MASTER

HEDL-SA-2140FP

CONF-800551--17

MEASUREMENTS AND EVALUATIONS OF NUCLEAR DATA TO SUPPORT EARLY DESIGN NEEDS OF THE FMIT FACILITY

D. L. Johnson, F. M. Mann, and R. E. Schenter

APRIL 1980

Symposium on Nuclear Data
from 10 to 50 MeV
May 12-14, 1980
Brookhaven National Laboratory

HANFORD ENGINEERING DEVELOPMENT LABORATORY
Operated by Westinghouse Hanford Company, a subsidiary of Westinghouse Electric Corporation, under the Department of Energy Contract No. DE-AC14-76FF02170
P.O. Box 1970, Richland, Washington 99352

MEASUREMENTS AND EVALUATIONS OF NUCLEAR DATA TO SUPPORT EARLY DESIGN NEEDS OF THE FMIT FACILITY

D.L.Johnson, F.M.Mann, and R.E.Schenter

Hanford Engineering Development Laboratory
Richland, Washington 99352

ABSTRACT

The Fusion Material Irradiation Test (FMIT) facility is currently being designed for use in the study of neutron radiation effects in fusion reactor materials. This facility will make use of the intense source of high energy neutrons produced by a beam of 35 MeV deuterons incident upon a thick target of liquid lithium. In the forward direction, the neutron spectrum from this source peaks near 14 MeV as in a fusion device. However, the neutron energy spectrum in the FMIT facility will be broader and there will be a significant number of neutrons emitted with energies up to about 30 MeV. A small fraction will be emitted with even higher energies, up to a maximum of 50 MeV. Since ENDF/B evaluations of neutron-cross section data extend only to 20 MeV (with little data above 15 MeV) there is a great need for neutron data from 15 to 50 MeV for the FMIT facility. Furthermore, nuclear reaction cross sections induced by deuterons up to 35 MeV are a vital part of design and operation considerations, and are even less well understood than the neutron data. The time scale of the design of the FMIT facility has been so rapid that it has precluded large amounts of new nuclear data coming from outside the project. This report outlines work carried out within the FMIT project to supply the most immediate nuclear data needs. Nuclear data needs for remaining design considerations and for long term operational uses will be discussed.

INTRODUCTION

The Fusion Materials Irradiation Test (FMIT) facility is being designed for construction at the Hanford Engineering Development Laboratory (HEDL) with accelerator design by Los Alamos Scientific Laboratory (LASL). Figure 1 shows a schematic diagram of the general layout of the facility. Deuterons are accelerated in a linear accelerator to an energy of 35 MeV. The design specifies a beam current of 100 mA on target. The beam will be transported to one or the other of two targets via a series of bending and focusing magnets as shown.

Those familiar with acceleration of deuterons know that a major design consideration is the enormous quantities of prompt neutron and gamma radiation, and also residual gamma radiation, that will be associated with even tiny fractional losses of the deuteron beam which will occur during acceleration and transport to the target.

The beam will be normally incident upon a target of liquid lithium ($\sim$ 2 cm thick) within which the deuterons are stopped (range $\sim$ 1.5 cm), the neutrons are produced, and the deposited heat is carried away. A stainless steel plate, (about 0.16 cm thick) backs the lithium and separates it from the test cell where neutron irradiation experiments will be conducted. In the vicinity of the target and lithium systems, major design considerations are associated with the huge yield of very energetic neutrons from the Li(d,xn) reaction. Also important is deuteron induced activation of the liquid target material.

The major objective of the work described here was to provide data for immediate design needs. There is considerable overlap between design needs and needs for operation and analysis of irradiation experiments. However, because of the short time scale we have gone no further than was absolutely required for design purposes.

A preliminary design (Title I) for the FMIT facility was completed in late 1979 and cost estimates were based on that design. Since final design (Title II) is now being done and will be complete in early 1981, relatively little new data can be incorporated beyond what is described here. Data associated with operation and interpretation of irradiation experiments is not required as urgently, however, much of that data should be available before initial operation of the facility, which is currently scheduled for late 1984.

There are three general categories of nuclear data that will be discussed in the body of this report. They are (1) sources of prompt neutron, gamma ray, and charged particle radiation induced by deuterons; (2) neutron and gamma ray transport and radiation heating data; and (3) neutron and deuteron induced activation data. Particular data that have been emphasized will be described. Plans for obtaining data for remaining design needs will be discussed as well as data needs for operation and interpretation of irradiation experiments.

Sources of Prompt Radiation Induced by Deuterons

A. Deuterons on Lithium

Neutron source data were required to (1) allow maximizing the volume within the test cell having a neutron flux of $10^{15} n/cm^2$-s or greater resulting from a 100mA beam of 35 MeV deuterons incident on a thick target of lithium, and (2) provide the source for use in evaluations of shielding requirements, radiation heating, activation, effects on instrumentation and dosimeters and estimates of radiation damage in irradiation experiments and facility components in the vicinity of the test cell.

The data required for evaluating the high neutron flux region ($\sim 10^{15} n/cm^2$-s) in the test cell are the double differential neutron production cross sections ($d\sigma(E_d)/d\Omega dE_n$) as a function of deuteron energy up to 35 MeV. These data are needed (rather than thick target data) to take explicit account of the spatial distribution of source neutrons for distances very close to the target. The spatial distribution is about 3 cm wide because of the need to spread the beam to reduce lithium flow requirements. Such differential data are not directly available either from experiment or theory. The approach that has been taken is to obtain the needed differential data by fitting a simple model of the microscopic differential cross section to integral data obtained from measurements with thick lithium targets (in which an integral over deuteron energy is obtained). This approach is described more fully in references [1] and [2].

To partially meet the need for experimental data at the FMIT energy, measurements were conducted at the University of California at Davis of the neutron yield and spectra from 35 MeV deuterons on a 2 cm thick target of natural lithium. The spectra covered a range of emission angles from 0° to 150° and an energy range from $\sim$ 1 MeV to 50 MeV, the maximum kinematically allowed energy. Additional measurements were made to study the very low energy portion of the spectra ($E_n < 1$ MeV) and also with a target enriched in the isotope ^6Li. The measurements and results are described in more detail in reference[3]. Figure 2 shows the spectra as a function of emission angle as obtained from these measurements.

The double differential neutron production cross sections were then obtained as a function of deuteron energy by fitting to the measurements described above and in reference [3] for 35 MeV deuterons and also to data obtained at other energies from deuterons on targets of thick lithium. The results of this procedure and calculations of the neutron flux-spectra at various positions (unperturbed by the presence of test samples) within the FMIT test cell, based on this model, are described in reference [1] (earlier versions are described in references [2] and [4].

