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ADDITIONAL MEASUREMENTS OF THE RADIATION ENVIRONMENT AT THE
LOS ALAMOS SPALLATION RADIATION EFFECTS FACILITY AT LAMPF

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Abstract: Foil activation dosimetry experiments were conducted in a "rabbit" system at the completed Los Alamos Spallation Radiation Effects Facility (LASREF). The "rabbit" system contains four tubes spaced radially outward 0.12, 0.18, 0.27, and 0.38 meters off beam centerline. Foils were irradiated for 3 to 62 hours to measure the neutron flux and energy spectrum radially from beam centerline, along the beamline, and the effect of the Isotope Production (IP) target loadings on the neutron flux in the neutron irradiation locations. Irradiations showed a decrease in the radial flux by a factor of 6 in 0.15 meters of iron outside the IP targets. An enhancement was seen in the 24-keV energy region outside 0.15 meters. There was little difference in the shape of the spectra outside the IP targets and the beam stop with the exception of the high energy tail (energies above 20 MeV). The decrease in the high energy tail outside the beam stop is due to the degradation of the energy of the proton beam in the IP targets. Irradiations outside the beam stop with zero and eight IP targets gave the same spectral shape with the exception of the high energy tail. The magnitude of the integral flux decreased by a factor of 2 when eight IP targets were present. Irradiations with five "rabbits" stacked on top of each other showed no difference in the integral flux below, on and above beam centerline.

Key Words: neutron, proton, integral flux, differential flux, foil, activation, dosimetry, spectrum, cross section, spallation

Introduction

The Los Alamos Spallation Radiation Effects Facility (LASREF) began operation in May, 1985, at the Los Alamos Meson Physics Facility (LAMPF). The facility is located at the beam stop area (Target Station A-6) at LAMPF. Monte Carlo calculations [1] were done previously to predict the neutron flux and spectrum at the facility using a geometry that approximated the final facility. Measurements of the neutron flux and

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energy spectrum, using activation foil techniques, were then made at the existing beam stop area [2]. For these measurements, we were limited to only one location. Also the geometry was somewhat different from what LASREF will eventually have. Thus at the onset of the operation of LASREF, a special insert ("rabbit" system) was built and placed in service so that multiple activation foil measurements in several locations could be made. This work was necessary to facilitate further design of experiments at LASREF and gave a map of the neutron flux and spectrum at the facility.

The expected radiation damage parameters at LASREF have been reported [3,4]. We are also reporting our experience in operating the facility [5] as well as giving a description of radiation-hardened equipment that we have developed.

"Rabbit" System Description and Measurement

A schematic, in isometric form, of LASREF is shown in Fig. 1. Note the relation of the "rabbit" insert to the neutron-producing Isotope Production (IP) targets and the copper beam stop. Note also the location, outside the concrete "hut" surrounding the facility, of the iron casks used for retrieval of the activation foils. Figure 2 shows, in schematic form, a more detailed view of the relation of the "rabbit" system to the isotope production targets and the LAMPF beam stop. The "rabbit" insert contains four tubes spaced radially outward 0.12, 0.18, 0.27, and 0.38 meters off beam centerline.

Aluminum capsules ("rabbits"), 10.16 mm in diameter and 19.05 mm long, are pneumatically driven by helium gas to the irradiation location. They are placed into the system and later retrieved at the cask position, outside the hut, as shown in Fig. 1; this allows experiments to be irradiated and terminated without interruption of LAMPF operations. Each

of the four tubes can accept five capsules; when properly placed they can record the neutron flux and energy spectrum above, on, and below beam centerline. Each capsule can contain numerous foils. As in previous work [2] the high-purity foils were chosen to obtain a clear picture of the neutron flux and spectrum. Capsules contained iron, cobalt, nickel, titanium, vanadium, scandium, aluminum, zinc, gold, and copper foils for the neutron measurements. Secondary protons are produced by spallation reactions as the primary beam interacts with the targets. Measurements of this proton flux were made using iron, titanium and copper foils. Foils were punched 5.6 mm in diameter and 0.013 to 0.127 mm thick, with a center hole. They were strung in a specific order on an aluminum wire to assure identification. Foils of iron, cobalt, gold, and scandium were wrapped in 0.03-mm thick gadolinium foil and placed in the bottom of the "rabbit" to determine the thermal-to-epithermal flux.

