HEDL-SA-2145 - FP

MASTER

CONF-800531--14

FUSION MATERIALS HIGH ENERGY-NEUTRON STUDIES — A STATUS REPORT

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ABSTRACT

The objectives of this paper are (1) to provide background information on the U. S. Magnetic Fusion Reactor Materials Program, (2) to provide a framework for evaluating nuclear data needs associated with high energy neutron irradiations, and (3) to show the current status of relevant high energy neutron studies. Since the last symposium, the greatest strides in cross section development have been taken in those areas providing FMIT design data, e.g., source description, shielding, and activation. In addition, many dosimetry cross sections have been tentatively extrapolated to 40 MeV and integral testing begun. Extensive total helium measurements have been made in a variety of neutron spectra. Additional calculations are needed to assist in determining energy dependent cross sections.

Materials irradiations with high energy neutrons are currently centered at RTNS-II, with emphasis on achieving the highest practical fluences. It has been found possible, generally speaking, to correlate the very low fluence data obtained to date with 14 MeV, d-Be, and fission neutrons by weighting fluences with simple spectrum sensitive parameters. The definition of both the irradiation environment and the associated derived damage parameters still suffer from a serious lack of data and calculated cross sections at high energies.

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INTRODUCTION

Let us begin this review by considering what technical areas are common to this conference and to the Fusion Materials Program of the Office of Fusion Energy. Clearly, the purpose of the latter is to develop materials for use in fusion reactors. Assuming that such reactors are shown to be feasible in the next few years, their conversion from a scientific wonder to an important national resource will depend largely on development of improved materials. One of the major considerations, of course, is the effect of the neutron environment on the material. Since the first fussion reactors will employ the D-T reaction, we must determine the effects of neutrons of energies up to and including 14 MeV on materials. The first planned fusion device with provisions for materials studies is the Engineering Test Facility (ETF) [1]. Such studies are not planned until the facility has been in operation for several years, hence not expected before about 1993. In the interim, the only facility that will produce high energy neutrons at high damage rates for materials studies is the Fusion Materials Irradiation Test (FMIT) Facility [2], expected on line in 1984.

To build and use such a facility requires high energy neutron cross sections for facilities design, environmental definition, and damage calculations. Because the FMIT will produce a broad range of neutron energies, these cross sections are required well above the 14 MeV output of the D-T reaction.

Let us be somewhat more specific. FMIT facility design requires neutron cross section data in four areas: source description, shielding, energy deposition, and component activation. A paper in the first session of this symposium described the current status of neutron yields from the D-Li reaction [3]. The status of neutron cross sections for shielding design of FMIT was discussed in the previous review paper by Carter [4].

A primary concern, because of the large impact on facility costs, is the degree to which maintainence must be done remotely. This is determined by the activation of various components by deutrons, the subject of a subsequent paper in this session [5], and by neutrons. Neutron activation is also a concern in the design of the experimental test cell and of associated equipment which must be removed from the test cell such as neutron detectors and experimental modules. Another use for activation cross sections is in estimating the activation of test specimens themselves, a non-trivial concern of the experimenters.

A by-product of the high energy neutron fluxes in FMIT is a high rate of energy deposition in test specimens and test equipment. The high absolute values coupled with strong gradients mean that energy deposition calculations are very important in designing the test modules.

Carter has discussed neutron activation and energy deposition calculations for FMIT in some detail [4]. In particular, he has presented a summary of important activation reactions.

The data analyst, on the other hand, is concerned with the definition of the radiation environment to which the specimens are

exposed. This includes the actual dosimetry and diagnostics needed to determine flux-spectra and fluences and the conversion of these data to damage parameters needed in damage correlation calculations. The status of dosimetry cross sections for FMIT [6] and a description of the FMIT environment in terms of damage parameters [7] are described in subsequent papers in this session.

Most damage calculations have been for metals. However, since the last BNL conference there has been significant work done on damage calculations for insulators.

Before going into more detail regarding high energy studies, let us consider briefly the fusion materials program to which they are being applied.

THE FUSION REACTOR MATERIALS PROGRAM

Program

Changes in Program Emphasis

The US Fusion Program has undergone some changes since the time of the last BNL conference. The logic for the magnetic confinement portion of major device development is indicated in Figure 1 [1]. The Tokamak Fusion Test Reactor (TFTR), currently under construction, is to be in operation in 1982. It is expected to be the first device to demonstrate energy breakeven. The next major fusion facility will be the Engineering Test Facility (ETF) currently being designed at ORNL. The target date for ETF operation is 1990. This is intended to be a multipurpose machine. After a few years of operation as an engineering test facility to qualify technology and components for first generation power reactors, it will also become a materials irradiation test facility. The ETF is to be followed by one or more demonstration reactors, then on to a commercial reactor. It should be added that concurrently with the development of the ETF the U.S. is participating in an international program to design the very similar INTOR machine [8]. The recent concentration of effort on the ETF has had an impact on the fusion materials program as might be expected.

Task Group Reorganization

The Fusion Materials Program is carried out through several task groups. Since the first BNL conference four Program Plans [9] have been completed and implementation of these has begun. The Damage Analysis and Fundamental Studies (DAFS) and Alloy Development for Irradiation Performan (ADIP) task groups have undergone some reorganization since the first conference [10,11]. The current structure is shown in Figures 2 and 3. The reorganization was in part to help stress near-term objectives, particularly those pertaining to ETF and to FMIT. The call for increased and improved nuclear data is from the DAFS Subtask Group on Dosimetry and Damage Parameters, under L. R. Greenwood. This group is responsible for seeing that the irradiation environments associated with fusion materials experiments are adequately and systematically characterized.

A review of this work is included in the symposium [12].

Materials Priorities

As might be anticipated, there have been some changes in the priorities assigned particular materials in the fusion materials program [10]. The current materials emphases in the ADIP program are included in Figure 3. The major changes relative to 1977 are 1) niobium has been pushed to a back burner, 2) the number of titanium alloys has been decreased, and 3) a general class of ferritic steels (9-12% Cr) has been added (new Path E). While it has been known for some time that thermal stresses in a ferritic steel first wall are significantly lower than in an austenitic steel wall, and that ferritic steels exhibit considerable radiation resistance for certain properties, these steels were eliminated from the fusion materials program early on because it was believed that their ferromagnetism precluded their use in a magnetic fusion reactor. Recent studies have concluded that, because the applied magnetic field is well above the saturation value, this concern is not well-founded and these materials are now under intense investigation [13].

Facilities

Rotating Target Neutron Source (RTNS-II)

Description

The RTNS-II facility comprises two independent sources of 14 MeV neutrons [14]. One is currently operating and is the world's most intense 14 MeV source. The design, based on experience with RTNS-I, calls for a 1 cm diameter, 150 ma beam of 400 keV deuterons incident on a water-cooled, titanium tritide target rotating at 5000 rpm. The target, constructed of a copper alloy, is to be 50 cm in diameter and expected to last for about 100 hours. The design yield is 4×10^{13} n/s. The major components of one source are shown in Figure 4 and a schematic of the target and a photograph of an irradiation capsule in place are shown in Figure 5. The method of cooling the target is illustrated in Figure 6.

Facility Status

One source is currently operating 80 hours per week. A 23 cm diameter target (the size used in RTNS-I) is in use with a 40 ma deuteron beam which produces a neutron yield of about 1×10^{13} n/s (peak neutron flux of about 2.5×10^{12} n/cm^2-s). Target life is about 80 hours. Difficulties in fabricating the 50 cm targets are expected to be resolved soon, but large target operation is not expected to begin before April 1981.

Irradiation began at RTNS-II in March 1979; the irradiations carried out to date are summarized in Table I. These experiments can be divided into several categories:

(1) Postirradiation Studies of Metals and Alloys

Two types of specimens have been irradiated at RTNS-II. One is disks for TEM examination and the other is wires for tensile testing. Only a small fraction of these specimens have been tested to date. Very low fluence irradiations of pure elements and simple

alloys have been for the purpose of comparison with model calculations of damage production. The irradiations of more complex materials are intended to be compared with fission reactor irradiations of the same materials to infer the effects of high energy neutrons. In order for these comparison studies to be made at similar damage rates, the Omega-West reactor at Los Alamos will be employed for the fission reactor irradiations. These irradiations are to begin this summer.

(2) In-Situ Studies of Metals and Alloys

The initial change in resistivity of pure metals irradiated near 4°K has been measured at RTNS-II. These experiments are currently being analyzed to infer the number of defects produced for comparison with models. A second type of in-situ experiment concerns the effect of high energy neutrons on creep, from which inference of free defect production rates will be attempted. A feasibility experiment was completed; more irradiations are planned.