Measurements of the prompt gamma ray yields and spectra were made simultaneously with the neutron measurements described above and in reference [3]. The interest in these data was potential gamma heating in the FMIT test samples. Only preliminary analysis has been performed so far, largely because it was observed that the gamma production consisted of very weak production of low energy gamma rays. The dominant gamma ray is ∿ 0.5 MeV and is emitted approximately isotropically. The most likely candidates for this are the .478 MeV gamma ray from deuteron inelastic scattering to the first excited state of ^{7}Li and possibly the 0.428 MeV decay of the first excited state of ^{7}Be formed by both the $^{7}Li(d,2n)$ and $^{6}Li(d,n)$ reactions. Both of the candidate gamma decays are isotropic.

Calculations of the proton emission from deuterons on lithium have been made with the assumption that it is identical to the neutron emission except for the high energy shoulder portion of the spectrum (neutrons > 30MeV in Figure 2), which, for protons, is limited to 40MeV. The concern was that a large flux of protons could significantly increase the rate of heating and damage to the stainless steel backing plate or even penetrate to the test samples. Protons having energies up to 40 MeV can be produced from deuterons on lithium (the $^{6}Li(d,p)$ reaction has the highest positive Q- value of about 5 MeV). Fortunately the protons are rapidly degraded in the lithium and a flux only about 1% or less of the neutron flux is expected to hit the backing plate, if one assumes the proton yield is identical to the neutron yield. Hence no significant increase in heating or damage is expected from the proton flux. Furthermore, the maximum proton energy emerging from a 2 cm lithium target will be only about 24 MeV which is insufficient to penetrate the backing plate.

B. Deuterons on Accelerator and Beam Transport System Materials

Sources of prompt radiation are required as input to calculations to determine (1) shielding requirements when the beam is on, and (2) neutron and gamma radiation fields which effect beam diagnostic and control instrumentation when the beam is on, (3) radiation damage to accelerator and beam transport components, (4) neutron activation of the accelerator, beam transport system, and surrounding materials, and (5) radiation induced gas production which affects the accelerator vacuum.

Prompt neutron and gamma production will be directly dependent upon the small losses of the beam which will occur along the linear accelerator during acceleration and throughout the system used to transport it to the target. After beam tuneup, it is expected that the losses will be greatest at the low energy end and will diminish the farther the beam travels toward the high energy end. Neutron flux levels are expected to be much higher at the high energy end than at the low energy end, however, despite the reduction in losses as the beam is transported through the machine. This is because neutron production rates increase dramatically with increasing deuteron energy and they are emitted predominantly in forward directions.

No measurements of (d,xn) yields and spectra from accelerator materials have been done for the FMIT project and very little evaluation has been done. This is primarily because there is some data already in the open literature, and because the trends in the cross sections and spectra as a function of deuteron energy and target mass are fairly well understood and reasonably smooth for the energies of importance. For example, the Serber model of deuteron breakup reactions [5] can be used here to provide a method for interpolating and/or extrapolating experimental data. Currently, the primary source of (d,xn) yields and spectra that is being used for FMIT design is the experimental data of Meulders et al,[6] which is for deuterons of 16, 33, and 50 MeV incident on thick targets of Be, C, Cu, Mo, Ta, and Au. The choice of these targets is fortunate since the linear accelerator will have large quantities of copper. Furthermore, thin pieces of gold and tantalum are under consideration as materials to prevent the beam from hitting copper or for beam collimation. This is because the (d,xn) yields from gold and tantalum are smaller than lighter mass materials such as copper and their activation may be acceptably low. The current feeling is that for steady state operation, the uncertainty in the neutron sources due to deuteron beam losses is dominated by uncertainties in predicting the beam losses rather than by uncertainties in (d,xn) data. In situations where the beam loss is better defined, (e.g. while tuning a known beam current into a collimator or beam stop), then more accurate (d,xn) data may be desirable.

There is a great need for (d,xγ) yields and spectra for materials in the FMIT accelerator and beam transport system. The main application is to define prompt gamma radiation fields that will effect instrumentation used for beam diagnostics and control. In particular, current plans are to observe the gamma radiation produced by deuteron loss during accelerator tuning (e.g. on a collimator) in order to minimize beam loss and maximize transmission. It is believed that observation of prompt gamma radiation will be a much better indication of local beam losses than observation of neutrons. Unfortunately, there is very little (d,xγ) data. In fact we are unaware of any experimental data in the literature which could be applied directly to FMIT needs as (d,xn) data can be. No measurements or calculations of (d,xγ) data have been done in support of the FMIT project to date, however plans are being developed to fill this important need.

There may also be a need for data on production of gases within the FMIT accelerator and vacuum system. For example, nuclear reactions such as (d,α) and (n,α) on materials within the FMIT vacuum system could generate quantities of helium and other gases that would be difficult to pump with conventional vacuum pumping systems. Scoping calculations have not yet been made to evaluate this question.

Neutron and Gamma Ray Transport and Radiation Heating Data

Data for calculations of neutron and gamma transport and radiation heating are required for the same reasons as listed in the previous section, which described sources of prompt radiation induced by deuterons.

The types of data include cross sections for differential elastic scattering, nonelastic scattering, neutron emission spectra, charged particle emission spectra, gamma ray emission spectra, and KERMA factors. Neutron total cross sections are of use to aid in evaluation of the data above.

Data were needed for energies up to 50 MeV because, as shown in Figure 2, the spectra from the Li(d,xn) reaction extend that high. Furthermore, although the fraction of neutrons emitted in the Li(d,xn) spectra with energies greater than $\sim$ 30 MeV is only about 1% of the total, the transport properties of these highest energy neutrons are extremely important because they dominate the penetration of thick shields made of ordinary and high density concrete. This is explained in more detail by Carter and Morford in reference [7].

A major effort has been expended by the FMIT project to minimize the requirements and hence the cost for shielding, particularly near the test cell where the source is largest, the shielding is thickest and uncertainties due to neutron transport data are largest.

Initial calculations for shielding, radiation heating, and activation, were made with a combination of transport data primarily from the following sources: (1) ENDF/B-IV data for neutron energies less than 15 MeV, (2) Optical model calculations of elastic scatterings for E_n>15 MeV, (3) Nonelastic cross sections and neutron emission spectra and distributions from evaluations by Wilson [8] and Alsmiller and Barish [9] for E_n>15-20 MeV. The details of the data used and its application are given in ref. [7].

Most of the transport data used for neutron energies greater than 15 MeV were based on some nuclear model calculation with very little experimental data available for comparison and establishment of uncertainties. Data on neutron total cross sections were the notable exception to this generalization. Unfortunately, it is the components of the total cross section (elastic and nonelastic cross sections) which are actually used and the division between the two is often uncertain. It was determined that uncertainties in transport data for neutrons on the constituents of ordinary and high density concrete were large enough that significant cost increases would result from designing conservatively to account for such uncertainties.

A collaborative program was initiated with the neutron physics group at the University of California at Davis to measure some of the most important cross sections for concrete in the energy region of 20 - 50 MeV. The primary goal was to measure nonelastic cross sections at a few energies for the important shielding materials C, O, Ca, and Fe. In addition, the removal cross section was desired for "back of the envelope" calculations of neutron penetration in thick shields. This cross section is the sum of the nonelastic cross section plus the fraction of the elastic scattering cross section which leads to scattering to angles greater than 25°

(see ref. [7] for further description). An accurate knowledge of the neutron total cross section was needed at each energy that the nonelastic cross section was measured. For targets of Ca and Fe it was necessary to measure the total cross sections in order to determine them with sufficient accuracy. The nonelastic cross sections were measured at energies of about 40 and 50 MeV and the total cross sections were measured at about 35, 40, and 50 MeV. The experiments and results are reported in another contribution to this symposium [10].

