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Neutron Monitoring and Neutron Measurements; Experimental Possibilities at the INS Source

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Neutron Monitoring and Neutron Measurements; Experimental Possibilities at the INS Source

R. Dierckx

ABSTRACT

Radiation damage experiments to be performed at the Intense Neutron Source (INS) facility need to be characterized for fluence as well as for the mean neutron spectrum. A continuous monitoring system of the neutron output is described and proposed.

Many various experiments are possible with the INS because it compares favorably with other neutron sources for cross-section work in collimated-beam geometry, 14-MeV cross-section work, and integral experiments.

INTRODUCTION TO THE AUTHOR

The author, Dr. Ronald Dierckx, is a Belgian national working at the Euratom facility at Ispra, Italy. During his 14 years at Ispra, Dr. Dierckx has been assigned to the Reactor Physics section of the Physics Division, where he does mostly reactor physics research and reactor neutron dosimetry.

Dr. Dierckx is on temporary appointment to the Los Alamos Scientific Laboratory as a member of a scientific exchange program under an implementing agreement between the International Energy Agency and the United States government's Energy Research and Development Administration, ERDA. More specifically, Dr. Dierckx is assigned to the construction of the Intense Neutron Source, INS, facility at Los Alamos, New Mexico. The INS is being constructed for the ERDA's Division of Magnetic Fusion Energy, Materials and Radiation Effects Branch for the purpose of providing a major facility for research in the field of radiation damage in those materials to be considered for use in fusion power reactors.

Because of his extensive experience in neutron dosimetry, Dr. Dierckx has been asked to present his views on the dosimetry problems at the INS facility, and any other related topics which he chooses to discuss. This document is his response, which does not necessarily reflect the direction or policy to be adopted by the INS project; however, his views will be of great value in designing equipment related to the INS dosimetry problem.

It is with great pleasure that we enjoy the consultation and scientific exchange with Dr. Dierckx on this project of international interest.

C. Robert Emigh
INS Group Leader

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1. INTRODUCTION

The Intense Neutron Source (INS) facility will use a tritium ion beam impinging on a deuterium jet target to produce 14-MeV neutrons. Within the target volume of about 1 cm^3 , the source will produce 10^{15} n/s and will be used to study neutron irradiation effects in a pure or tailored 14-MeV neutron spectrum. For experiments in which a sample is irradiated near the source as in radiation damage studies, measurement of activation cross sections, total He or H production, or total gas production, the INS will be the most intense 14-MeV neutron source available. A discussion of these experiments is found in the Intense Neutron Source Facility Final Environmental Impact Statement.¹

Besides this primary use, the 14-MeV neutrons can be used for more basic and fundamental work such as cross-section measurements, benchmark integral experiments for fusion application, and fusion blanket mock-up studies. This report will explore the experimental possibilities of the INS source compared to other neutron sources.

The experiments to be executed at the INS facility need to be characterized for total neutron fluence, ϕE , and the neutron spectrum. It is best accomplished by directly measuring the neutron output from the source, rather than relying on normalizations based on the ion current; therefore, a monitoring system is proposed.

An experimental hall and a beam-tubes arrangement are proposed.

2. NEUTRON MONITORING

The neutron monitoring consists of two parts: the spectral characterization and the fluence determination. The experimental measurements are combined with theoretical calculations.

2.1 Spectral Characterization

Several methods are proposed to measure the neutron spectrum, especially in the case of a tailored spectrum. Simultaneous use of these methods produces a reliable picture of the neutron spectrum. A computer code "RADAK" developed at Winfrith-UKAEA permits a simultaneous analysis of the measured data coming from different spectrometers.²

The following methods are proposed for determining the spectra: a telescope (np) spectrometer, a telescope $\text{Li}^6(\text{n}\alpha)\text{T}$ spectrometer, spectrometers needing unfolding, time-of-flight technique, and multiple foil technique.

2.1.1 Telescope (np) spectrometer

With a telescope counter, consisting of a radiator foil, two proportional chambers, and a scintillation or solid state detector,* the neutron spectrum may be measured using triple coincidence techniques. It is characterized by good resolution, low background, but low efficiency. The telescope counter will be placed so that only protons emitted at a certain angle θ will be counted. Figure 1 gives a schematic view of the counter and its setup.

