Proceedings of International Collaboration on Advanced Neutron Sources (ICANS-VII), 1983 September 13-16
Atomic Energy of Canada Limited, Report AECL-8488

SPALLATION NEUTRON SOURCES WITH INTERMEDIATE ENERGY PROTONS

M.A. Lone
Atomic Energy of Canada Limited
Chalk River Nuclear Laboratories
Chalk River, Ontario, KOJ 1JO, Canada

Abstract

An assessment is made of the neutron source strength, thermal neutron flux characteristics, and target heat-removal limitations in sources driven by proton beams of intermediate energies. It is shown that a 70 mA, 200 MeV proton accelerator with a Pb-Bi eutectic liquid target would provide an unperturbed peak thermal neutron flux of $\approx 2 \times 10^{15}$ $n.cm^{-2}.s^{-1}$ in a D_2O moderator.

Introduction

The long range goal of development of an Accelerator Breeder (AB) at AECL envisages[1] construction of high current proton accelerators of energies up to 1 GeV. This will be achieved in several steps as outlined by Dr. Schriber in an earlier presentation at this Conference[2]. In particular the second step calls for the development of a high current continuous wave (cw) proton accelerator of intermediate energy, say 100 to 200 MeV. This will provide the front end of a full-demonstration breeder and an Electronuclear Materials Test Facility (EMTF).

My talk is based on a feasibility study[3] of the prospects of the EMTF beam dump as a neutron source for basic research. The scope of this study was to assess the source strength, thermal neutron flux characteristics and target heat-removal limitations assuming various conceptual target-moderator configurations and 100 to 200 MeV proton beam energy.

Neutron Yield Calculations and Measurements

Calculations

We used the CRNL version of the NMTC/MORSE codes for calculation of the neutron yields and thermal neutron flux distributions inside various moderating media. The NMTC code is an earlier version of the currently popular HETC code. These codes have been tested at high energies ($E_p > 400$ MeV) with the experimental data obtained in several laboratories[4]. The codes are based on theoretical models that are generally considered to be applicable at proton energies above 50 MeV. However, none of the previous studies had tested the codes for proton energies below 400 MeV.

For verification of the theoretical calculations at lower energies we measured total neutron yields and thermal neutron flux distributions in a water moderator from 100 MeV proton bombardment of thick targets of Li, Fe, Cu, Pb and Th. Lithium and lead are important elements for high beam power sources which would require liquid targets whereas iron and copper are important accelerator structure materials. Thorium provided us with an estimate of the neutron yield due to fast fission which was not included in the NMTC calculations.

Measurements

Experimental details of the measurements were described by Dr. Jones at the ICANS-VI Conference[5,6]. Here I will give a brief outline and update of the results. Figure 1 shows a schematic diagram of the water moderator tank with about 70 gold foils placed at various locations for measurement of

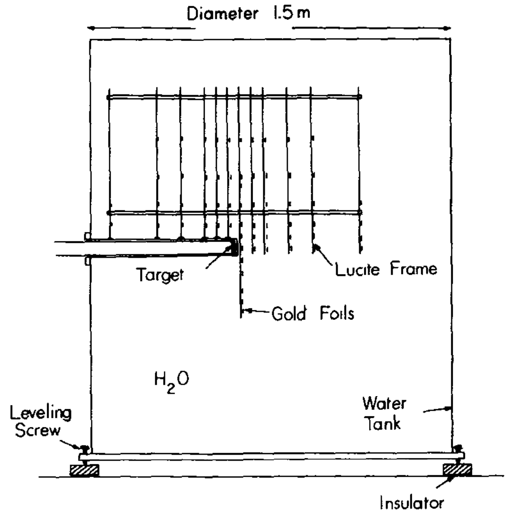

Fig. 1 Schematic setup of the experiment for neutron yield and flux distribution measurements.

thermal neutron flux distribution. The insulated water tank, 1.5 m diameter, 1.5 m high was used as a Faraday cup for proton beam current measurement to an accuracy of 1.5%. The total neutron yields were determined from the volume integral of the measured thermal neutron flux distributions and the known absorption cross section of water.

