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TECHNICAL PROGRESS REPORT
HELIUM GENERATION IN FUSION REACTOR MATERIALS
FOR PERIOD
APRIL — SEPTEMBER 1977

DOE Research and Development Report

*Prepared for the U.S. Department of Energy,
Division of Magnetic Fusion Energy
under Contract Number EY-76-C-03-0701*

Rockwell International

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Program:	Fusion Program - Development and Technology		
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I. PROJECT OBJECTIVES

1. Determine the helium generation rates and spectrum-integrated (n, α) cross sections of a number of pure elements, isotopes, and alloys in neutron environments being used for fusion reactor development.
2. Use this information to predict the helium production rates in any selected fusion reactor wall materials.
3. Develop helium accumulation fluence monitors for measuring neutron fluences in fusion experimental and blanket irradiations.

II. SUMMARY

The near-term objectives of this program are to measure the spectrum-integrated helium generation rates and cross sections of a number of pure elements and alloys in several high-intensity neutron sources, and to develop and demonstrate neutron dosimetry procedures using some of these materials. To this end, four neutron irradiation experiments have now been run: one using accelerator-produced d-Be neutrons, two using the accelerator-produced d-T reaction, and one in the neutron field of a mixed-spectrum fission reactor. All of these irradiations have incorporated a large number of helium-generation materials.

The accelerator runs have additionally included extensive sets of foils for activation neutron dosimetry. These foils are being used to further develop activation dosimetry techniques, in response to the need for a detailed characterization of each neutron environment for the analysis of the helium generation data. The foil dosimetry is being carried out in collaboration with personnel from Argonne National Laboratory (ANL) and Lawrence Livermore Laboratory (LLL).

The d-Be neutron irradiation took place at the Crocker Nuclear Laboratory of the University of California at Davis (UC-Davis) in July 1977. This experiment, described in detail in Section III, is intended both to measure the spectrum-averaged helium production cross sections of numerous pure elements and alloy materials of interest to the magnetic fusion reactor development program, and to characterize the neutron yield from the d-Be source in detail. The results are expected to be pertinent to the d-Li neutron source now being planned for fusion materials irradiations. The irradiation package included a small primary capsule containing 180 helium-generation specimens and activation dosimetry foils, mounted 1 cm from the beryllium target face, and a large support structure surrounding and behind the capsule. The support structure contained additional helium-generation and foil activation materials at well-defined angles and distances up to 30 cm from the target. The post-irradiation counting of the activated dosimetry materials, taking place at ANL and LLL, is nearly complete.

The two d-T neutron irradiations were carried out at the Rotating Target Neutron Source (RTNS-I) at LLL. The description of the first irradiation, the

results of its foil activation dosimetry analysis, and the preliminary results of the helium generation rate measurements have been reported previously.⁽¹⁻³⁾ All of the helium-generation specimens from this irradiation have now been analyzed using the high-sensitivity gas mass spectrometer system at Atomics International (AI). The final neutron fluence map and helium-generation cross sections will be calculated when all of the helium-generation data reduction is completed. The second RTNS-I irradiation, described in detail in Section IV, incorporated an expanded list of helium-generation and foil activation dosimetry materials, and will serve in part as a reference point for the interpretation of the d-Be results. The γ -ray counting of the neutron-activated materials has been completed at ANL and LLL, and the subsequent weighing of these materials for the fluence calculations is in progress at AI.

The mixed-spectrum fission irradiation at the High Flux Isotopes Reactor (HFIR) at Oak Ridge National Laboratory (ORNL) was completed during this report period. The analysis of the 29 different irradiated pure elements, isotopes, and alloys will provide information needed to correlate the total helium generation in the d-Be environment with that fraction produced by the low energy neutron component. The two irradiation capsules, described in Section V, are presently highly radioactive and are cooling in temporary storage at ORNL.

Two symposium papers and a U.S.-Soviet exchange presentation covering the experimental work to date were given during this report period, and are summarized in Section VI. AI personnel have also participated in meetings of the DOE-DMFE Task Group on Damage Analysis and Fundamental Studies (Section VII).

III. d-Be NEUTRON IRRADIATION

A complex assembly of helium-generation and neutron dosimetry materials was irradiated during the period July 20-24, 1977, at the Crocker Nuclear Laboratory of UC-Davis using a d-Be neutron source. The experiment was initiated as part of an AI program to measure helium-generation rates in fusion reactor materials. However, the complexity of the d-Be neutron field demanded a detailed characterization of the neutron fluence and energy spectra over the entire experimental volume in order to comprehensively interpret the results. This specific characterization required that dosimetry information be obtained by direct measurement within the experimental volume, using multiple radiometric foils and helium-generation materials. A joint experiment was thus undertaken with R. R. Heinrich and L. R. Greenwood of ANL and M. W. Guinan of LLL, who have also been collaborating in programs to develop radiometric foil procedures for the characterization of both the RTNS-I⁽¹⁾ and the d-Be neutron environments.^(4,5) The joint experiment permitted the testing of both types of dosimetry procedures together in one experiment, and provided the best possible dosimetry information for the correlation of important helium-generation measurements. The dosimetry procedures and source characterization are expected to provide a basis for the understanding and use of the d-Be and future d-Li neutron sources.