(3) Postirradiation Studies of Insulators

Postirradiation examination of insulators includes measurements of mechanical properties, as with metals, plus determination of changes in electrical properties.

(4) Postirradiation Examination of Engineering Materials

Although the flux available at RTNS-II is much lower than that of a fusion reactor, it is nevertheless possible to get engineering data on some materials that will be exposed to low lifetime fluences. Recent examples include window and insulating materials for TFTR and components of superconducting magnets. The latter includes both the superconductor itself and the aluminum or copper matrix material.

Fusion Materials Irradiation Test (FMIT) Facility

Facility Description

The FMIT facility is to comprise basically 1) a linear deuteronaccelerator, 2) a flowing lithium target, and 3) test cells in which specimens can be irradiated under a variety of conditions. Neutrons are produced predominantly by a stripping reaction as the 100 ma beam of 35 MeV (or 20 MeV) deuteron is stopped in the 2 cm thick lithium target. The resulting neutron field is strongly forward peaked. The flowing lithium serves also as a heat dump. The configuration of the major components is shown in Figure 7.

The source strength of the FMIT facility is expected to be about 3×10^{16} neutrons per second with a beam area of 1×3 cm (fwhm values of Gaussian distributions in both the vertical and horizontal directions). Average flux values of 10^{15} n/cm^2·s are calculated for a volume of 16 cm^3, 10^{14} n/cm^2·s for nearly 1000 cm^3. Put another way, a test volume of 140 cm^3 will provide displacement rates greater than that for a wall loading of about 1 MW/m^2; in 6 cm^3, the rate will exceed that for about 5 MW/m^2.

The facility is designed to have two identical target/test cells in order to reduce outage time during experiment setup

or target maintenance. Each cell provides for routine target access from the side via horizontal test assemblies and access for special equipment from the top. The horizontal test assembly nearest the target provides for simultaneous irradiations at three temperatures in capsules cooled by flowing NaK.

The test cell provides for limited active neutron dosimetry.

Facility Status

Construction of FMIT was initiated on February 22, 1980 at HEDL. The development of the accelerator, the responsibility of the Los Alamos Scientific Laboratory, is proceeding on schedule. An experimental lithium system featuring a full size mock-up of the free-flowing lithium target is about to commence operation. Hydraulic studies with water have been completed. The FMIT facility is at the Title II or final design stage, and is scheduled for completion in 1984.

Characterization of FMIT

The characterization of the FMIT test volume has been carried out as well as can be done with available cross sections in terms of flux-spectra, damage parameters, and energy deposition. The current status of the damage parameter characterization is described in detail in a later paper [7] in this session, and will not be repeated here. The energy deposition calculations, described briefly by Carter in the preceding paper, have yielded heating rates as high as 15 w/g close to the source, about three quarters of which is due to neutrons and one quarter due to gammas. These heating rates have been used in designing the temperature control devices for the horizontal test assemblies that will hold the specimens.

Test Matrix

A preliminary test matrix has been developed for the first few years of FMIT operation [15]. The purpose of this matrix is to guide the design of experimental test facilities, and to aid in the evaluation of certain design features. A portion of the matrix is shown in Table II.

Dosimetry

The formulation of appropriate dosimetry procedures for FMIT has been a lively topic from the outset. One reason for this has been the uncertainty as to how well the neutron source can be defined by deuteron beam diagnostics. Beam stability in both space and time, as well as the ability to characterize these variations on the deuteron side of the target, are in question. Hence, it has been felt necessary that the neutron source be characterizable directly in terms of neutron output. Furthermore, there are dosimetry systems that could be accommodated in the design of the facility that could aid in its future utilization, but which add to costs and which may not be essential for the materials irradiations for which it is being built. A primary source of dosimetry data will be passive monitors included with the experiments. Active systems are being developed for spatial and temporal source characterization and absolute spectrum determination. The strategy and

systems are described in detail by R. Gold, et al. in a paper [6] in this session.

MATERIALS STUDIES WITH HIGH ENERGY NEUTRONS

Purpose

The RTNS-II is the only high energy neutron irradiation facility dedicated to fusion materials research. Until FMIT begins operation in 1984, materials irradiation at RTNS-II will have three objectives. One is to aid in developing models for fusion/fission/charged particle correlations. A second objective, which has become more significant with the advent of the ETF project, is to build up fluences as high as practical for direct correlation with fission reactor irradiations. While practically attainable fluences are less than 10^{20} n/cm^2 (0.3 dpa in iron), this is sufficient, at temperatures below about 200°C, to produce large changes in strength and ductility of candidate alloys for ETF. Saturation property levels are expected to be reached in some cases. A third objective is to actually achieve lifetime exposures at RTNS-II for certain reactor components such as superconductors.

Status

High energy neutron irradiations to date have necessarily been limited to very low fluences, hence have been concerned primarily with damage production and the onset of the evolution of a damage microstructure. The principal diagnostic tools have been resistivity measurements, tensile tests, and transmission electron microscopy. A primary objective has been to correlate observed effects, on a physical basis, with those produced in fission reactor spectra.

The quantitative correlations to date have all been in the form of a simple spectrum dependent factor with which to scale neutron fluence. The universally used procedure is to convert fluences to "damage energy" or, equivalently, to displacements per atom (dpa). The damage energy is that portion of the energy deposited in a material which is available to produce displacement damage. Its value per neutron increases with neutron energy. The common exposure unit, dpa, is proportional to the damage energy.

In reviewing the results of the dozen or so room temperature correlation experiments which had been completed in September 1976, Wiffen and Stiegler [16] summarized as follows: "The quantitative response of a property change to 14 MeV neutron irradiation (as compared to fission reactor irradiation) depends on the sensitivity of that property to various defect configurations. Properties dependent on the total number of defects scale directly with damage energy. Properties which depend on the type and distribution of clustered defects will require more complex analysis of the damage distribution." Now that the available data base has more than doubled and has been extended to more complex materials and to both

elevated and cryogenic temperatures, their summary is still appropriate.

Table III summarizes the quantitative fission-fusion correlation experiments which have been completed since Wiffen and Stiegler's review. Also included are a number of comparisons between irradiations with 14 MeV and D-Be (30-40 MeV deuterons) neutrons. Progress has been made in a number of areas.

Total defect production rates, as measured by electrical resistivity at 4.2 K, are proportional to damage energy for Nb, V, Mo, Cu and Pt. The results for Cu are also in quantitative agreement with the work of Averback, et al [40] on Cu in which ion bombardment was used to study defect production over a wide range of recoil energies.

Free (i.e., mobile) defect production rates near room temperature are also found to scale directly with damage energy in the case of interstitials in Cu and vacancies in α-brass.

Clustered defect size distributions and number densities are still found to show some differences when comparisons are made at equivalent damage energy levels in high purity Cu and Nb. In 316 stainless steel, on the other hand, the cluster density scales more closely with damage energy. Yield stress measurements on pure V, Cu and Nb do not scale with damage energy; high energy neutrons are found to be 1.6 to 2 times more effective than fission reactor neutrons in increasing the yield stress. Measurements on Nb-1% Zr alloy, on the other hand, scale well with damage energy, while measurements on 316 stainless steel seem to scale better than those on pure metals. Further evidence of differences in defect distributions are evident from flux pinning effects in Nb_3Sn and NbTi superconductors, annealing studies in platinum, and positron trapping experiments in Pt.

Disordering by collision cascades in superconducting Nb_3Sn, which leads to decreases in critical temperature and current, appears to scale with damage energy. Flux pinning effects, which lead to initial increases in critical current, do not.

Two experiments on nonmetals are included in Table III. Point defect production (as measured by optical absorption) in Al_2O_3 is consistent with damage energy scaling, as was found earlier in MgO, although uncertainties in both fission reactor exposure and damage energy calculations are high. Only estimates of the damage energy cross section for graphite are available. Recent experiments show that they all underpredict 14 MeV neutron damage relative to fission neutron damage (as indicated by changes in the basal plane shear modulus).

In summary, total defect production in a wide range of materials irradiated by both fission and fusion energy neutrons is directly proportional to damage energy. There is some evidence that, in mid-atomic number materials at least, free defect production also scales with damage energy. Furthermore, there is an indication that the amount of disorder scales similarly.