The data obtained from the measurements described above were then used to aid in updating the evaluation of the total, nonelastic, elastic, and removal cross sections over the energy range of 20 - 60 MeV for neutrons on C, O, Si, Ca, and Fe. Additional experimental data, which were obtained from the CSISRS file at Brookhaven National Laboratory, were also used in the evaluation. Other new total cross section data by ORNL [11] were only in preliminary form at the time of this evaluation.

An example of the updated evaluation is shown in Figure 3 of the nonelastic cross section for neutrons on iron. The dashed curve is the cross section used in initial Monte Carlo calculations and corresponds to the evaluation of Wilson [8]. The solid curve is the new evaluation which is the result of a generalized least squares fit to the experimental data and the a priori data using the code FERRET [12]. Note that the previous evaluation is outside the error bars of the new data and is about 13% higher than the new evaluation. Therefore, use of the older evaluated data for the iron in high density concrete would have lead to wall thicknesses that would be too thin to reduce the dose sufficiently. Further updates of these data are planned if time is available, to take into account such things as optical model systematics, proton data, and new neutron data. A recent evaluation by LASL [13] for neutrons up to 40 MeV on iron may be sufficient for current needs.

As noted by Carter and Morford in reference [7], calculations of heat deposition are sensitive to neutron transport, neutron KERMA factors, and gamma production cross sections. The shortcomings and improvements in KERMA factors have been noted in ref. [7 & 14]. Data on $(n,x\gamma)$ reactions for many materials are reasonably well understood below 20 MeV. Recent theoretical evaluations have provided some $(n,x\gamma)$ data for higher energies (see ref. [13]). Experimental data is extremely sparce for energies above 20 MeV.

One area where an integral measurement has been employed to understand a design question is related to heat deposition in the FMIT test cell walls. An early design of the walls had thick iron surrounded by concrete with gas cooling channels passing through. A major concern was whether the cooling design was adequate to remove the heat deposited in the concrete. Transport calculations indicate that the source spectra as in Figure 2 is degraded in thick iron ($\sim$ 30 cm (12") or more) such that most of the neutrons emerging have energies less than 1 MeV. The transport data, KERMA factors, and $(n,x\gamma)$ data for such low energy neutrons are fairly well understood for the constituents of concrete [14]. Therefore, a primary uncertainty that remains in calculations of heating in test cell walls is in the transport of the high energy source neutrons through the thick iron.

An experiment was conducted at the University of California at Davis to measure the transmission of FMIT-like neutrons through thick iron. The neutrons were produced by a beam of 35 MeV deuterons incident upon a lithium target that was 2.5 cm diameter x 2 cm thick. The same target was used for measurements of the Li(d,xn) data shown in Figure 2,and the evaluation in ref. [1] has provided source data suitable for transport calculations. The source was placed approximately at the center of a nearly cubical block of solid iron that was about 60 cm (2 feet) on a side.

Neutron spectra were measured with detectors placed about 10 cm (4 in.) outside the block at 0° and 90° with respect to the beam direction. Proton recoil spectrometers were used to observe the portion of each spectra from ∿ 10 KeV to ∿ 1.5 MeV, where most of the neutrons were expected. An NE213 liquid scintillator was used to observe the high energy portion of the spectra which overlapped with the proton recoil spectral data. Additional data on gamma dose fields were obtained with thermoluminescent dosimeters (TLD's). Also a few solid state track recorders (SSTR's) and nuclear emulsions were exposed to observe the neutron spectra.

This experiment is similar to measurements and calculations of the transmission of 14 MeV neutrons through a 76 cm diameter sphere of iron as described in reference [15]. In that work, discrepancies between experiment and calculation in the low energy portion of the leakage neutron spectrum were found. When the data from the present experiment have been analyzed, they will be compared to predictions by the same code used for calculations of heat depositions. Adjustments in such calculations may then be necessary, depending upon the magnitude of a possible discrepancy.

Neutron and Deuteron Induced Activation Data

Activation data is needed to establish gamma radiation levels: (1) When the beam is on in places where such levels are dominated by decay radiation rather than prompt radiation, and (2) During shutdown after operation.

A. Activation Data for Radiation Levels During Operation

There will be locations within the FMIT facility where access is limited or excluded during operation because of high levels of decay radiation rather than prompt radiation. Short-lived nuclides are of most importance and both deuteron and neutron-induced activation are significant.

Examples where activation data plays a role are as follow:

(1) Rooms containing lithium piping and nearby spaces will experience large gamma radiation fields due to decay of short-lived isotopes produced in the liquid lithium primarily by deuteron induced reactions in the lithium and its contaminants. An example would be $^{23}Mg(T_{1/2} \sim 11\ s)$ produced by a reaction on a contaminant ($^{23}Na(d,2n)^{23}Mg$).

(2) Rooms containing cooling water piped from the accelerator and beam transport system will have large decay gamma fields due to short-lived radioisotopes produced by neutron-induced activation of the water and its contaminants. For example, a large contributor to this radiation is due to decay of ^{16}N, which has a half life of $\sim$7 sec. and emits very penetrating gamma rays of $\sim$ 6 MeV. It is produced via the $^{16}O(n,p)^{16}N$ reaction.

(3) Spaces containing an atmosphere which has been exposed to the neutron flux in either the accelerator tunnel (air) or test cell (nitrogen).

B. Activation Data for Radiation Levels after Shutdown

A major goal of the FMIT project is to minimize maintenance time in order to maximize availability of the facility for irradiation exposures. An availability of 80% is desired but will be challenging to meet because of the high activation levels that can be expected from both deuteron and neutron induced reactions. Current plans are for remote maintenance of the components in the test cell and hands-on maintenance, wherever practical, elsewhere. Here the problem is long-lived radionuclides.

Examples of cases where activation data are important are as follow:

(1) Maintenance of the lithium system where radionuclides such as ^{7}Be (from $^{7}Li(d,2n)$ and $^{6}Li(d,n)$ reactions) and ^{22}Na (from the contaminant $^{23}Na(d,t)$ reaction) will remain on the walls of the piping even after draining. Reference [16] describes evaluation of shielding requirements for maintenance of the lithium system.

(2) Maintenance of the accelerator and beam transport system where large quantities of radioactive nuclides will be produced directly from deuteron induced activation and also from activation by the secondary neutrons that are prolifically produced whenever a high energy deuteron hits any material. It is desired to minimize the radiation dose that results from the sum of both deuteron and neutron induced contributions to activation levels for a particular location in the facility. This would tend to discourage the use of some materials which might otherwise be useful. An example is the use of graphite (carbon) as a beam collimator. Al-

though the deuteron induced activation of graphite is known to be very low, the deuteron induced neutron production from such a light material is high compared to heavier materials. Hence, the neutron induced activation of components surrounding the graphite could be prohibitively high.