Such a spectrometer may result in a resolution of $\Delta E/E \approx 5\%$, an efficiency of $\epsilon = 6 \times 10^{-8}$ counts/n cm⁻², and it may be used down to about 5 MeV. By using a combination of radiator foil thicknesses, high efficiency response for both high energy as well as low energy neutrons can be obtained. Thinner radiator foils will permit the spectrometer performance to extend to lower energies (≈ 1 MeV). Thicker radiator foils will increase the efficiency for the 14-MeV neutrons, at the cost of resolution.

The telescope counter will be placed behind the concrete shielding wall in a flux of $\sim 10^8$ n/cm² s, giving rise to 6 counts/s at full power.

2.1.2 Telescope Li⁶(n α)T spectrometer

The use of the Li⁶(n α)T reaction is proposed for measuring the lower energy part of the spectrum. The triton (T) and alpha (α) particles are detected with a solid state detector or CsI crystal. The Li⁶ radiator is placed inside the neutron beam and the charged particle detectors outside the beam, in an arrangement similar to the (np) counter.

With solid state detectors, the lowest energy neutron detectable with a good resolution is ~ 10 keV; with a CsI crystal, this lowest energy will increase at least by an order of magnitude.

In principle there is no upper energy limit, and 14-MeV neutron spectrometry is possible with this system. However, the cross section and the angular distribution of the charged particles are not well known, especially at higher energies. Therefore, its solitary use is not recommended.

2.1.3 General Spectrometry

Other spectrometers can be utilized inside the source cell. Usually their measured data need unfolding to obtain the neutron spectrum. They will measure

* The use of solid state detectors may be limited due to their short life caused by radiation damage.

the flux at special positions. With some of these spectrometers, special measurement runs at INS will be needed, some of them at low power. Some direct spectrometers are the following: gas proton-recoil counters with different gas pressures, He^3 sandwich spectrometer, Li^6 sandwich spectrometer, and scintillation-proton recoil counters.

The energy range can be extended from 10 keV to 14 MeV with the use of several of these spectrometers.

2.1.4 Time-of-Flight Technique (T-O-F)

The telescope counter and spectrometers can not be used to measure the lower energy range of a tailored spectrum; therefore, a T-O-F technique is necessary to measure the lower energy tail of the spectrum accurately. With T-O-F it is also possible to measure the fast neutron spectrum, providing a check of the telescope counter results and giving more confidence in the measured spectrum and its absolute value.

INS is a continuous source, so a mechanical device, or fast chopper, must be used to create a pulse of 600-ns width with a frequency of 400 p/s. The fast chopper may be used at full power of the source or at a reduced power level (at about 10%), with the INS source pulsed at 20- to 30- μs pulses. The latter operation results in a lower background. Convenient locations for the measuring stations are at 200 m, 50 m, and 25 m. (A detailed study of the fast chopper facility is given in Appendix A.)

2.1.5 Multiple Foil Method

Both the telescope and T-O-F techniques measure a directional spectrum which can deviate from the flux spectrum at the location of sample irradiation. Foils placed in the beam and at the irradiation position will monitor the difference between the beam and the irradiation-spectrum. Then comparisons may be made by calculations.

With the use of unfolding codes, SAND II (HEDL-McElroy) and/or CRYSTAL-BALL (Oak Ridge - KAM),³ the multiple foil activities may be analyzed. A mean spectrum without much detail will be obtained. Evidence for resonance structure has to be obtained out of the telescope and T-O-F results.

In order to make multiple foil techniques a potent instrument, use of a reference or standard spectra is necessary as a comparison for all measurements. These standard spectra may be calculated and measured by refined methods. Two standard spectra are necessary: (1) the pure 14-MeV spectrum,

from the INS source, (2) a degraded, first-wall fusion-like spectrum--a Li or B₄C block fed by the INS source may be used.

Foil and detection chains are calibrated by means of the standard spectra. Further, only relative measurements versus these standard spectra need to be used.

2.2 Fluence Determination

Each sample irradiated by the INS source has to be monitored for the neutron spectrum in which it has been irradiated and for the time-integrated neutron flux or neutron fluence.

The fluence may be determined by two means: by the telescope counters and by multiple foil method with a limited set of foils.

2.2.1 Telescope Counters

The telescope counters described in 2.1.1 and 2.1.2 will function continuously and will register as a function of time the source strength and mean neutron spectrum. Connected to the process computer, an exact picture of the neutron output and its characterization could always be available.

