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Analytic and Experimental Decay Heat Determinations of 800-MeV Proton Irradiated Aluminum

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ANALYTIC AND EXPERIMENTAL DECAY HEAT DETERMINATIONS OF 800-MeV PROTON IRRADIATED ALUMINUM

by

L. N. Kmetyk and W. F. Sommer

ABSTRACT

Postirradiation radiochemistry analysis of 800-MeV proton irradiated ultrahigh purity aluminum has been done with standard gamma-ray counting equipment determining the Na^{22} activity in the activated aluminum. The results of these measurements are compared in this paper to the predicted values obtained from CINDER, a general nuclide depletion and fission-product code. This program can be used easily to calculate the activity of materials under arbitrary irradiation, provided that the source terms for the various radionuclides produced are known. The required production cross sections have been calculated by using the nucleon-meson transport code NMTC to determine the nuclear reactions produced by the protons, and the theory of Lindhard et al. to evaluate the resultant damage energy deposited in the target.

I. INTRODUCTION

A 5-μA beam of 800-MeV protons, generated at the Clinton P. Anderson Meson Physics Facility (LAMPF), has been used to conduct a materials science radiation damage experiment.[1] The results of postirradiation radiochemistry analysis of 800-MeV proton irradiation of ultra high purity aluminum have already been reported.[2] Standard gamma-ray counting equipment, including a Ge-Li detector, a multichannel analyzer and associated electronics, was employed to count the Na^{22} activity in the aluminum. Because activation is proportional to proton fluence, relative dose levels could be determined; also, use of a selected production cross section[3] for Na^{22} in aluminum and a calculated damage energy cross section[4,5] for 800-MeV proton bombardment allowed determination of a calculated value for the number of displacements per atom (dpa) that the material received.

This calculation has now been augmented by a more detailed analysis of the irradiation and decay heat using the depletion and fission-product code CINDER, which allows the production and subsequent decay of all the many radionuclides produced during high-energy bombardment of any material to be modelled in detail. In aluminum, because all but two radionuclides produced are extremely short-lived, and because those two are independently formed, the increased complexity of the model thus available is not really necessary. However, in heavier materials such as copper, molybdenum, and stainless steel, the characteristic half-lives of many of the radionuclides formed are comparable to the problem time;

thus no analytic solution for activity and decay heat is obtainable readily. Also, the effects of arbitrary combinations of different irradiation and annealing times can be determined accurately (important in long intermittent irradiations). Benchmarking the results obtained for 800-MeV proton aluminum irradiation from the CINDER code against experiment helps validate the application of such an analysis to other materials for decay heat and activity calculations.

II. CINDER

CINDER[6,7] originally was developed to model the rate of production and buildup of various fission-product nuclides during the operation of a power reactor to optimize the utilization of nuclear fuel. Also it provided information about the heat generated during the radioactive decay of such nuclides, required for loss of coolant and safety analyses.

The temporal concentrations of fission-product nuclei produced in a nuclear reactor are described by a large set of coupled differential equations, each nuclide concentration being determined by a history of gains from direct fission yield, transmutation and radioactive decay from parent nuclei, and losses from its own decay and particle absorption. The depletion and fission-product computer code CINDER simplifies the solution for fission-product concentrations by resolving the complicated nuclide couplings into linear chains. Each linear chain represents a unique linear path from nuclide to nuclide, resulting in small independent sets of coupled differential equations describing the rate of change of partial concentrations of nuclides in each chain. The solution of a large set of coupled differential equations thus is reduced to the solution of a number of small sets of coupled differential equations, each characterized by a single generalized form. Because of the linear nature of the chain (a result of the Markov process), the generalized equations may be solved sequentially for the partial concentration of each nuclide in the chain. Nuclide concentrations are then obtained by summing partial concentrations. The mathematical treatment is described in detail in Ref. 8.

The CINDER program easily can be used to calculate the activity of materials under arbitrary irradiation (such as the 800-MeV proton beam at LAMPF) provided the source terms for the various radionuclides produced are known. The calculation of the required production cross sections is described in the next section and the resultant CINDER-7 input[9] for aluminum irradiated at LAMPF is given in Appendix A. This is a relatively simple case, with only 56 linear chains. (Molybdenum irradiated at LAMPF, for example, requires 211 linear chains.)

III. PRODUCTION CROSS SECTIONS FOR PROTON-IRRADIATED ALUMINUM

Because there has been little or no theoretical information available concerning the damage effects of medium-energy protons in metals, a general characterization of proton damage[4] was attempted to determine damage energy and impurity deposition. One of the main effects of the protons is to generate inelastic nuclear interactions in the target, with the consequent production of heavy spallation and light evaporation nuclei covering a large part of the periodic table below the target nucleus mass numbers. Except for targets made from the lightest metals, the species produced in this fashion will number in the hundreds. For each such nuclide produced in significant amounts, the production cross section, the recoil energy distribution, and the damage efficiency of the nuclide in the target material must be determined.

The nucleon-meson transport code NMTC[10] incorporates Bertini's intranuclear cascade-nuclear evaporation code[11] as a key element. It calculates the reactions produced when a nucleon or charged pion is incident on a given target, which may consist of several different spatial regions of various shapes, each containing a variety of specified nuclides with assigned densities. In generating a nuclear interaction, the program first allows the primary particle to interact with a target nucleus in an intranuclear cascade in which scattering, possibly inelastic, of the primary particle from individual nucleons occurs. The scattering events are calculated by Monte Carlo methods according to experimentally determined cross sections in energy regions where these cross sections are available, and according to certain theoretical estimates of these cross sections in regions where they are not. At the completion of the intranuclear cascade, the resultant excited nucleus is allowed to evaporate neutrons and light nuclei (p, n, H^2, H^3, He^3, and He^1); no nuclei more massive than He^4 are emitted in the evaporation model used. The helium and heavy hydrogen isotopes and the spallation nucleus remaining after the evaporation phase are dropped by the code after the data characterizing them are recorded. Charged pions ejected from the nucleus in the intranuclear cascade phase, and nucleons emitted in either the cascade or evaporation phase, are transported further and allowed to have additional nuclear interactions with target nuclei. This is continued as long as their energies remain above certain cutoffs, required because the intranuclear cascade-nuclear evaporation model ceases to yield acceptably accuate results for incident nucleon energies below a few tens of MeV, and for charged pion energies below a few MeV. Nucleons and charged pions that drop below their respective cutoff energies are not transported further by the code, except that stopped negative pions may be required to have nuclear interactions. Transported charged particles experience energy losses to electrons and optional Coulomb spreading of their trajectories. For the purposes of this calculation Coulomb recoil of the target nuclei has also been included in the code although it is not part of the standard version of NMTC. Various types of events are calculated including nuclear interactions with and without emission of high-energy particles, particle crossings of internal or external boundaries, and slowing of a charged particle to cutoff. In addition, points on the trajectories of above-cutoff protons and charged pions can be made available for tabulation of electronic energy losses and similar quantities.