(3) Maintenance in spaces containing an atmosphere which has been exposed to the neutron flux in either the accelerator tunnel (air) or the test cell (nitrogen) and release of this atmosphere to outside of containment. A few reactions such as $^{14}N(n,nT\alpha)^{7}Be$, $^{14}N(n,p)^{14}C$, and $^{40}Ar(n,2n)^{39}Ar$ lead to very long-lived products and have cross sections large enough for concern.

C. <u>Deuteron Induced Activation Data</u>

In general there is less data available on deuteron activation at the high energies of interest than on neutron activation. On the other hand, only those materials directly exposed to deuterons can be activated, which considerably limits the number of materials that must be considered. Those materials are (1) the lithium target plus contaminants (Na, Ca, K, etc.) and corrosion products (Fe, Ni, Cr, etc.) that may be in it, and (2) the materials near the beam centerline in the accelerator and beam transport system. The linear accelerator has large quantities of copper but consideration is being given to coating those parts exposed to deuterons with a material such as gold or tantalum in order to reduce activation. The high energy beam transport system has not yet been finalized, however materials that have been considered for the beam tube are stainless steel and aluminum. Furthermore, beam scrapers or collimators made from materials such as carbon, tantalum or gold are under consideration.

One feature of activation in the FMIT facility that may not be widely appreciated is that the quantity of deuteron induced activation can far exceed that produced by the secondary neutrons that are associated with the incident deuterons. For example, with 35 MeV deuterons on a thick lithium target, only about 5 neutrons are emitted for every 100 incident deuterons. There are even fewer neutrons emitted when deuterons hit heavier mass targets. Hence the deuterons have a much greater chance for inducing activation reactions. The preponderance of deuteron induced activation would not necessarily remain in a situation where the neutron activation cross sections are much larger (e.g. for thermalized neutrons), or where the quantity of material that neutrons are exposed to is very much larger than deuterons are exposed to. However, that is not believed to be the case near the accelerator or beam transport system. Activation from the secondary neutrons will of course be more spatially diffuse than from the deuteron induced activation and will dominate radiation dose levels in some locations.

There was some data in the literature on cross sections for deuteron induced activation that lead to medium and long-lived products. Very little data is available on production of very short-lived isotopes that are of interest for the lithium system when the beam is on.

The initial design of the shielding around the lithium system is based upon rough estimates of upper limits of activation cross sections plus a measurement of the ^{7}Be production. This was necessary because of the large number of reactions and limited experimental data and time. The differential cross section for each unknown deuteron induced activation reaction was assumed to be a constant 0.5 barns for deuteron energies above the Coulomb barrier or threshold energy, which ever is greater. Thick target yields were then evaluated using such cross sections for each reaction that could occur with 35 MeV deuterons on a target of thick lithium plus estimated trace contaminants. Measured data for production of ^{7}Be (the most abundantly produced radionuclide) were used instead of an estimate. Furthermore, comparisons were made to some data available in the literature to verify that under-estimates of the activation were not being made. This procedure is expected to result in a very conservative design since such activation cross sections are not generally as large as 0.5 barns.

Initial scoping evaluation of deuteron induced activation of accelerator and beam transport materials was done using a simple extension of the THRESH code (ref. [17]) which is used for estimation of neutron induced activation cross sections. Comparisons were made with available experimental activation data such as given by Fulmer and Williams for deuterons up to 40 MeV on copper [18]. The comparison indicated that the model calculations were only accurate enough for order of magnitude scoping studies. Figure 4 shows the dose as a function of decay time calculated from the estimated activation cross sections. The relative doses calculated for activation of C, Al, Fe, Cu, and Ta tend to agree roughly with previous dose calculations [19] for the same elements which were based upon experimental activation data.

A program to measure deuteron induced activation was begun for the following reasons: (1) There were no reliable data available for some elements of known importance for energies of interest. For example, the production of ^{7}Be by deuterons on lithium had not been measured up to 35 MeV; (2) Previous experiments may have missed some weakly produced radionuclides having long half lives which could be important for dose considerations because of their buildup in long irradiations. For example, we are not aware of previous observation of the long lived isotopes ^{58}Co, ^{60}Co, and ^{59}Fe produced by deuterons on copper, however, for 35 MeV deuterons they are energetically allowed via such reactions as $^{63}Cu(d,\alpha T)^{58}Co$, $^{63}Cu(d,\alpha p)^{60}Co$, and $^{65}Cu(d,2\alpha)^{59}Fe$; (3) There is a need to find materials having very low deuteron activation doses for special applications such as for beam scrapers or collimators, beam tube liners, and low activation coatings of accelerator parts that are exposed to deuterons.

Measurements were conducted on stacked foil targets using a beam of 35 MeV deuterons from the cyclotron at the University of California at Davis. Targets included Li, C, Al, Fe, Ni, Cu, Mo, Ta, Au and Pb. Other measurements are planned on targets of Na, K, Ca, Cr, and Mn and possibly other materials estimated to have low activity for special applications.

An example of preliminary results from this program is shown in Figure 5 which illustrates the thick target activation of copper as a function of deuteron energy. Note that the long-lived isotopes ^{58}Co, ^{60}Co, and ^{59}Fe were indeed observed at 35 MeV with production rates that are large enough to be significant for dose considerations.

D. Neutron Induced Activation Data

The major need for neutron activation cross sections is for energies above 20 MeV. There are extensive sets of neutron activation cross sections up to 20 MeV in ENDF/B and other libraries, although not all activation cross sections that might be important are included.

Scoping studies of neutron induced activation have been done for such varied materials as air, water, concrete, iron, copper, and aluminum in spectra that have significant portions of the spectra above 20 MeV. This work is described more fully in ref. [7] and will only be outlined here.

First, the most important reactions are selected by calculating the dose for a particular neutron flux-spectrum exposure, irradiation time and decay time using estimated upper limits to the activation cross sections as a function of energy. Then improved dose calculations are made using cross sections estimated by the THRESH code (ref. [17]) which was extended to 40 MeV. These cross sections were joined at 20 MeV to ENDF/B-V activation cross sections when they were available. Next, improved calculations of a few selected reaction cross sections have been made using the code HAUSER*5 [20] which treats the reactions in the formalism of Hauser-Feshbach statistical reaction theory with pre-equilibrium emission.

Some neutron induced activation reactions are not expected to be reliably calculated by any of the methods described above and they have not been measured. An example is the production of ^{7}Be from neutrons on ^{14}N. Nitrogen will be in the test cell and accelerator tunnel. A likely path for this reaction involves the following cascade, $^{14}N(n,nT\alpha)^{7}Be$ which has a threshold of $\sim$ 32MeV.