2.2.2 Multiple Foil Method

In the multiple foil method, a limited set of foils will accompany the samples to be irradiated, experiencing similar conditions (time, neutron spectrum, and temperature).

The foils will occupy a small place in small tube assemblies (2 mm of diameter, 20 mm of length) which will contain up to 12 foil materials, all having a long half-life. This is a technique developed by McElroy at Hanford (HEDL).⁵ In this way the neutron fluence may be determined as a function of irradiation position for all samples irradiated.

2.3 Calculations

Extended two- or three-dimensional Sn and Monte Carlo calculations will be necessary. Comparing the theoretical results with the experimental measurements will give a high degree of confidence in the neutron fluence and mean neutron spectrum.

2.4 Experimental Layout

For each neutron source three permanent setups are possible for telescope counter placements and one permanent setup for later installation of a T-O-F channel.

2.4.1 Telescope Counter Setup

Three beams, M-1, M-2, and M-3, could be equipped for neutron source monitoring, so that at least two will always be functioning. (Fig. 2).

Each of them may consist of the following: (Fig. 3)

1. A beam tube through the shielding with a physical safety barrier near the source cell,
2. A boron-paraffin, heavy-particle loaded collimator,
3. Copper inserts defining the neutron beam, total length ~ 80 cm. (According to a study done at Oak Ridge (ORNL), copper should be the best collimator lining material. It will define a circular beam opening of a few cm^2 .)
4. Boron-loaded water shutters,
5. Detector and its shielding, (the place of the detector-radiator may be inside the shielding at about 1 m from the outside border), and
6. A beam stop ~ 3 m from the detector to prevent backscattering contamination.

Channel M-1 is located at the west side of the source cell. (Figs. 2 and 4) It is a horizontal channel looking through the ion-beam tube directly into the source. With the detector located at M-1, the pure 14-MeV source may be monitored independently from any experiment in the source cell.

Channel M-2 may be located in the southeast corner of the source cell, looking towards the source and spectrum modifier. The channel will be at an angle of about 30° above the horizontal so that the detector may be placed near the ceiling leaving the space below free. The detector will measure the 14-MeV source and the backscattered spectrum from a spectrum modifier.

Channel M-3 may be located at the north side of the source cell and is identical to channel M-2.

2.4.2 T-O-F Channel NM-1. (Figs. 2 and 4)

The T-O-F setup consists of the following:

1. Beam tube through the shielding with a barrier for physical safety in the source cell wall, (the smallest opening will be rectangular, 20 cm by 40 cm, so that samples above the source may be centered)
2. A boron-paraffin, heavy-particle loaded collimator, with copper inserts (about 80 cm) defining the neutron beam,
3. Boron-loaded water shutters,
4. A chopper assembly including a prelinar, two synchronous running rotors, and one after-liner.

5. Measuring stations at 25 m, 50 m, and 200 m with collimator detector shielding, and
6. A 200-m evacuated flight path (~ 1 torr) with a diameter of 60 cm up to a distance of 50 m, and then diverging to 100 cm diameter.

2.5 Planning

Figure 5 gives the Program Evaluation and Review Technique (PERT-planning) for the neutron-monitoring system. The decision is still to be made whether and when to build the T-O-F system. Possible experiments assigned to the T-O-F system are the following:

1. To measure the lower energy tail of the tailored spectra,
2. To measure the standard spectra used in foil-detector calibration, and
3. To control the telescope counter results.

Furthermore, the T-O-F installation can be used for cross-section measurements (total neutron-emission spectra, semi-integral sphere scattering, and transmission measurements) and for integral experiments.

3. NEUTRONIC MEASUREMENTS

At the INS, the source can maintain a continuous yield because of the unique gas target. This arrangement also allows the specific yield to be increased an order of magnitude over other neutron sources. The target is made small in order to permit samples to be close, which will maximize the neutron fluxes.

Neutronic measurements could include the following:

1. Radiation damage studies--bulk effects, surface physics experiments, and effects on electrical properties,
2. He, H, and total gas production,
3. Blanket neutronic studies placed in the vicinity and around the source,
4. 14-MeV activation cross-section work, and
5. Calibration.

These measurements may be done in the pure 14-MeV source spectrum, as well as in tailored spectra simulating the first-wall of a fusion reactor. The tailored spectra obtainable at INS will be the object of separate study.