Figure 3 shows a top view of LASREF and denotes the numbering system and location of the 12 inserts that may be placed in the facility and receive neutron irradiation. For the present experiment, positions 2 and 6 were used; the "rabbit" system was designed for use in any of 12 locations. Locations 2 and 6 were chosen because calculations [1] predicted the highest neutron flux at these locations for the target geometry described below. A total of 12 irradiations were made at LASREF during which foils were irradiated for 3 to 62 hours. Table 1 describes the IP target loading and achieved exposure in μA -hours for the four irradiations that will be discussed in this paper. "Rabbits" were stacked on top of two solid aluminum spacers so the "rabbits" were at beam centerline unless otherwise stated.

Activity Measurement and Spectral Analysis

Foils were mounted on aluminum counting plates and counted with a calibrated high-purity germanium crystal (HPGe). The gamma-ray spectra were analyzed using the SPECANL computer code [6]. Recorded beam current histories were used to correct the activity for decay during irradiation. The corrected activities along with a calculated spectrum, activation cross sections, and variance-covariance information were input into the STAY'SL computer code [7]. STAY'SL uses a least-squares technique to calculate the most probable neutron energy spectrum. Strong correlations were assumed between nearby groups in the flux and cross sections. Cross sections were taken from several sources. Below 20 MeV, cross sections were from ENDF-V-B [8]. Between 20 and 44 MeV, cross sections were based on experimental and calculated data tested in a Be(d,n) neutron field [9]. Proton spallation cross sections were used to extend the activation cross section file to 800 MeV [10-12].

The reactions analyzed and their corrected activities are listed in Table 2 for irradiation 936-5, tube one. The energy limits indicate a substantial contribution from high energy neutrons (energy above 44 MeV). This is particularly evident for spallation reactions such as $\text{Al}(n,x)^7\text{Be}$, $\text{Cu}(n,x)^{46}\text{Sc}$, $\text{Cu}(n,x)^{51}\text{Cr}$ and $\text{Cu}(n,x)^{52}\text{Mn}$. Other reactions such as $^{58}\text{Ni}(n,p)^{58}\text{Co}$, $^{59}\text{Co}(n,p)^{59}\text{Fe}$ and $^{59}\text{Co}(n,2n)^{58}\text{Co}$ have no significant response above 36 MeV. The listed errors show reasonable agreement between the measured and calculated (STAY'SL) activities. $\text{Ni}(n,x)^{57}\text{Ni}$, $\text{Cu}(n,x)^{60}\text{Co}$, and $\text{Cu}(n,x)^{59}\text{Fe}$ have large, positive errors. Their response is due primarily to high-energy neutrons where cross-section uncertainties are large and cross sections are based on proton, not neutron, measurements. The error for these two reactions was positive and large for all irradiations. The measured activity for $^{27}\text{Al}(n,x)^{22}\text{Na}$ was low by 64.7%

from the calculated activity. The measured activity was consistently low for all irradiations. This response is not well understood.

Irradiation 936-2 was made to measure differences in the neutron flux above and below beam centerline. Five "rabbits" each with iron, nickel, and cobalt foils were stacked on top of each other in tube one; "rabbit" one was on the bottom and "rabbit" three at beam centerline. The corrected activities listed in Table 3 show no difference in flux with location other than statistical fluctuations in the data.