Plans are being considered for integral measurements of such neutron activation cross sections in spectra that will be prototypic of the FMIT facility. Note that measurements in Be(d,xn) spectra with 35 MeV deuterons would not be suitable for the ^{14}N reaction described above, since the d,Be spectrum extends only to $\sim$ 40 MeV and is not prototypic of the Li(d,xn) spectra which extends to 50 MeV. A lithium target, which will be cooled to allow high deuteron beam currents and corresponding high neutron flux levels is being designed for possible use in activation measurements at the University of California at Davis.

Remaining Needs and Plans

There is much nuclear data that is still needed for completion of design. Plans are being developed within the FMIT project to provide for immediate needs as much as possible within the time limits as stated earlier. Primary areas where work is being considered are:

(1) Measurements and evaluation of (d,xγ) and (d,xn) data for accelerator and beam transport materials.

(2) Further calculations and possible integral measurements of neutron activation cross sections.

(3) Completion of measurements and evaluations of deuteron induced activation cross sections.

(4) Updating evaluation of neutron transport and heating data for FMIT structural materials.

(5) Providing data for evaluation of neutron radiation damage for key FMIT structural components.

(6) Providing data on deuteron and neutron induced production of gases in materials exposed to the FMIT vacuum system.

For operation of the FMIT facility and interpretation of irradiation experiments, nuclear data needs are largely related to neutron dosimetry and damage prediction in irradiation experiments. Detailed discussions of these needs are given in other contributions to this conference [21 & 22]. Important needs include the following:

(1) Neutron activation cross sections for dosimetry applications.

(2) Neutron transport data for prediction of neutron flux-spectra in experimental samples.

(3) Neutron data for prediction of displacement damage, gas production, and transmutation in experimental samples.

(4) Neutron KERMA factors and gamma production data for prediction of radiation heating in experimental samples.

A more complete list of needs is given in reference [23].

Acknowledgements

This work is funded by U.S.D.O.E. under contract DE-AC14-76FF02170.

We would like to acknowledge the major contributions to this effort which have been made by the following people: F.P.Brady, J.W.Watson, J.L.Ullmann,J.L.Romero, C.M.Castaneda, C.I.Zanelli, M.L.Johnson, W.G.Wyckoff, G.L.Woodruff, F.Schmittroth, R.J.Morford,

REFERENCES

1. F. M. Mann and F. Schmittroth, "Neutron Environment in d+Li Facilities," proceedings of this symposium (also HEDL-SA-2123).

2. D. L. Johnson et al, "Measurements and Calculations of Neutron Spectra from 35 MeV Deuterons on Thick Lithium for the FMIT Facility," Jour. of Nucl. Mat'ls. 85 & 86 (1979) 467.

3. D. L. Johnson et al, "Thick Target Neutron Yields and Spectra from the Li(d,xn) Reaction at 35 MeV," proceedings of this symposium (also HEDL-SA-2141).
D.L.Johnson et al, "Measurements of Neutron Spectra from 35 MeV Deuterons for the FMIT Facility," proceedings of the International Conference on Nuclear Cross Sections for Technology, Knoxville,TN., Oct. 22-26, 1979 (also HEDL-SA-1905).

4. J. O. Schiffgens, et al., "Spatial Variations of Damage Parameters in FMIT and Their Implications," Jour. of Nucl. Mat'ls 85 & 86 (1979) 491.

5. R. Serber, Physical Review 72 (1947) 1008.

6. J. P. Meulders, et al., "Fast Neutron Yields and Spectra from Targets of Varying Atomic Number Bombarded by Deuterons from 16 to 50 MeV," Phys. Med. Biol. 20 (1975) 235.

7. L. L. Carter and R. J. Morford, "Nuclear Data Relevant to Shield Design of FMIT Facility," proceedings of this symposium.

8. W. B. Wilson, "Nuclear Data Development and Shield Design for Neutrons Below 60 MeV," LA-7159-T Los Alamos Scientific Laboratory, Los Alamos, NM, Feb. 1978.

9. R. G. Alsmiller, Jr., and J. Barish, "Neutron-Photon Multigroup Cross Sections for Neutron Energies < 60-MeV," Nuclear Science and Engineering 69, 378-388 (1979) (also ORNL/TM-6486 Aug. 1978).
R. G. Alsmiller, Jr., and J. Barish, "NCDATA-Nuclear Collision Data for Nucleon-Nucleus Collisions in the Energy Range 25 to 400MeV," ORNL-4220, Oak Ridge, TN, 1968.

10. C. I. Zanelli, F. P. Brady, J. L. Romero, C. M. Castaneda, M. L. Johnson, G. A. Needham, J. L. Ullmann, P. P. Urone, D. L. Johnson, "Measurements of Neutron Total and Nonelastic Cross Sections for C, O, Ca, and Fe at UC Davis," proceedings of this symposium.

11. D. C. Larson, J. A. Harvey and N. W. Hill, "Transmission Measurements up to 50 MeV for FMIT Design," proceedings of this symposium.

12. F. Schmittroth, "FERRET Data Analysis Code," HEDL-TME-79-40, Hanford Engineering Development Laboratory, Sept. 1979.

13. E. D. Arthur and P. G. Young, "Evaluation of Neutron Cross Sections to 40 MeV for $^{54,56}Fe$," proceedings of this symposium.

14. R. E. MacFarlane, "Energy Balances of ENDF/B-V," Trans. Am. Nuclear Society, 33, 681 (1979).

15. N. E. Hertel, R. H. Johnson, J. J. Dorning, and B. W. Wehring, "Measurements and Analyses of Neutron Transport Through Iron," proceedings of the International Conference on Nuclear Cross Sections for Technology, Knoxville, TN, Oct. 22-26, 1979.

16. S. T. Huang, A. M. Shapiro, W. C. Miller, and J. B. Lee, "Shielding Consideration for a Deuteron Activated Liquid Lithium System," proceedings of the 8th Symposium on Engineering Problems of Fusion Research, San Francisco, CA, Nov. 13-16, 1979 (also HEDL-SA-1904).

17. S. Pearlstein, "Neutron Induced Reactions in Medium Mass Nuclei," Journal of Nuclear Energy, 27, 81-99 (1973). Updated by Proceedings of the Conference on Nuclear Cross Sections and Technology, Washington DC (1975), NBS special publication number 425, page 324 (1975).

18. C. B. Fulmer and I. R. Williams, "Excitation Functions for Radioactive Nuclides Produced by Deuteron Induced Reactions in Copper," Nuclear Physics A155(1970) 40.

19. C. B. Fulmer and G. Kindred, "Calculated Residual Radiation Levels for Some Elements Used in Cyclotron Structures," ORNL-TM-2834, Oak Ridge National Laboratory, Oak Ridge, TN. (Aug. 1970).

20. F. M. Mann, "HAUSER*5, A Computer Code to Calculate Nuclear Cross Sections," HEDL-TME-78-83 (1979).

21. R. Gold, W. N. McElroy, E. P. Lippincott, D. L. Oberg, J. H. Roberts, F. H. Ruddy, and F. M. Mann, "Cross Sections Required for FMIT Dosimetry," proceedings of this symposium.

