ICANS-V
MEETING OF THE INTERNATIONAL COLLABORATION ON
ADVANCED NEUTRON SOURCES
June 22-26, 1981

A COMPARISON OF HIGH-ENERGY FISSION MODELS FOR THE HETC-TRANSPORT CODE

PART II: THICK TARGETS

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1 Introduction

To clarify the influence on practical calculational problems of the different "High-Energy Fission" (HEF) models and the relationship between the models, a series of calculations were performed and partly compared with existing experimental data taken from the BNL-Cosmotron experiment (see Refs. 1,2). This experiment consisted of a H_2O tank of 1.83 m diameter and 1.83 m height. Several targets of different sizes and materials, among them depleted uranium and lead were investigated in the center of the tank. The total capture rate in the H_2O tank was measured by foil-activation techniques. For the calculations we considered one depleted uranium target (0.22 wt % ^{235}U, length 609.6 mm and radius 50.8 mm) and a lead target of the same size. The calculations were done using HETC-, MORSE CG- and SIMPEL-spallation computer code system of KFA-IRE as described in Ref. 3. The fractional standard deviation in the Monte Carlo calculations is less than 1%, unless stated explicitely in the tables.

2 Neutron Production Using the HEF Model in the HET Code

For these calculations and in most of the following ones the BNL-Cosmotron setup with incident proton beam energy of 960 MeV was assumed. Calculations of the evaporation part of neutron production spectrum with and without the "Rutherford and Appleton Laboratories"- (RAL) HEF model /4/ incorporated in HETC were made. In Figure 1 the two spectra are given. Some spectral hardening in the case of HEF is clearly to be seen. The total neutron production (see Table 1) including low energy fission (< 15 MeV) is about 6-10 % higher using HEF model. Most of this effect is obviously due to low energy fission from spectral hardening.

3 Check of the HEF-RAL Model against the HEF-ORNL Model /5/

For comparison purposes of the two HEF models the calculations were performed first with their appropriate "standard" B_o values of the level-density formula (ORNL model, B_o=10 MeV /1/ and RAL model, B_o=14 MeV); and second the RAL model was run with two additional values of B_o namely 8 MeV and 10 MeV. The standards differ by 20 % in production and capture rates. If we assume an intermediate but equal value for B_o of 10 MeV, the difference is reduced to only 10 % (see Table 2). The neutron production spectra appear to be identical (Figure 2). The effect of different B_o values for the RAL-HEF model is shown in Table 3 and illustrated in Figure 3.

4 Neutron Captures in H_2O Compared with BNL-Cosmotron Experimental Results

According to the Cosmotron experiments /1,2/ calculations were made at incident proton beam energies 590, 960 and 1470 MeV. The measured and calculated quantity is the neutron capture rate in the H_2O tank. A variety of B_o values was applied to calculations with RAL- and ORNL-HEF models. As was found earlier, this parameter is an essential one. The last column of Table

4 shows the ratios of experimental and calculational results. With B_o=10 MeV RAL- and ORNL-HEF models give very similar results, which are in good agreement with experimental results (the "standard" RAL model B_o=14 MeV /6/ underestimates the experiment) for all incident proton energies upto 1 GeV, the energy of interest of SNQ. At energies above 1 GeV the deviation from experiment is higher and significant in case of the ORNL- HEF model (B_o=10 MeV,the "standard", /1/), the RAL model, however, meets the experiments even at B_o=14 MeV. Additional information of neutron production and neutron-reaction rates about the previous calculations is given in Table 5, and some spectral information is shown in Fig. 4.