Besides the irradiation experiments, INS looks like an attractive 14-MeV source for neutronic measurements in collimated-beam geometry. Its beam

intensity is comparable to a pulsed Van de Graaff machine, although unfolding of the measured data is necessary.

It was concluded by the Nuclear Cross Section and Technology Conference (1975) and the Magnetic Fusion Energy Blanket and Shield Workshop (1976) that there is still a need for cross sections applicable to magnetic fusion energy (MFE).^{4,5}

These conclusions are summarized in Appendix B, together with a list of required cross-section measurements. Part of these cross-section requirements can be fulfilled at the INS. The INS source will be compared with a white spectrum source and a 14-MeV monoenergetic source.

3.1 Fusion Blanket, Shield Mock-ups, and Benchmark Experiments

3.1.1 One-Dimensional Benchmark Experiments with a Plane Source

At the inner source cell boundary, the approximately parallel 14-MeV neutron source is a homogeneous plane source with 6×10^8 n/cm² s. By feeding a large block with this plane source, the neutron fluxes and related quantities along the central symmetry axis can be compared with one-dimensional calculations. Only small corrections for radial leakage have to be applied, but these small corrections can be easily calculated.

The experiment may be done in several ways. (Fig. 6)

- Exp. 1. Large one-material plates may be stacked one after the other, starting first with a thin plate and letting the stack grow in thickness. For each thickness the transmitted spectra are measured, using the T-O-F installation and direct spectrometers at different angles. Inside the plates, foil activation gives radial and axial neutron flux distributions. The whole set forms a series of one-dimensional benchmarks.
- Exp. 2. A large, thick, one-material block with axial and radial channels is fed by the 14-MeV plane parallel source. The channels may be partially or fully filled. Again T-O-F, direct spectrometry, foil activation, and tritium-production measurements are executed. This is another type of benchmark experiment.

Exp. 3. A small sphere (or cylinder) is fed through a central entrance hole, arranged so that the T-O-F installation sees either the transmitted beam (expt. 3a), or the scattered beam at an angle of 54.7° (zero of P-2 polynomial expansion), or some other angle. Other angles are measured by direct spectroscopy methods. Also, foil activation and tritium-production inside the sphere or cylinder is possible.

The difference between these three experimental setups and classical sphere-scattering experiments is that the latter ones are fed by an isotropic source. At INS the experiments are fed by a parallel beam and the outside beam spectra experiments measure only scattered neutrons.

3.1.2 Fusion Blanket and Shield Mock-Ups

Experimental setup 2 can be used for testing real mock-ups of blankets and shielding in one-dimensional geometry.

3.1.3 Integral Experiments within the Source Cell

Integral experiments are possible by surrounding the source with cylindrical assemblies of pure material or composite blankets or shield mock-ups. Figure 7 shows the experimental setup. Through empty, partially, or totally filled re-entrant holes (H-1, H-2), the spectra inside the assembly may be measured. In addition, foil activation and tritium-production measurements are possible. The advantage of this experimental setup is a higher flux level, but it is no longer a one-dimensional experiment. Two- or three-dimensional Sn and Monte Carlo calculations are necessary for comparison of experimental results and theoretical calculations.

Another possibility is to take the experimental setup for total neutron-emission spectrum measurement (Fig. 8), replace the thin samples with thick blocks or spheres, and then measure the leakage spectra by the T-O-F. Moving the thick sphere along the dotted line, different average emitting angles for the leakage spectrum measurements are possible. The advantage is the high neutron flux level produced. The leakage spectra as a function of angle are all measured by T-O-F. On the other hand, the wall-background neutrons scattered by the large sphere may be significant. The source subtends a large angle towards the sphere, which makes the theoretical calculations more difficult.

3.2 Experiments in Continuous 14-MeV Neutron Beams

At the outside of the INS shielding, a collimated beam of 14-MeV neutrons is obtained, with a neutron flux

at 5.7 m (~ 1 m inside shielding)	of 2.45×10^8 n/cm ² s
at 6.7 m (border shielding)	of 1.8×10^8 n/cm ² s, and
at 8 m (outside shielding)	of 1.2×10^8 n/cm ² s.