There is clear evidence of significant differences in the number densities and smaller differences in the size distributions of defect clusters in fission-fusion correlation experiments in pure materials. These differences may be due in part to

the 25-30°C discrepancies in ambient temperatures. In most cases, however, the property changes can be scaled with damage energy if a lower cut-off in recoil energy of about 10 keV is employed, consistent with the expectation that high energy cascades are more effective in producing defect clusters. In Nb-1Zr and, to a lesser extent in 316 SS, damage energy scaling prevails without invoking a low energy cut-off. An assessment of possible differences in the development of irradiation microstructures in pure metals and alloys will have to await the analysis of recently completed irradiations, and the performance of higher fluence experiments at elevated temperatures.

Future Plans

Rotating Target Neutron Source (RTNS-II)

Operation of RTNS-II at 80 hours per week is expected to continue in 1981; the facility should reach design neutron yields by mid-1981. The major emphasis will be on obtaining fluences up to 3×10^{19} or higher at temperatures ranging from 50-500°C.

FMIT

FMIT will not produce materials data until about 1985. By then a correlation methodology [41] will have been developed for applying data obtained in fission reactors to fusion environments. The first experiments in FMIT will be designed to validate that methodology, to fill in vital holes that will undoubtedly exist, and to obtain the first goal exposure data with high energy neutrons on materials of interest to the fusion program. Although it is expected that some types of FMIT data will be directly applicable to fusion reactors through a simple fluence normalization, this is not expected to be true in general. Correlation models will be needed for this transference of data. The displacement rate obtainable at RTNS-II is one-to-two orders of magnitude below that expected in a fusion reactor first wall. Early low exposure experiments in FMIT will be compared with experiments performed in RTNS-II to see if flux effects are as predicted.

NUCLEAR DATA FOR MATERIALS STUDIES

Damage Calculations

Descriptions of displacement damage in irradiated materials begin with the calculation of primary knock-on spectra. For high energy neutrons, this requires knowledge of the cross sections of essentially all nuclear reactions because they all result in sufficient energy transmitted to the target nucleus to displace it from its normal lattice site. Required information is differential angular cross sections for elastic and inelastic scattering and the energy and angular distributions of emitted particles. Damage energy cross sections are the result of

combining primary knock-on atom spectra with an energy partition model that designates the fraction of recoil energy available to cause further displacements.

Damage energy and displacement cross sections have been standardized as calculated from ENDF/B-IV, although these will be updated shortly to ENDF/B-V. Therefore, they extend only to 20 MeV. Recently, Greenwood [42] has added some approximations to high energy cross sections developed by Alsmiller and Barish [42] and extended the damage energy cross sections for Fe, Cr, and Ni to 50 MeV (see Figure 8). Still lacking are sufficient experimental data to tie down the calculated nuclear cross sections at high energies.

In the first BNL conference, the need for evaluating the usual assumption of isotropic emission of secondary particles was discussed [11]. This need still exists.

The program to make total helium measurements in a variety of neutron spectra is continuing at Rockwell International. It has a twofold objective: 1) helium production rates must be known for experiment design and analysis, and 2) once the cross sections are known, total helium production measurements in various materials provide a good measure of neutron fluence. Papers on both topics are included in this conference. Measurements at 14.8 MeV have been made on C, Al, Ti, V, Fe, Ni, Cu, Zr, Nb, Mo, Pt, Au, and 316 SS [44]. Measurements in a Be (30 MeV d, n) field have been made for Al, Fe, Ni, and Cu [45]. The helium production cross section for copper has been extended theoretically to high energies by Mann using the code HAUSER *5 [46]. Good agreement with experiment is obtained at 14 MeV; further comparisons will be made with measurements made in D-Be spectra when the spectral definition is completed. Calculations are needed for many other materials.

No attempt has yet been made to extend the cross sections needed to calculate other transmutation products in FMIT spectra.

It is expected that ceramic insulators that will be exposed to the plasma in a magnetic fusion reactor will be tested at FMIT. Relevant cross sections have not been extended above 20 MeV. However, a significant new development is the extension to polyatomic insulators of the methodology for calculating damage energy cross sections [47].

A brief summary of nuclear data needs for damage calculations is given in Figure 9.

Dosimetry

The status of nuclear data for the characterization of the FMIT test environment is described in detail in other papers in this symposium [6,12]. Three complementary approaches to FMIT dosimetry have been identified, viz., passive, active and calculational. As shown in the paper by Greenwood [12], a good start has been made on developing radiometric monitors for passive, in-situ dosimetry. He has had gratifying success in extrapolating cross sections above 20 MeV and integrally testing them in high energy neutron spectra [48,49]. The set of cross sections used is given in Table IV and the good agreement obtained with time-of-flight measurements in a d-Be spec-

trum is shown in Figure 10.

Other cross sections also need better definition at high energy for dosimetry application. Two examples are total helium cross sections and fission cross sections. The former provide stable product monitors for measuring high fluences. The latter, for use with track recorders, provide high energy thresholds for spectral definition.

While the most obvious nuclear data need is high energy cross section data and associated nuclear parameters, there is a continuing need for better monitors below 1 MeV. This region is important for damage production in mixed spectrum reactors and in fusion reactors for components outboard of the shielding. As pointed out by Gold, et al [6], such monitors will be needed in FMIT because the rear of the test cell will be useful for testing materials for such components.

A number of systems are being considered for active dosimetry in FMIT; the associated nuclear data needs are discussed by Gold, et al [6].

The nuclear data needs for neutronic calculations are essentially the same as discussed by Carter for shielding calculations [4,6].

For in depth discussions of the application of dosimetry techniques in the fusion materials program, see the recent reviews by Greenwood [50] and Smith [51].

Neutron Activation

Neutron activation calculations for FMIT have been described in detail by Carter [4]. A neutron activation library has been established at HEDL [52]. The cross sections are tied to ENDF/B-V below 20 MeV, and extended to higher energies using THRESH. As critical reactions are identified, more accurate calculations will be made.

Source/Shielding for Facility Design

In calculations needed for FMIT design, use has been made of all available high energy neutron data. In some cases, data were developed with FMIT in mind. The most extensive data are the total neutron cross section measurements made at Oak Ridge National Laboratory on many materials, including C, O, Al, Si, Ca, Cr, Fe, Ni, Cu, Au, and Pb [53]. Total and nonelastic cross sections for C, O, Ca and Fe have also been made at UC-Davis [54]. These data and their application to FMIT have been discussed by Carter [4].

Nuclear Models

A discussion of developments in nuclear modeling is beyond the scope of this paper. Some relevant work is described in a recent review paper by Haight [55]. A productive approach is to search for systematics that can be used to extend data from one material to another. Considerable success has been achieved for (n, x) reactions [56].

SUMMARY

We have attempted to describe briefly the current status of high energy neutron studies within the framework of the fusion materials program. Materials irradiation experiments are centered on RTNS-II, the only high energy neutron facility dedicated to fusion materials research. Nuclear data development, on the other hand, is focused on FMIT. This does not imply, however, that all data needs are in the 10-50 MeV range addressed explicitly by this symposium. Some progress has been made on meeting nuclear data needs since the last symposium. Much of this was obtained under the pressure of design milestones for FMIT. While some of these data are applicable to damage calculations, most of the needs described at the 1977 symposium still exist. With respect to dosimetry needs, early testing of some radiometric monitors has met with considerable success and significant progress has been made in developing helium accumulation fluence monitors suitable for use in FMIT spectra. As plans for FMIT characterization progress, however, new nuclear data needs are surfacing, and accuracy requirements are becoming better defined.

It is clear that, as vital as some key measurements are, a sustained effort must be mounted to evaluate existing and forthcoming data and to incorporate such data into calculations of necessary nuclear quantities.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge assistance provided by L. L. Carter, H. Farrar, R. Gold, L. R. Greenwood, D. L. Johnson, F. Mann, W. N. McElroy, E. K. Opperman, and R. E. Schenter and the many accounts of research provided prior to publication by authors whose work is cited in Table III.

This work was supported by the Office of Fusion Energy of the U. S. Department of Energy.