Comparison

Table I shows the measured and calculated total neutron yields for various target materials. It is evident that even at this low energy the NMTC code predicts the total neutron yield to an accuracy of about 20% or better. The biggest discrepancy between the measured and calculated yields is for a lithium target. This is not surprising since the evaporation model and the global parameters used in the CRNL version of the NMTC code are optimized for heavier nuclei. It will be interesting to compare the data with the predictions of the KFA version of the HETC code[7] which includes updated input data for nuclear models used in the calculations of evaporation neutrons.

Table 1

Target	Yield Per Proton		
	Experiment	Calculated	Deviation
^{7}Li	0.123	0.160	+ 33%
^{56}Fe	0.115	0.122	+ 6%
Cu	0.145	0.169	+ 17%
Pb	0.343	0.363	+ 6%
Th	0.530	0.449	- 15%

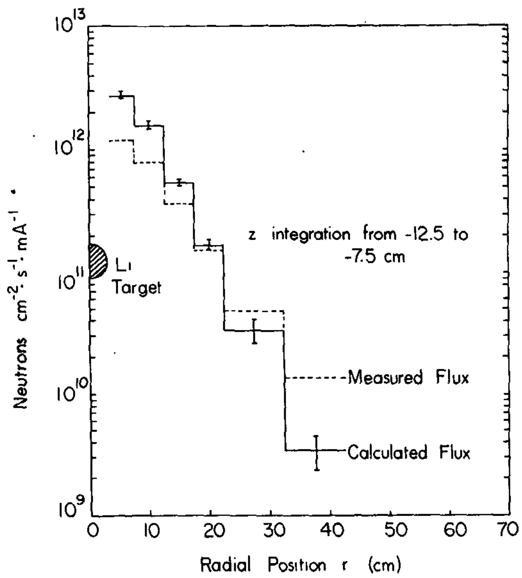

Fig. 2 Comparison between the calculated and measured volume averaged thermal neutron radial flux distributions, inside an H_2O moderator, from ^{7}Li, (p,xn) reaction at 100 MeV. The axial interval for averaging is -2.5 cm to +2.5 cm. The error bars show the statistical uncertainties in the Monte Carlo results.

A comparison of the calculated and measured thermal neutron flux distributions for the Li and Pb targets is shown in Figures 2 and 3. The agreement is quite good in case of Pb but not so good for lithium. In case of lithium the calculated peak thermal flux is high by almost a factor of 2.5. Furthermore the calculated fluxes fall off more rapidly than the measured fluxes with radial distance. A better fit to the Li data would require changing the average energy of the calculated source spectrum from 6 MeV to about 16 MeV. This discrepancy emphasizes the inadequacy of the evaporation model with isotropic neutron emission presently incorporated in the NMTC code. Inclusion of the pre-equilibrium neutron emission with an isotropic angular distribution may provide better agreement with the data[8].

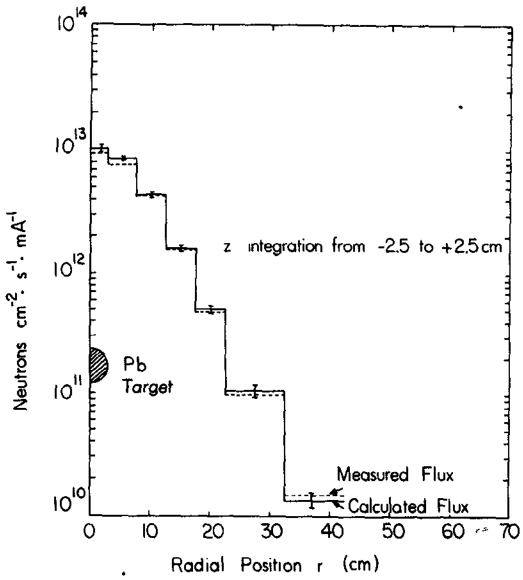

Fig. 3 Comparison of the calculated and measured volume averaged thermal neutron radial flux distributions, inside an H_2O moderator, from Pb(p,xn) reaction at 100 MeV. The axial interval for averaging is -2.5 cm to +2.5 cm. The error bars show the statistical uncertainties in the Monte Carlo results.

Neutron Yield Versus Energy

Figure 4 shows the calculated neutron yield per incident proton for several elements as a function of proton energy from 100 to 400 MeV. The neutron yield increases with atomic number of the target element as well as the proton energy. For practical reasons a high intensity neutron source produced with intermediate energy protons would require a liquid target for transfer of megawatts of heat dissipated in a relatively small volume of the target.