Irradiations 936-5, 936-6, and 936-7 were made to measure the neutron flux and energy spectrum along the beamline, radially from the beam centerline, and to determine the effect of the IP target loading on the spallation neutron flux. The differential neutron flux for irradiation 936-5 is shown in Fig. 4. Above 0.01 MeV, the spectra are similar for tubes one, two, and three. Tube four shows a decrease in the high-energy flux due to spallation and an enhancement at approximately 50 keV. This enhancement is due to the 24-keV transmission window in the iron cross section. Neutrons born in this region and those scattered into it will enhance the flux. The peak energy is greater than 24 keV because of the limited reactions ($\text{Co}(n,\gamma)^{60}\text{Co}$ and $\text{Fe}(n,\gamma)^{59}\text{Fe}$) that are responsive to neutrons below 0.1 MeV. The integral fluxes for tube one, two, three, and four are 2.81×10^{13} , 1.26×10^{13} , 4.98×10^{12} , and 1.52×10^{13} n/cm²-s-mA respectively. Figure 5 shows the normalized activity for irradiation 936-5 radially from beam centerline. The activities are normalized to the corresponding activity in tube one. The reactions $^{58}\text{Fe}(n,\gamma)^{59}\text{Fe}$, $^{58}\text{Ni}(n,p)^{58}\text{Co}$, $^{54}\text{Fe}(n,\alpha)^{51}\text{Cr}$, and $\text{Cu}(n,x)^{52}\text{Mn}$ were chosen because of the neutron energy limits of the reaction. These energy groups are thermal/epithermal, 1-20, 36-440, and 110-520 MeV, respectively.

$^{52}\text{Cu}(p,n)^{52}\text{Mn}$ was added to compare the decrease in the activation for a proton-induced reaction to the neutron-induced reactions. The activity for $^{58}\text{Fe}(n,\gamma)^{59}\text{Fe}$ and $^{58}\text{Ni}(n,p)^{58}\text{Co}$ decrease radially at the same rate. $^{54}\text{Fe}(n,\alpha)^{51}\text{Cr}$ decreases at an intermediate rate to low and high energy reactions. The high-energy neutron and proton activities decrease at the same rate between tubes one and four. Figure 6 shows the activity in atoms/atom-s for the same reactions. Note that the proton-induced activity decreases by two orders of magnitude between tube one and four.

Tubes one and two show a similar spectral shape for irradiations 936-6 and 936-7 (Figs. 7 and 8 respectively). Tube three shows a slight enhancement above 0.01 MeV for both irradiations. This enhancement is increased for tube four. Again the peak is shifted to higher energies because of the limited reactions analyzed in this energy region. The scatter in the spectra above 40 MeV is due to uncertainties in the cross sections and input spectra. The integral fluxes for irradiation 936-6 are 4.64×10^{13} , 1.55×10^{13} , 1.44×10^{13} , and 1.84×10^{13} n/cm²-s-mA for tubes one, two, three, and four respectively. The integral fluxes for irradiation 936-7 are 2.24×10^{13} , 9.85×10^{12} , 1.18×10^{13} , and 1.45×10^{13} n/cm²-s-mA for tubes one, two, three, and four respectively.

The fluxes for irradiations 936-5 and 936-7, tube one, are shown in Fig. 9 to compare the energy spectra along the beamline. The spectra are similar below 20 MeV. The integral fluxes are 2.81×10^{13} compared to 2.24×10^{13} n/cm²-s-mA for irradiations 936-5 and 936-7 respectively. The difference in the spectra outside the IP targets and the beam stop lies in the high-energy tail (energies above 20 MeV). In this energy region, the flux decreases by a factor of two for irradiation 936-7 compared to irradiation 936-5. Fewer high-energy neutrons for irradiation 936-7 result

from the degradation of the energy of the proton beam in the IP targets prior to interaction with the beam stop. Table 4 lists the group energy fluxes for irradiations 936-5 and 936-7.

The effect of IP target loading is shown in Fig. 10 for irradiation 936-6 and 936-7, tube one. The shape of the spectra is the same within statistical variations. This indicates that the shape is primarily determined by the target interacting with the proton beam (i.e., the copper beam stop). The magnitude of the integral flux changes from 4.64×10^{13} to 2.24×10^{13} n/cm²-s-mA. The high energy tail is a factor of two lower for irradiation 936-7 than 936-6. A comparison of the group energy fluxes is listed in Table 4.