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TABLE I

Irradiation Experiments Performed at RTNS-II

DATE STARTED	MATERIALS IRRADIATED	MEASUREMENT	LABORATORY	MAXIMUM FLUENCE n/cm^2
3/19/79	Ni, Nb & SS	Mechanical Properties	PNL	3.4×10^{17}
3/19/79	TFTR Glass	Density & Optical Properties	ANL	$\sim 2.0 \times 10^{18}$
3/19/79	A15 Superconductors	Transision Temperature Critical Field & Current	BNL/LLL	$\sim 9.0 \times 10^{17}$
3/19/79	Nb Sn	Critical Current	LLL	$\sim 8.0 \times 10^{17}$
3/19/79	Ni, Nb & SS	Mechanical Properties	PNL	2.0×10^{18}
4/03/79	Au TEM Foils	Sub-Cascade Structure	ANL	4.9×10^{15}
4/03/79	TFTR SS	Hydrogen Trapping	SANDIA	1.4×10^{16}
4/05/79	Cu, Ni, V, Nb, Ti & SS TEM Disks	Microstructure/ Microhardness	HEDL/UCSB	3.9×10^{17}
6/06/79	Cu, Ni, V, Nb, Ti & SS TEM Disks	Microstructure/ Microhardness	HEDL/UCSB	1.2×10^{18}
6/06/79	Ni-Al & Ni-Si TEM Disks	Nucleation Studies	LLL/ANL	5.4×10^{17}
7/02/79	Zr Al TEM Disks	Cascade Size & Structure	UW/LLL	6.5×10^{15}
8/14/79	Nb	In-Situ Creep 400°-600°C	LLL	7.5×10^{16}

TABLE I
(cont'd)

9/24/79	MACOR Ceramic (TFTR Insulators)	Thermal/Mechanical	LASL	1.0×10^{16}
9/24/79	Glass-Bonded Mica (TFTR Insulators)	Thermal/Mechanical	LASL	1.0×10^{18}
9/24/79	MACOR Ceramic (TFTR Insulators)	Thermal/Mechanical	LASL	1.0×10^{18}
10/29/79	Binary Alloys Based on Ni and Cu	Microstructure/ Microhardness	HEDL	$\sim 1.0 \times 10^{18}$
2/20/80	SS Strips	Microstructure/Tensile	U.Va	1.0×10^{18}
2/27/80	316 SS, Ni, Ti-6 Ti-6Al-4V	Microstructure/ Microhardness/Tensile	HEDL	$\sim 1.2 \times 10^{18}$
3/13/80	Fiber Optic Cables	Optical Attenuation	LLL	$\leq$25 krad
5/07/80	NbTi Cu, Al	Critical Current. 4°K Magnetoresistance and Initial Damage Rates (Resistivity)	LLL	$\sim 1.0 \times 10^{17}$

TABLE II

A Sample of the Proposed FMIT Test Matrix

HIGH FLUX	# MATERIALS	REDUNDANCY	FLUENCES	SUBTOTAL	# TEMPS
TEM (Chemical Variation, Micro, Rate)	30	4	(5, 10, 20, 50, 100 dpa)	600	4
Creep (Rate Effect)	5	2	(Interim to 100)	10	3
MODERATE FLUX					
TEM (Micro, Rate)	15	10	(2, 5, 10 dpa)	450	4
Creep/Rupture	15	5	(Interim to 50)	75	3
Stress Relax (In-Situ)	15	2	(3 Preirradiated)	90	3
In-Situ Cyclic Flux (Specimen Oscillated)	10	2	(5, 20, 50)	60	3
LOW FLUENCE					
TEM (Seed Microstructure)	15	6	(0.2, 0.5, 2)	270	3
Creep (Rate Effect)	5	2	(Interim to 5 dpa)	10	3

TABLE III.

High Energy Neutron Correlation Studies

Material	Ref.	Property Measured	Sensitivity	Neutron Spectrum	Maximum Fluence (n/cm^2)	Relative Response Per Unit Damage Energy	Comments
Cu	(17)	Resistivity at 4.2K	Total defects	BSR	3×10^{17}	1.0	Annealing to 300K similiar.
				40MeV d-Be	4.5×10^{17}	$0.9 \pm .2$	
	(18)	"	"	CP-5(VT53)	$> 10^{18}$	$0.9 \pm .2$	
	(19)	Modulus changes from $\perp$ pinning at 330K	Free interstitials	14.1 MeV	$10^{11} - 10^{12}$	1.0	Mono-energetic neutrons.
				1.9 "	"	$1.6 \pm .4$	
				3.9 "	"	$1.2 \pm .6$	
				5.9 "	"	$1.1 \pm .4$	
				23.4 "	"	$0.9 \pm .2$	
	(20)	TEM	Defects retained in clusters	BSR	1.0×10^{18}	1.0	Comparable size and number distributions.
				RTNS	1.8×10^{17}	1	
				40MeV d-Be	1.8×10^{17}	1	
	(21)	X-ray diffuse scattering	Defect cluster size distribution	BSR	1.0×10^{18}	See Comments	Some differences in size and number distributions.
				RTNS	1.8×10^{17}		
				40MeV d-Be	2.0×10^{17}		
	(22)	Yield stress at ambient and 480K	Defect clusters	LPTR	5×10^{18}	1.0	Two stage hardening at 480K for LPTR.
				RTNS	7×10^{17}	$2.0 \pm .2$	
				30MeV d-Be	1.2×10^{18}	$2.0 \pm .2$	

TABLE III. (continued)

Material	Ref.	Property Measured	Sensitivity	Neutron Spectrum	Maximum Fluence (n/cm^2)	Response Per Unit Damage	Comments
Nb	(23)	Resistivity	Total	BSR	2.6×10^{17}	1.0	Nb-.03%Zr
	(24)	at 4.2K	defects	LPTR(FNIF)	8.4×10^{14}	$1.2 \pm .2$	Nb-.03%Zr
	(25)	"	"	30MeV d-Be	1.3×10^{16}	$0.9 \pm .2$	Nb-.03%Zr
		"	"	RTNS	8.6×10^{15}	$0.9 \pm .2$	Nb-.03%Zr
	(17)	"	"	BSR	$> 10^{17}$	$1.1 \pm .2$	
		"	"	40MeV d-Be	3.7×10^{15}	$0.9 \pm .2$	
	(18)	"	"	CP-5(VT53)	$> 10^{18}$	$0.8 \pm .2$	
	(22)	Yield stress	Defect	LPTR	5×10^{18}	1.0	
		"	clusters	RTNS	1.2×10^{17}	$1.6 \pm .3$	
				30MeV d-Be	9×10^{17}	$1.6 \pm .3$	
	(26)	Yield stress	Defect	RTNS	2×10^{17}	See	Two stage hardening,
	(27)	and TEM	clusters	40MeV d-Be	1×10^{18}	Comments	levels differ.
	(28)	Creep	Clustered and	30MeV d-Be	2.0×10^{12}/s	See	Qualitatively
	(29)	750-900K	free defects	RTNS-II	1.2×10^{12}/s	Comments	similiar response.
Mo	(23)	Resistivity	Total	BSR	2.4×10^{17}	1.0	Mo-.03%Zr
	(30)	at 4.2K	defects	LPTR(FNIF)	8.4×1014	$1.1 \pm .2$	Mo-.03%Zr
	(25)	"	"	30MeV d-Be	1.3×10^{16}	$0.9 \pm .2$	Mo-.03%Zr
		"	"	RTNS	8.6×10^{15}	$1.0 \pm .2$	Mo-.03%Zr
	(18)	"	"	CP-5(VT53)	$> 10^{18}$	$0.7 \pm .2$	

TABLE III. (continued)

Material	Ref.	Property Measured	Sensitivity	Neutron Spectrum	Maximum Fluence (n/cm^2)	Response Per Unit Damage	Comments
V	(23)	Resistivity	Total	BSR	5.2×10^{17}	1.0	V-.03%Zr
	(24)	at 4.2K	defects	LPTR(FNIF)	8.4×10^{14}	$1.2 \pm .2$	V-.03%Zr
	(25)	"	"	30MeV d-Be	1.3×10^{16}	$0.9 \pm .2$	V-.03%Zr
		"	"	RTNS	8.6×10^{15}	$1.0 \pm .2$	V-.03%Zr
	(22)	Yield stress	Defect	LPTR	4×10^{18}	1.0	
		"	clusters	RTNS	3×10^{17}	$2.1 \pm .2$	
				30MeV d-Be	1×10^{17}	$2.1 \pm .2$	
Pt	(17)	Resistivity	Total	BSR	$> 10^{17}$	1.0	Less annealing at 300K for d-Be.
		at 4.2K	defects	40MeV d-Be	4.1×10^{15}	$0.8 \pm .2$	
	(18)	"	"	CP-5(VT53)	$> 10^{18}$	$0.9 \pm .2$	
	(31)	Positron	Vacancy-like	HFBR	$> 10^{18}$	1.0	
		trapping	defects	30MeV d-Be	3.4×10^{16}	$0.8 \pm .2$	
Au	(20)	TEM	Defects in	BSR	1.0×10^{18}	1.0	
		"	clusters	40MeV d-Be	6.0×10^{16}	5	
Ni	(26)	Yield stress	Defect	RTNS	2×10^{17}	1.0	
	(27)	and TEM	clusters	40MeV d-Be	1×10^{18}	$1.0 \pm .3$	