5 Ratios of Thermal Peak Fluxes in H_2O Moderator Using Lead, Depleted Uranium and Natural Uranium Targets

The arrangement for the calculations is again the BNL-Cosmotron setup using an incident proton beam energy of 960 MeV. The thermal flux distribution in the H_2O tank was calculated around the lead and uranium targets. The peak values of the thermal flux (10^{-5}-0.41 eV) were intercompared to see the influences of the material and the B_o parameter on the maximum thermal flux that can be attained. The ratios are shown in Table 6. There is no significant influence of high-energy fission on the thermal peak flux with a uranium target. However, the ratio of the fluxes between depleted uranium target and lead target is about 1.3-2.5, depending on B_o and whether the HEF model is applied or not. The influence of B_o from 8-14 MeV is remarkable for lead, but this is not true for depleted uranium. Natural uranium as target material gains 20 % more thermal flux in the peak than depleted uranium. The neutron production numbers and neutron reaction rates are given in Table 7, together with evaporation spectra in Figure 5.

6 Conclusion

Spectrum hardening with high energy fission models incorporated in the HET code is evident. The neutron captures in water surrounding finite depleted uranium targets are found to be 5-10 % higher with HEF. Significant differences of RAL- and ORNL-HEF models are found at incident proton beam energies above 1 GeV. The RAL model gives lower values than the ORNL model. The B_o value seems to be model and somewhat energy dependend.

REFERENCES

/1/ R.G. Alsmiller Jr.,T.A. Gabriel, J. Barish, F.S. Alsmiller: "Neutron Production by Medium Energy (≃1.5 GeV) Protons in Thick Uranium Targets", ORNL/TM-7527 (1981)

/2/ J.S. Fraser et al.:"Neutron Production in Thick Targets Bombarded by High-Energy Protons", Phys. in Canada 21,17 (1965)

/3/ T.W. Armstrong, P. Cloth, D. Filges, R.D. Neef:"Theoretical Target Physics Studies for the SNQ Spallation Neutron Source", Jül-Spez-120 (July 1981)

/4/ F. Atchison:"The Inclusion of Fission in the High-Energy Particle Transport Code, HETC", Bulletin of the American Physical Society 24, 874 (1979)

/5/ F.S. Alsmiller, R.G. Alsmiller Jr., T.A. Gabriel, R.A. Lillie, J. Barish:"A Phenomenological Model for Particle Production from the Collisions of Nucleons and Pions with Fissile Elements at Medium Energies", ORNL/TM-7528 (1981)

/6/ F. Atchison:"A Theoretical Study of a Target Reflector and Moderator Assembly for SNS", RL-81-006 (1981)

TABLE 1

Calculations with and without High-Energy Fission Model (HEF)
(Proton Beam Energy 960 MeV, Target Material Depleted Uranium)

	neutron production per proton		number of fissions in target per proton from		number of captures in uranium target per proton	number of neutron captures in H_2O per proton
	≤ 15 MeV	> 15 MeV	(a) neutrons ≤ 15 MeV	(b) neutrons and charged particles > 15 MeV		
without HEF*	29.16	4.21	5.17	-	7.74	30.90
with HEF**	30.11	4.05	5.56	1.77	8.02	32.56
ratio of calculations with HEF vs. without HEF	-	-	1.08	-	1.04	1.06

* Rutherford high energy fission model (RAL model)

** B_o parameter 8 MeV

TABLE 2

Comparison of RAL- and ORNL-HEF Model for Different B_o Parameters
(Proton Beam Energy 960 MeV, Target Material Depleted Uranium)

HEF Model	B_o (MeV)	neutron production per proton		number of fissions in target per proton from		number of captures in uranium target per proton	number of neutron captures in H_2O per proton
		≤ 15 MeV	>15 MeV	(a) neutrons ≤15 MeV	(b) neutrons and charged particles >15 MeV		
RAL	8	30.11	4.05	5.56	1.77	8.02	32.56
RAL	10	28.48	4.26	5.39	1.73	7.87	30.88
ORNL	10	31.73	4.49	6.18	1.93	8.72	35.23
RAL	14	26.03	4.43	5.03	1.71	7.01	29.03
ratio of							
RAL(B_o=14) vs. ORNL(B_o=10) (Standard)		0.82		0.81		0.80	0.82
RAL(B_o=10) vs. ORNL(B_o=10)		0.89		0.87		0.90	0.88