Conclusions

"Rabbits" with high-purity activation foils were successfully irradiated to measure the neutron flux and energy spectrum radially, and above and below beam centerline. The neutron flux in neutron irradiation location 2 decreased by a factor of 6 in iron moving radially from beam centerline from tube one to three. Between 0.27 and 0.38 meters, irradiation 936-5 showed an increase in the integral neutron flux due to the enhancement in the 24 keV region. Irradiations outside the beam stop with zero and eight IP targets showed little effect on the spectral shape but a decrease by a factor of two in the magnitude of the flux. This decrease was particularly evident in the high energy tail (energy above 20 MeV) for the irradiation with eight IP targets. For similar IP target loadings, the integral flux outside the IP targets was similar to that outside the beam stop yet the flux above 20 MeV was a factor of 2 greater outside the IP targets. This is due to degradation of the energy of the proton beam in the IP targets prior to interaction in the copper beam stop. Irradiations placing five

"rabbits" on top of one another in tube one showed no difference in the activities below, on, and above beam centerline. As a result of the irradiations, a modified dosimetry package has been chosen based on known cross sections and reactions. The foil package will include iron, nickel, cobalt, and copper foils and will be irradiated with all experiments at LASREF.

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References

- [1] Davidson, D. R., W. F. Sommer, J. N. Bradbury, R. E. Prael and R. C. Little, Los Alamos National Laboratory Report, LA-UR-83-33, Los Alamos, NM (1983).
- [2] D. R. Davidson, L. R. Greenwood, R. C. Reedy, and W. F. Sommer, "Measured Radiation Environment at the Clinton P. Anderson Los Alamos Meson Physics Facility (LAMPF) Irradiation Facility," Effects of Radiation on Materials: Twelfth International Symposium, ASTM STP 870, F.A. Garner and J.S. Perin, Eds., American Society for Testing and Materials, Philadelphia, 1985, pp. 1199-1208.
- [3] M. S. Wechsler and W. F. Sommer, Journal of Nuclear Materials, Vol. 123, 1984, p.1078.
- [4] M. S. Wechsler, D. R. Davidson, L. R. Greenwood, and W. F. Sommer, "Calculation of Displacement and Helium Production at the Clinton P. Anderson Los Alamos Meson Physics Facility (LAMPF) Irradiation Facility," Effects of Radiation on Materials: Twelfth International Symposium, ASTM STP 870, F.A. Garner and J.S. Perin, Eds., American Society for Testing and Materials, Philadelphia, 1985, pp. 1189-1198.
- [5] W. F. Sommer, W. Lohmann, K. Graf, I. K. Taylor, and R. M. Chavez, "Operating Experience at the Los Alamos Spallation Radiation Effects Facility," abstract accepted and paper submitted to the Thirteenth International Symposium-Effects of Radiation on Materials, to be held in Seattle, June 1986.
- [6] Gunnink, R., and J. B. Niday, "Computerized Quantitative Analysis by Gamma-Ray Spectrometry. Vol. 1. Description of the GAMANAL Program", UCRL-51061, Lawrence Livermore Laboratory, Livermore, CA 94550. Modified at Los Alamos National Laboratory, Los Alamos, NM 87545.
- [7] Perey, F. G., Oak Ridge National Laboratory Report, ORNL/TM-6062, Oak Ridge, TN (1971) as modified by L. R. Greenwood.
- [8] Kinsey, R., Compiler, "ENDF-201 ENDF/B Summary Documentation," Brookhaven National Laboratory Report, BNL-NCS-17541 ENDF 201, 3rd edition (ENDF/B-V) (July 1979).
- [9] Greenwood, L. R., R. R. Heinrich, M. J. Saltmarsh, and C. B. Fulmer, Nuclear Science Engineering, 72 (1979) 175.
- [10] Greenwood, L. R., and R. K. Smither, Measurement of Spallation Cross Sections at IPNS, Damage Analysis and Fundamental Studies Quarterly Progress Report, DOE/ER-0046/14, pp. 19-24, August 1983.
- [11] Toballem, J., Cross Sections of the Nuclear Reactions Induced by Protons, Deuterons, and Alpha Particles, CEA-N1466, 1971.
- [12] Michel, R., and R. Stuck, On the Production of Cosmogenic Nuclides in Meteorites by Primary Galactic Particles: Cross Sections and Calculations, Journal of Geophysical Research, Vol. 89, Sup., pp. B673-684, 1984.

TABLE 1-IRRADIATIONS IN "RABBIT" SYSTEM AT LASREF.