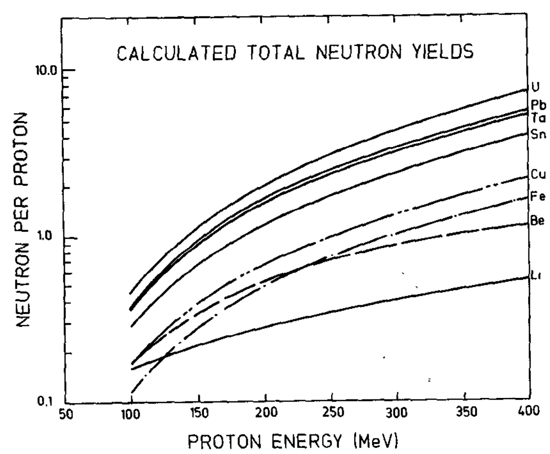

Fig. 4 Calculated neutron yield per incident proton as a function of the proton energy.

Two materials that could be used as liquid targets are lithium and a Pb-Bi eutectic. The neutron yield from lithium is low but the proton range in lithium is considerably larger than in Pb-Bi, see Table II. Thus at lower proton energies much higher beam power may be dissipated in a lithium target than a Pb-Bi target.

Preliminary estimates of the neutron yields and the target heat-dissipation limitations indicated that, with 100 MeV protons, a lithium target would provide the highest possible peak thermal neutron flux whereas, with 200 MeV protons, a Pb-Bi target would be better.

Table II

Element	Melting Point °C	Boiling Point °C	Proton Range 100 MeV cm	Proton Range 200 MeV cm
Li	180.6	1342	17.3	58.2
Pb-Bi (44.5% Pb)	124	1677	1.6	5.1

Target-Moderator Assemblies

Thermalhydraulic considerations of liquid targets of various configurations, e.g. coaxial, jet and falling curtain, indicated that a maximum of 30 MW beam power of 100 MeV protons could be dissipated in a liquid lithium target. Whereas a maximum of 14 MW power of 200 MeV proton beam could be dissipated in a Pb-Bi liquid target. Estimates of target flow rates and temperatures under these conditions are summarized in Table III. In both cases the target flow rates are quite high but practicable.

Detailed calculations of the thermal neutron flux distribution in various moderating media, C, H_2O and D_2O were carried out assuming the idealized geometries of target-moderator assemblies shown in Figure 5. A proton beam of circular cross section 10 cm in diameter, having uniform density within the beam area, was assumed to be incident on the front face of the target.

Table III

Target Temperature and Flow Rates

Beam Energy	100 MeV	200 MeV
Target	Li	Pb-Bi
Power	30 MW	14 MW
Target Inlet Temperature	275°C	275°C
Mean Target Outlet Temp.	375°C	375°C
Target Mass Flow Rate	72 kg/s	952 kg/s
Target Volume Flow Rate	145 ℓ/s	93 ℓ/s

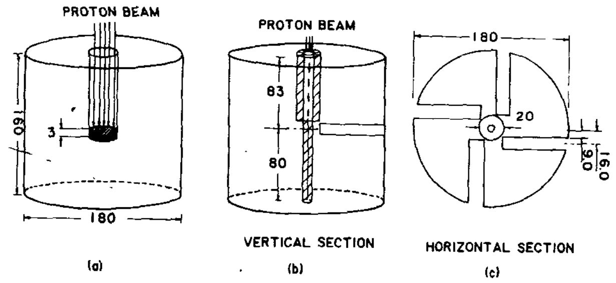

Fig. 5 Schematic drawings of the idealized geometries of target moderator assemblies used in calculations of the moderated neutron flux distributions.

Thermal Neutron FLux Distributions for a 100 MeV, 30 MW Li(p,xn) Source

For a 30 MW beam of 100 MeV protons incident on a lithium disk target the calculated axial thermal neutron flux distributions are shown in Figure 6. The peak values, 6.0, 5.0 and 4.4×10^{14} $n.cm^{-2}.s^{-1}$ occur at distances of approximately 1, 10 and 14 cm from the back face of the lithium target for H_2O, D_2O and graphite respectively. Axial fast neutron flux distributions inside a graphite moderator are shown in Figure 7. The effect of a Be multiplier blanket around the lithium target was investigated but showed little enhancement of the peak thermal flux.