The specific objectives of this joint experiment are as follows:

- 1) Measure the spectrum-integrated helium-generation cross sections of 23 pure elements, a number of separated isotopes, and several candidate alloys for fusion-reactor applications, in the d-Be neutron environment for an incident deuteron bombarding energy of 30 MeV.
- 2) Characterize the d-Be neutron environment in detail using the multiple radiometric foil method with fluence mapping and spectrum unfolding techniques, and test the integral cross sections of other potential dosimetry reactions.

- 3) Evaluate and use helium accumulation fluence dosimetry materials for further characterization of the neutron field, demonstrating the use of different pure elements to obtain neutron energy spectrum information.
- 4) Measure the relative contributions to the d-Be neutron yield from direct and compound nucleus reaction mechanisms in the beryllium target, using radiometric foil dosimetry techniques, to better understand the low-energy component of the neutron spectrum.
- 5) Using the d-Be neutron spectrum, develop both long-lived radiometric foils and helium-generation materials as integral dosimeters for future application in long-term neutron irradiations using fusion neutron test environments (in particular, the d-Li neutron facility), and eventually in operating fusion reactors.

The neutron irradiation environment was produced by bombarding a 3.5-mm-thick beryllium target with 30-MeV deuterons from the UC-Davis 76-Inch Isochronous Cyclotron. The beryllium target assembly was designed and provided by C. Logan of LLL. The irradiation lasted 93 hours, with an average deuteron beam current of 25 μ A and a total integrated charge of 8.46 C. The deuteron beam was collimated using a graphite disc with a 6.35-mm-diameter hole, and rastered $\sim \pm 0.5$ mm in a two-dimensional pattern to average out any hot spots in the deuteron beam profile. The irradiation was stopped for one 1.5-h period four hours into the irradiation, in order to remove a predetermined group of dosimetry foils from the irradiation assembly (for reasons described later).

The irradiation assembly used in this experiment consisted of a small capsule containing helium-generation specimens and radiometric dosimetry foils, and a larger trailing structure holding additional specimens and foil materials. The capsule will provide most of the helium-generation information. The neutron fluence and energy spectra will be mapped carefully over its volume, using several helium-generation and foil dosimetry materials incorporated in the capsule. The trailing assembly was designed to support additional foils and helium-generation materials for characterizing the d-Be neutron environment at well-defined angles at distances up to 30 cm from the beryllium target. This will provide information

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Figure 1. Cross Sectional View of the d-Be Irradiation Capsule

on the relative contributions from the direct and compound d-Be reaction mechanisms, and on fluence gradients and neutron energy spectra at irradiation locations similar to those that will be used in a d-Li neutron facility.

The small irradiation capsule is shown schematically in Figure 1. It was a 2-cm-diameter by 8.9-mm-thick Type 304 stainless steel assembly containing three layers of helium-generation materials sandwiched between four layers of dosimetry foils. Cover plates of 0.127-mm (5-mil) thick Type 304 stainless steel were attached to the top and bottom faces. The capsule was mounted concentrically with the deuteron beam axis, with its front (upstream) face 1 cm from the outside face of the beryllium target assembly. This capsule-target distance was a compromise between the need for a relatively large distance to reduce the target averaging effects that complicate the neutron dosimetry, and the need to minimize this distance to give sufficient neutron flux to generate readily measurable quantities of helium in the various samples.

The helium-generation materials loaded in the capsule included 11 helium accumulation dosimetry wire rings and 122 individual specimens ("chunks") weighing nominally 1 to 20 mg. These materials included 22 pure elements, 21 separated isotopes, 16 alloys, and 3 compounds, as listed in Table 1 (omitting elemental boron). Most of the specimens were 1 mm thick, to allow for an acid etching following the irradiation to remove the effects of α -recoil. Many of the chunks will be segmented later for multiple helium analyses. The inclusion of both alloyed metals and the pure elements of which they are composed will provide information on alloy impurities, such as nitrogen, whose helium-generation cross sections are not readily measured. Photomicrographs of the top two layers of helium specimens in the capsule are shown in Figure 2. The elemental chunks were generally loaded in a geometry that placed multiple samples of each element at different effective neutron source angles, and thus in neutron spectra with differing energy distributions.

