BROOKHAVEN NATIONAL LABORATORY
Associated Universities, Inc.
Upton, L.I., N.Y.

DEPARTMENT OF APPLIED SCIENCE
Informal Report

A PRELIMINARY NEUTRON FOIL DOSIMETRY CHARACTERIZATION
OF THE BLIP NEUTRON FACILITY

Don M. Parkin

and

Norman D. Dudey,* R. R. Heinrich* and M. J. Fluss*

August 29, 1973

*Argonne National Laboratory

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

**A PRELIMINARY NEUTRON FOIL DOSIMETRY CHARACTERIZATION
OF THE BLIP NEUTRON FACILITY**

Don M. Parkin

and

Norman D. Dudey, R. R. Heinrich and M. J. Fluss

ABSTRACT

The Brookhaven Linac Isotope Producer (BLIP) produces neutrons from 200 MeV proton bombardment of a transparent (relative to 200 MeV protons) Be target. Neutron foil Dosimetry techniques were utilized to characterize the BLIP neutron spectra which includes neutrons with energies greater than 15 MeV. Some operational characteristics of spallation neutron sources were also determined. The derived BLIP neutron spectrum has a hard component (neutrons between 6-12 MeV which peaks at 8-9 MeV) and a soft component characteristic of neutron scattering. Between 10 and 30% of the neutrons have energies below 0.25 MeV and less than 0.1% of the neutrons have energy in excess of 15 MeV. The derived neutron flux is $8.0 \pm 3 \times 10^9$ n/cm² μ C.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

149

I. Introduction

The Brookhaven Linac Isotope Producer (BLIP) is a facility designed to utilize a surplus of the 200 MeV proton beam from the LINAC injector to the AGS. An isometric view of the facility is shown in Fig. 1. The source of neutrons for the CTR irradiation program is a transparent (relative to 200 MeV protons) Be target. The goal of this effort was to establish the necessary techniques to construct targets suitable for dosimetry measurements, characterize the BLIP neutron spectra, and obtain experience in the operation of spallation neutron sources utilizing high energy proton beams. Considerable experience and insight were gained in these areas and the results and conclusions are presented in this report.

II. Dosimetry Target

Beryllium was chosen as the target material because calculations indicated that a higher energy neutron source spectrum was expected from Be than for heavier elements. Available target space in the existing BLIP target guide tubes and the proton beam size required that the Be target be a cylinder of dimensions 0.75 in. thick and 1.5 in. diameter. To shield the dosimetry foils from the spallation proton flux, the Be core was surrounded with a 0.25 in. ring made of a high density tungsten alloy. This target package was positioned on the target axis by an aluminum holder and then sealed by two 0.010 in. aluminum windows. These windows were later

used to provide ^{22}Na activation samples for determining the focus of the proton beam. A drawing of the target is shown in Fig. 2. For irradiation, the target was sealed in a stainless steel jacket which provided a 0.04 in. duct of cooling water on each face of the target (see Fig. 3).

III. Characterization of the BLIP Neutron Spectrum

The primary intent of the dosimetry study was to characterize the neutron flux intensity and spectrum in a region close to the Be target which potentially might be utilized for studying neutron irradiation effects. At the outset, estimates of the neutron flux and spectrum were derived from internuclear cascade calculations. These estimates were considered sufficiently uncertain and therefore measurements were required to characterize the environment. It was decided to utilize the measurement techniques developed for fast-reactor dosimetry. As these techniques are optimized for neutron energies below 10 MeV, an important aspect of the BLIP measurements was to determine the extent to which these dosimetry techniques might be applicable to higher energy neutron fields more typical of anticipated CTR neutron spectra. Spallation neutron sources (such as BLIP) were expected to produce sizable neutron fluxes up to 14 MeV as well as flux components at energies considerably higher than 14 MeV. This program was concerned not only with the application of existing dosimetry method to neutrons in the 14 MeV energy range

but also with neutrons above 14 MeV.

To utilize the procedures and techniques developed for fast-reactor dosimetry for spectral characterization of BLIP the ANL dosimetry group was asked to participate in the program. The physical arrangement of the BLIP facility precluded any direct measurement technique other than foil activation. Because of their compact size, compatibility with hostile environments, their non-interacting nature, and, in general, their wide range of utilization, foils and the foil-activation methods have become nearly the exclusive means for monitoring the flux and spectra of neutron irradiation experiments. For this reason a brief presentation of this technique is presented to clarify the later discussion.