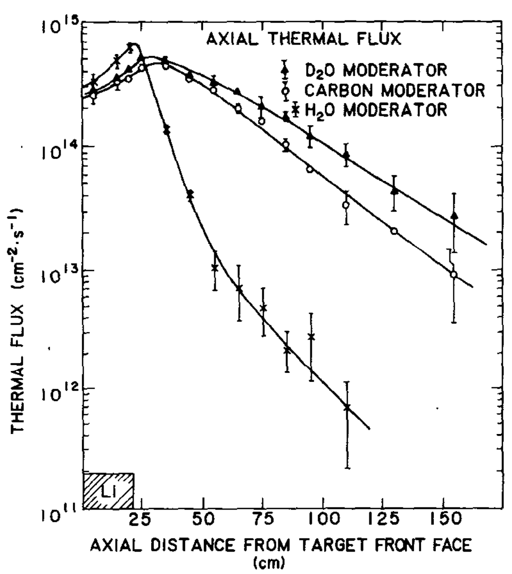

Fig. 6 Axial distribution of the neutron fluxes, inside various moderators, from ^{7}Li (p,xn) reaction at 100 MeV.

Measurements of the thermal neutron flux from bombardment of a lithium target with a well collimated (1 cm diameter) 100 MeV proton beam and an H_2O moderator gave a peak value which is ≈ 2.5 times lower than the calculated value. From this we estimate that, for the extended proton beam 10 cm in diameter, the calculations overpredict the peak thermal neutron flux by as much as a factor of 2.

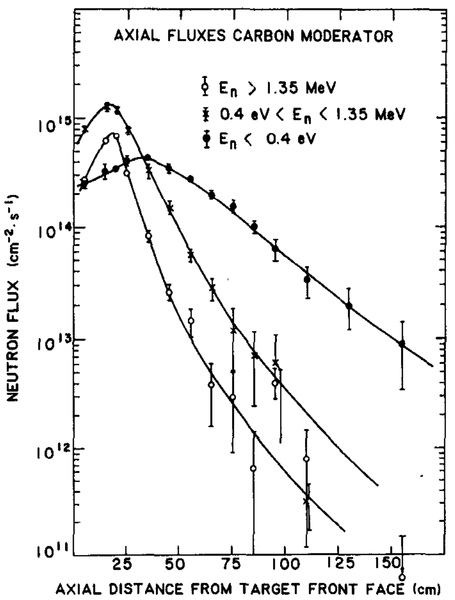

Fig. 7 Fast neutron flux distributions inside a carbon moderator from the $^7Li(p,xn)$ reaction at 100 MeV.

Thus a 30 MW beam power of 100 MeV protons incident on a lithium target would produce a peak thermal flux of only about $3\times10^{14} n.cm^{-2}s^{-1}$ which is already available from our 25 year-old NRU reactor.

Thermal Neutron Flux Distributions for a 200 MeV, 14 MW Pb(p,xn) Source

For higher thermal fluxes the proton energy must be increased. At higher proton energies the increase in neutron yield from lithium is much slower than from Pb or Bi, see Figure 4. For this reason we considered only a Pb-Bi eutectic target with a 200 MeV proton beam of 14 MW power. Two moderators, H_2O and D_2O, were considered. Flux perturbation due to the extended target tube for a liquid target and external neutron beam holes through the moderator was studied by assuming the simple conceptual design shown in Figures 5b and 5c. In addition to the liquid target inlet and outlet tubes, four external neutron beam tubes, each 12 cm ID, were placed as shown in these figures. The location of these tangential tubes was based on the results of unperturbed flux calculations.

For investigation of the perturbed fluxes, parasitic absorption in the target material and in the external neutron beam tube was included in the calculations. The beam tubes were assumed to be made of aluminum tubing of 1 cm wall thickness. The target and its containment tube material was assumed to be Pb. The neutron yield from Bi is comparable to that from Pb but thermal neutron absorption is less. For calculations of fluxes of moderated neutrons the density of the lead target was assumed to be equal to that of the Pb-Bi eutectic.