TABLE 3

Effect of Different B_o Parameters (8,10 and 14 MeV)
Using RAL-HEF Model
(Proton Beam Energy 960 MeV, Target Material Depleted Uranium)

ratio of	neutron production per proton		number of fissions in target per proton from		number of captures in uranium target per proton	number of neutron captures in H_2O per proton
	$\leq$ 15 MeV	$>$15 MeV	(a) neutrons $\leq$ 15 MeV	(b) neutrons and charged particles $>$15 MeV		
B_o=8 MeV vs. B_o=10 MeV	1.06	0.95	1.03	1.0	1.02	1.05
B_o=8 MeV vs. B_o=14 MeV	1.16	0.91	1.11	1.0	1.14	1.12

TABLE 4

Comparison with Cosmotron Data (Fraser et al./2/)

Depleted Uranium Target, H_2O Captures per Incident Proton

incident proton energy (MeV)	experiment	HEF	B_0 (MeV)	theory	theory vs. experiment
540	15.1±0.8	ORNL	10*	15.2±0.8	1.07
		RAL	14	13.5±1.1	0.81
960	32.3±1.6	ORNL	10*	33.7±1.0	1.04
		ORNL	10**	35.2±0.6	1.09
		RAL	10	30.9±0.3	0.96
		RAL	8	32.6±0.3	1.00
		RAL	14	29.0±0.3	0.89
1470	44.8±0.2	ORNL	10*	53.6±1.5	1.20
		RAL	14	46.0±0.4	1.03

* Calculations of Alsmiller et al.,ORNL-TM-7527

**KFA-IRE calculations using uranium cross sections with self-shielding corrections

TABLE 5

Neutron Production and Reaction Rates at Different Proton Beam Beam Energies with HEF Model* (B_o=14 MeV)

incident proton energy (MeV)	neutron production per proton		number of fissions in target per proton from		number of captures in uranium target per proton	number of neutron captures in H_2O per proton
	≤ 15 MeV	>15 MeV	(a) neutrons ≤15 MeV	(b) neutrons and charged particles >15 MeV		
540	12.46	1.73	2.25	-	3.14	13.48
960	26.03	4.43	5.03	1.71	7.01	29.03
1470	42.03	7.65	8.03	-	11.99	46.03

*"Rutherford" high energy fission model (RAL model)

TABLE 6

Ratios of Thermal Peak Fluxes[*] in the Cosmotron Experiments
Between Pb, Depleted U and Natural U Targets
(Proton Beam Energy 960 Mev)

B_o (MeV)	U_{dep} without HEF vs. Pb without HEF	U_{dep} with HEF vs. U_{dep} without HEF	U_{nat} with HEF vs. U_{dep} with HEF	U_{dep} with HEF vs. Pb with HEF
8	1.9	0.96	-	-
14	-	-	1.2	2.5
Ratio of Pb (B_o=8 MeV) vs. Pb (B_o=14 MeV) = 1.3 Ratio of U_{dep} with HEF (B_o=8 MeV) vs. U_{dep} with HEF (B_o=14 MeV) =1.05				

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[*] fractional standard deviation 5-7%

TABLE 7

Comparison of Calculated Results for Lead, Depleted Uranium and Natural Uranium for the RAL-HEF Model
(B_o=14 MeV at 960 MeV Proton Energy)

target material	neutron production per proton		number of fissions in target per proton from		number of captures in uranium target per proton	number of neutron captures in H_2O per proton
	≤15 MeV	>15 MeV	(a) neutrons ≤15 MeV	(b) neutrons and charged particles >15 MeV		
lead	19.46	4.30	-	-	0.502	18.75
depleted uranium	26.03	4.43	3.40 U238 1.63 U235	1.71	7.01	29.03
natural uranium	27.19	4.44	3.91 U238 4.07 U235	1.71	7.27	33.79
ratio of calculations						
natural U vs. depleted U	1.05		1.59	-	1.04	1.16
depleted U vs. lead	1.39	-	-	-	1.39	1.55