The method is to irradiate materials (foils) which produce neutron reaction products whose reaction rates have differing sensitivity to neutrons as a function of neutron energy. For convenience, reaction products are chosen which can be counted by absolute gamma-ray spectroscopy. A computer code, SAND-II,⁽¹⁾ has been developed to iteratively deduce the neutron flux and spectrum from the measured data by the following algorithm: An input spectral shape (distribution) is chosen as the best estimate for the analysis. This distribution is partitioned into 621 energy groups between 0-18 MeV. A library of differential cross-section data is required (in the same group structure) for each

reaction to be used in the analysis. The trial input spectrum is multiplied by the cross section, on a group by group basis, and the product summed to provide a calculated reaction rate. This is done individually for each reaction. The ratio of measured to calculated reaction rate is computed for each reaction and the standard deviation of these ratios is computed. Based upon the fact that each reaction has a different sensitivity to the assumed neutron energy distribution, a weighting function is computed which enables the initial spectrum to be adjusted such that the overall measured/calculation standard deviation is reduced. This iterative process is continued until either the desired standard deviation of the measured to calculation ratio is achieved (consistent with the accuracy of the measured data) or until improvement cannot be achieved by further iteration of the spectrum. The final 621 energy groups are typically collapsed into, e.g., 29 groups which describes the spectrum, and the integral of all groups represents the flux intensity.

The accuracy of the final results are dependent upon (1) the accuracy of the cross sections used in the analysis, (2) the accuracy of the measured reaction rates, (3) the initial choice of input spectrum, and (4) the selection of reaction rates used. The last item is always a compromise determined by the half-lives of

the reaction products, the spectra and flux to be measured, and the availability of cross sections. All of these are superseded by the requirement to maintain a set of foils which have differing, yet overlapping, responses to different portions of the neutron spectrum. These four main items define the utility and limitations of the foil technique and will be referred to often in the remaining discussion.

III-1. Experimental Measurements

One of the initial problems in designing experiments to characterize BLIP was the lack of detailed information on the trial or input spectrum. The internuclear cascade calculation provided a basis for estimating the spectrum; however because these results were given in energy groups of 10 MeV not enough information was available to outline the spectrum below 10 MeV where the most detail was necessary. This complicated the analysis as well as efforts to identify the proper foils to use. Therefore, the first BLIP irradiation (BLIP-I) was designed to provide a rough estimate of the flux and spectrum, and secondarily, to ascertain the significance of the neutrons above 18 MeV, the analysis limit in SAND-II as it is conventionally used. Since virtually all experience with the spectral-unfolding techniques were associated with degraded fission spectra, the first question to answer was the applicability of the technique to spallation reactions.

The first test was to measure the neutron spectrum produced by 15 MeV deuterons on a thick beryllium target. This neutron spectrum had recently been measured at ANL⁽²⁾ and other laboratories⁽³⁾ by time-of-flight techniques and represented a bench mark with which to test the foil technique in a spallation (although less than 18 MeV) type neutron environment. The dc beam of the ANL tandem accelerator was used. The flux levels were of the order of 5×10^9 n/Ω·μC which dictated that only short-lived reaction products could be used in order to achieve adequate counting rates. Seven reactions were measured: $^{63}\text{Cu}(n,\gamma)$, $^{63}\text{Cu}(n,2n)$, $^{197}\text{Au}(n,\gamma)$, $^{197}\text{Au}(n,2n)$, $^{115}\text{In}(n,n')$, $^{115}\text{In}(n,\gamma)$, and $^{56}\text{Fe}(n,p)$. The foils were irradiated for 4 hours, counted on absolute calibrated Ge(Li) detectors, reduced to saturated activities (disintegrations per second/target atom) and analyzed by SAND-II. The ANL 16 MeV T-O-F spectra were used as input, and the final results are compared with the instrumentally measured results in Fig. 4. For neutron energies above 1 MeV the agreement is excellent, demonstrating the validity of the foil activation and spectral unfolding techniques.

Several comments regarding these results as they relate to the BLIP experiments are appropriate. First, the reactions, chosen for this test experiment had cross sections that were well established. Second, an independent experimentally measured input spectrum, the T-O-F result, was available not only as a trial solution but as a

bench mark to compare with the SAND-II result. Third, five of the seven reactions used have half-lives <1 day which would indicate that for normal dosimetry experiments in BLIP or for purposes of monitoring irradiation experiments they would not be useful. The final factor is that no neutrons were expected with energy greater than about 18 MeV whereas neutrons exceeding 50 MeV may be present in BLIP.