The helium accumulation dosimetry rings were elemental wires of Al, Fe, Ni, Cu, and Au. These rings were positioned concentrically with the capsule-deuteron beam axis. The capsule included at least two rings of different ring diameters for each element, to examine the neutron energy variations at different radial

TABLE 1
HELIUM-GENERATION MATERIALS IN THE
d-Be NEUTRON IRRADIATION

Be	Cu	^6LiF	^{63}Cu
B	Y	^7LiF	^{65}Cu
C (diamond)	Zr	^{10}B	^{92}Mo
Al	Nb	^{11}B	^{94}Mo
Si	Mo	^{54}Fe	^{95}Mo
Ti	Ag	^{56}Fe	^{96}Mo
V	Sn	^{58}Fe	^{97}Mo
Cr	Ta	^{58}Ni	^{98}Mo
Mn	W	^{60}Ni	^{100}Mo
Fe	Pt	^{61}Ni	
Co	Au	^{62}Ni	
Ni	PbS	^{64}Ni	

Type 316 stainless steel
 Type 304 stainless steel
 5 Type 316 SS alloys with differing Mn, C, N content
 NBS standard alloy 444
 Nb - 1 Zr
 Mo - 0.5 Ti
 TZM
 V - 10 Cr
 V - 20 Ti
 PE-16
 Inconel 600
 Inconel 718

TABLE 2

ACTIVATION DOSIMETRY FOILS FOR CURRENT EXPERIMENTS

Material	RTNS-I AI Run 1	RTNS-I AI Run 2	d-Be (30 MeV)	d-Be Capsule Foil Stacks*
Al			•	A B C D E
Sc ₂ O ₃			•	A E
Ti			•	A E
Fe		•	•	A B C D E
⁵⁴ Fe			•	
⁵⁶ Fe			•	
Co		•	•	A B C D E
Ni	•	•	•	A B C D
Y ₂ O ₃			•	A E
Zr		•	•	A B C D
Nb	•	•	•	A B C D E
In [†]			•	A E
Tm ₂ O ₃			•	E
Au	•	•	•	A B C D E
²³⁵ U [§]			•	E
²³⁸ U [§]			•	A E

*See Figure 1 for capsule foil stack geometry. Stacks A-D were generally composed of 0.025 to 0.051 mm (1 to 2 mil) foils and Stack E of 0.127 to 0.254 mm (5 to 10 mil) foils.

†The indium foils were mounted on the outside faces of the capsule covers for removal early in the irradiation.

§The uranium foils were sandwiched between Al foil covers to retain the fission fragments.

locations. These rings will be etched and segmented later for individual helium analysis of each segment. The results will complement the foil activation fluence dosimetry, providing additional details on total fluence and neutron energy.

The radiometric dosimetry foils included in the capsule are listed in Table 2, and the individual dosimetry reactions that were used are listed in Tables 3 and 4. Most of the foil materials were supplied by ANL and LLL. The purpose of the large number of foil materials and reactions is to provide a large base of integral counting data for unfolding the broad-band d-Be neutron energy spectra. Several of these foil materials have also been irradiated in AI's RTNS-I helium-generation experiments, as shown in Table 2 and described in part in Section IV. The RTNS-I results will provide a reference point at ~ 14.8 MeV which will aid in the unfolding of the d-Be neutron spectra.

The helium generation capsule contained a total of 53 foils: 2 niobium autoradiograph foils, 43 dosimetry foils, and 6 aluminum cover foils (to retain recoiling uranium fission fragments). Two indium dosimetry foils were attached to the capsule outside faces. The thicknesses and stacking order of these foils are shown in Table 5. The primary radiometric foil dosimetry for the capsule volume is provided by the 0.025-mm (1-mil) and 0.051-mm (2-mil) thick Fe, Co, Ni, Zr, Nb, and Au foils from Stacks A, B, C, and D (Figure 1). They were chosen on the basis of their different neutron energy sensitivities over the energy range important to the helium-generation reactions. The additional dosimetry foils in Stacks A and E, before and following the bulk of the capsule, plus the aluminum foils in Stacks B, C, and D, were included to further define both the neutron fluence and energy spectra, extend the neutron characterization to lower neutron energies, and provide information on additional potential dosimetry reactions. The three oxides were plastic-laminated materials.