This code has been shown to be reasonably accurate in calculating inelastic nuclear interactions produced by protons and neutrons in the energy range from ~100 MeV to 3.5 GeV. The code determines numbers and kinetic energies of spallation nuclei, light nuclei, and neutrons produced by the interactions, and so yields impurity production directly. A separate determination of damage energy deposited in the target is then necessary, using as input data the production cross section and energy distribution information generated by NMTC, as shown in the listing of results for 800-MeV proton irradiated aluminum in Appendix B. These production cross sections can also be used by the CINDER code to calculate target activity and decay heat.

IV. RESULTS

A 5-μA beam of 800-MeV protons generated at LAMPF was used to conduct a materials science radiation damage experiment in which thin aluminum targets were irradiated. Because of the length of the experiment, the down times are significant and the actual irradiation history is shown in Fig. 1. (Any structure whose time constant is minutes or hours rather than days has been averaged out.) The samples were then removed and 228 days later the Na^{22} activity in the central, most heavily irradiated region was experimentally found to be 1.79 mCi/g. Simple calculations related this to a total proton fluence of 3.07 10^{19} p/cm^2 and an implied damage level of 0.0454 dpa.

This analysis has now been augmented by a more detailed study of the irradiation and decay heat using the depletion and fission-product code CINDER. A description of the CINDER-7 input data for the irradiation shown in Fig. 1, followed by a 228-day cooling period, is given in Appendix A. The flux history according to the experimental specifications is:

Period (days)	Flux
13	3.5 μA => 1.7724 10^{13} $\frac{p}{cm^2\ s}$
11.5	0
3	5 μA => 2.5321 10^{13} $\frac{p}{cm^2\ s}$
6.5	0
5.5	6 μA => 3.0385 10^{13} $\frac{p}{cm^2\ s}$
228	0

The CINDER-7 activity results for this flux history, clearly showing the irradiation and annealing periods, are:

Period (days)	Activity	
13	$4.561\ 10^{10}\ \frac{\text{atoms}}{\text{s - cm}^3}$	456.6 mCi/g
11.5	$1.917\ 10^{8}\ \frac{\text{atoms}}{\text{s - cm}^3}$	1.92 mCi/g
3	$6.470\ 10^{10}\ \frac{\text{atoms}}{\text{s - cm}^3}$	647.6 mCi/g
6.5	$2.613\ 10^{8}\ \frac{\text{atoms}}{\text{s - cm}^3}$	2.62 mCi/g
5.5	$7.821\ 10^{10}\ \frac{\text{atoms}}{\text{s - cm}^3}$	782.9 mCi/g
228	$3.032\ 10^{8}\ \frac{\text{atoms}}{\text{s - cm}^3}$	3.04 mCi/g

The calculated activity (3.04 mCi/g) is quite a bit larger than the 1.79 mCi/g experimental value. However, re-examination showed that the total proton fluence was determined using a Na^{22} production cross section[2] of 13.6 mb, whereas the CINDER program is using a production cross section of 23.65 mb for Na^{22} (as seen in Appendixes A and B). When this discrepancy is taken into account, the CINDER result for the last time calculated becomes

$$3.04 \text{ mCi/g} \left(\frac{13.6 \text{ mb}}{23.65 \text{ mb}}\right) = 1.75 \text{ mCi/g}.$$

This is only 2% lower than the experimental value and verifies that the fission-product CINDER code can be used for decay heat calculations for irradiation in the LAMPF 800-MeV proton beam.

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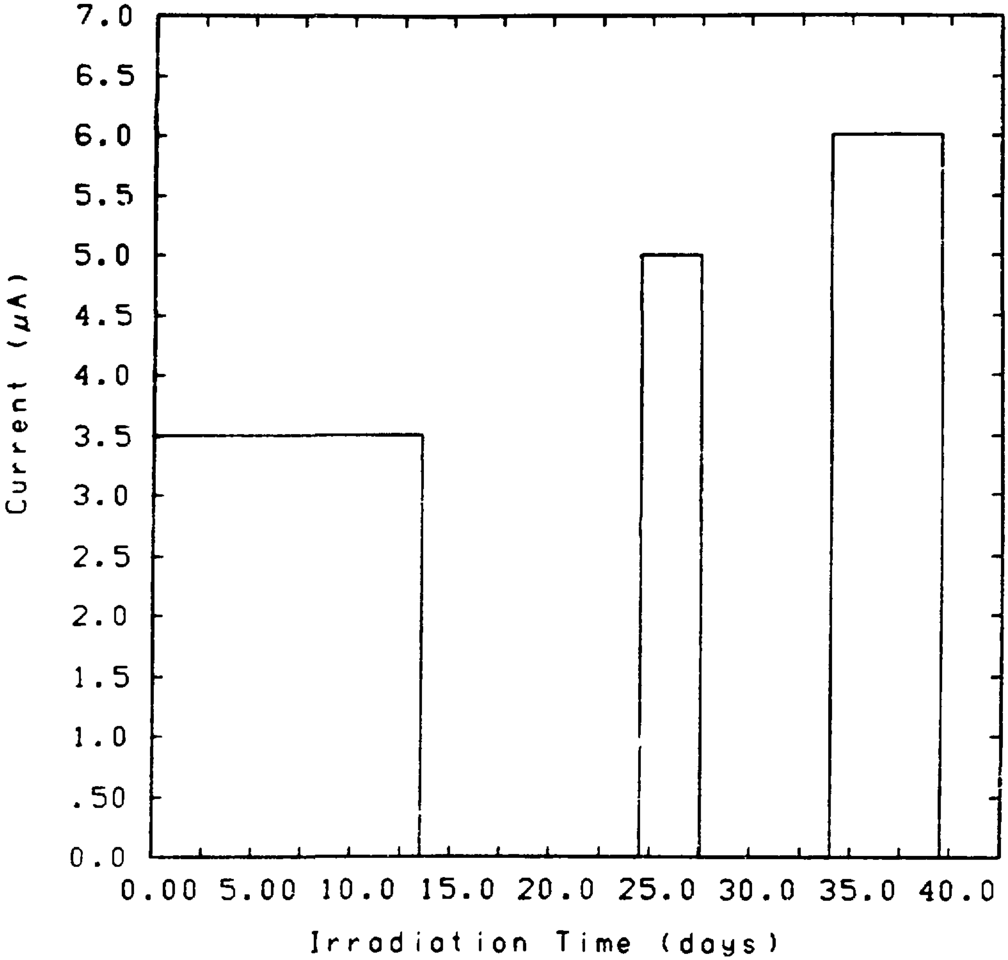