TABLE III. (continued)

Material	Ref.	Property Measured	Sensitivity	Neutron Spectrum	Maximum Fluence (n/cm^2)	Response Per Unit Damage	Comments
Nb-1%Zr	(22)	Yield stress	Defect	LPTR	5×10^{18}	1.0	
		"	clusters	RTNS	7×10^{17}	$1.0 \pm .1$	
-Brass	(32)	Resistivity/ SRO	Free vacancies	LPTR	2×10^{17}	1.0	
				RTNS	7×10^{16}	$1.1 \pm .2$	
316 SS	(33)	Yield stress ductility and TEM	Defect clusters	LPTR	2.6×10^{19}	1.0	Similiar scaling for all three properties.
				RTNS	2.2×10^{17}	$1.1 \pm .3$	
				30MeV d-Be	3.8×10^{18}	$1.1 \pm .3$	
Nb_3Sn	(34)	Transition temperature	Disordering	HFBR	8×10^{19}	1.0	
				RTNS	2×10^{18}	$1.1 \pm .2$	
	(35)	Critical current	Fluxoid pinning	RTNS	7×10^{16}	1.0	Corrected to same temperature and transverse field
				30MeV d-Be	7×10^{17}	1.0 -1.6	
	(36)	4.2K-6K	"	CP-5(VT53)	2×10^{18}	$0.6 \pm .2$	
Al_2O_3	(37)	Optical absorbtion	Point defects	NRLR	1×10^{18}	1.0	
				RTNS	1×10^{17}	$1.0 \pm .3$	
Graphite	(38) and (39)	Basal plane shear modulus	Defect pinning	BNLR	1.2×10^{17}	1.0	Ratios based on ENDF/III-B damage analysis.
				RTNS	1.1×10^{17}	$1.5 \pm .3$	
				5.5MeV d-Be	4.6×10^{16}	$2.0 \pm .4$	

TABLE IV

Ratio of Measured-to-Calculated Activities
Using Time-of-Flight Spectra

Relative errors are 1.5%, absolute errors ±10%,
except as noted.

REACTION	90% Energy[a] Range (MeV)	Ratio at 0° (~3.5°)	Ratio at 15° (~17°)
	(0° Spectrum)		
$^{45}Sc(n,\gamma)^{46}Sc$	7.6^{-3} - 25.0	1.00[b]	1.17[b]
$^{59}Co(n,\gamma)^{60}Co$	1.6^{-4} - 22.7	1.26[b] ±10%	1.35[b] ±10%
$^{197}Au(n,\gamma)^{198}Au$	2.5^{-4} - 19.5	1.03[b]	1.10[b]
$^{238}U(n,\gamma)^{239}Np$	4.3^{-4} - 4.2	1.02[b]	0.88[b]
$^{235}U(n,f)$	0.6 - 29.7	0.99[c]	0.94[c]
$^{238}U(n,f)$	5.0 - 30.8	1.00[c]	0.94[c]
$^{115}In(n,n^1)^{115m}In$	1.8 - 23.1	1.04	0.96
$Ti(n,p)^{46}Sc$	9.0 - 33.0	*1.84 (0.83)[d]	*1.93 (0.88)[d]
$Ti(n,p)^{47}Sc$	12.0 - 33.0	*8.82 (1.18)[d]	*7.14 (1.13)[d]
$^{48}Ti(n,p)^{48}Sc$	9.9 - 26.6	0.97	0.99
$Fe(n,p)^{54}Mn$	6.0 - 33.0	*1.89 (0.94)[d]	*1.88 (1.04)[d]
$^{56}Fe(n,p)^{56}Mn$	8.6 - 23.5	1.05	1.02
$^{59}Co(n,p)^{59}Fe$	8.1 - 24.2	0.85 ±15%	0.95 ±15%
$^{58}Ni(n,p)^{58}Co$	4.4 - 23.4	0.93	0.88
$^{60}Ni(n,p)^{60}Co$	7.9 - 23.0	0.97 ±5%	0.98 ±7%
$^{27}Al(n,\alpha)^{24}Na$	9.0 - 21.5	1.02	0.96
$^{54}Fe(n,\alpha)^{51}Cr$	9.5 - 28.0	*1.28	*1.43
$^{59}Co(n,\alpha)^{56}Mn$	9.3 - 24.4	1.05	1.02
$^{45}Sc(n,2n)^{44m}Sc$	13.9 - 27.5	0.95	0.98
$^{59}Co(n,2n)^{58}Co$	12.8 - 26.6	1.06	1.04
$^{58}Ni(n,2n)^{57}Ni$	14.8 - 28.2	0.82 (1.26)[e]	0.84 (1.34)[e]
$^{90}Zr(n,2n)^{89}Zr$	14.1 - 28.1	0.99	1.02
$^{93}Nb(n,2n)^{92m}Nb$	11.2 - 22.0	0.93	0.94
$^{169}Tm(n,2n)^{168}Tm$	10.4 - 23.3	0.91	0.92

TABLE IV
(cont'd)

$^{169}Tm(n,3n)^{167}Tm$	17.9 - 30.6	1.05	1.08
$^{197}Au(n,2n)^{196}Au$	10.7 - 23.5	0.99	0.98
$^{197}Au(n,3n)^{195}Au$	18.0 - 29.4	0.87 ±4%	1.06 ±7%
$^{197}Au(n,4n)^{194}Au$	27.2 - 39.8	1.03 ±10%	0.88 ±13%
$^{238}U(n,2n)^{237}U$	7.7 - 16.4	1.21	1.10
Std. DeV. (%)		*9.7	*10.8
Total Flux (n/cm^2 - sec)		6.26×10^{10}	3.21×10^{10}

*Reactions not included in standard deviation.

[a]90% of the activation integral falls within this energy range. 7.6^{-3} means 7.6×10^{-3}. The range at 15° is only slightly changed.

[b](n,γ) ratios are somewhat arbitrary since the time-of-flight data stops at 2 MeV. A smooth extrapolation was chosen to give a reasonable fit to the data.

[c]14 MeV fission yields were used.

[d]Ratios not in parentheses were calculated assuming mono-isotropic production [e.g. $^{54}Fe(n,p)$]; ratios in parentheses include production from higher mass isotops based on THRESH calculations. Energy limits are for total production.

[e]Cross-section from ENDF/B-IV and LASL; values in parentheses from ENDF/B-IV only.

FIGURE CAPTIONS:

1. Magnetic Fusion Facility Development.

2. Organization of Damage Analysis and Fundamental Studies (DAFS) Program.

3. Organization of the Alloy Development for Irradiation Performance (ADIP) Program.

4. Major Components of a Single Neutron Source at the RTNS-II Facility.

5. Cylindrical Specimen Capsule Positioned Close to the Rotating Target at RTNS-II.

6. A Section of the Etching Mask Used to Produce Water-Cooling Channels Within a Rotating Target. The dark lines are etched into a sheet of copper alloy, which is then covered by diffusion bonding a second sheet to the first to produce convoluted channels.

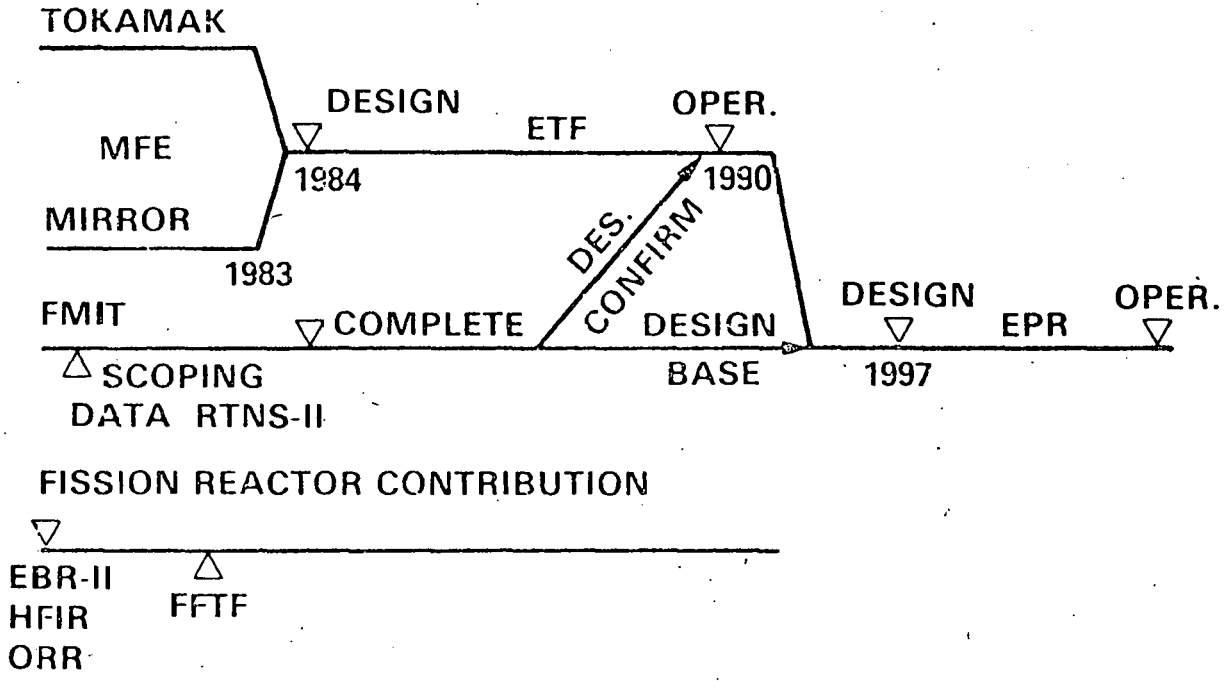
7. Major Components of the Fusion Materials Irradiation Test (FMIT) Facility. HVPS = High Voltage Power Supply; RFQ = Radio Frequency Quadrupole; HEBT = High Energy Beam Tunnel.