All of the dosimetry foils, with the exception of the niobium autoradiograph foils, were scribed prior to the irradiation, as shown in Figure 3. Following the irradiation, the foils were segmented along these lines to count the post-irradiation activities of the individual segments. This information will be used to map out the neutron fluence and energy spectra as a function of position

TABLE 3
d-Be FOIL ACTIVATION DOSIMETRY REACTIONS
(Primary Reactions)

Foil	Reaction	Product Half-Life	Reaction Q-Value (MeV)*	Effective Threshold (MeV) [†]
Al	$^{27}\text{Al}(n,\alpha)^{24}\text{Na}$	15.0 h	-3.123	6
Sc ₂ O ₃	$^{45}\text{Sc}(n,2n)^{44\text{m}}\text{Sc}$	58.6 h	-11.592	12
	$^{45}\text{Sc}(n,\gamma)^{46}\text{Sc}$	83.8 d	8.767	0
Ti	$^{46}\text{Ti}(n,p)^{46}\text{Sc}$	83.8 d	-1.585	4
	$^{47}\text{Ti}(n,p)^{47}\text{Sc}$	3.41 d	0.182	2
	$^{48}\text{Ti}(n,p)^{48}\text{Sc}$	43.7 h	-3.208	7
Fe	$^{54}\text{Fe}(n,p)^{54}\text{Mn}$	312.5 d	0.088	2
	$^{54}\text{Fe}(n,\alpha)^{51}\text{Cr}$	27.7 d	0.841	2
Co	$^{59}\text{Co}(n,2n)^{58}\text{Co}$	71.3 d	-10.460	11
Ni	$^{58}\text{Ni}(n,2n)^{57}\text{Ni}$	36.0 h	-12.203	13
	$^{58}\text{Ni}(n,p)^{58}\text{Co}$	71.3 d	0.395	2
Y ₂ O ₃	$^{89}\text{Y}(n,2n)^{88}\text{Y}$	106.6 d	-11.468	12
	$^{89}\text{Y}(n,3n)^{87}\text{Y}$	80.3 h	-20.845	22
Zr	$^{90}\text{Zr}(n,2n)^{89}\text{Zr}$	78.5 h	-11.983	12
Nb	$^{93}\text{Nb}(n,2n)^{92\text{m}}\text{Nb}$	10.16 d	-8.961	10
In	$^{115}\text{In}(n,n')^{115\text{m}}\text{In}$	4.50 h	-0.335	1
Tm ₂ O ₃	$^{169}\text{Tm}(n,2n)^{168}\text{Tm}$	93.1 d	-8.060	8
	$^{169}\text{Tm}(n,3n)^{167}\text{Tm}$	9.3 d	-14.873	16
Au	$^{197}\text{Au}(n,\gamma)^{198}\text{Au}$	2.7 d	6.513	0
	$^{197}\text{Au}(n,2n)^{196}\text{Au}$	6.17 d	-8.080	9
	$^{197}\text{Au}(n,3n)^{195}\text{Au}$	184. d	-14.748	16
	$^{197}\text{Au}(n,4n)^{194}\text{Au}$	39.5 h	-23.152	25
²³⁵ U	$^{235}\text{U}(n,f)$	multiple [§]	192.50	0
²³⁸ U	$^{238}\text{U}(n,f)$	multiple [§]	194.00	1
	$^{238}\text{U}(n,\gamma)^{239}\text{U} \rightarrow ^{239}\text{Np}$	2.35 d	4.803	0

*N.B. Gove and A.H. Wapstra, Nucl. Data Tables 11, 127 (1972) and Nucl. Data Tables 9, 265 (1971); B. A. Magurno, ed., ENDF/B-IV Dosimetry File, Brookhaven National Laboratory, National Neutron Cross Section Center Report BNL-NCS-50446 (1975).

[†]Approximate value, defined here as the neutron energy for which the rising reaction cross section reaches 5% of its maximum value.

[§]Fission-product nuclei with the strongest applicable activities include ⁹⁵Zr (64.4 d); ¹⁰³Ru (39.4 d); ¹³¹I (8.04 d); ¹⁴⁰Ba (12.8 d) and ¹⁴⁰La (40.3 h) counted in equilibrium; ¹⁴⁴Ce (284 d); and ¹⁴⁷Nd (10.99 d).

TABLE 4

d-Be FOIL ACTIVATION DOSIMETRY REACTIONS
(Other Reactions of Potential Interest)