FIG. 1. Irradiation History

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APPENDIX A

CINDER-7 INPUT FOR 800-MeV PROTON IRRADIATED ALUMINUM

Table A-I lists the CINDER-7 input data for the irradiation shown in Fig. 1, followed by a 0.624-yr (228-day) cooling period.

The yield fractions of the various nuclei produced are found by normalizing the individual production cross sections given in Appendix B by the total production cross section summed over the various nuclei produced.

There are 10 energy groups modelled:

Group	Content
1	betas
2	positrons
3	0-0.5 MeV gammas
4	0.511 MeV gammas
5	0.511-1.0 MeV gammas
6	1.0-1.5 MeV gammas
7	1.5-2.0 MeV gammas
8	2.0-2.5 MeV gammas
9	2.5-3.0 MeV gammas
10	3.0 MeV and up gammas

TABLE A-I

CINDER-7 INPUT FOR 800-MeV PROTON IRRADIATED ALUMINUM

```
LISTING OF INPUT DATA FOR CASE  1
          * CINDER 7 RUN FOR ALUMINUM TARGET AT EXP 407
          *      TIME AND FLUX CARDS
****      100001, 1.0,1.0,0,0.0,0.0,0.0,0
****      200001, 312.,0.0,0.0,0.0,1.0,1.2997+13,1.0
****      200002, 276.,0.0,0.0,0.0,1.0,0.0,1.0
****      200003, 72.,0.0,0.0,0.0,1.0,1.8558+13,1.0
****      200004, 156.,0.0,0.0,0.0,1.0,0.0,1.0
****      200005, 132.,0.0,0.0,0.0,1.0,2.2292+13,1.0
****      200006, 5472.,0.0,0.0,0.0,1,0,0.0,1.0
          *      FUEL CARDS
****      1100101,AL-27,6.02-2,1.0-30,1,3
****      2100101,0.0,0.0,0.0,0.4357076
****      3100101,0.0,0.0,0.0,0.4357076
****      100008,00101
****      100009,1
          *      A=27 DECAY CHAINS
****      1200101,MG-27,0.0,1.21605-3,1,2
****      9200101,0.555324,0.0,1.26-3,0.0,.599,.303,/4/0.0
****      1200102,AL-27,6.02-2,1.0-30,1,1
****      9200102,/10/0.0
****      800111,0.00717386A,0.0
****      1200201,AL-27,6.02-2,1.0-30,1,1
****      9200201,/10/0.0
****      800211,0.0322466
****      1200301,SI-27,0.0,.145035,1,2
****      9200301,0.0,1.2375,0.0,1.02,/5/0.0
****      1200302,AL-27,6.02-2,1.0-30,1,1
****      9200302,/10/0.0
****      800311,6.41-3,0.0
          *      A=26 DECAY CHAINS
****      1200401,NA-26,0.0,.573147,1,2
****      9200401,2.211,0.0,/4/0.0,1.84,/3/0.0
****      1200402,MG-26,0.0,1.0-30,1,1
****      9200402,/10/0.0
****      800411,5.995-4,0.0
****      1200501,MG-26,0.0,1.0-30,1,1
****      9200501,/10/0.0
****      800511,0.11993066
****      1200601,AL-26,0.0,2.9562-14,1,2
****      9200601,0.0,.3961,0.0,.8697,0.0,.0448,1.81,/3/0.0
****      1200602,MG-26,0.0,1.0-30,1,1
****      9200602,/10/0.0
****      800611,.06907,0.0
****      1200701,SI-26,0.0,.3466,1,2
****      9200701,0.0,1.2639,0.0,1.02,/6/0.0
****      1200702,AL-26M,0.0,.10663,1,2
****      9200702,0.0,1.0533,0.0,1.02,/6/0.0
****      1200703,MG-26,0.0,1.0-30,1,1
****      9200703,/10/0.0
****      800711,2.095545-3,/2/0.0
          *      A=25 DECAY CHAINS
****      1200801,NA-25,0.0,.01155,1,2
****      9200801,1.2630,0.0,.0546,0.0,.2292,0.0,.0956,/3/0.0
****      1200802,MG-25,0.0,1.0-30,1,1
****      9200802,/10/0.0
****      800811,9.65221-3,0.0
****      1200901,MG-25,0.0,1.0-30,1,1
****      9200901,/10/0.0
****      800911,.09535717
****      1201001,AL-25,0.0,.09627,1,2
****      9201001,0.0,1.0492,0.0,1.02,/5/0.0
****      1201002,MG-25,0.0,1.0-30,1,1
****      9201002,/10/0.0
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TABLE A-I (Cont.)

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****    801011,1.1959-2,0.0
****    1201101,SI-25,0.0,3.0136934,1,2
****    9201101,0.0,1.3,0.0,1.02,/5/0.0
****    1201102,MG-24,0.0,1.0-30,1,1
****    9201102,/10/0.0
****    801111,8.255-4,0.0
        *      A=24 DECAY CHAINS
****    1201201,NE-24,0.0,3.4179955-3,1,2
****    9201201,.633547,0.0,.474,0.0,.0794,/5/0.0
****    1201202,NA-24,0.0,1.2836053-5,1,2
****    9201202,.4584,0.0,/3/0.0,1.369,/2/0.0,2.754,0.0
****    1201203,MG-24,0.0,1.0-30,1,1
****    9201203,/10/0.0
****    801211,2.5016646-3,/2/0.0
****    1201301,NA-24,0.0,1.2836053-5,1,2
****    9201301,.4584,0.0,/3/0.0,1.369,/2/0.0,2.754,0.0
****    1201302,MG-24,0.0,1.0-30,1,1
****    9201302,/10/0.0
****    801311,.022,0.0
****    1201401,MG-24,0.0,1.0-30,1,1
****    9201401,/10/0.0
****    801411,.07254
****    1201501,AL-24,0.0,.33037,1,2
****    9201501,0.0,2.935,0.0,1.37,0.0,1.369,/2/0.0,2.754,0.0
****    1201502,MG-24,0.0,1.0-30,1,1
****    9201502,/10/0.0
****    801511,2.53462-3,0.0
        *      A=23 DECAY CHAINS
****    1201601,NE-23,0.0,.0182497,1,2
****    9201601,1.4,0.0,.145,/3/0.0,.01475,/3/0.0
****    1201602,NA-23,0.0,1.0-30,1,1
****    9201602,/10/0.0
****    801611,5.207-3,0.0
****    1201701,NA-23,0.0,1.0-30,1,1
****    9201701,/10/0.0
****    801711,.066278
****    1201801,MG-23,0.0,.05775,1,2
****    9201801,0.0,1.68,.0334,1.02,/5/0.0
****    1201802,NA-23,0.0,1.0-30,1,1
****    9201802,/10/0.0
****    801811,7.107868-3,0.0
        *      A=22 DECAY CHAINS
****    1201901,F-22,0.0,.1733,1,2
****    9201901,3.1878,/4/0.0,1.28,0.0,2.05,/2/0.0
****    1201902,NE-22,0.0,1.0-30,1,1
****    9201902,/10/0.0
****    801911,7.62-4,0.0
****    1202001,NE-22,0.0,1.0-30,1,1
****    9202001,/10/0.0
****    802011,1.2946-2
****    1202101,NA-22,0.0,8.447999-9,1,2
****    9202101,0.0,.546,0.0,.9199,0.0,1.275,/4/0.0
****    1202102,NE-22,0.0,1.0-30,1,1
****    9202102,/10/0.0
****    802111,5.42856-2,0.0
        *      A=21 DECAY CHAINS