8. Damage Energy Cross Sections for Fe, Cr, and Ni Extended to High Energies by Greenwood.

9. Brief Summary of Nuclear Data Needs for Damage Calculations.

10. Comparison of a Time-of-Flight (input) Be (d,n) Spectrum with the Spectrum Adjusted Using Extrapolated Reaction Cross Sections in the SAND-II Code.

FUSION FACILITY DEVELOPMENT



KEY MILESTONES | ETF OPERATION | EPR DECISION | EPR OPERATION

FIGURE 2

ORGANIZATION OF DAFS PROGRAM

Task Group

D. G. Doran, Chairman

M. M. Cohen, DOE/OFE

L. R. Greenwood, Chairman, Subtask Group A, Dosimetry and Damage Parameters

R. H. Jones, Chairman, Subtask Group B, Fundamental Mechanical Behavior

G. R. Odette, Chairman, Subtask Group C, Correlation Methodology

W. G. Wolfer, Consultant

Program Participants

OFE programs in the three areas currently exist at:

Subtask Group A	Subtask Group B	Subtask Group C
ANL	ANL	ANL
BNL	HEDL	HEDL
HEDL	MIT	LLL
LASL	NRL	MIT
LLL	PNL	PNL
ORNL	UCSB	USCB
RI	U.Va.	U.Wisc.
	U.Wisc.	W-R&D
	W-R&D	

There is significant participation from outside the OFE programs.

FIGURE 3

ORGANIZATION OF THE ADIP PROGRAM

Task Group

E. E. Bloom, Chairman

T. C. Reuther, DOE/OFE

R. E. Gold, Chairman, Subtask Group A, Alloy Development for Near Term Application

F. W. Wiffen, Chairman, Subtask Group B, Alloy Development for Long Term Application

J. J. Holmes, Chairman, Subtask Group C, Analysis and Evaluation

Materials of Primary Interest

Subtask Group A - Solid solution strengthened austenitic stainless steels (Path A alloys, i.e., AISI 316 and modifications thereof)

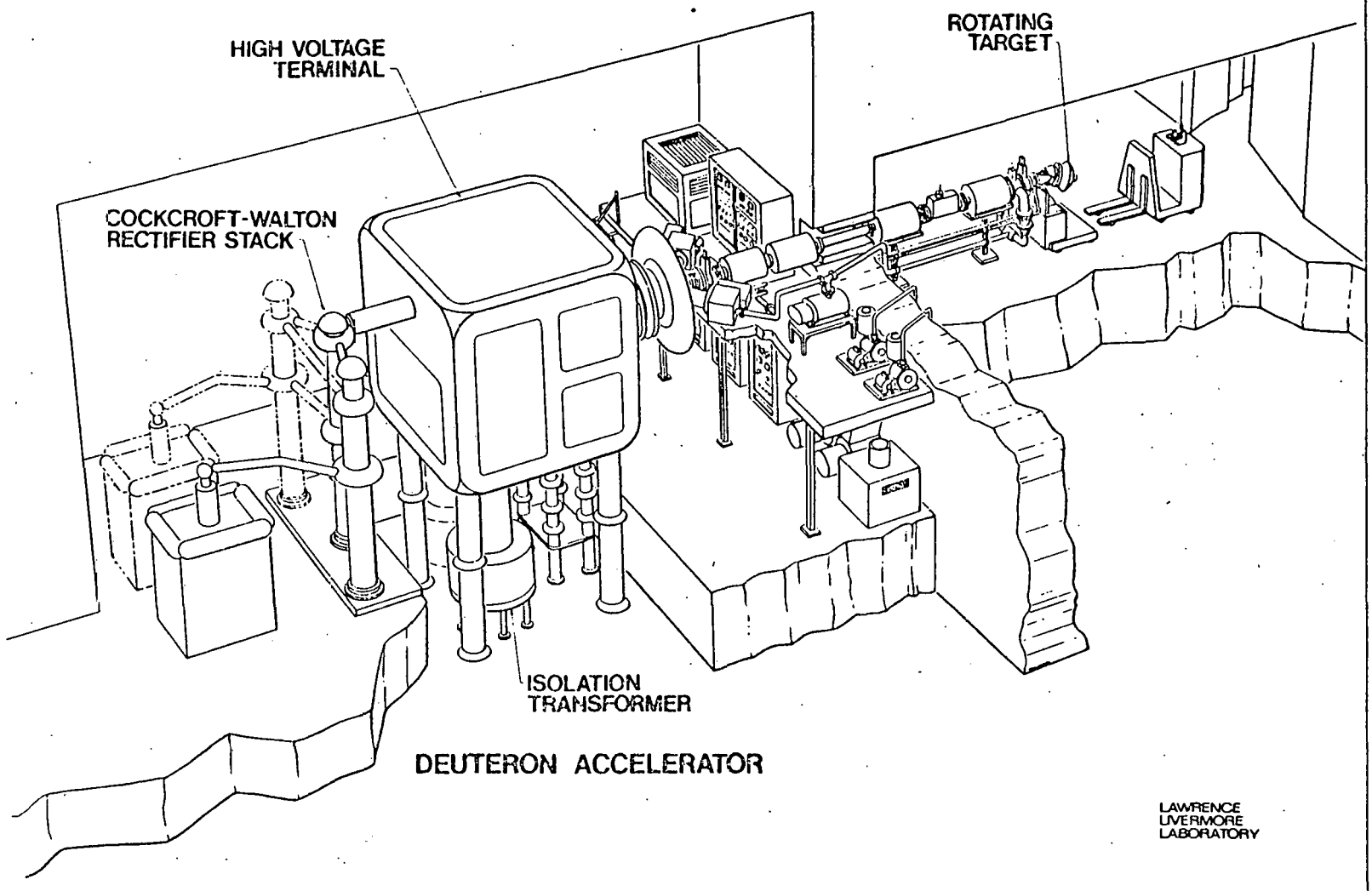
- Ferritic stainless steels (Path E alloys, e.g., HT-9)

Subtask Group B - Precipitation hardened developmental austenitic steel alloys (Path B)