For the H_2O moderator the axial distribution of the unperturbed neutron fluxes, averaged over a cylindrical slice extending from 5 to 10 cm radius, are shown in Figure 8. The peak unperturbed thermal neutron (E_n < 0.4 eV) flux is $\approx 2\times10^{15} n.cm^{-2}.s^{-1}$ and it occurs very close to the target. The flux falls off very rapidly with distance from the primary source and the region of peak thermal flux is small. Insertion of the external neutron beam tube and the extended target tube in this region perturbs the flux considerably. At the base of the 12 cm ID, 1 cm thick wall Aℓ external beam tube, the thermal neutron flux drops by almost a factor of 3.3. Because of this large perturbation of the flux an H_2O moderator is not suitable for a source with external neutron beam holes.

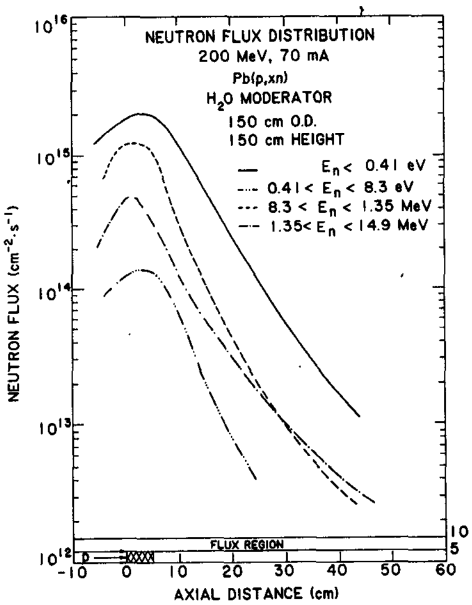

Fig. 8 Axial distributions of neutron fluxes, inside an H_2O moderator, from the Pb(p,xn) reaction at 200 MeV. The fluxes are averaged over a cylindrical slice extending from 5 to 10 cm radius.

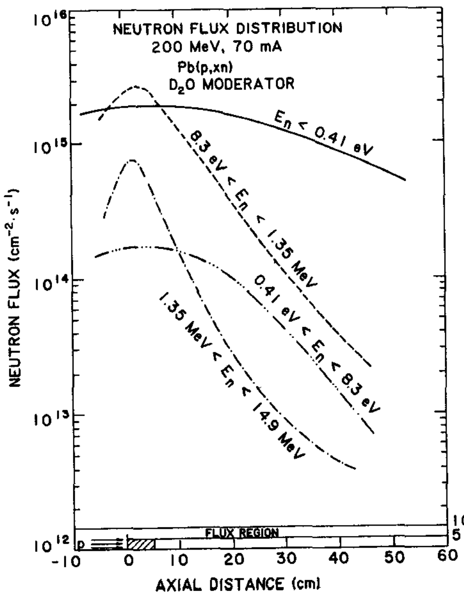

Fig. 9 Axial distributions of neutron fluxes, inside a D_2O moderator, from the Pb(p,xn) reaction at 200 MeV. The fluxes are averaged over a cylindrical slice extending from 5 to 10 cm radius.

Figure 9 shows the axial distribution of the unperturbed neutron fluxes inside a D_2O moderator. Here the peak thermal flux is ≈ 1.9×10^{15} $n.cm^{-2}.s^{-1}$ and falls off gradually with distance from the target. The vertical arrows indicate the location nearest to the target where a tangential external beam tube could be placed.

The distribution, of the perturbed neutron fluxes in the D_2O moderator calculated for a region adjacent to the external beam tube, see Figure 5c, is shown in Figure 10. In this case the thermal neutron flux at the base of the tangential beam tube reduces to ≈ 10^{15} $n.cm^{-2}.s^{-1}$.

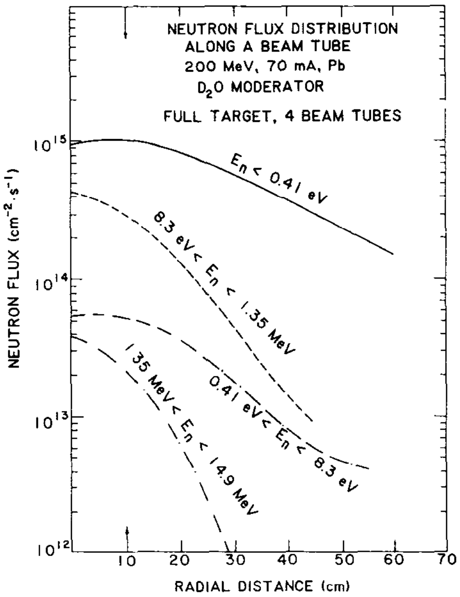

Fig. 10 Neutron flux distributions along a beam tube, see Fig. 7c, for D_2O moderator and Pb(p,xn) reaction at 200 MeV. The arrows indicate the location of the base of the external beam tube.