The 16 MeV deuteron spectrum was used as the estimate for the BLIP-I scoping experiment. Foils of Au, ^{237}Np , Ti, ^{238}U , ^{235}U , and Al were irradiated for ~16 hours in BLIP on March 6, 1973. The dosimetry foils were placed around the 2 in. diameter BLIP target core. A second gold foil was also included in the experiment and wrapped around the hub of the target to measure the flux asymmetry around the target. It was cut into 45° (acceptance angle) lengths to determine this factor. The sample counts indicated significantly higher activity levels than anticipated and further analysis indicated reaction products in the monitor foils which were suggestive of proton interactions. From the gold symmetry foil we determined the region around the target in which proton interactions appeared to be minimal. Only the Ti, Au, ^{237}Np , and ^{235}U monitor foils were considered usable due to the proton spillage onto the remaining dosimeters.

The foil data were reduced to saturated activities and analyzed by SAND-II. The input spectrum for SAND-II was that of

1.6 MeV deuterons on Be for neutrons above 1 MeV, extrapolated below 1 MeV by a $1/E$ form. These results provided the basis for subsequent BLIP-II irradiation. The BLIP-I result was used in designing the foil weights and reactions to be used in the BLIP-II experiment. In BLIP-II all dosimetry foils were stacked into a single package and placed on the Be target at the location expected to have a minimum of proton spillage. Foils of Au, Ti, ^{235}U , ^{232}Th , ^{237}Np , Ni, and Al were used. A gold wire was also wrapped around the target in BLIP-II to measure the asymmetry of the neutron flux.

III-2. Dosimetry Results

A. Modification to SAND-II

The normal SAND-II code is limited to the analysis of neutron spectra less than 18 MeV. Should a significant number of neutrons above 18 MeV be present, the analysis could be distorted. Thus, prior to the analysis of the BLIP-II data, we proceeded to extend the code to accommodate neutrons up to 50 MeV. This was accomplished by rearranging the group structure above 1 MeV (below 1 MeV no changes were made). These changes required reconstruction of the cross-section library to conform to the new 600 energy group structure. The major difficulty was the lack of cross-section data above 20 MeV for most of the reactions of interest. When available, the high energy cross sections were taken from the literature (an exhaustive literature search was not carried out).

If no data were available, the cross sections were estimated by extrapolation according to the generally expected shapes.

The mechanics of the extended SAND-II code were tested in the following manner: Reaction-rate data measured in a degraded fission neutron spectrum were analyzed in both the normal and extended versions of the code. The same input spectrum was used in both cases. The derived flux from the two versions of SAND-II agreed to within $\leq 1\%$ for both the integral derived flux and individual group flux (spectra) values. Thus the modified version provides identical analysis for neutron spectra below 18 MeV. Above 18 MeV the results will be influenced by cross section uncertainties but the mechanics of the code have been demonstrated to operate correctly.

B. Results from the BLIP-I and BLIP-II Tests

Table I lists the dosimetry reactions used to monitor the spectra for the two tests, summarizes the reaction rates which we measured by absolute Ge(Li) gamma counting, and shows a comparison of the reaction-rate ratios for the two tests. The ^{22}Na activities shown in Table I are relative counts, measured from the aluminum window which covered the Be target area. The measurements were made directly over the dosimetry foils and represents a measure of the primary proton beam which may have struck the foils. Table II presents some parameters relative to the characteristics

of the proton beam which are useful in comparing the two different irradiations. Figure 5 shows the results of the SAND-II analysis of the neutron spectra for BLIP-I and BLIP-II. The former was derived from the 5 reaction rates given in Table I together with the 16 MeV (d+Be) neutron spectrum. The latter used the BLIP-I result as input and the 8 reaction rates given in Table I. The normal SAND-II code was used for BLIP-I and the extended version was used for BLIP-II. The same spectral data are tabulated in Tables III and IV. Note that the units are different in the two spectral tables, BLIP-I being time integrated flux (fluence) per MeV (Table III), and for BLIP-II the units are flux per MeV (Table IV).