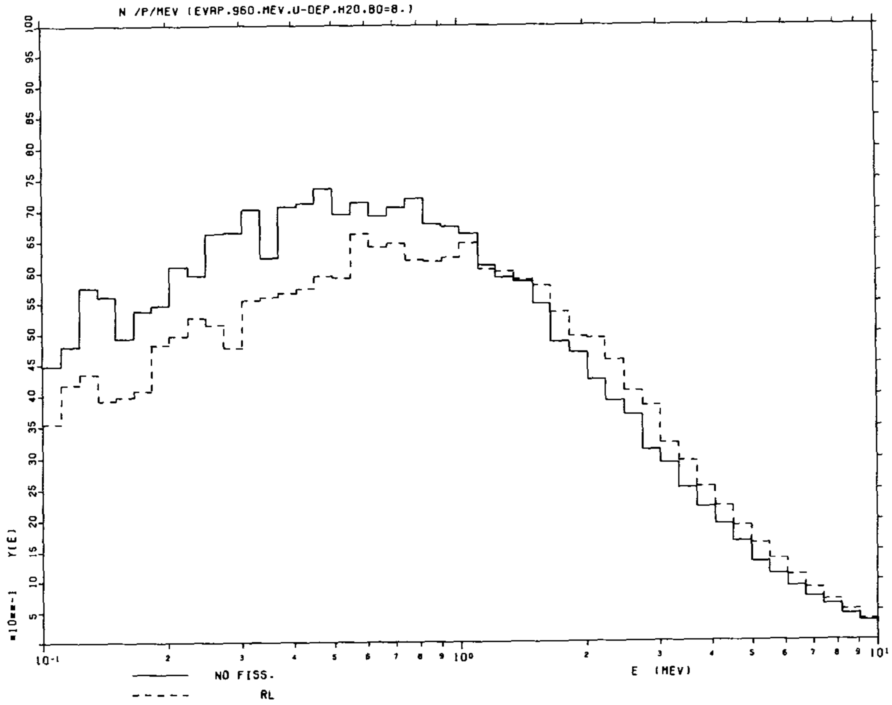

Fig. 1 Evaporatin neutrons with (solid curve) and without (dashed curve) RAL-HEF model (B_o=8 MeV, proton-beam energy 960 MeV, target material depleted uranium)