22. D. G. Doran, "Fusion Materials High Energy Neutron Studies--A Status Report," proceedings of this symposium.

23. R. E. Schenter, F. M. Mann, and D. L. Johnson, "Nuclear Data Needs for FMIT," proceedings of the International Conference on Nuclear Cross Sections for Technology, Knoxville, TN., Oct. 22-26, 1979.

FIGURE CAPTIONS

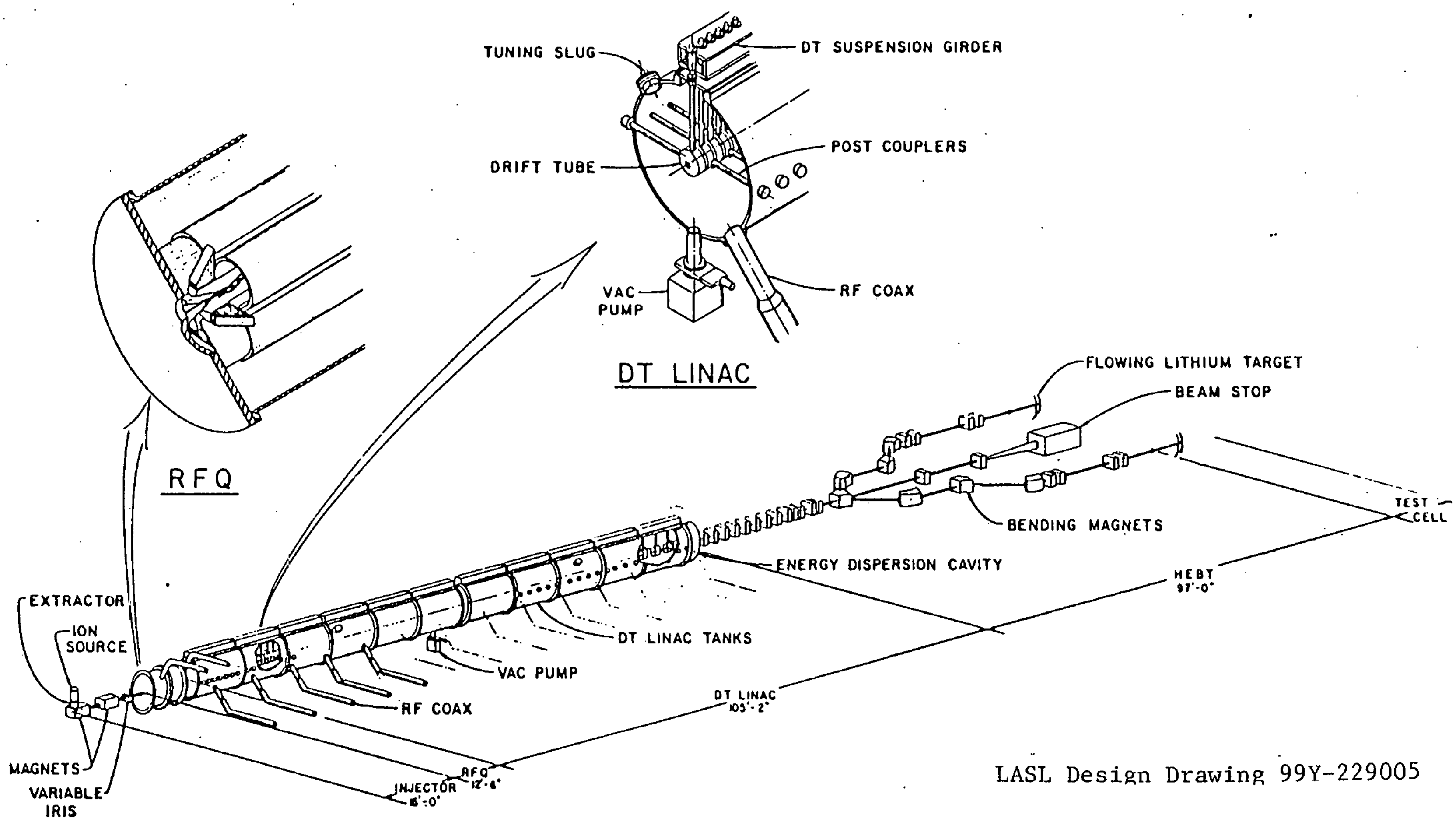
(1) General layout of FMIT linear accelerator, high energy beam transport system, and targets.

(2) Measured neutron yield spectra as function of emission angle in the laboratory for 35 MeV deuterons on thick natural lithium.

(3) Updated evaluation of the non-elastic cross section for neutrons between 20 and 60 MeV on iron. A priori data were from the previous evaluation by Wilson [8].

(4) Residual unshielded gamma ray doses at a distance of 1 meter for deuteron induced activation of various thick targets. Irradiation was with a 1 mA current of 35 MeV deuterons for a period of 1 year. Activation cross sections were estimated using an extension of the THRESH code [17].

(5) Rates measured for production of various gamma decaying radionuclides from deuterons up to 35 MeV incident upon a thick copper target.



LASL Design Drawing 99Y-229005

FIGURE 1.

A General Layout of FMIT Linear Accelerator, High Energy Beam Transport System, and Targets.