The results of the gold flux asymmetry foil and wire which were wrapped around the Be target are presented in Table V. Both the (n,γ) and $(n,2n)$ reactions were measured in BLIP-I and these two reactions plus the $(n,4n)$ reaction were measured in BLIP-II. The BLIP-I foil was 0.5 mil thick, whereas for BLIP-II, a wire of 15 mil diameter was used. There is evidence to suggest that neutron self-shielding influences are present in the 15 mil diameter wire which could result in a reduction in the (n,γ) reaction rate. Neutron self-shielding is to be expected if the majority of the (n,γ) activation occurs from low energy neutrons as suggested by our derived spectrum for BLIP-II. The magnitude can

be accurately determined from the 0.5 mil foil which was irradiated within the dosimetry packet. The magnitude of the foil (n, γ) reaction rate when compared to that of the wire indicates that the wire reaction rate is less than the foil by a factor of 2.4. This correction was made to the wire data presented in Table V. The data in Table V have been normalized to unity for the (n, γ) reaction rate at the location of the dosimetry foil packets, so the reaction rates shown represent the relative number of atoms as a function of location and reaction-type which occurred in the gold.

C. Discussion of Results

1. Incident Proton Beam Interference - A major complication to the interpretation of both BLIP experiments comes from the possibility of direct proton interactions with the dosimetry foils. This problem was most evident in BLIP-I in which spallation product activities of W and Ta were observed in the gold foils. Care was taken to minimize this problem for BLIP-II, but it was not entirely eliminated. Pieces of the aluminum window which were directly over the dosimetry foils were gamma counted in order to estimate the extent of this effect. The ^{22}Na activity has been used as a monitor for the proton fluence on the foils, and the neutron fluence, of course, determined from the foils themselves. The ratio of neutron to proton fluence in BLIP-I was 13 and for BLIP-II was about 165 at the location of the dosimetry foil packets. However, this

ratio was not constant around the target, hence, interpretation of the gold asymmetry foil data was complicated. Proton interactions interfere primarily with the (n,xn) reactions because a $[p,p(x-1)n]$ reaction produces the same product. Therefore, proton interference will tend to make the $(n,2n)$ reaction appear too large, whereas the (n,γ) reaction is unaffected by this interference. The interpretation of this type of an effect will result in an erroneous "harder" spectrum than would exist if no protons were present.

2. Gold Asymmetry Foils (See Table V) - Considering first the (n,γ) reaction (which is primarily sensitive to neutrons below $\sim 1-2$ MeV) we see neutron flux asymmetries of less than a factor of 2 around the Be target. This asymmetry is attributed to the proton beam not being centered on the Be target. Looking next at the $(n,2n)$ data we see asymmetries of 20:1 for BLIP-I and 50:1 for BLIP-II. The $(n,2n)$ reaction can be produced either from neutrons of energy greater than ~ 8 MeV, from the (p,pn) reaction, or both. However, we would expect the (p,pn) cross section for 200 MeV protons to be at least a factor of 10 less than the $(n,2n)$ cross section.

In the BLIP-II test we were able to measure the $(n,4n)$ reaction from the gold asymmetry foils. The threshold for this reaction is 23 MeV so it is primarily sensitive to neutrons of energy greater than 25-28 MeV. This same reaction product could

have been produced by the (p,p3n) reaction on gold. Given the neutron spectrum we derive for BLIP-II (<.02% of the neutrons exceed 25 MeV), and the fact the (n,4n) reaction rate is only a factor of 2-3 less than the (n,2n) reaction all around the rim, it is tempting to conclude that proton interferences are contributing greatly to the asymmetries in these two reactions.

3. Proton Beam and Geometrical Effects - The incident 200 MeV proton beam struck the Be target at somewhat different locations in the two BLIP irradiations. Figure 6 is a sketch of where the center of the two beam spots were located; the quadrant nomenclature and foil locations are also shown. These spots were located by an analysis of the dosimetry foils as well as the ^{22}Na activity of the Al window. This conclusion is consistent with the following observations. The total integrated neutron flux/ μC in BLIP-I is twice the value for BLIP-II, but the flux above 1 MeV is 10 times larger. Clearly, proton spillage on the foils contributes to the harder derived spectrum in irradiation I. If the beam profiles are comparable in the two irradiations and if I was centered closer to the foils, then more spillage on the dosimetry foils is expected.

