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UNITED STATES ATOMIC ENERGY COMMISSION

BASIC INELASTIC NEUTRON DATA FOR AGE CALCULATIONS FOR VARIOUS FUEL AND MODERATOR COMPOSITIONS

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BASIC INELASTIC NEUTRON DATA FOR AGE CALCULATIONS
FOR VARIOUS FUEL AND MODERATOR COMPOSITIONS

The attached graphs have been prepared as basic inelastic neutron data requested for neutron age calculations to be made using the following fuel and moderator compositions:

Composition No.	Component	Mole %	Wt %	Liquidus Temp., °C	Density g/cc at 1400°F
(1)	71 ¹	NaF	54.1	520	3.02 ²
		ZrF ₄	45.9		
(2)	9 ¹	BeF ₂	100	543	1.95 ²
(3)		LiF	50		1.92 ²
		BeF ₂	50		
(4)		ZrH	100	100	

As the age calculation permits only four cross sections to be used, and the elastic cross section for each element is required, T , nuclear temperature (Mev) vs E_0 , incident neutron energy (Mev) was obtained only for F, Be, and Zr.

The emitted neutron spectrum resulting from the interaction of E_0 - Mev neutrons is essentially Maxwellian for large neutron energies ($E_0 > \sim 3$ Mev). As the incident neutron energy becomes small relative to

1. C. J. Barton, Fused Salt Compositions, ORNL CF-55-9-78 (Sept. 16, 1955).
2. S. I. Cohen, Oak Ridge National Laboratory, private communication to C. M. Copenhaver (1956).

the level spacing in the residual nucleus the levels become evident and the emitted neutron spectrum is definitely not Maxwellian.

In basic gamma-ray data for ART heat calculations, $\overline{E}_n$ the average energy of the emitted neutrons for F and Zr was determined for small E_o and at 14 Mev from experimental data, and extrapolated in the intermediate range using a theoretical expression. Thus, if it is assumed that the emitted neutron spectrum resulting from the interaction of E_o neutrons is Maxwellian for all permissible E_o 's, an equivalent T ($T = \overline{E}_n/2$) vs E_o can be obtained as follows:

$$\text{Assumption: } F(E_n) = C E_n e^{-E_n/T(E_o)} \text{ for all } E_o$$

$$T(E_o) = \frac{\overline{E}_n}{2} \quad \frac{\overline{E}_n}{E_o} = 1 - \delta_n$$

$$T(E_o) = \frac{(1 - \delta_{in}) E_o}{2} \quad \delta_{in} \text{ for F, and Zr from Ref. 3.}$$

Beryllium creates a problem since the non-elastic scattering cross section is comprised primarily by the (n,2n) cross section over the energy range of interest. As an example, at $E_o = 3.0$ Mev, $\sigma(n,n',\gamma) \simeq 0.01$ barns and $\sigma(n,\alpha) \simeq 0.05$ barns, while $\sigma(n,2n) \simeq 0.5$ barns. An equivalent T for beryllium can be obtained by averaging $\overline{E}_{n1}$ and $\overline{E}_{n2}$, the average energies of the "first" and "second" emitted neutrons respectively. Be^9 appears to have uniform level spacing from ground state to 14 Mev.⁴ From the nuclear levels of Be^9 an average nuclear temperature, $\overline{T}$, was obtained as follows:

4. F. Ajzenberg and T. Lauritsen, Rev. Mod. Phys. 24, No. 4, 385 (1952).

T EQUIVALENT FOR BERYLLIUM

E_0 (MeV)	$T(E_0)$ (MeV)	$\bar{E}_{n1} = 2 T(E_0)$ (MeV)	ξ	$\bar{E}_{n2}$ (MeV)	$\bar{E}_\gamma$ (MeV)	T Equivalent (MeV)
2	0.15	0.3	2.0	0.1	1.6	0.10
4	1.10	2.2	2.0	0.5	1.3	0.68
6	1.75	3.5	2.0	1.2	1.3	1.2
8	2.2	4.4	2.9	2.3	1.3	1.7
10	2.6	5.2	3.2	3.3	1.5	2.1

$$T \text{ equivalent} = \frac{\bar{E}_{n1} + \bar{E}_{n2}}{4}, \quad \bar{E}_\gamma = E_0 - \bar{E}_{n1} - \bar{E}_{n2}$$

Although the equivalent T obtained here could easily be in considerable error, the fact that the arbitrarily defined $\bar{E}_\gamma$ appears to be roughly equivalent to the threshold energy for all E_0 seems reasonable.

The equivalent T for beryllium is a fictitious temperature which gives an estimate of the average neutron energy of neutrons emitted in an (n,2n) reaction.