****    1202201,F-21,0.0,.1575334,1,2
****    9202201,1.722,0.0,.3668,/2/0.0,.15926,.016,/3/0.0
****    1202202,NE-21,0.0,1.0-30,1,1
****    9202202,/10/0.0
****    802211,1.77804-3,0.0
****    1202301,NE-21,0.0,1.0-30,1,1
****    9202301,/10/0.0
****    802311,.045581
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TABLE A-I (Cont.)

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****    1202401,NA-21,0.0,.030137,1,2
****    9202401,0.0,.829,8.05-3,1.02,/6/0.0
****    1202402,NE-21,0.0,1.0-30,1,1
****    9202402,/10/0.0
****    802411,5.332-3,0.0
        *      A=20 DECAY CHAINS
****    1202501,O-20,0.0,.0495,1,2
****    9202501,.9075,/4/0.0,1.06,/4/0.0
****    1202502,F-20,0.0,.063,1,2
****    9202502,1.7853,/8/0.0,1.63,/3/0.0
****    1202503,NE-20,0.0,1.0-30,1,1
****    9202503,/10/0.0
****    802511,5.71512-4,/2/0.0
****    1202601,F-20,0.0,.063,1,2
****    9202601,1.7853,/5/0.0,1.63,/3/0.0
****    1202602,NE-20,0.0,1.0-30,1,1
****    9202602,/10/0.0
****    802611,8.4453-3,0.0
****    1202701,NE-20,0.0,1.0-30,1,1
****    9202701,/10/0.0
****    802711,.03924
        *      A=19 DECAY CHAINS
****    1202801,O-19,0.0,.0239,1,2
****    9202801,1.25,0.0,.19109,/2/0.0,.3083,/4/0.0
****    1202802,F-19,0.0,1.0-30,1,1
****    9202802,/10/0.0
****    802811,1.079522-3,0.0
****    1202901,F-19,0.0,1.0-30,1,1
****    9202901,/10/0.0
****    802911,.0119356
****    1203001,NE-19,0.0,.0395,1,2
****    9203001,0.0,.74,0.0,1.02,/5/0.0
****    1203002,N-19,0.0,1.0-30,1,1
****    9203002,/10/0.0
****    803011,1.524-3,0.0
        *      A=18 DECAY CHAINS
****    1203101,N-18,0.0,1.1,1,2
****    9203101,3.102,/3/0.0,.4939,0.0,2.9535,1.0127,/2/0.0
****    1203102,O-18,0.0,1.0-30,1,1
****    9203102,/10/0.0
****    803111,2.54-4,0.0
****    1203201,O-18,0.0,1.0-30,1,1
****    9203201,/10/0.0
****    803211,3.176465-3
****    1203301,F-18,0.0,1.050223-4,1,2
****    9203301,0.0,.2032635,0.0,.7994,/6/0.0
****    1203302,O-18,0.0,1.0-30,1,1
****    9203302,/10/0.0
****    803311,.0162447,0.0
****    1203401,NE-18,0.0,.474759,1,2
****    9203401,0.0,1.104576,0.0,1.02,0.0,.0729,/4/0.0
****    1203402,F-18,0.0,1.050223-4,1,2
****    9203402,0.0,.2032635,0.0,.7994,/5/0.0
****    1203403,O-18,0.0,1.0-30,1,1
****    9203403,/10/0.0
****    803411,2.54-4,/2/0.0
        *      A=17 DECAY CHAINS
****    1203501,N-17,0.0,.016727,1,2
****    9203501,1.4,0.0,/2/0.0,.0251,/2/0.0,.01095,/2/0.0
****    1203502,O-17,0.0,1.0-30,1,1
****    9203502,/10/0.0
****    803511,1.90504-4,0.0
****    1203601,O-17,0.0,1.0-30,1,1
****    9203601,/10/0.0
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TABLE A-I (Cont.)

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****      803611,.0135259
****      1203701,F-17,0.0,.01950233,1,2
****      9203701,0.0,.5742,0.0,1.02,/5/0.0
****      1203702,O-17,0.0,1.0-30,1,1
****      9203702,/10/0.0
****      803711,1.651-3,0.0
          *       A=16 DECAY CHAINS
****      1203801,N-16,0.0,.0275,1,2
****      9203801,1.86067,0.0,/6/0.0,.0275,4.5852
****      1203802,O-16,0.0,1.0-30,1,1
****      9203802,/10/0.0
****      803811,1.016-3,0.0
****      1203901,O-16,0.0,1.0-30,1,1
****      9203901,/10/0.0
****      803911,.0582
          *       A=15 DECAY CHAINS
****      1204001,C-15,0.0,.3080554,1,2
****      9204001,2.049,0.0,/7/0.0,3.60332
****      1204002,N-15,0.0,1.0-30,1,1
****      9204002,/10/0.0
****      904011,6.35-5,0.0
****      1204101,N-15,0.0,1.0-30,1,1
****      9204101,/10/0.0
****      804111,.0262834
****      1204201,O-15,0.0,5.59-3,1,2
****      9204201,0.0,.5742,0.0,1.02,/5/0.0
****      1204202,N-15,0.0,1.0-30,1,1
****      9204202,/10/0.0
****      804211,4.-3,0.0
          *       A=14 DECAY CHAINS
****      1204301,C-14,0.0,3.8-12,1,2
****      9204201,.05148,/9/0.0
****      1204302,N-14,0.0,1.0-30,1,1
****      9204302,/10/0.0
****      804311,1.08-3,0.0
****      1204401,N-14,0.0,1.0-30,1,1
****      9204401,/10/0.0
****      804411,.052
****      1204501,O-14,0.0,2.74-3,1,2
****      9204501,0.0,.6041,0.0,1.02,/3/0.0,2.29,/2/0.0
****      1204502,N-14,0.0,1.0-30,1,1
****      9204502,/10/0.0
****      804511,6.35013-5,0.0
          *       A=13 DECAY CHAINS
****      1204601,C-13,0.0,1.0-30,1,1
****      9204601,/10/0.0
****      804611,.0239376
****      1204701,N-13,0.0,1.16-3,1,2
****      9204701,0.0,.396,0.0,1.02,/5/0.0
****      1204702,C-13,0.0,1.0-30,1,1
****      9204702,/10/0.0
****      804711,3.80961-3,0.0
          *       A=12 DECAY CHAINS
****      1204801,B-12,0.0,34.66,1,2
****      8204301,4.346,0.0,/7/0.0,.2551237
****      1204802,C-12,0.0,1.0-30,1,1
****      9204802,/10/0.0
****      804811,3.8101-4,0.0
****      1204901,C-12,0.0,1.0-30,1,1
****      9204901,/10/0.0
****      804911,.0483141
****      1205001,N-12,0.0,63.0134,1,2
****      9205001,0.0,5.3012,/7/0.0,.471
****      1205002,C-12,0.0,1.0-30,1,1
```