A Cockcroft-Walton or Van de Graaff machine may be run in steady state operation with a source strength of $S = 2 \times 10^{10}$ n/s, leading to a flux at 5 cm from the source of 6.4×10^7 n/cm² s and at 10 cm a flux of 1.6×10^7 n/cm² s.⁸

For steady state experiments, the INS has the following advantages over a Cockcroft-Walton due to the unique design with the INS collimated beam at a large distance from the point source:

1. A parallel beam of 14-MeV neutrons in a very low neutron background,
2. High fluxes varying only slowly with distance from the source,
3. Large homogeneous beam possible, and
4. Detectors for reaction products located in low background environment.

Examples of possible experiments with 14-MeV neutrons are the following:

1. Neutron spectra measurements with T-O-F techniques using as a start signal
 - a. a typical gamma ray for inelastic scattered neutrons, or
 - b. a fission chamber pulse for fission spectra,
2. The measurement of (n,n',x) and (n,x) cross sections (in which x is a charged particle) by counting the charged particles and angular correlation measurements,
3. Total neutron output,
4. Neutron output as a function of angle,
5. Neutron-emission spectra as a function of angle, measured with direct neutron spectrometers (unfolding of spectral data necessary), and
6. Total gamma production as function of angle.

3.3 Comparison with a 14-MeV Pulsed Monoenergetic Source

The operational 14-MeV source output of ns-pulsed machines, such as the Van de Graaff (with gas target)⁸ or the ICT Machine at Livermore,⁹ is 10^9 n/s

from the D-T reaction. Table I gives a comparison of a typical experimental setup at such a machine and at the INS-chopper source.

Table II shows that the INS-chopper combination is comparable to a ns-pulsed 14-MeV machine in both count rate and energy resolution. The neutron detector at INS is located in a low gamma and neutron background environment. Background from beam-scattered neutrons may be determined by the usual black absorber technique and with a closed chopper. Some experiments may be designed for which the INS-chopper is a more suitable neutron source and others for which the pulsed 14-MeV machine is more suitable. Experiments can be duplicated on both machines with other experimental conditions, reducing the effect and detecting possible systematic errors.

Examples of possible experiments are the following:

1. Total neutron-emission spectra (n, n' ; $n, 2n$; n, f) as functions of angle (θ, E'_n) for $E_n = 14$ MeV. A possible experimental setup is shown in Fig. 8. The reacting sample can be moved along the dotted line, obtaining in this way different scattering angles.
2. To measure fission spectra, the sample can be a fission chamber, and the starting pulse for T-O-F. the fission chamber signal. In this case no chopper is needed and a much smaller flight path can be used, and
3. Cross-sections for ($n, n'x$) reactions, with x a charged particle, are possible detecting the charged particle and associated neutron in a correlation experiment. Eventually in the same measurement, the emitted neutron spectrum can be measured.

3.4 Comparison with a White Spectrum Source

The following is a comparison of the INS-plus-chopper with the Weapons Neutron Research facility (WNR) at the Clinton P. Anderson Medium Energy Physics Facility, LASL. WNR is a white spectrum source and at 14-MeV and 120-Hz operation, the neutron output at full-design power (S^{14}) per micropulse is ¹⁰

$$S^{14} = 4.8 \times 10^9 \text{ n/s MeV.}$$

In a macropulse of 600 ns, we have 120 micropulses, and a neutron output at 14 MeV (S_m^{14}) at full-design power

$$S_m^{14} = 4.8 \times 10^9 \times 120 = 5.76 \times 10^{11} \text{ n/s MeV.}$$

TABLE I. COMPARISON OF TYPICAL EXPERIMENTS AT A 14-MeV, 1-ns
PULSED MACHINE AND INS-CHOPPER OPERATION

	<u>14-MeV monoenergetic pulsed source</u>	<u>INS-chopper</u>
Peak neutron source (n/s)	10^{12}	10^{15}
Pulse width (ns)	1	600
Frequency (p.s)	10^6	400
Chopper transmission		0.15
Mean neutron source (n/s)	10^9	3.6×10^{10}
Flight path (m), (0.3 ns/m)	3.33	200^*
Sample response	R^+	R^+
Flux at detector ($n/cm^2 s$)	$7.17 \times 10^2 R$	$7.16 R$
Total count rate (n/s)	$(10\text{-cm}^2 \text{ detector})^+$	$(1000\text{-cm}^2 \text{ detector})^+$
	$7.17 \times 10^3 R$	$7.17 \times 10^3 R$

*Special analysis of count rates by unfolding, see Appendix A. The peaks are measured without loss in statistical accuracy versus a time resolution experiment. For a continuous spectrum this analysis gives a loss in statistical accuracy.