A list of the attached graphs is included here. The T's in Figs. 1, 2 and 3 are the equivalent T's. Figures 9 and 10 are included to show that the inelastic cross sections for compositions (1) and (3) are reasonably represented by the fluorine inelastic cross section.

Figure No.

1	T vs E_0 for Fluorine
2	T vs E_0 for Zirconium
3	T vs E_0 for Beryllium
4	Inelastic Cross Section for Fluorine
5	Inelastic Cross Section for Zirconium
6	Non-elastic ($\sim$ n,2n) Cross Section for Beryllium
7	Inelastic Cross Section for Sodium
9	Inelastic Cross Section for Composition 71
10	Inelastic Cross Section for 50 mole % LiF, 50 mole % BeF ₂

$$\bar{T} = \frac{\int_{1.67}^{14} [D(E_0) E_0]^{1/2} dE_0}{14 - 1.67} \simeq 4 \text{ Mev},$$

where $D(E_0)$ = level spacing at E_0 (Mev). Threshold for $n, 2n$ reaction = 1.67 Mev. $T(E_0)$ for beryllium was obtained from an uncorrected δ_{in}^3 , using $\bar{T} = 4$ Mev at high energies and as $1.67/E_0$ for E_0 less than 3 Mev. For uniform level spacing the energy distribution of "second" neutrons from NYO 636⁵ is:

$$F(E_{n2}) = 2\sqrt{\frac{a}{E_0}} \left\{ \xi e^{-(\xi - \bar{X})} + \bar{X} \left[(\xi - 1) e^{-\xi} \int_{\bar{X}}^{\xi} \frac{e^y}{y} dy - 1 \right] \right\},$$

$$\bar{X} = \sqrt{\frac{a}{E_0}} E_{n2},$$

$$\xi = \sqrt{\frac{a}{E_0}} (E_0 - E_b),$$

$$T = \sqrt{\frac{E_0}{a}},$$

E_b = binding energy of the second neutron in the nucleus (Mev).

Using these relations, $\bar{E}_{n2}$ can be determined directly from

$$\bar{E}_{n2} = \frac{\int_0^{E_0 - E_b} E_{n2} F(E_{n2}) dE_{n2}}{\int_0^{E_0 - E_b} F(E_{n2}) dE_{n2}}.$$

The pertinent computed values are listed in the following table:

4. 5. B. T. Feld et.al., NYO-636 (1951).

FIG. 2 - T VERSUS E_0 FOR ZIRCONIUM

ORNL-LR-DWG-11125

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FIG. 3 - T VS E_0 FOR BERYLLIUM

ORNL-LR-DWG-21126

FIG. 4 - INELASTIC SCATTERING CROSS SECTION FOR FLUORINE

References:

 $E_0 = 0 - 1.0$ MevJ. M. Freeman, Phys. Rev. 99, 1446 (1955). $E_0 = 1.0 - 2.2$ MevJ. M. Freeman, Op.Cit.J. J. Van Loef and D. A. Lind, Phys. Rev. 101, 113 (1956). $E_0 = 2.5$ Mev: Cross section of 1.55 level = 0.52 ± 0.18 barns⁴ $E_0 = 2.56$ MevR. E. Day, Phys. Rev. 102, 775 (1956). $E_0 = 2.6 - 10$ Mev

Curve Theoretical

Inelastic Cross Section (barns)

2
1 E_0 - Neutron Energy (Mev)

Inelastic Cross Section (barns)

References:

----- J. B. Guernsey and C. Goodman, Phys. Rev. 101,
294 (1955).

Δ J. R. Beyster and M. Walt, Bulletin Am. Phys.
Soc. Series II, 1, No. 4, 176 (1956).

$\circ$ J. R. Beyster et al., Phys. Rev. 98, 1216 (1955).

FIG. 5 - INELASTIC SCATTERING CROSS SECTION FOR ZIRCONIUM

E_0 - Neutron Energy (MeV)

FIG. 6 - NON-ELASTIC SCATTERING CROSS SECTION FOR BERYLLIUM

$$\sigma(\text{Non-elastic}) \approx \sigma(n, 2n)$$

References:

o BNL 325

Δ H. L. Taylor, O. Lönsjö and T. W. Bonner, Phys. Rev. 100, 174 (1955).

Non-elastic Cross Section (barns)

0.8
0.6
0.4
0.2

0 2 4 6 8 10 12 14

E_0 - Neutron Energy (Mev)

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FIG. 7 - INELASTIC SCATTERING CROSS SECTION FOR SODIUM

References:

No references found.

Curve is entirely theoretical.

Inelastic Cross Section (barns)

1.2
1.0
0.8
0.6
0.4
0.2

0 2 4 6 8 10 12 14

 E_0 - Neutron Energy (Mev)

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