TABLE A-I (Cont.)

```
****      9205002,/10/0.0
****      805011,6.35013-5,0.0
          *     A-11 DECAY CHAINS
****      1205101,B-11,0.0,1.0-30,1,1
****      9205101,/10/0.0
****      805111,4.5056-3
****      1205201,C-11,0.0,5.539-4,1,2
****      9205201,0.0,.3201,0.0,1.02,/5/0.0
****      1205202,B-11,0.0,1.0-30,1,1
****      9205202,/10/0.0
****      805211,1.968543-3,0.0
          *     FINAL DECAY CHAINS
****      1205301,B-10,0.0,1.0-30,1,1
****      9205301,/10/0.0
****      805311,.01022372
****      1205401,LI-9,0.0,.9155,1,2
****      9205401,4.0095,/9/0.0
****      1205402,BE-8,0.0,1.0-30,1,1
****      9205402,/10/0.0
****      805411,6.35013-5,0.0
****      1205501,LI-7,0.0,1.0-30,1,1
****      9205501,/10/0.0
****      805511,5.715-4
****      1205601,BE-7,0.0,1.5137-7,1,2
****      9205601,0.0,0.0,.049131,/7/0.0
****      1205602,LI-7,0.0,1.0-30,1,1
****      9205602,/10/0.0
****      805611,4.-4,0.0
****      1205701,LI-6,0.0,1.0-30,1,1
****      9205701,/10/0.0
****      805711,4.6355-3
```

APPENDIX B

PRODUCTION CROSS SECTION AND DAMAGE ENERGY CALCULATIONS FOR 800-MeV PROTON IRRADIATED ALUMINUM

The results of the NMTC calculation described in Sec. III are given in Table B-I. The production cross sections required by CINDER are on the third through sixth page, and need only be normalized by summing over all the nuclides produced.

TABLE B-I

PRODUCTION CROSS SECTION AND DAMAGE ENERGY CALCULATIONS

FOR 800-MeV PROTON IRRADIATED ALUMINUM

THE NUCLEON-MESON TRANSPORT CODE AND THE LINDHARD THEORY HAVE BEEN USED TO ESTIMATE DAMAGE EFFECTS PRODUCED BY 800 MEV PROTONS INCIDENT NORMALLY ON A ALUMINUM TARGET 1.00 CM THICK. THE AVERAGES AND RMS VARIATIONS OBTAINED FOR SEVERAL DAMAGE-RELATED QUANTITIES FROM ANALYSIS OF 40 BATCHES OF 15000 PROTONS EACH ARE SHOWN BELOW.