⁺The sample response and detector size are variable and depend on the type of experiment. It is felt however that this table represents a typical average experiment.

At actual power load (2 mA instead of 17 mA design power), the neutron output is

$$S_m^{14} = 5.76 \times 10^{11} \cdot \frac{2}{17} = 6.8 \times 10^{10} \text{ n/s MeV.}$$

These figures will increase in the proton-storage-ring mode of operation. The INS - 600-ns chopper combination, at 400-Hz operation, with a chopper transmission of 15%, has a design neutron output of (S_I) 14-MeV neutrons with a full width at half maximum (FWHM) of about 1 MeV, where

$$S_I = 3.6 \times 10^{10} \text{ n/s MeV ,}$$

which is a factor of 2 lower than WNR in actual operation (reached) and a factor of 10 lower than WNR at full-design power. At shorter pulse length operation, the WNR facility will have a further gain in intensity, which makes it clear that for transmission work with 14-MeV neutrons or tailored spectra the INS source can not compete.

Nevertheless, if the chopper assembly and flight path are installed, transmission measurements and total cross-section determination for 14-MeV neutrons can be done easily with the INS source.

It may be that by duplicating experiments on both machines under various conditions, such as a dominant 14-MeV neutron beam or various background conditions, a total cross-section determination and any other feasible cross-section measurement will provide a one-point check of the white beam experiments.

3.5 Medical Cancer Research

The 14-MeV neutron flux in a beam outside the shielding is

$$\phi = 10^8 \text{ n/cm}^2 \text{ s ,}$$

giving rise to 40 rads/min or 400 rem/min.¹¹

This high dose is needed in cancer research. The monoenergetic character of the source makes it very interesting. The INS source is well suited to do research work in this field. A beam on the east side of the cell (Fig. 2) will always deliver a pure 14-MeV neutron beam whatever experiment is built up around the source. This is a horizontal channel viewing the neutron source area directly through the diffuser and ion beam tube. An irradiation cell at the same place will make it possible to install variable shielding thicknesses and varied collimators making it possible to do local as well as whole body irradiations.

A vertical beam through the ceiling would provide a second possibility for cancer-scope irradiations.

3.6 Rabbits

Two automatic sample transport systems or rabbits may be installed at the INS source, a slow and a fast rabbit. The slow rabbit may be used for longer irradiations (activation products with half-lives of the order of minutes or longer). It ends up outside the experimental building or in the hot cell for demounting. The counting of the samples will be done in the low-background counting room of the office building.

A fast rabbit may be used to produce short-lived activation products with a range from ms up to some minutes. Transfer times of the samples should be a few ms. After irradiation, the samples should enter a counter installed in the experimental hall.

3.7 Conclusions

From this analysis it is clear that besides the normal irradiation experiments for which INS is built, the INS source can be used in a meaningful manner for cross-section work, fusion blanket and benchmark experiments, and for cancer research.

1. INS is an excellent source for fusion-applicable integral experiments.
2. INS is an excellent source for experiments to be done in a continuous 14-MeV neutron beam.
3. INS is comparable to 14-MeV ns pulsed monoenergetic sources.
4. INS is not comparable with short-pulsed white spectrum neutron sources. Nevertheless INS may be used for one-point (14-MeV) check measurements, and for duplicating cross-section experiments under different experimental conditions.
5. For medical cancer research, INS is a well-suited source.

4. LAYOUT OF BEAM TUBES AND EXPERIMENTAL HALL

The following experimental facilities are proposed for secondary neutron work experiments outside the irradiation cell: (Fig. 9)

1. Three beam tubes for neutron monitoring, (see Sec. 2.4) M-1, M-2, and M-3,
2. One beam tube for neutron monitoring and experimental work, provided with chopper facility and 200-m flight path, (see Sec. 2.4) NM-1,