Foil	Reaction	Product Half-Life	Reaction Q-Value (MeV)*	Effective Threshold (MeV) [†]
Co	$^{59}\text{Co}(n,\gamma)^{60}\text{Co}$	5.27 y	7.492	0
	$^{59}\text{Co}(n,p)^{59}\text{Fe}$	44.6 d	-0.783	4
	$^{59}\text{Co}(n,3n)^{57}\text{Co}$	271. d	-19.032	19
Ni	$^{58}\text{Ni}(n,3n)^{56}\text{Ni}$	6.10 d	-22.470	23
	$^{58}\text{Ni}(n,np)+(n,d)^{57}\text{Co}$	271. d	-8.177	8
	$^{60}\text{Ni}(n,p)^{60}\text{Co}$	5.27 y	-2.041	5
Zr	$^{90}\text{Zr}(n,3n)^{88}\text{Zr}$	85. d	-21.290	23
Tm_2O_3	$^{169}\text{Tm}(n,\gamma)^{170}\text{Tm}$	129. d	6.594	0
	$^{169}\text{Tm}(n,4n)^{166}\text{Tm}$	7.70 h	-23.597	26
^{238}U	$^{238}\text{U}(n,2n)^{237}\text{U}$	6.75 d	-6.144	7

*N. B. Gove and A. H. Wapstra, Nucl. Data Tables 11, 127 (1972) and Nucl. Data Tables 9, 265 (1971); B.A. Magurno, ed., ENDF/B-IV Dosimetry File, Brookhaven National Laboratory, National Neutron Cross Section Center Report BNL-NCS-50446 (1975).

[†]Approximate value, defined here as the neutron energy for which the rising reaction cross section reaches 5% of its maximum value.

TABLE 5

CAPSULE DOSIMETRY FOIL STACKING GEOMETRY FOR THE d-Be IRRADIATION

Stack	Foil	Thickness (mils)	Stack	Foil	Thickness (mils)
Front Cover	In	5	Stack E	Ti	5
	304 SS*	5		Au	5
Stack A				Fe	5
	Nb*	1		Nb	5
	Al†	2		Co	10
	²³⁸ U	5.5		Al†	2
	Al†	2		²³⁸ U	5.5
	Ti	1		Al†	2
	Al	2		Al†	2
	Au	1		²³⁵ U	4.5
	Ni	1		Al†	2
	Nb	1		Tm ₂ O ₃	10
	Fe	1		Sc ₂ O ₃	10
	Zr	1		Y ₂ O ₃	10
	Co	2		Al	5
	Sc ₂ O ₃	10		Nb*	5
	Y ₂ O ₃	10	Back Cover	304 SS*	5
Stacks B, C, D	Al	2		In	5
	Au	1			
	Ni	1			
	Nb	1			
	Fe	1			
	Zr	1			
	Co	2			

*Autoradiograph foil

†Uranium cover foil

STACK A FOILS

STACK B FOILS

STACK C FOILS

SCALE (cm)

STACK D FOILS

STACK E FOILS

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Figure 3. Capsule Dosimetry Foil Segmenting Patterns and Identification Numbers for the d-Be Irradiation

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Figure 4. Experimental d-Be Irradiation Assembly

within the capsule. The neutron spectral information is needed both to calculate helium-production cross sections and to define the specific neutron environment to which each cross section corresponds.

Three of the dosimetry reactions of interest, $^{27}\text{Al}(n,\alpha)^{24}\text{Na}$, $^{115}\text{In}(n,n')^{115\text{m}}\text{In}$, and $^{169}\text{Tm}(n,4n)^{166}\text{Tm}$, have reaction product half-lives (4.5 to 15.0 h) significantly shorter than the irradiation period. These activities were therefore dominated by the neutron flux level during the latter part of their irradiation exposure, and will not provide a measure of the total fluence received during the irradiation. They will be used, however, to provide additional neutron energy information. This points out the importance of examining reactions with long-lived activities as integral dosimeter candidates for very long (~ months) irradiations. Examples that are being studied in this experiment include $^{54}\text{Fe}(n,p)^{54}\text{Mn}$ (312.5 d), $^{89}\text{Y}(n,2n)^{88}\text{Y}$ (106.6 d), and $^{197}\text{Au}(n,3n)^{195}\text{Au}$ (184 d). It should be noted that reactions used for this application generally do not require cross sections as high as those needed for short-term irradiations.

The entire irradiation assembly is shown schematically in Figure 4 and photographically in Figure 5 (before loading). Figure 6 shows the loaded assembly mounted on the d-Be target at the UC-Davis cyclotron. The assembly is an open structure designed for mounting the capsule and a large number of additional helium generation samples, helium dosimetry wires, and radiometric dosimetry foils at well-defined spatial positions relative to the d-Be source. It was bolted directly to the beryllium source target flange.

The six 2-mm-diameter thin-walled stainless steel tubes mounted behind the capsule (Figures 4 and 5) contained 235 chunks and twelve 6.3- to 13.9-cm-long wires for later helium analysis. The materials included are the same as those listed in Table 1, with the omission of chunks of PbS and the five stainless steel alloys with differing Mn, C, and N contents. Figure 7 is an X-radiograph of four of the six tubes and their contents, where the tubes are numbered in the order of their increasing distance from the target. The other two tubes were loaded with straight wires extending their entire lengths. These wires will be segmented for analysis, providing additional angular fluence-spectrum information.