If the BLIP II beam was located ~ 4 cm from the foils and near the edge of the Be target and BLIP-I was ~ 3 cm from the foils and near the center of the target, the flux ratio and differing

spectra can be accounted for within experimental error by secondary source and geometry considerations. The primary neutrons produced in the Be from BLIP-II transversed 30% more material in reaching the foils than for BLIP-I. Thus, in II we would expect considerably more scattering which in turn would be more evident from the higher energy neutrons, the result being a lower $\phi/\mu C$ for >1 MeV neutrons than for >1 MeV neutrons. The gold asymmetry data support this idea. The (n,γ) rates are ~50% higher at 4Q1 compared to 2Q1 (see Fig. 6), yet the $(n,2n)$ is 50 times higher in BLIP-II compared to 20 times in BLIP-I. Finally, the $(n,4n)$ reaction rate is a factor of 80 times greater at 4Q1 vs 2Q1. A further and important contribution to the low energy neutron component comes from proton bombardment of material components of the target capsule other than the Be. The BLIP-II beam was not centered on the Be and a large fraction of the beam would strike the tungsten and stainless steel parts of the capsule. The neutron spectra from these secondary sources would be lower in energy than that from Be and contribute to the neutron flux below 1 MeV.

4. Accuracy of the Derived Flux and Spectra - The above arguments explain why the BLIP-I and II spectra might be expected to differ, thus comparisons of the two spectra are not a valid test of accuracy. Considering the portion of the spectra above ~15 MeV we have two major sources of uncertainty: proton

interference (which is much greater for BLIP-I) and the uncertainty in the extended SAND-II cross sections. Thus we could expect uncertainties of the order of 2 or 3 above 15 MeV.

Between 0.25 and 15 MeV the cross-section data are considered reliable. The principal uncertainty here resides in the accuracy of the reaction rate data, ± 5 -10%, and the sensitivity to the input spectrum, ± 20 %. In general, we expect this region to be reliable to about ± 30 %.

Below 0.25 MeV the major uncertainty is sensitivity to the input spectrum. This occurs, for the most part, because only two low energy dosimetry reactions were used, coupled with the fact that we had no indication as to what to expect in this region prior to the experiments.

Because of little prior knowledge regarding the spectrum, we have out of necessity, taken a bootstrap approach; that is, the neutron spectra from 16 MeV deuterons on beryllium, extrapolated by a $1/E$ form below 1 MeV, was used as the input to BLIP-I. The BLIP-I spectrum was derived using the normal SAND-II cross sections. This output was then used as input for analysis of BLIP-II via the energy-extended SAND-II code. The bootstrapping was continued by using the BLIP-II output as input for reanalysis of BLIP-I data by the energy-extended SAND-II. This output was introduced as input for BLIP-II analysis. The results of the BLIP-II

spectrum from the first pass and the bootstrapped pass are both tabulated in Table IV. The only sizable change is seen to occur in the spectrum above 30 MeV but because the flux levels are so low in this region (and the reaction rates are very insensitive) these differences are not necessarily significant. The preferred approach would be to run a third irradiation, including more low energy monitors, and bootstrap with BLIP-II and III data.

In summary, we believe the derived flux/ μ C to be accurate to 30-50%. Between 0.25 MeV and 15 MeV the group fluxes are probably good to ± 30 -50% and above and below this region errors as large as 2-3 could be present in the group flux values.

5. Cross Sections and Reaction Rates - A total of 13 reaction rates were measured in the BLIP-II test, yet, only eight could be adequately analyzed in SAND-II. The problems associated with the other five are apparently due to cross section and fission yield problems. The two $\text{Ti}(n,p)$ reaction rates are considered very accurate, the fact that these data are not consistent with the derived spectra is probably due to the cross section sets in SAND-II. Inconsistencies between integral and differential cross sections for ^{46}Ti and ^{47}Ti have been observed also in fast reactor dosimetry measurements. The current ENDF/B data file is expected to contain revised cross sections for the $^{46}\text{Ti}(n,p)$ reaction. The problem with $^{58}\text{Ni}(n,2n)$ may be due to cross sections and/or proton interferences. This reaction is not commonly used in reactor dosimetry so

the cross sections have not been carefully evaluated. It does have a response function which makes it ideal for the harder, spallation-type neutron sources so further evaluations of these cross sections are desirable.