QUANTITY	AVERAGE	RMS VARIATION
TOTAL CHARGED-PARTICLE DAMAGE ENERGY CROSS SECTION (BARN-KEV)	62.44460	12.69111
SPALLATION NUCLEUS DAMAGE ENERGY CROSS SECTION (BARN-KEV)	48.86297	9.45607
ENERGETIC PROTON COULOMB DAMAGE ENERGY CROSS SECTION (BARN-KEV)	10.11087	2.28380
SPALLATION NUCLEUS PRODUCTION CROSS SECTION (BARNS)	.43822	.09382
SPALLATION NUCLEUS RECOIL ENERGY CROSS SECTION (BARN-KEV)	1452.20271	291.02521
HEAVY NUCLEUS ELASTIC RECOIL ENERGY CROSS SECTION (BARN-KEV)	20.61368	4.49459
LIGHT NUCLEUS DAMAGE ENERGY CROSS SECTION (BARN-KEV)	3.47124	.75826
LIGHT NUCLEUS PRODUCTION CROSS SECTION (BARNS)	.96285	.20122
NEUTRON KINETIC ENERGY CROSS SECTION (BARN-MEV)	3.14502	.63033
NEUTRON PRODUCTION CROSS SECTION (BARNS)	.61244	.12569

THE AVERAGE KINETIC ENERGIES AND PRODUCTION CROSS SECTIONS FOR THE LIGHT PARTICLES AND LIGHT NUCLEI, TOGETHER WITH THE DAMAGE ENERGY CROSS SECTIONS FOR THE LIGHT NUCLEI, ARE GIVEN BELOW.

PARTICLE/NUCLEUS	AVERAGE KINETIC ENERGY (MEV)	PRODUCTION CROSS SECTION (BARNS)	DAMAGE ENERGY CROSS SECTION (BARN-KEV)
PROTON	10.67237	.7903310	2.492630
DEUTERIUM	10.67472	.5055612E-01	.2077269
TRITIUM	11.62694	.9088724E-02	.9110125E-01
HELIUM 3	14.24879	.8159836E-02	.1034319
HELIUM 4	9.004800	.9503841E-01	.6063103
NEUTRON	5.135216	.0620501 .612VV	
PI+	2.942768	.1731366E-01	
PI-	2.924417	.6927375E-02	
MU+	0.	0.	
MU-	0.	0.	

TABLE B-I (Cont.)

THE AVERAGE NUMBERS AND KINETIC ENERGIES OF PARTICLES ESCAPING THE BACK SURFACE OF THE TARGET PER INCIDENT PROTON ARE SHOWN IN THE FOLLOWING TABLE. AVERAGE MASS ENERGY LOSS IS ALSO GIVEN FOR THE MUONS AND PIONS.

PARTICLE	AVERAGE NUMBER PER PROTON	AVERAGE KINETIC ENERGY PER PROTON (MEV)	AVERAGE MASS ENERGY PER PROTON (MEV)
PROTON	1.057327	821.9313	
NEUTRON	.4024571E-01	6.666536	
PI+	.4012108E-02	.5905799	.4717814
PI-	.1108341E-02	.1144855	.1607756
MU+	0.	0.	0.
MU-	0.	0.	0.

THE TOTAL ELECTRONIC ENERGY LOSS CROSS SECTION IN THE TARGET IS .1218IE+03 BARN-MEV, WITH .99806E+02 BARN-MEV CONTRIBUTED BY ABOVE-CUTOFF LIGHT PARTICLES, .10157E+02 BARN-MEV CONTRIBUTED BY BELOW-CUTOFF LIGHT PARTICLES AND LIGHT NUCLEI, .10034E+00 BARN-MEV CONTRIBUTED BY SPALLATION NUCLEI, .10503E+05 BARN-MEV CONTRIBUTED BY ELASTICALLY-SCATTERED NUCLEI, AND .62605E+02 BARN-MEV CONTRIBUTED BY STOPPING TARGET NUCLEI. INDIVIDUAL CROSS SECTIONS FOR THE LIGHT PARTICLES AND NUCLEI ARE SHOWN BELOW.

PARTICLE	ELECTRONIC ENERGY LOSS CROSS SECTION (BARN-MEV)	ELECTRONIC ENERGY LOSS PER PROTON (MEV)
PROTONS AND ABOVE-CUTOFF LIGHT PARTICLES		
PROTON	98.17651	5.913956
PI+	1.025757	.6178958E-01
PI-	.2839189	.1710271E-01
MU+	0.	0.
MU-	0.	0.
LIGHT NUCLEI AND BELOW-CUTOFF PROTONS		
PROTON	8.517591	.5130827
DEUTERIUM	.5391614	.3247801E-01
TRITIUM	.1168807	.[illegible]7608E-02
HELIUM 3	.1105320	.6099203E-02
HELIUM 4	.8699865	.52406[illegible]E-01

THE TOTAL MASS ENERGY LOSS PER INCIDENT PROTON DUE T[illegible] CH[illegible]GED PIONS AND MUONS DECAYING WITHIN THE TARGET IS .5722653E-03 MEV. THE CONTRIBUTIONS OF THE INDIVID[illegible]L PARTICLES ARE GIVEN IN THE FOLLOWING TABLE.

PARTICLE	MASS ENERGY LOSS PER PROTON (MEV)
PI+	.[illegible]730360E-03
PI-	.9922928E-04
MU+	0.
MU-	0.

TABLE B-I (Cont.)