Figure 5. The d-Be Irradiation Assembly Without the Dosimetry Foil Stacks

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Figure 6. Photograph of Loaded d-Be Irradiation Assembly Mounted on the Beryllium Target Assembly

Figure 7. X-radiograph of 4 of the 6 Loaded Tubes Irradiated in the d-Be Experiment

The radiometric dosimetry foils were mounted on three 0.25-mm (10-mil) thick Type 304 stainless steel foil arcs, which were in turn mounted concentrically with the center of the beryllium target at radii of 5, 15, and 30 cm. The 15- and 30-cm arcs held stacks of 12.7-mm-diameter discs of the fourteen foil materials listed in Table 3, at source angles of 0° , 15° , 30° , 45° , and 60° . These stacks were prepared at LLL, with a stacking order similar to those given for capsule Stacks A and E in Table 5. Selected stacks also contained foils of the separated isotopes ^{54}Fe and ^{56}Fe . These isotopic foils will be used to determine the relative activity contributions from $^{54}\text{Fe}(n,p)^{54}\text{Mn}$ and $^{56}\text{Fe}(n,nnp)^{54}\text{Mn}$ (where $nnp = 2np, nd, \text{ or } t$), and from $^{54}\text{Fe}(n,\alpha)^{51}\text{Cr}$ and $^{56}\text{Fe}(n,2n\alpha)^{51}\text{Cr}$. The innermost (5-cm) arc held single 6.35-mm-wide strips of Al, Ti, Fe, Co, Zr, Nb, and Au foils extending the length of the arc, plus individual 6.35-mm-square foils of In, Y_2O_3 , Sc_2O_3 , Tm_2O_3 , ^{235}U , and ^{238}U at nominal source angles of 0° , 7.5° , 22.5° , 37.5° , and 52.5° . All uranium foils were wrapped in aluminum foil covers, and all of the foils were mounted on the outside (downstream) surfaces of the arcs, as shown in Figure 4. The exceptions were the indium foils, which were mounted separately on the inside arc surfaces to facilitate their removal after the first four hours of the irradiation for counting the short-lived (4.5 h) $^{115\text{m}}\text{In}$ reaction product.

The foil dosimetry for this irradiation included an additional 6.35-mm-diameter foil stack mounted 0.4 mm from the face of the beryllium target assembly. The information obtained from this stack will provide a normalization point to characterize the source as a function of distance from the face of the target for later experiments. Since these foils received a much higher neutron flux, inducing high activity levels, they were also removed after the first four hours of the irradiation. Each was segmented into a center disc and an annular ring before counting.

This irradiation also included a number of superconducting wires and mixed rare earths for unrelated LLL programs. The superconducting wires, consisting of one $\text{Nb}_3[\text{SnGa}]$, two Nb_3Sn , two V_3Ga , and two NbTi samples 0.25- to 0.38-mm in diameter, were taped directed to the center of the beryllium target assembly face. The rare earths, irradiated for use in LLL detector calibrations, were mounted on the outside of the trailing assembly near the capsule location.

The whole assembly was centered on the deuteron beam axis at the beginning of the irradiation by the use of copper autoradiograph foils placed on the face of the beryllium target assembly. The centering was later checked with autoradiographs of the front indium capsule foil when the indium foils were removed. Approximately 12 h after the termination of the irradiation the capsule and dosimetry foil stacks were removed from the assembly, the capsule was unloaded, and the capsule dosimetry foils were segmented along their pre-scribed lines for subsequent γ -ray counting. Autoradiographs made of the capsule front cover, two niobium foils, and two aluminum foils before those foils were segmented showed that the capsule was centered on the neutron source axis to within ~ 0.5 mm. The counting of the activated foils and foil segments is now nearing completion. Lawrence Livermore Laboratory is analyzing the Al, Sc_2O_3 , Ti, Ni, In, Tm_2O_3 , and Au foils, and Argonne National Laboratory the Fe, Co, Y_2O_3 , Zr, Nb, ^{235}U , and ^{238}U foils. A few helium generation specimens are also being counted.