The difficulties with the ^{238}U and ^{232}Th fission reactions probably reside in the fission yields. Above 1 MeV very little information is available on the energy dependence of fission yields. We have used ^{140}Ba as a monitor, which is on the peak of the heavy mass fission yield of ^{235}U , ^{238}U , and ^{239}Pu . For this reason we would expect its sensitivity to spectra to be minimal, but changes of a few % (lower) are certainly probable. The value for the ^{140}Ba fission yield from ^{232}Th which we used was 5.5%. This value might be expected to increase somewhat with increasing neutron energy. Proton induced fission of ^{232}Th and ^{238}U could be contributing to the problems we are experiencing for these reactions. The neutron cross sections for the fission reactions are considered to be reliable and are not thought to be the source of the problem. Both ^{238}U and ^{232}Th fission rates are very important in spectral determination of high energy neutron spectra. We recommend that some research effort be devoted to establishing the energy dependence of e.g. ^{140}Ba , ^{95}Zr , and ^{137}Cs fission yields for ^{235}U , ^{239}Pu , ^{237}Np , ^{238}U , and ^{232}Th over the energy range 1-30 MeV.

IV. Conclusions

1. The BLIP Facility

The neutron spectrum in the BLIP facility (using 200 MeV protons and a Be target) has two principal components. A hard component (neutrons between 6-12 MeV which peaks at 8-9 MeV) and a soft component characteristic of neutron scattering from the H₂O surrounding the target. Between 10 and 30% of the neutrons have energies below 0.25 MeV and less than 0.1% of the neutrons have energy in excess of 15 MeV.

The neutron flux intensity and neutron spectrum are dependent on the behavior of the proton beam. This results because of the very close geometrics and variations in the position, uniformity and size of the proton beam. These facts make it difficult to estimate the neutron flux or spectrum within BLIP on the basis of the proton beam current. Complete neutron dosimetry will be required for each irradiation experiment in BLIP. This does not mean that BLIP cannot be used as a fast neutron irradiation facility, it simply requires that each experiment has individual monitoring. Furthermore, under the existing experimental arrangements, the direct proton beam incident upon an experiment may be 2-3% of the neutron beam.

The flux intensity and spectral characterization in the work to date is of the accuracy of about $\pm 50\%$. Future measurements

in BLIP could approach 20-30% accuracies.

2. Foil Dosimetry Technique

The most significant conclusion regarding CTR dosimetry measurements that this work has shown is that extension of fast-reactor dosimetry technology to the energy region of interest to CTR applications is not as straightforward as had been hoped. The foil techniques developed in the fast-reactor program are applicable; however, some development work in the areas of cross sections, fission yields, and additional monitor reactions will be required to achieve the necessary accuracies in flux and spectrum.

The most significant problem might be referred to as a cross-section problem; that is, determining differential cross sections up to 50 MeV which are self-consistent. This problem is not exclusively limited to the energy region above 10 MeV. Fast-reactor programs, e.g., ENDF/B data testing, have found a number of situations in which integral and differential reaction rate data are inconsistent. The foil-activation iterative-unfolding technique can only utilize those reactions for which integral and differential data are consistent. In order to define those reactions which are consistent, measurements must be made in a neutron spectrum which is characterized independently of the foil method. This, of course, has been done for fast-reactor applications; it

will be required for higher energy "CTR-type" neutron spectra as well.

The most expeditious route to solving these cross-section problems, that is, to establish reliable dosimetry monitor reactions, is to perform a complete series of foil activation-rate measurements in two well known, but different, neutron spectra. The SAND-II code would be used to compare the integral (foil-activation rate) data with various sets of differential cross-section data based upon the known spectra. The consistent reactions could immediately be identified and used. Those reactions which are inconsistent would be recommended for further differential cross section work as a long term solution. In addition, the SAND-II code could be operated in reverse to derive a self-consistent set of cross sections based upon the known spectrum. This latter approach is not scientifically satisfying but it does offer an expedient alternative means for establishing usable dosimetry monitor reactions.

One method of obtaining known neutron spectra is to utilize time-of-flight measurements for the portion of the spectra above 1 MeV and use proton recoil techniques to measure the neutron spectrum below 1 MeV. Two possibilities of obtaining useful neutron spectra are to use the 16 MeV deuterons on Be spectra as discussed previously and the proposed T-O-F experiment at LAMPF.

The former has already been measured above 1 MeV and the proton recoil measurements should not be difficult. The spectral measurements at LAMPF on Cu (LASL) and Be (BNL) have already been proposed. Simultaneously, the fission yields of the fission rate monitors could be measured in the same spectra, thus clarifying another of the existent dosimetry problems.

V. Summary and Conclusions Relating to CTR Programs

The principal goal of the first year's effort to characterize the BLIP neutron source have been achieved. Through inter-laboratory collaboration, a preliminary but reliable description of the neutron spectrum available in BLIP has been given. The operating characteristics of the facility have been identified and their relationship to neutron irradiations in BLIP have been discussed. A further result is the development of important information which applies not only to BNL but to CTR irradiation programs in general.