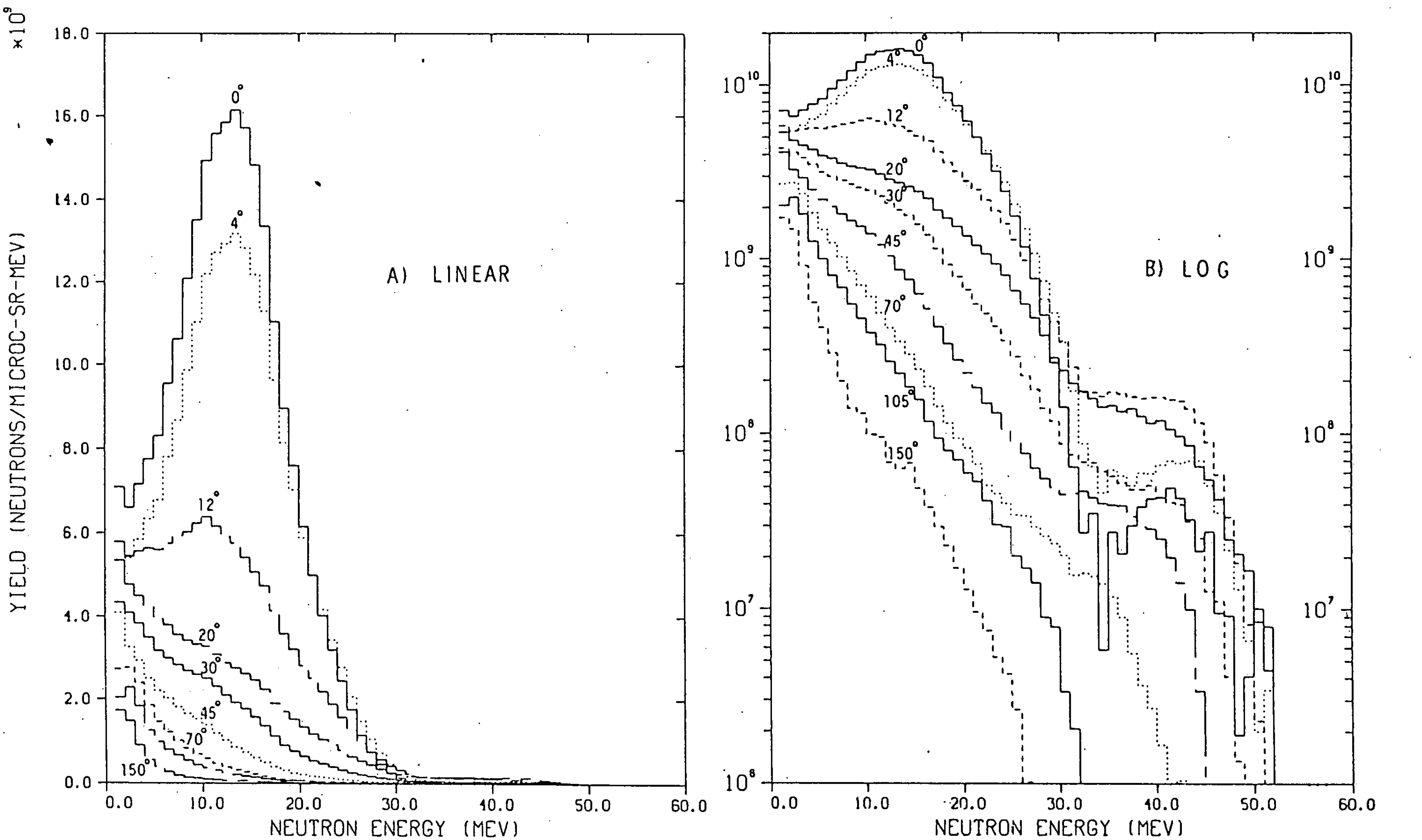


Figure 2.

Measured neutron yield spectra as a function of emission angle in the laboratory for 35 MeV deuterons on thick natural lithium.

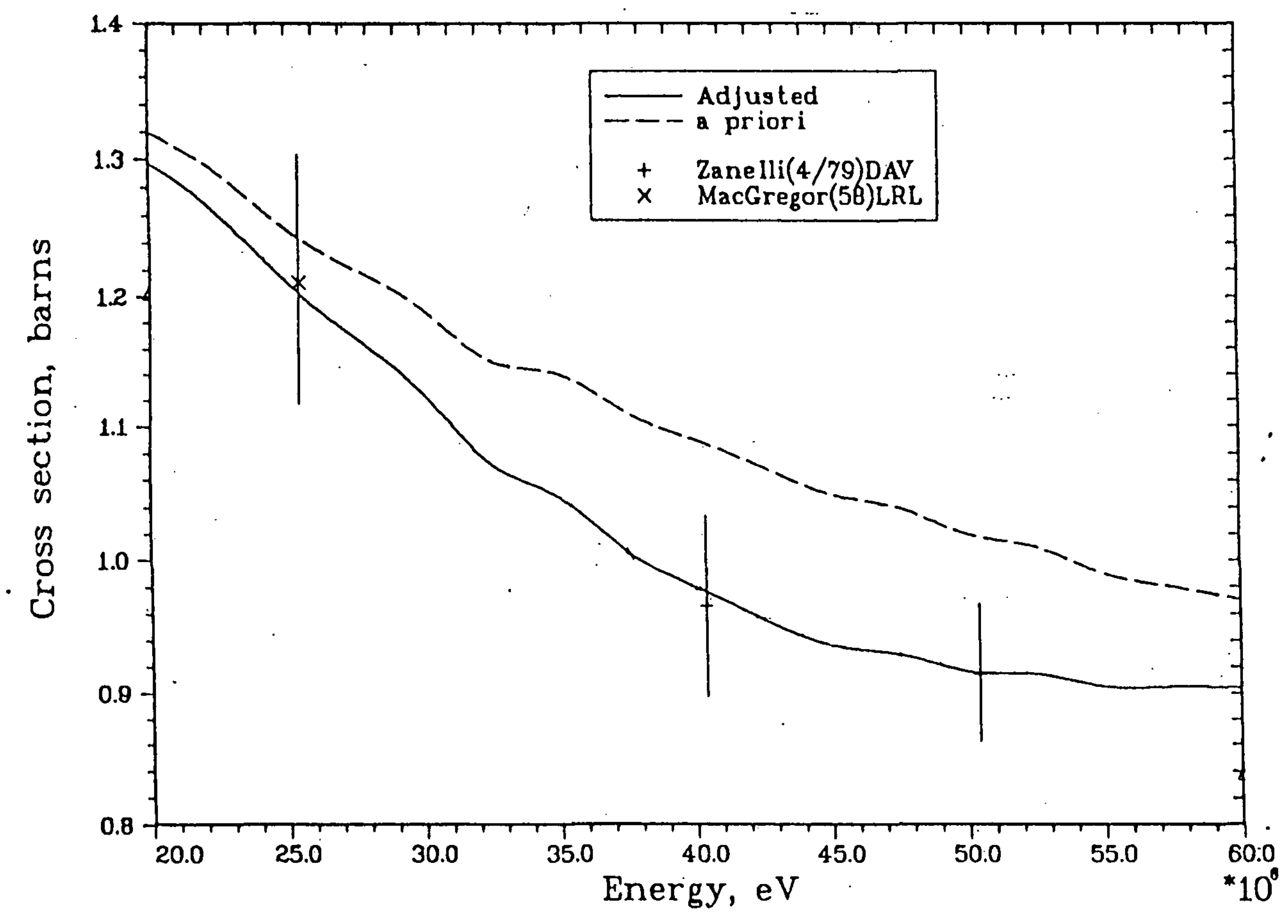


Figure 3.

Updated evaluation of the non-elastic crosssection for neutrons between 20 and 60 MeV on iron. A priori data were from the previous evaluation by Wilson [8].