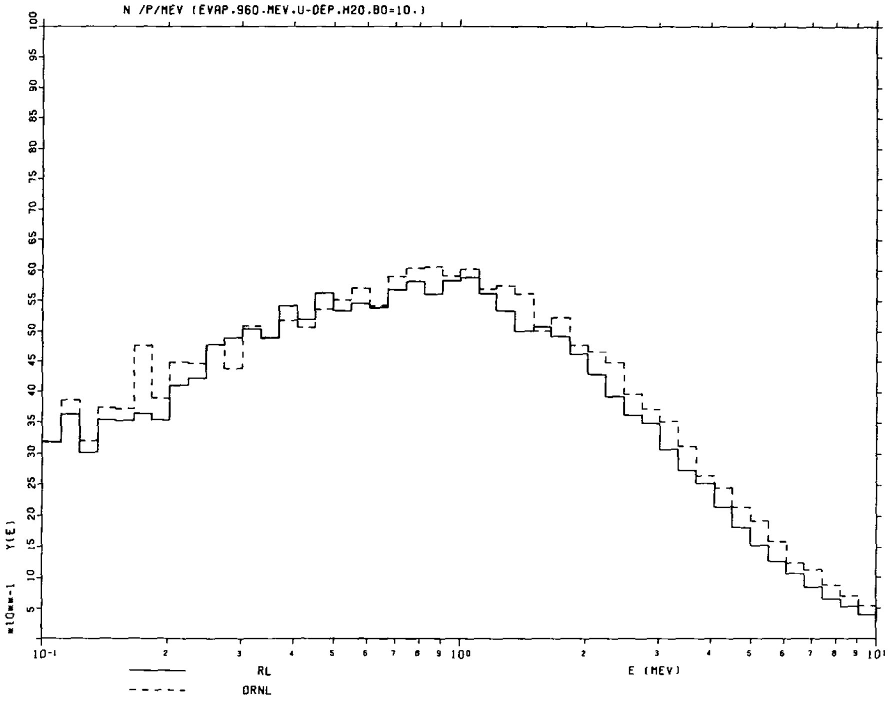

Fig. 2 Evaporation neutrons with RAL-HEF model (solid curve) and ORNL-HEF model (dashed curve) (B_o=10 MeV, proton beam energy 960 MeV, target material depleted uranium)

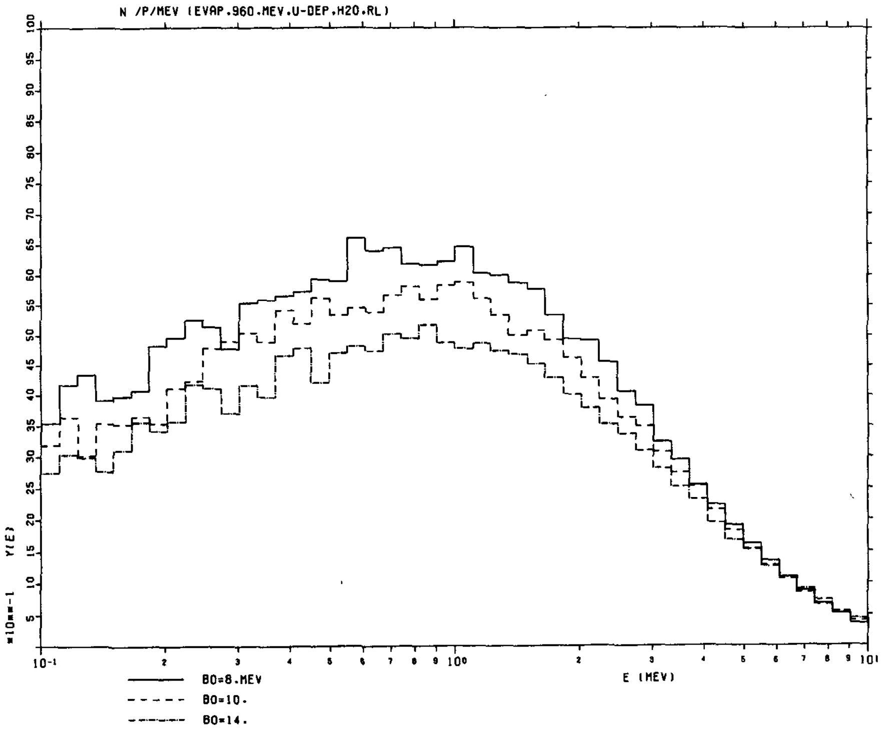

Fig. 3 Evaporation neutrons with RAL-HEF model at B_o=8 MeV (solid curve), B_o=10 MeV (dashed curve) and B_o=14 MeV (dashed-dotted curve) (proton beam energy 960 MeV, target material depleted uranium)