THE PRODUCTION CROSS SECTION, RMS VARIATION IN THE PRODUCTION CROSS SECTION, AVERAGE KINETIC ENERGY, RMS VARIATION AND SKEWNESS IN THE KINETIC ENERGY, AND MAXIMUM AND MINIMUM KINETIC ENERGY ARE GIVEN BELOW FOR EACH SPALLATION NUCLEUS, IN ORDER OF DECREASING A/INCREASING Z. (PAGE 1/ 4)

A	Z	PRODUCTION CROSS SECTION (MBARN)	RMS VARIATION IN CRSSEC (MBARN)	AVERAGE KINETIC ENERGY (MEV)	RMS VARIATION IN ENERGY (MEV)	SKEWNESS	MAXIMUM KINETIC ENERGY (MEV)	MINIMUM KINETIC ENERGY (MEV)
27	12	3.125695	1.710895	.027207	.083891	2.117611	2.618190	.017637
27	13	10.850999	2.128145	.605729	.614592	1.913145	3.496651	.014862
27	14	2.792558	1.917418	.788853	.668668	1.534235	2.709948	.065479
27	15	.055336	.241204	1.375159	.054883	0.000000	1.429162	1.321156
26	11	.390348	.552668	.983907	1.152330	1.401931	3.574237	.063671
26	12	52.254686	8.791715	.443701	.597181	4.811367	6.236677	.008888
26	13	30.894615	3.480228	.820387	.832337	3.217190	9.290825	.041195
26	14	.913805	.954848	.954833	.832107	1.375414	3.380317	.018394
26	15	.027668	.172787	2.560257	0.000000	0.000000	2.560257	2.560257
25	10	.110672	.332016	2.851793	1.713145	.275122	5.398887	.639366
25	11	4.285548	1.529519	1.226500	1.874615	2.[illegible]4538	7.356255	.031069
25	12	41.552186	5.997877	1.343928	1.197186	2.727126	13.369883	.003280
25	13	5.116662	1.252481	1.192260	1.122518	2.036602	7.733121	.037700
25	14	.359688	.797580	2.463005	2.817171	1.657177	10.006300	.056363
25	15	.055336	.241204	2.568688	2.102428	0.000000	4.663112	.058256
24	9	.027668	.172787	1.670891	0.000000	0.000000	1.670891	1.670891
24	10	1.133565	1.198888	1.688128	1.239284	.488378	4.503065	.078812
24	11	9.599662	2.702444	1.520285	1.585951	1.980571	9.711940	.015637
24	12	30.220479	5.814596	1.653353	1.613018	2.766512	10.460934	.011626
24	13	1.104352	.958092	1.813898	1.455169	1.955531	7.672075	.255538
24	14	.221344	.402608	2.052201	2.110107	1.272843	7.642601	.025417
23	9	.137442	.363673	2.000071	1.476356	.920187	4.710811	.295412
23	10	2.260778	1.463008	2.326332	2.046988	1.535161	9.172488	.040265
23	11	20.877015	4.227473	2.161804	2.197457	2.213632	20.312031	.002997
23	12	3.096952	1.467996	2.393421	2.275269	2.750494	16.489738	.001630

TABLE B-I (Cont.)

THE PRODUCTION CROSS SECTION, RMS VARIATION IN THE PRODUCTION CROSS SECTION, AVERAGE KINETIC ENERGY, RMS VARIATION AND SKEWNESS IN THE KINETIC ENERGY, AND MAXIMUM AND MINIMUM KINETIC ENERGY ARE GIVEN BELOW FOR EACH SPALLATION NUCLEUS, IN ORDER OF DECREASING A/INCREASING Z. (PAGE 2/ 4)

A	Z	PRODUCTION CROSS SECTION (MBARN)	RMS VARIATION IN CRSSEC (MBARN)	AVERAGE KINETIC ENERGY (MEV)	RMS VARIATION IN ENERGY (MEV)	SKEWNESS	MAXIMUM KINETIC ENERGY (MEV)	MINIMUM KINETIC ENERGY (MEV)
23	13	.384348	.494167	2.656378	1.443439	.979999	6.069710	.782092
22	7	.027668	.172787	11.454000	0.000000	0.000000	11.454000	11.454000
22	8	.055336	.241204	9.723479	3.707063	0.000000	13.430542	6.016416
22	9	.332016	.664033	3.381633	2.836816	1.251506	10.542266	.189725
22	10	5.640573	1.634320	2.876792	2.458848	1.822687	15.541580	.040027
22	11	23.652096	.252017	2.987682	2.482778	1.687146	16.786008	.071153
22	12	.553361	.782570	2.829518	2.433752	1.298777	9.118328	.118181
22	13	.138348	.366816	1.898459	2.346727	1.458265	6.557176	.459081
21	7	.027668	.172787	3.008878	0.000000	0.000000	3.008878	3.008878
21	8	.083004	.291501	2.523367	.478858	.543867	3.878879	1.575010
21	9	.774785	.964817	2.752853	2.251885	2.062333	11.287813	.024680
21	10	19.859979	2.650167	3.588526	3.124471	1.920179	21.553852	.004602
21	11	2.323220	1.327406	3.869835	4.048625	2.874948	26.168965	.220045
21	12	.249012	.524234	4.378149	2.440172	.328879	9.[illegible]8281	.252510
20	8	.249012	.462107	2.672249	1.407684	.230179	4.085299	.510000
20	9	3.679676	1.756467	4.326208	4.130247	1.940899	21.595858	.053108
20	10	17.096817	3.354589	4.107017	3.981973	2.287128	26.640828	.023615
20	11	.304348	.741095	5.708297	5.704718	1.325866	20.019468	.363958
19	6	.055336	.241204	10.351841	5.012591	.000000	15.364032	5.339250
19	8	.470356	.680466	4.768528	2.935749	.862180	10.635680	.023461
19	9	5.200866	2.574050	4.551928	3.965315	1.880[illegible]18	26.139507	.055779
19	10	.664033	.850809	5.126240	5.206744	2.655461	26.080476	.376206
19	11	.083004	.291501	1.643775	.772086	-.707107	2.189666	.551998
18	7	.110672	.332016	6.898996	4.247613	.135789	13.165408	1.022032
18	8	1.383401	1.042611	5.796121	3.329410	.918051	14.781661	.031131

TABLE B-I (Cont.)