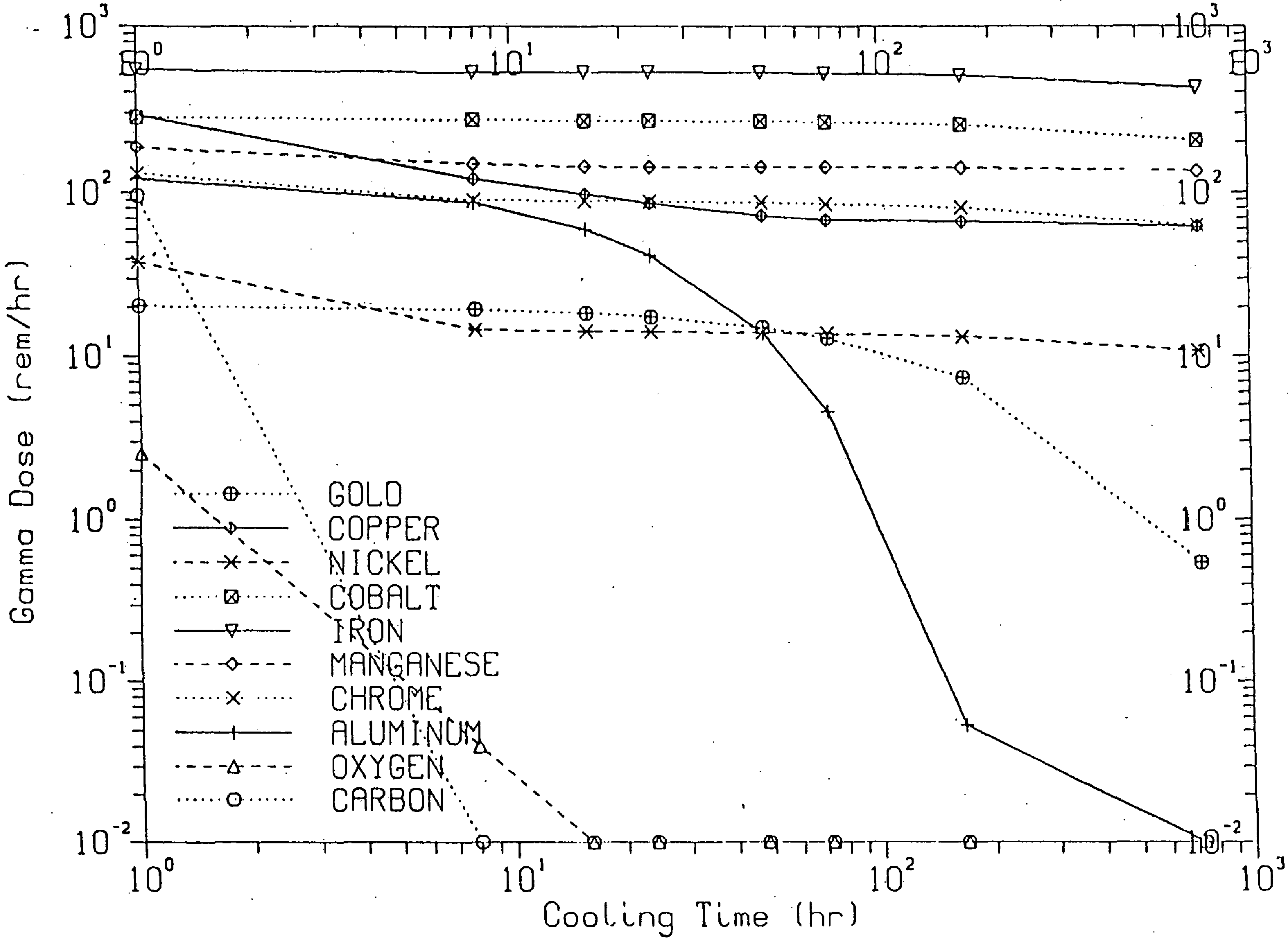


Figure 4.
Residual unshielded gamma ray doses at a distance of 1 meter for deuteron induced activation of various thick targets.

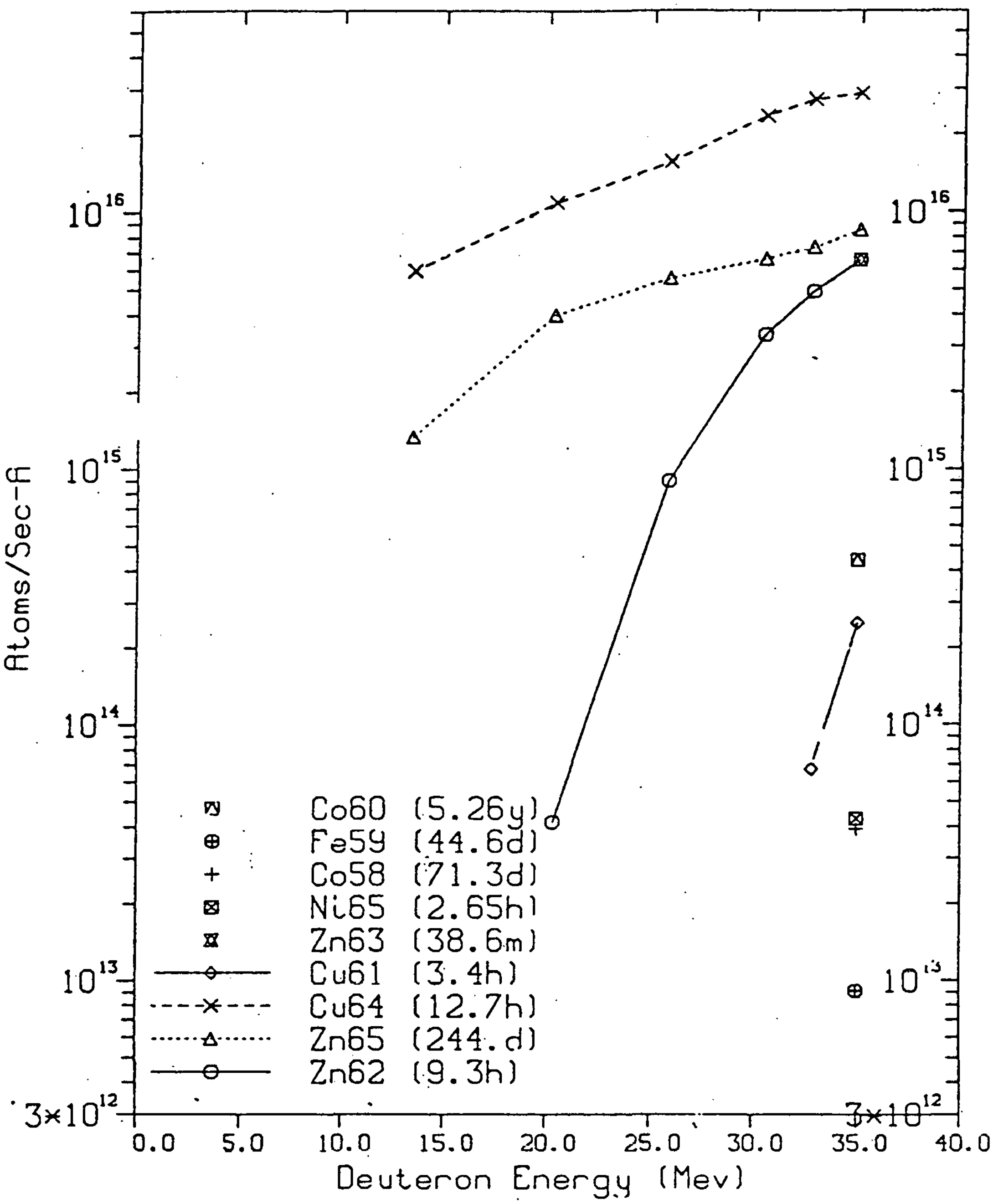


Figure 5.

Rates measured for production of various gamma decaying radionuclides from deuterons up to 35 MeV incident upon a thick copper target.