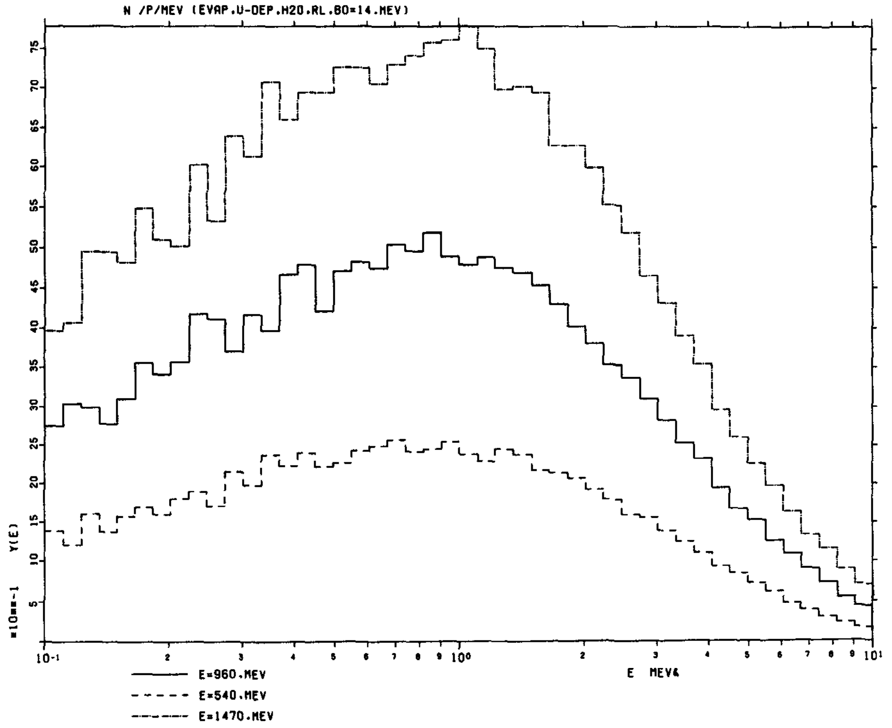

Fig. 4 Evaporation neutrons with RAL-HEF model at proton beam energy E=540 MeV (dashed curve), E=960 MeV (solid curve) and E=1470 MeV (dashed-dotted curve) with B_o=14 MeV

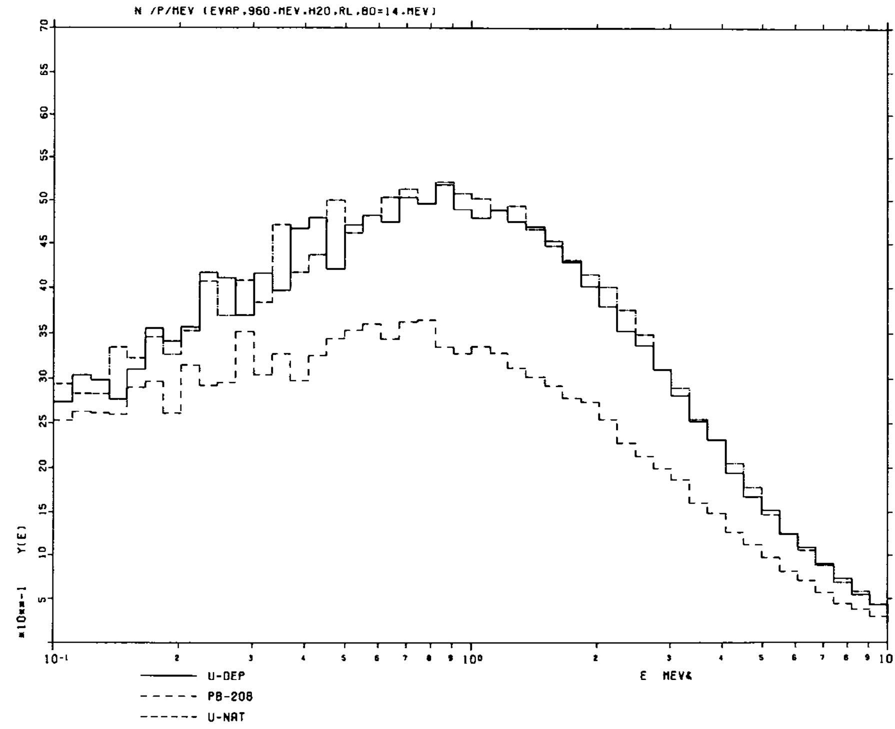

Fig. 5 Evaporation neutrons with RAL-HEF model for target material of depleted uranium (solid curve), natural uranium (dashed curve) at 960 MeV proton-beam energy and B_o=14 MeV