Sigma_s(E_0)}, \text{ one obtains}$$

$$\beta\gamma = \frac{\Sigma_a(E_0)}{\Sigma_s(E_0)} = \frac{\left\{ 1 + \frac{1}{\Sigma_s(E_0)} [\Sigma_a(E_0) + DB^2(E_0)] \right\} E_0 \phi(E_0)}{\int_0^{E_0} \left(\frac{E_0}{E} \right)^{1/2} \phi(E) dE + \frac{1}{\Sigma_a(E_0)} \int_0^{E_0} DB^2(E) \phi(E) dE} \quad (19)$$

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The quantity on the left side of Equation (19) can be calculated from a knowledge of the matrix materials in the central slug and yields a theoretical spectrum hardening factor which is consistent with that of Wigner and Wilkins for hydrogen as a moderator. It is the result of this calculation which is entered in Table I as the theoretical $\beta\epsilon$ value. The quantity on the right side of Equation (19), entered in Table I as the experimental $\beta\epsilon$ value, can be calculated from a knowledge of the cross sections, the energy dependence of the leakage, and the experimentally observed spectrum corrected for longitudinal flux gradients. Since the explicit variation of the term $DB^2(E)$ is unknown, the leakage integral in Equation (19) was evaluated in two parts, the first from 0 to E_3 and the second from E_3 to E_0 where E_3 is defined by Equation (2). Over the first range of integration, the value of DB_{th}^2 given in Table V was used as an average value of the leakage, whereas over the second range of integration, DB_{epi}^2 given in Table V was used as an average value of the leakage. This arbitrary splitting of the range of integration is justified on the basis that the quantity DB^2 changes sign in going from thermal energies to energies of the order of one electron volt. The energy E_3 occurs at the point where the spectrum changes from a slowing down spectra to a thermal spectra. Since the local peaking at the slug boundaries is a thermal effect rather than a slowing down effect, this splitting of the integral should yield a reasonably good approximation.

A less precise presentation for the comparison between the experimentally observed spectrum and the theoretical spectrum can be obtained by fitting the experimental data to a theoretically calculated spectrum. A calculation of this type of spectrum has recently completed³ for various values of $\beta\epsilon$. In Figures 1 through 4, the experimentally observed points are plotted as points

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and the theoretical curves are shown as solid lines. The experimental points as plotted have not been corrected for the effect of longitudinal flux gradient or leakage. The gradient correction would increase the thermal flux relative to epi-thermal flux by approximately 5%.

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RELATIVE FLUX / $\text{ev}^{1/2}$

FIG 1 COLD WATER SPECTRUM
MATRIX 1

CELL COMPOSITION

MATERIAL	Gms/cm ³
U ²³⁵	0.027
H ₂ O	0.3409
AL	0.4289
Zr	2.833
SS	0
B	0.00387
H ₂ O	0.3409

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22

RELATIVE FLUX / e^v

MATRIX 2
CELL COMPOSITION

MATERIAL	gms/cm^3
U^{235}	0.1027
H_2O	0.3476
Al	0.4289
Zr	2.833
SS	0
B	0
H_2O	0.3476
NEUTRON	0.001
WATER	0.001

ENERGY (eV)

410 019

23

24

RELATIVE FLUX/ev

ENERGY (ev)

413 020

25

26

RELATIVE FLUX/ev

27

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FIRST MADE FOR

SPECTRUM HARDENING EXPERIMENT

REVISIONS

FIG. 5

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APPROVALS

S. A. P. Smith

DIV. OR
DEPT.

LOCATION

CONT. ON SHEET

SH. NO.

28

RELATIVE COUNTS

SLUG BOUNDARIES

FIG. 6 RADIAL ACTIVATION

Ca COVERED U²³⁵

INCHES FROM CENTRAL

AXIS

$$f(r) = \cos \frac{\pi r}{15}$$

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Fig. 8 f_g - RELATIVE FLUX GRADIENT
 CORRECTION FACTOR