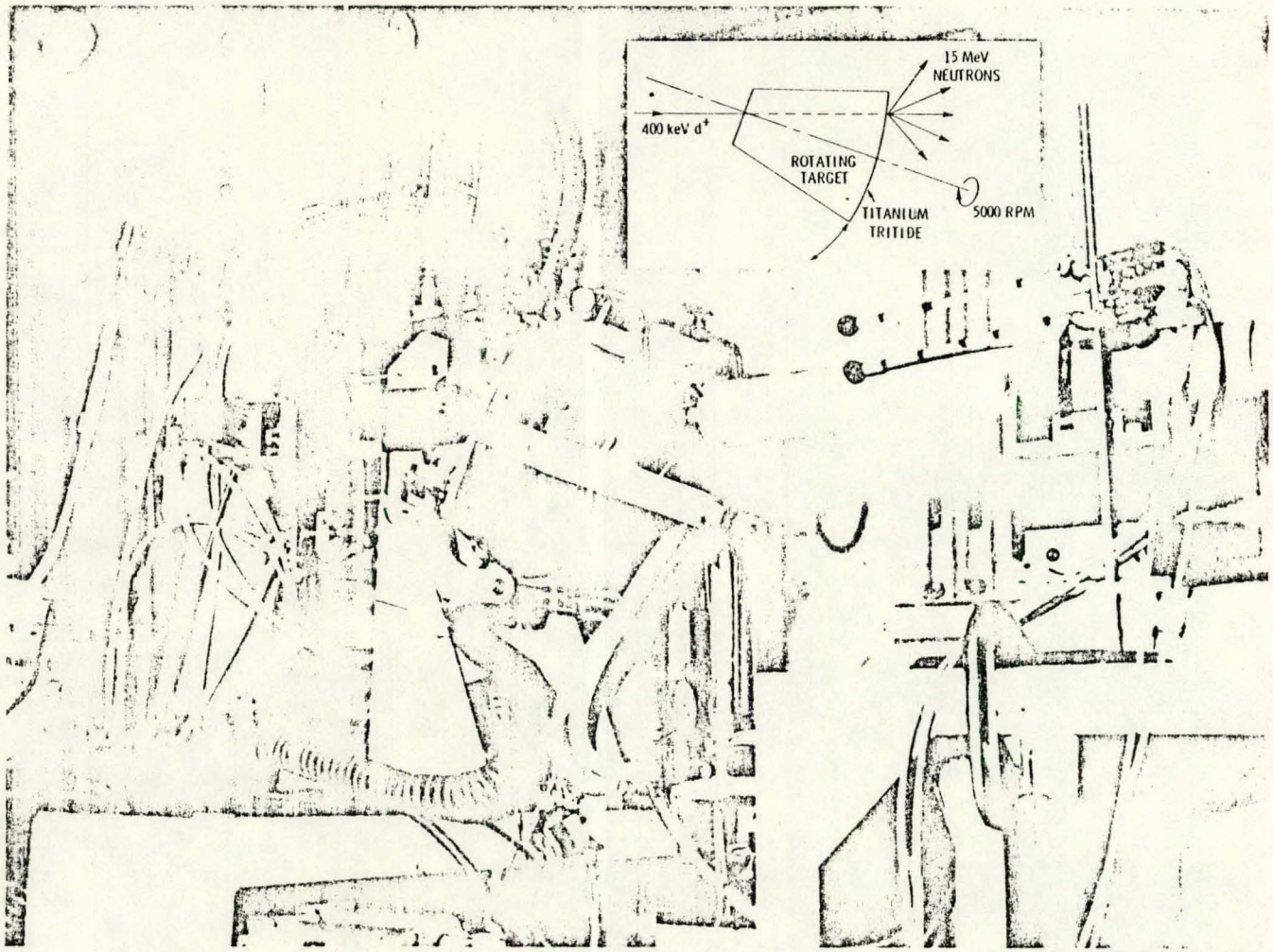
- Vanadium and titanium alloys (Path C)