Irradiation 936-2:"Rabbit" system in neutron irradiation location 2
Proton dose on beamline targets: 9.14×10^4 μ A-hours

IP Targets in place

2 - CsCl
3 - MnCl
4 - CsCl
5 - Mo
7 - RbBr

Irradiation 936-5:"Rabbit" system in neutron irradiation location 2
Proton dose on beamline targets : 1.87×10^4 μ A-hours

IP Targets in place

2 - ZnO
3 - CsCl
4 - CsCl
5 - MnCl
6 - Mo
8 - In

Irradiation 936-6:"Rabbit" system in neutron irradiation location 6
Proton dose on beamline targets : 1.08×10^4 μ A-hours

IP Targets in place

none

Irradiation 936-7:"Rabbit" system in neutron irradiation location 6
Proton dose on beamline targets : 2.5×10^4 μ A-hours

IP Targets in place

2 - ZnO
3 - RbBr
4 - CsCl
5 - MnCl
6 - Mo
7 - Al
8 - In
9 - RbBr

TABLE 2-SATURATED ACTIVITIES FOR "RABBIT" 936-5, Tube 1.

Reaction	Activity, atom/atom-s	Error, % (M-A/M)x100	90% Energy Limits, MeV
$^{59}\text{Co}(n,\gamma)^{60}\text{Co}^*$	1.01×10^{-11}	7.4	$3.0 \times 10^{-5} - 1.0 \times 10^{-4}$
$^{58}\text{Fe}(n,\gamma)^{59}\text{Fe}$	4.13×10^{-13}	5.5	$1.0 \times 10^{-4} - 2.0 \times 10^{-1}$
$^{58}\text{Fe}(n,\gamma)^{59}\text{Fe}^*$	2.77×10^{-13}	-35.7	$1.0 \times 10^{-4} - 2.0 \times 10^{-1}$
$\text{Fe}(n,x)^{54}\text{Mn}$	1.74×10^{-12}	-4.4	3-400
$\text{Fe}(n,x)^{51}\text{Cr}$	9.12×10^{-13}	-3.4	32-440
$^{58}\text{Ni}(n,p)^{58}\text{Co}$	4.19×10^{-13}	-23.7	2-20
$^{58}\text{Ni}(n,x)^{57}\text{Ni}$	2.71×10^{-14}	70.0	140-200
$^{60}\text{Ni}(n,p)^{60}\text{Co}$	4.58×10^{-14}	-13.4	6-180
$^{59}\text{Co}(n,p)^{59}\text{Fe}$	1.94×10^{-14}	-0.6	3-24
$^{59}\text{Co}(n,2n)^{58}\text{Co}$	2.18×10^{-13}	6.1	12-36
$^{59}\text{Co}(n,3n)^{57}\text{Co}$	8.28×10^{-14}	29.0	20-60
$^{27}\text{Al}(n,x)^{22}\text{Na}$	1.41×10^{-14}	-64.7	28-400
$^{27}\text{Al}(n,x)^7\text{Be}$	1.36×10^{-15}	0.4	48-560
$\text{Cu}(n,x)^{46}\text{Sc}$	8.46×10^{-16}	7.9	180-560
$\text{Cu}(n,x)^{51}\text{Cr}$	1.01×10^{-14}	18.1	120-540
$\text{Cu}(n,x)^{52}\text{Mn}$	3.54×10^{-15}	-4.0	110-520
$\text{Cu}(n,x)^{60}\text{Co}$	2.71×10^{-14}	66.7	36-460
$\text{Cu}(n,x)^{59}\text{Fe}$	2.43×10^{-15}	65.2	72-500

* Gadolinium-wrapped foils

TABLE 3: CORRECTED ACTIVITIES FOR IRRADIATION 936-2. "RABBITS" ARE STACKED ON TOP OF EACH OTHER IN TUBE ONE. "RABBIT" 3 IS AT BEAM CENTERLINE.