The problems associated with the variability of flux and spectrum which was discussed regarding the BLIP facility are a general problem associated with all spallation neutron sources. Any measurements which require close-in geometries (to maximize flux) are inherently sensitive to flux and spectral changes due to small changes in the primary proton beam or experimental position. Spallation neutron sources require thick, i.e. the neutrons are produced over a considerable path length, targets to be

effective, and even for non close-in geometries are susceptible to neutron spectrum and flux shifts if any change in the location, distribution or energy of the incident beam occurs. All of these variables are compelling reasons for requiring spectral monitors for each individual irradiation damage experiment.

The foil dosimetry technique can be used for CTR dosimetry needs. Important areas that require research and development are indicated in this report. At the present there are neutron sources available to support this effort (BLIP for example). It is our recommendation that such a program be continued at a modest level. This technique will be necessary to support all presently proposed and currently funded irradiation programs as well as any dosimetry measurements in CTR environments.

References

1. W. N. McElroy and S. Berg, A Computer Automated Interaction Method for Neutron Flux Spectra Determination by Foil Activation, Volumes I, II, III and IV, AFWL-TR-67-41, Air Force Weapons Laboratory (1967).
2. F. T. Kuchnir, L. S. Skaggs, A. Elwyn, F. P. Mooring and N. A. Frigerio in 6th International Cyclotron Conf., Vancouver, Canada, July 18-21, 1973, p. 638.
3. K. A. Weaver, J. D. Anderson, H. H. Barschall and J. C. Davis, Neutron Spectra from Deuteron Bombardment of D, Li, Be and C, Nucl. Sci. Eng. 52, 35 (1973).

Table I

Reaction Rates from BLIP Tests

Reaction	Atoms Produced/Target Atom		I/II
	BLIP-I	BLIP-II	
$^{197}\text{Au}(n,\gamma)^{198}\text{Au}$	7.76×10^{-8}	2.6×10^{-9}	30
$^{197}\text{Au}(n,2n)^{196}\text{Au}$	9.88×10^{-9}	7.6×10^{-11}	130
$^{235}\text{U}(n,f)\text{F.P.} (^{140}\text{Ba})$	1.44×10^{-7}	5.1×10^{-9}	28
$^{237}\text{Np}(n,f)\text{F.P.} (^{140}\text{Ba})$	7.22×10^{-8}	4.1×10^{-10}	176
$^{48}\text{Ti}(n,p)^{48}\text{Sc}$	7.01×10^{-10}	2.7×10^{-12}	260
$^{27}\text{Al}(n,\alpha)^{24}\text{Na}$		7.3×10^{-12}	
$^{58}\text{Ni}(n,p)^{58}\text{Co}$		8.0×10^{-11}	
$^{238}\text{U}(n,\gamma)^{239}\text{Np}$		3.2×10^{-9}	
$^{238}\text{U}(n,f)\text{F.P.} (^{140}\text{Ba})^*$		2.7×10^{-10}	
$^{46}\text{Ti}(n,p)^{46}\text{Sc}^*$		1.2×10^{-10}	
$^{47}\text{Ti}(n,p)^{47}\text{Sc}^*$		1.15×10^{-10}	
$^{232}\text{Th}(n,f)\text{F.P.} (^{140}\text{Ba})^*$		1.3×10^{-10}	
$^{58}\text{Ni}(n,2n)^{57}\text{Ni}^*$		1.55×10^{-11}	
$^{27}\text{Al}(p,3p3n)^{22}\text{Na}^a$	3.4×10^{15}	7.3×10^{13}	46

^aRelative counting rates measured by BNL.

*Not used in spectral analysis for reasons discussed in the text.