Conclusions

This preliminary investigation shows that a 70 mA, 200 MeV accelerator with a Pb-Bi eutectic target and a D_2O moderator would provide a peak thermal neutron flux of 10^{15} $n.cm^{-2}.s^{-1}$ at the base of several external tubes with a Cd ratio of ≈ 4.

In this preliminary study we have not investigated the cost effectiveness of the intermediate energy proton induced spallation source reaction for neutron production. However, qualitatively the competitiveness of this reaction can be judged from Figure 11 which shows the neutron yield per incident particle and the target-heat dissipation per available neutron from various source reactions of interest. By comparison, thermal fission reactions yield about 1 available neutron with 200 MeV heat production per fission event. The low energy T(d,n) reaction generates about 2500 MeV per neutron produced. Deuteron induced spallation reactions give about 25% higher neutron yield than do protons at comparable beam power. However, the deuteron beam produces more activation in the accelerator structure. The only reaction that will be very efficient with respect to the heat release is the (t,d) fusion reaction which presently is not technically feasible for very high intensity neutron sources.

Thus if neutron yield and the target heat removal were the only considerations Figure 11 shows clearly the superiority of proton induced spallation reactions, even at intermediate energies ($E_p > 100$ MeV), for high intensity neutron sources. In addition the γ-ray production will be considerably less for (p,xn) than for (e,xn) reactions or fission. Of course higher proton energies provide higher efficiencies and probably more versatility in the design of a source with special characteristics, such as a pulse-time structure, but probably at the expense of higher background from fast neutrons and high energy γ-rays.

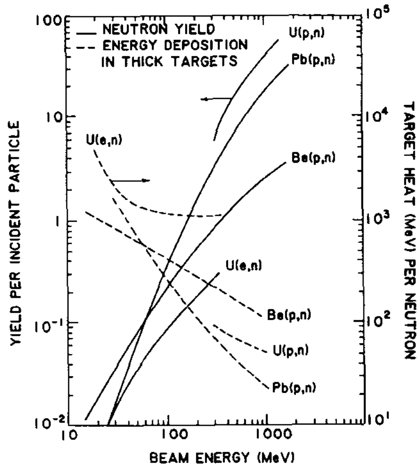

Fig. 11 Comparison of neutron yields and energy disposition in various reactions in targets of thickness equal to the beam penetration.

References

1. G.A. Bartholomew, ICANS-V, Proc. 5th Meeting of Int. Collaboration on advanced Neutron Sources, Jülich 1981, G.S. Bauer and D. Filges eds. Jül-Conf-45 (1981) p. 89.
2. S.O. Schriber, see proceedings of this conference.
3. M.A. Lone, W.N. Selander, B.M. Townes, J. Latouf, E.C. Svensson and G.A. Bartholomew. Atomic Energy of Canada Report AECL-7839 (1983).
4. T.W. Armstrong and D. Filges, ICANS-V, 5th Meeting of Int. Collaboration on Advanced Neutron Sources, Jülich 1981, G.S. Bauer and D. Filges eds. Jül-Conf-45 (1981) 173.
5. R.T. Jones, M.A. Lone, A. Okazaki, B.M. Townes, D.C. Santry, E.D. Earle, J.K.P. Lee, J.M. Robson, R.B. Moore and V. Raut. ICANS-VI, 6th Meeting of Int. Collaboration on Advanced Neutron Sources, Argonne 1982, J. Carpenter ed. ANL-82-80 (1982) p. 583.
6. M.A. Lone, R.T. Jones, A. Okazaki, B.M. Townes, D. Santry, E.D. Earle, J.K.P. Lee, J.M. Robson, R.B. Moore, V. Raut and L. Nikkinen, Nucl. Instr. & Meth. 214 (1983) 339
7. P. Cloth, D. Filges, G. Sterzenbach, T.W. Armstrong and B.L. Colborn. The KFA Version of HETC and the Generalized Evaluation Code SIMPEL KFA report Jül-SPE2-196 (1983).
8. T.W. Armstrong and P. Garvey, private communications (1983).