Reaction	"Rabbit" 1	"Rabbit" 2	"Rabbit" 3	"Rabbit" 4	"Rabbit" 5
$\text{Fe}(n,x)^{54}\text{Mn}$	1.5×10^{-12}	1.5×10^{-12}	1.58×10^{-12}	1.4×10^{-12}	1.4×10^{-12}
$\text{Fe}(n,x)^{51}\text{Cr}$	7.6×10^{-13}	7.7×10^{-13}	7.6×10^{-13}	7.3×10^{-13}	7.2×10^{-13}
$^{58}\text{Fe}(n,\gamma)^{59}\text{Fe}$	3.2×10^{-13}	3.3×10^{-13}	3.2×10^{-13}	3.1×10^{-13}	3.3×10^{-13}
$^{59}\text{Co}(n,p)^{59}\text{Fe}$	9.2×10^{-15}	1.2×10^{-14}	1.1×10^{-14}	1.1×10^{-14}	9.6×10^{-15}
$^{59}\text{Co}(n,\gamma)^{60}\text{Co}$	7.2×10^{-12}	9.0×10^{-12}	9.0×10^{-12}	9.0×10^{-12}	8.1×10^{-12}
$^{59}\text{Co}(n,2n)^{58}\text{Co}$	1.1×10^{-13}	1.4×10^{-13}	1.45×10^{-13}	1.47×10^{-13}	1.2×10^{-13}
$^{59}\text{Co}(n,3n)^{57}\text{Co}$	4.3×10^{-14}	5.4×10^{-14}	5.4×10^{-14}	5.4×10^{-14}	4.8×10^{-14}
$^{58}\text{Ni}(n,p)^{58}\text{Co}$	5.0×10^{-13}	4.0×10^{-13}	4.1×10^{-13}	3.8×10^{-13}	3.8×10^{-13}
$^{60}\text{Ni}(n,p)^{60}\text{Co}$	6.9×10^{-14}	5.1×10^{-14}	6.0×10^{-14}	5.2×10^{-14}	4.9×10^{-14}

TABLE 4:GROUP FLUXES FOR IRRADIATION 936-5, 936-6, AND 936-7, tube one.

Energy, MeV	936-5 n/cm ² -s-mA	936-6 n/cm ² -s-mA	936-7 n/cm ² -s-mA
<0.1	9.69x10 ¹² (±12)	2.68x10 ¹³ (±13)	1.23x10 ¹³ (±15)
0.1-1.0	1.07x10 ¹³ (±8)	1.34x10 ¹³ (±8)	6.51x10 ¹² (±8)
1-10	3.70x10 ¹² (±10)	4.78x10 ¹² (±10)	2.79x10 ¹² (±12)
10-20	2.62x10 ¹² ±17	3.4x10 ¹¹ (±15)	1.70x10 ¹¹ (±10)
20-40	2.99x10 ¹¹ ±17	2.96x10 ¹¹ (±19)	1.10x10 ¹¹ ±14
40-100	2.88x10 ¹¹ (±18)	4.81x10 ¹¹ (±20)	2.11x10 ¹¹ ±17
100-200	3.26x10 ¹¹ (±28)	2.14x10 ¹¹ (±20)	1.52x10 ¹¹ (±26)
>200	4.79x10 ¹¹ (±20)	1.26x10 ¹¹ (±19)	1.98x10 ¹¹ (±16)
Total	2.81x10 ¹³ (±8)	4.64x10 ¹³ (±8)	2.24x10 ¹³ (±7)

FIGURE CAPTIONS

- Figure 1- Schematic of LASREF showing "rabbit" system beside the beam stop and the iron cask outside the concrete hut for retrieval of "rabbits."
- Figure 2- "Rabbit" system in neutron irradiation location two showing inlet and outlet helium lines.
- Figure 3- Top view of LASREF indicating 12 neutron and 3 proton irradiation locations and their location relative to the IP targets and beam stop.
- Figure 4- Differential flux for irradiation 936-5, tubes 1-4.
- Figure 5- Normalized activity versus radial distance from beam centerline for irradiation 936-5.
- Figure 6- Activity versus radial distance from beam centerline for irradiation 936-5.
- Figure 7- Differential flux for irradiation 936-6.
- Figure 8- Differential flux for irradiation 936-7.
- Figure 9- Comparison of the differential flux for irradiations 936-5 and 936-7, tube one.
- Figure 10- Comparison of the differential flux for irradiations 936-6 and 936-7, tube one.