- Innovative materials (Path D), e.g., long-range-order alloys

RTNS-II SOURCE

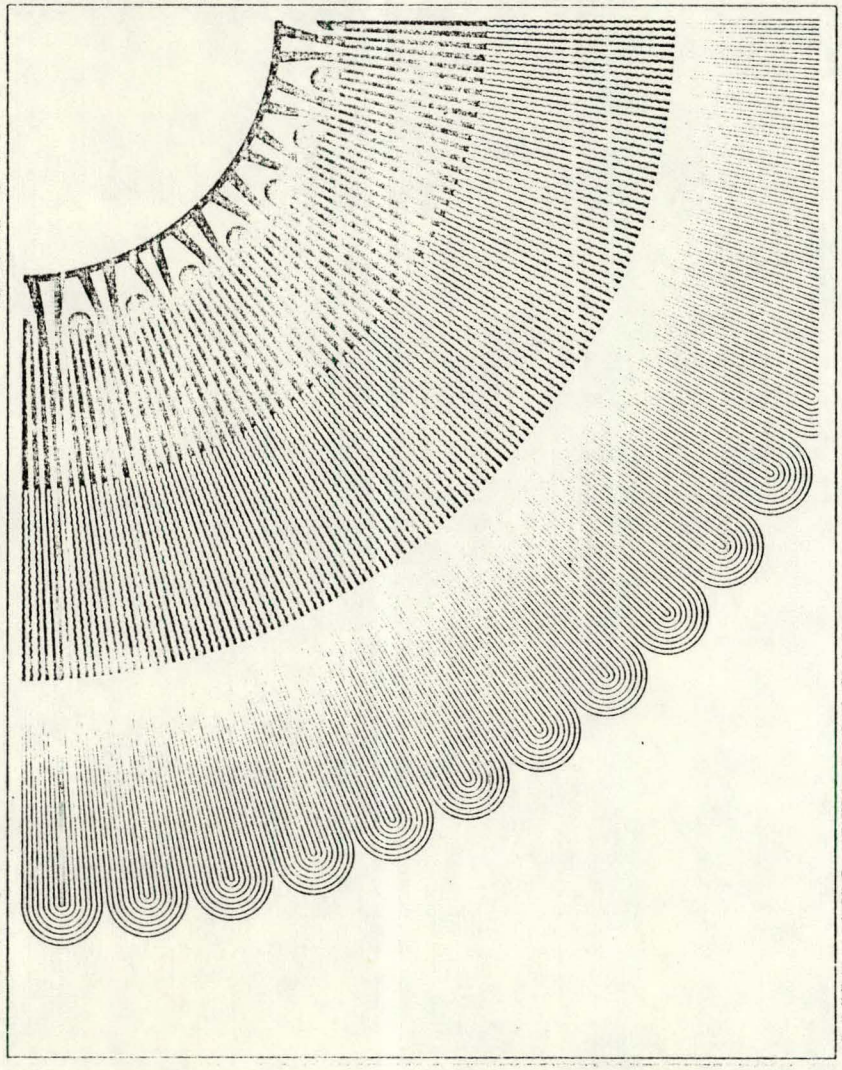


LAWRENCE LIVERMORE LABORATORY

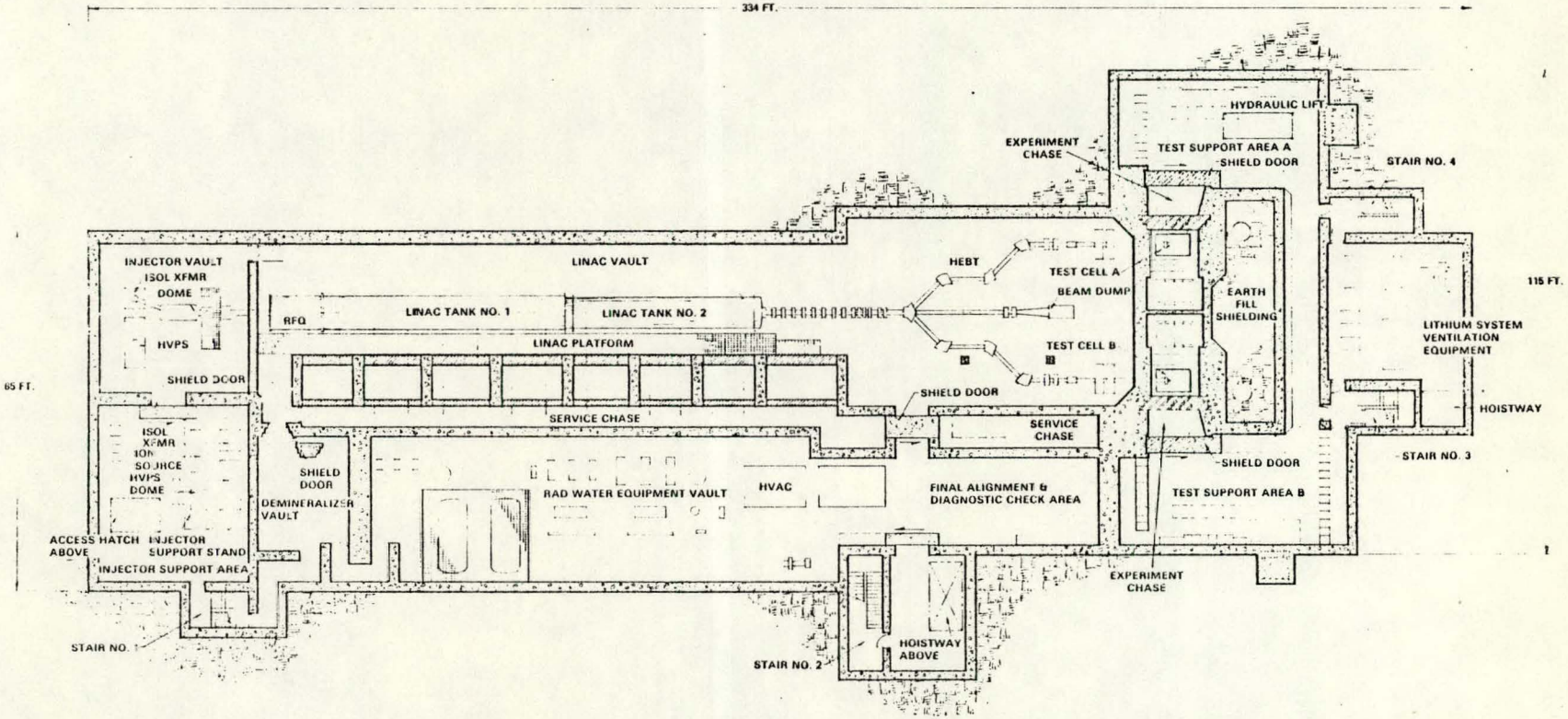


HEDL 8004-319.1

CHANNEL PATTERN FOR COOLING WATER IN TARGET



FMIT BASEMENT LEVEL FLOOR PLAN



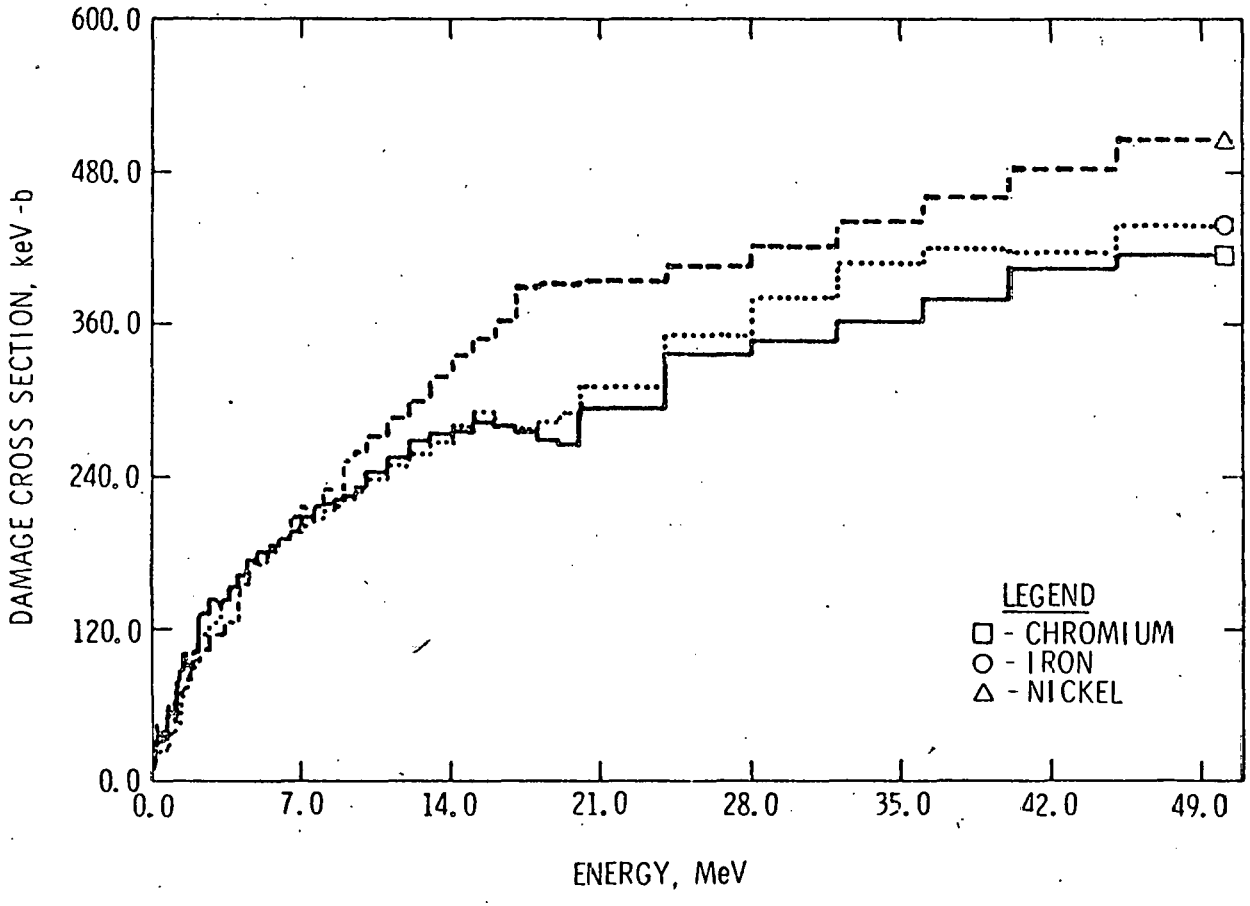


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FIGURE 9

BRIEF SUMMARY OF
NUCLEAR DATA NEEDS FOR
DAMAGE CALCULATIONS

Materials

Fe, Ni, Cr, Al, Cu, W, V, Nb, Ti

Energy Range

15-35 MeV

Data Needed

Differential angular cross sections for all reactions.

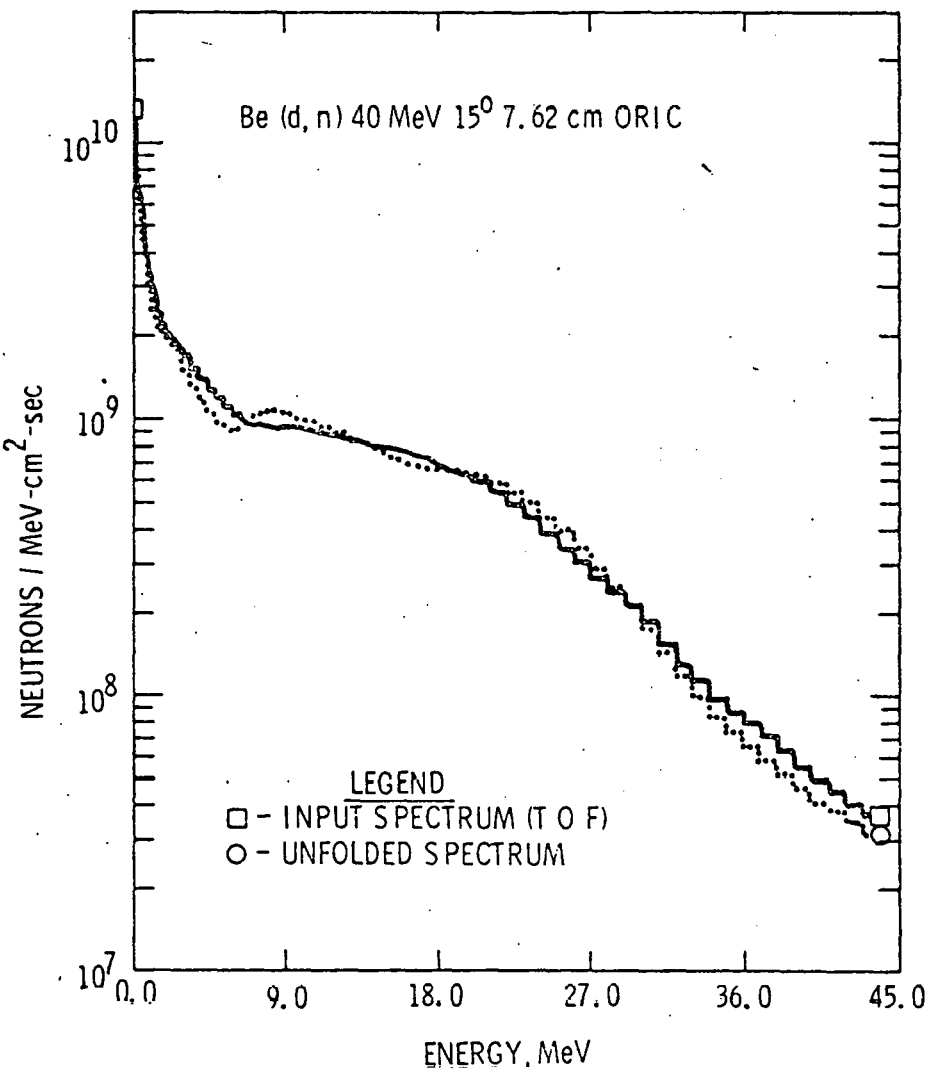
Angular and energy distributions of emitted particles (especially first particle out).

Total helium cross sections.

Total hydrogen cross sections.

Note

Some work done on some materials - see text.



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