When the radiometric counting is complete, the foils will be weighed and the results will be combined to determine the neutron activation of each foil or foil segment. This information will be used to unfold the neutron fluence and energy spectra as a function of position over the extent of the irradiation assembly, and to map these spectra in detail over the capsule volume. This work will be a joint ANL-LLL-AI effort, with the spectrum-unfolding analyses to be done primarily by ANL and LLL. The results will be combined with those of a number of other related experiments to help unfold the energy-dependent cross sections of the dosimetry reactions. These other experiments include a number of d-T irradiations using the RTNS-I facility,^(1,2) previous d-Be irradiations performed at UC-Davis for dosimetry purposes,^(4,5) several 16-MeV d-Be tandem accelerator irradiations performed at ANL,⁽⁶⁾ and 40-MeV d-Be irradiations conducted at ORNL.⁽⁷⁾

The chunk helium-generation specimens will be etched, segmented, weighed, and analyzed for helium using the high-sensitivity gas mass spectrometer system at AI. Spectrum-integrated helium-generation cross sections will be obtained by combining the measured helium generation with the neutron fluences calculated at the sample positions from the mapping and spectrum unfolding analyses. These analyses will also define the neutron energy spectrum with which each integral cross section is associated.

The helium accumulation dosimetry wires will be similarly etched, segmented, weighed, and analyzed for helium. The information obtained will be combined with the neutron fluence map information derived from the coarser radiometric dosimetry foil segments. The helium accumulation dosimetry results will also be compared with the neutron energy spectrum information derived from the radiometric foils, to evaluate the use of different wire materials as energy-sensitive helium dosimeters. The use of helium accumulation dosimetry wires to complement radiometric foil fluence mapping has been demonstrated recently in an RTNS-I irradiation.⁽³⁾

IV. SECOND RTNS-I IRRADIATION

The analysis has begun of the contents of the AI capsule irradiated at the RTNS-I facility for 76.7 h in January 1977. This capsule, shown in Figures 8 and 9, was mounted at the outside cover of the rotating tritium target assembly. The capsule contained two layers of 1.5- to 27-mg specimens for helium-generation cross section measurements, and 11 elemental wire rings for helium accumulation fluence dosimetry. These materials were sandwiched between three stacks of radiometric dosimetry foils (Foil Stacks A, B, and C+D in Figure 8). The capsule was a hollow Type 304 stainless steel disc with 0.127-mm-thick Type 304 stainless steel covers attached to the front and back faces. The capsule contents are listed in Table 6. The dosimetry foils, selected in part to correlate with their

TABLE 6
HELIUM-GENERATION MATERIALS IN THE SECOND
RTNS-I IRRADIATION

C (diamond)	Nb	^6LiF	^{64}Ni
Al	Mo	^7LiF	^{63}Cu
Si	Au	^{10}B	^{65}Cu
Ti		^{11}B	^{92}Mo
V		^{54}Fe	^{94}Mo
Cr		^{56}Fe	^{95}Mo
Mn		^{58}Fe	^{96}Mo
Fe		^{58}Ni	^{97}Mo
Ni		^{60}Ni	^{98}Mo
Cu		^{61}Ni	^{100}Mo
Zr		^{62}Ni	
Type 316 stainless steel			
Nb - 1 Zr			
Mo - 0.5 Ti			
TZM

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Figure 8. Cross Sectional View of the Capsule Used in the Second AI RTNS-I Irradiation

TABLE 7
DOSIMETRY FOIL STACKING GEOMETRY FOR THE SECOND RTNS-I IRRADIATION

Stack	Foil	Thickness (mils)	
Front Cover	Type 304 SS	5	
Stack A	Nb	1	Autoradiograph foil
	Nb	1	
	Ni	1	
	Fe	1	
	Co	2	
	Zr	1	
	Au	0.5	
Stacks B, C	Nb	1	
	Ni	1	
	Fe	1	
	Co	2	
	Zr	1	
	Au	1	
Stack D	Zr	10	
	Fe	5	
	Nb	5	
	Nb	5	For helium analysis, not segmented
	Nb	5	Autoradiograph foil
	Au	5	
	Co	10	
Back Cover	Type 304 SS	5	

use in the d-Be irradiation, were Au, Nb, Ni, Zr, Co, and Fe. Most of these foil materials were supplied by ANL. Their thicknesses and stacking order are given in Table 7. The assembly was centered on the deuteron beam axis for this irradiation by the use of autoradiographs taken at the beginning of the irradiation period, as described in Section III.

Three days after the end of the irradiation, the capsule was disassembled and the foils were cut into small segments for radiometric counting. The segmenting patterns are shown in Figures 10 and 11. The Nb and Ni foil segments, plus the helium-generation specimens of natural and isotopic Ni, were counted at LLL. The Au, Co, Zr, and Fe foil segments, plus helium-generation specimens of V, Mn, Fe, ^{54}Fe , ^{58}Fe , ^{63}Cu , Zr, ^{92}Mo , ^{95}Mo , ^{98}Mo , and ^{100}Mo , were counted at ANL. A few of the Nb and Ni foil segments, plus the Ni, ^{58}Ni , ^{60}Ni , and ^{62}Ni helium-generation specimens, were also counted at ANL, for later comparison of the absolute efficiencies of the ANL and LLL Ge(Li) detectors. The majority of the foil segments have been subsequently weighed at AI, using a weighing scheme and mass standards traceable to the National Bureau of Standards.