Table II
Irradiation Data

Item		BLIP-I	BLIP-II
1. <u>Proton Beam</u>			
Proton Current in Pulse	I_p	60 mA	40 mA
Pulse Width	τ	200 μ S	220 μ S
Pulses/Second		5	2.5
Average Current	I	60 μ A	22 μ A
Total Beam Time		890 min	174 min
Integrated Current		$3.2 \times 10^6 \mu$ C	$2.29 \times 10^5 \mu$ C
2. <u>Measured Parameters</u>			
Neutron Fluence (n/cm^2)	Φ	3.95×10^{16}	1.2×10^{15}
Fluence ($n/cm^2-\mu$ C)	Φ	1.2×10^{10}	5.2×10^9
Max. Proton Fluence		$10^{17} p/cm^2$	$10^{16} p/cm^2$
Ptoton Fluence on Foils		3.4×10^{15}	7.3×10^{13}

Table III

Derived 29-Energy Group BLIP-I Spectrum

Upper Energy (MeV)	BLIP-I
	Fluence/MeV (n/cm ² -MeV) x 10 ⁻¹⁵
0.25	5.27
0.50	2.94
0.75	2.46
1.00	1.79
1.25	1.49
1.50	1.38
1.75	1.31
2.00	1.28
2.25	1.30
2.50	1.35
2.75	1.47
3.00	1.63
3.25	1.78
3.50	1.88
3.75	1.94
4.00	1.96
4.50	1.98
5.00	1.99
5.50	2.11
6.00	2.37
6.50	2.92
7.00	4.07
8.00	6.72
9.00	8.20
10.0	4.00
11.0	1.76
12.0	1.20
18.0	0.35
50.0	0.0
Total 39.5 (n/cm ²)	

Table IV

Derived 35-Energy Group BLIP-II Spectrum

Upper Energy (MeV)	Flux/MeV	Bootstrapped Flux/MeV
	(n/cm ² -sec-MeV) x 10 ⁻⁹	(n/cm ² -sec-MeV) x 10 ⁻⁹
0.25	310	315
0.50	118	145
0.75	12.2	12.3
1.00	2.67	2.08
1.25	1.82	1.31
1.50	1.63	1.15
1.75	1.52	1.12
2.00	1.5	1.10
2.25	1.41	1.10
2.50	1.41	1.12
2.75	1.41	1.15
3.00	1.41	1.19
3.25	1.42	1.23
3.50	1.39	1.24
3.75	1.32	1.22
4.00	1.22	1.16
4.50	1.05	1.03
5.00	0.89	0.91
5.50	0.77	0.82
6.00	0.70	0.80
6.50	0.75	0.92
7.00	0.98	1.20
8.00	1.71	1.88
9.00	2.64	2.35
10.0	1.64	1.67
11.0	0.99	1.10
12.0	0.82	0.83
15.0	0.38	0.36
20.0	0.045	0.044
25.0	7.35 x 10 ⁻⁴	7.73 x 10 ⁻⁴
30.0	1.51 x 10 ⁻⁵	9.53 x 10 ⁻⁵
35.0	2.17 x 10 ⁻⁷	2.20 x 10 ⁻⁵
40.0	8.25 x 10 ⁻⁹	2.78 x 10 ⁻⁷
45.0	4.84 x 10 ⁻¹⁰	3.32 x 10 ⁻⁹
50.0	3.84 x 10 ⁻¹¹	6.60 x 10 ⁻¹¹
Total	127 (n/cm ² -sec)	134 (n/cm ² -sec)

Table V
Relative Gold Reaction Rates Around Target

Sample	BLIP-I			BLIP-II			
	(n, γ)	(n, 2n)	$\frac{(n, \gamma)}{n, 2n}$	(n, γ)	(n, 2n)	(n, 4n)	$\frac{(n, \gamma)}{(n, 2n)}$
1Q1	1.2	0.14	8.6	1.2	0.042	0.027	29
1Q2	1.3	0.21	6.2	1.0	0.030	0.012	33
2Q1	1.0	0.12	8.3	1.1	0.028	0.009	39
2Q2	1.1	0.25	4.4	1.5	0.067	0.030	22
3Q1	1.2	0.74	1.6	1.7	0.28	0.13	6.1
3Q2	1.7	2.0	0.85	1.8	0.96	0.50	1.9
4Q1	1.4	1.1	1.3	1.9	1.6	0.80	1.2
4Q2	1.4	0.4	0.35	1.4	0.35	0.19	4.0

Figure Captions

- Figure 1 - Isometric View of the BLIP Facility
- Figure 2 - Cross Section of BLIP Dosimetry Target
- Figure 3 - Stainless Steel Target Jacket
- Figure 4 - Time-of-Flight Neutron Spectrum and the SAND-II
Derived Spectrum for $E_D=16$ MeV on Be
- Figure 5 - SAND-II Derived Spectra for BLIP-I and BLIP-II
- Figure 6 - Sample and Beam Locations for BLIP-I and BLIP-II

Fig. 1

BLIP TARGET

Fig. 2

Fig. 3

Fig. 4

Fig. 6