THE PRODUCTION CROSS SECTION, RMS VARIATION IN THE PRODUCTION CROSS SECTION, AVERAGE KINETIC ENERGY, RMS VARIATION AND SKEWNESS IN THE KINETIC ENERGY, AND MAXIMUM AND MINIMUM KINETIC ENERGY ARE GIVEN BELOW FOR EACH SPALLATION NUCLEUS, IN ORDER OF DECREASING A/INCREASING Z. (PAGE 3/ 4)

A	Z	PRODUCTION CROSS SECTION (MBARN)	RMS VARIATION IN CRSSEC (MBARN)	AVERAGE KINETIC ENERGY (MEV)	RMS VARIATION IN ENERGY (MEV)	SKEWNESS	MAXIMUM KINETIC ENERGY (MEV)	MINIMUM KINETIC ENERGY (MEV)
18	9	7,077930	2,087475	5,256176	4,567727	1,356687	23,133650	,099550
18	10	,110672	,332016	8,252067	10,580624	,993092	25,976720	,353153
17	6	,055336	,241204	23,768425	0,000000	-,000000	23,768425	23,768425
17	7	,083004	,382380	4,087135	3,244801	,438198	8,423374	,663483
17	8	5,093290	2,068816	5,746032	5,685[illegible]23	2,841937	43,658368	,063856
17	9	,719369	1,006751	5,107339	3.391125	,876238	13,564450	,766239
16	7	,442688	,691147	7,768396	7,147387	1,182182	26,854669	,302607
16	8	25,364000	2,045032	5,966244	5,168228	1,650679	30,095272	,022375
15	6	,027668	,172787	4,179051	0,000000	0,000000	4,179051	4,179051
15	7	11,451070	1,076617	6,768184	6,159359	1,977778	39,318555	,052394
15	8	1,741707	1,158541	7,523140	5,527624	1,666806	31,937101	,508434
14	6	,470356	,695013	8,172535	7,183127	1,250981	25,725409	,649151
14	7	22,657498	4,328465	7,191339	6,083651	1,560204	40,902760	,151785
14	8	,027668	,172787	25,857253	0,000000	,000000	25,857253	25,857253
13	6	10,429797	3,019373	8,287517	6,814165	1,132264	33,420622	,151750
13	7	1,659026	,892140	7,921743	7,841377	2.325243	39,237832	,193296
12	5	,166000	,466270	14,162163	5,855485	,297582	24,282871	6,760077
12	6	21,858823	1,500859	8,253851	8,838405	2,993141	89,638844	,025071
12	7	,027668	,172787	5,1[illegible]285	0,000000	-,000000	5,100285	5,100285
11	5	1,964430	1,474215	11,635806	8,753417	1,702784	49,034920	,591701
11	6	,857709	,908843	10,988433	7,714949	1,549913	33,382007	1,09[illegible]00
10	5	4,454552	2,135821	11,203550	7,481132	,855926	32,453[illegible]50	,667161
9	5	,027668	,172787	6,776562	0,000000	,000000	6,776562	6,776562
8	3	,027668	,172787	5,655562	0,000000	,000000	5,655562	5,655562
7	3	,249012	,524234	16,396606	12,416333	,006879	39,492349	2,882910
7	4	,027668	,172787	9,054827	0,000000	,000000	9,054827	9,054827
6	3	2,019766	1,375354	8,730610	6,624577	1,196823	30,930270	,203526
6	4	,027668	,172787	5,115070	0,000000	0,000000	5,115070	5,115070
6	5	,083004	,382380	3,755730	1,597260	,784929	6,013823	2,575500

TABLE B-I (Cont.)

DAMAGE ENERGY CROSS SECTIONS FOR THE SPALLATION NUCLEI IN ORDER OF DECREASING A/INCREASING Z. (PAGE 1/ 2)

A	Z	DAMAGE ENERGY CROSS SECTION (BARN-KEV)	A	Z	DAMAGE ENERGY CROSS SECTION (BARN-KEV)	A	Z	DAMAGE ENERGY CROSS SECTION (BARN-KEV)
27	12	.2692710	23	13	.8813406E-01	18	9	.7684312
27	13	1.478488	22	7	.3169096	18	10	.1141431E-01
27	14	.3538288	22	8	.7554707E-02	17	6	.5227503E-02
27	15	.9676547E-02	22	9	.4805321E-01	17	7	.7078612E-02
26	11	.3231325E-01	22	10	.7146603	17	8	.5666081
26	12	8.316855	22	11	3.166938	17	9	.7578056E-01
26	13	3.598765	22	12	.7553280E-01	16	7	.3769446E-01
26	14	.1160576	22	13	.2615263	16	8	2.323009
26	15	.7803727E-01	21	7	.8324950E-01	15	6	.2050665E-02
25	10	.1614383E-01	21	8	.9391861E-02	15	7	.9210613
25	11	.5116251	21	9	.8934898E-01	15	8	.1560709
25	12	4.971360	21	10	2.584074	14	6	.3258780E-01
25	13	.6638628	21	11	.3084259	14	7	1.719704
25	14	.5166771E-01	21	12	.3625560E-01	14	8	.2576015E-02
25	15	.1416982	20	8	.2648562E-01	13	6	.6834219
24	9	.3562813E-02	20	9	.4274766	13	7	.1176385
24	10	.1369292	20	10	2.885389	12	5	.9833563E-02
24	11	1.160170	20	11	.3940658E-01	12	6	1.258730
24	12	4.543033	19	6	.5728301	12	7	.1834352E-02
24	13	.1612738	19	8	.5112918E-01	11	5	.1800332
24	14	.6313182	19	9	.5828457	11	6	.4000898E-01
23	9	.1622129E-01	19	10	.8045045E-01	10	5	.2044695
23	10	.2828746	19	11	.9207699E-02	9	5	.1148221E-02
23	11	3.794123	18	7	.1075111E-01	8	3	.5890753E-03
23	12	.4326049	18	8	.1446554	7	3	.5075546E-02
7	4	.7653759E-03	6	4	.6242478E-03	6	5	.3117409
6	3	.3807085E-01						