The counting and weighing results for the foil segments will be combined with the radiometric dosimetry reaction cross sections and the helium accumulation dosimetry results to map out the neutron fluence profile over the extent of the capsule. This map will then be combined with the helium generation analyses of the other specimens to determine helium-generation cross sections.

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Figure 10. Au, Co, Zr, Nb Dosimetry Foil Segmenting Patterns and Identification Numbers for the Second RTNS-I Irradiation

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Figure 11. Fe, Ni Dosimetry Foil Segmenting Patterns and Identification Numbers for the Second RTNS-I Irradiation

9077-4021

Figure 12. Loading Geometry of 2 Capsules
in HFIR

V. HFIR IRRADIATION

The irradiation of two helium-generation capsules loaded into the High Flux Isotopes Reactor (HFIR) in March 1977 has been completed. This 5-cycle irradiation lasted approximately 120 days. The capsule specimens were prepared at AI, and loaded at ORNL into capsules supplied by F. W. Wiffen and J. W. Woods. The purpose of the AI participation in this irradiation was to measure helium generated in magnetic fusion energy (MFE) alloys and pure elements in a mixed-fission spectrum neutron environment. Information on these helium generation rates is also necessary in assessing the amount of helium that will be generated by the considerable low-energy flux components of the d-Be and d-Li neutron energy spectra.

The approximate geometry of the capsule loading is shown in Figure 12, and the specimen materials are listed in Table 8. The 130 helium-generation specimens included 17 pure elements, 4 separated isotopes, 7 stainless steel alloys of varying nickel content, and one compound. The specimens weighed generally between 2 and 15 mg, and were all weighed and microphotographed at AI prior to shipment to ORNL, for later identification of the individual specimens. The specimens were loaded in layers, separated by 0.0127-mm-thick aluminum foil to provide thermal contact for heat removal. Six alloy discs with different known nickel contents were placed at the capsule top and bottom. Neutron fluence dosimetry was provided in each capsule by a 3-cm-long, 0.25-mm-diameter iron wire, provided by ORNL.

The irradiated capsules are presently in storage at ORNL, to allow their radioactive products to decay to lower levels before shipment to AI.

TABLE 8
HELIUM-GENERATION MATERIALS IN THE HFIR IRRADIATION

C (diamond)	Cu	⁵⁸ Ni
Al	Y	⁶⁰ Ni
Si	Zr	⁶³ Cu
Ti	Nb	⁶⁵ Cu
V	Mo	
Cr	Ag	
Mn	Pt	
Fe	Au	
Ni	SiO ₂	

Type 316 stainless steel

Six alloys with differing nickel contents

VI. PUBLICATIONS AND PRESENTATIONS

1. An AI-ANL paper entitled "Fluence Mapping of RTNS-I by Helium Accumulation and Foil Activation Methods," by H. Farrar IV, D. W. Kneff, R. A. Britten, and R. R. Heinrich, was presented at, and published in the proceedings of, the Symposium on Neutron Cross Sections from 10 to 40 MeV, held at Brookhaven National Laboratory in May 1977.⁽³⁾
2. A HEDL-ANL-AI paper entitled "MFE Damage Analysis Program Nuclear Data Needs," by D. G. Doran, R. R. Heinrich, L. R. Greenwood, and H. Farrar IV, was presented at, and published in the proceedings of, the Brookhaven Symposium on Neutron Cross Sections from 10 to 40 MeV.⁽⁸⁾
3. On August 4, 1977, H. Farrar IV and D. W. Kneff presented an overview of AI's Fusion Program to the U.S.S.R. Delegation on Irradiation Effects on Fusion Reactor Materials. The presentation outlined the fundamentals of AI's helium generation rate measurements, the design and capabilities of the high sensitivity gas mass spectrometer system, and the experiments and results obtained to date pertinent to fusion reactor material studies. The meeting included personnel from LLL and the Hanford Engineering Development Laboratory (HEDL), and was held at UC-Davis.

VII. TASK GROUP ON DAMAGE ANALYSIS AND FUNDAMENTAL STUDIES

H. Farrar IV, as a member of DMFE's Task Group on Damage Analysis and Fundamental Studies, participated in two additional meetings during the report period. The first was a subtask group meeting held on May 4, 1977, in conjunction with the Brookhaven Conference.⁽⁸⁾ The second was a meeting held with HEDL personnel in Richland, Washington on August 31, 1977, to discuss dosimetry for the proposed d-Li neutron source.

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