3. Two large irradiation cells, IC-1 and IC-2, in which alab-fusion benchmarks, mock-ups, and standard spectra assemblies could be irradiated by a plane source. (Largest surface source is 2 by 2 m²) The N-6 beam spectrum could be a pure noncontaminated 14-MeV spectrum despite the experiment located inside the cell or how the spectrum may be tailored. N-6 is especially suited for cancer research with 14-MeV neutrons.
The lateral beam tubes S1 and S2 may make it possible to measure 90° scattered spectra from benchmark experiments. They would be located some 30 cm below the source height so that they do not interfere with other beam tubes.
4. Beam tubes, N-1 to N-6 where various experiments in continuous beams may be performed, (N-4 may be inclined in order not to interfere with S1 and S2.)
5. A vertical beam tube, N-8, (Fig. 4)
6. Beam tube N-7 for measuring the scattered neutron spectra from semi-integral experiments,
7. A type of light-wall material to prevent neutron scattering from the walls. (For the same reason, the floor is a metal grid with a real floor some 2 m below experimental floor. Concrete walls will support the experimental equipment.)

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Fig. 1. Telescope counter for neutron monitoring at INS source.

Fig. 2. Plan view of the monitoring instrumentation and sections A-A' and B-B'.

Fig. 3. Telescope detector setup.

Fig. 4. Layout of monitoring instrumentation along C-C' axis (see Fig. 2.)

Fig. 5. Program Evaluation and Review Technique (PERT) planning.

Fig. 6. Experimental arrangements for four possible integral experiments.

Fig. 7. Source environment and integral experiment assembly.
(Units:mm)

APPENDIX A
THE FAST CHOPPER FACILITY

The fast chopper facility consists of a rotating mechanical device, an evacuated flight tube, and a counter-bank at the end of the flight path. The steady-state neutron beam is transformed in a pulsed beam, which has 600 ns pulses and a frequency of 400 p/s. The longest flight path is 200 m.

The energy resolution (ΔE) and intensity (I) are given by

$$\Delta E = 27.7 \frac{\Delta t}{L} E^{3/2} 10^{+8} , \quad (1)$$

in which

ΔE : energy resolution in MeV
 Δt : total time uncertainty in s
 L : flight path in cm
 E : energy in MeV

and

$$I(E) = S \cdot \phi(E) \cdot \Delta t \cdot f_c \cdot \Delta E \frac{T}{4\pi L^2} \frac{\Delta t_d}{\Delta t} , \quad (2)$$

with

$I(E)$: neutron flux at distance L in $n \text{ cm}^{-2} \text{ s}^{-1}$ as function of E
 S : source in n/s
 $\phi(E)$: normalized neutron spectrum, with $\int_0^\infty \phi(E) dE = 1$
 f_c : pulse frequency in s^{-1}
 T : chopper transmission
 Δt_d : detector channel width in s.

Using a detector channel width, Δt_d , of less than the chopper opening time, Δt_c , the measured data in one-time channel cover an energy interval ΔE . Using an unfolding technique, the effective resolution E_{eff} will be

$$\Delta E_{\text{eff}} = \Delta E \frac{\Delta t_d}{\Delta t_c} .$$

The count rate per unit area (C_i) in a time channel, i , may be written

$$C_i = \int_{\Delta E_i} \varepsilon(E) G_i(E) \cdot I(E) \cdot \Delta E^{-1} \cdot dE + B_i , \quad (3)$$

in which C_1 : measurement count rate in channel 1 per unit detector area

B_1 : background in channel 1, per unit detector area

$G_1(E)$: response form factor for the detector for channel 1

$\epsilon(E)$: detector efficiency.

$G_1(E)$ are a series of triangles spaced by ΔE_{eff} (Fig. 10).

Equation 3 may be written

$$C_1 = \sum_j \epsilon_j G_j F_j + B_1 \quad (4)$$

where

$$F_j = \int_{\Delta E_{j,\text{eff}}} I(E) \cdot \Delta E^{-1} dE.$$

In this system we have J count rates C_1 and knowing B_1 , by normal mathematical treatment the unknown quantities, F_j , are determined with an energy resolution ΔE_{eff} .

The peaks are measured without loss in statistical accuracy versus a fine resolution experiment. For a continuous spectrum this analysis gives a loss in statistical accuracy since the statistical error is proportional on the integrated count-rate in $N = \Delta t_c / \Delta t_d$ channels.

Table II summarizes the energy resolution and intensities for the source neutrons, and for a typical tailored spectrum at 2 cm from the source inside a Li block where $\phi_t = 10^{13}$ n/cm² s and with a reasonably effective source surface of 20 cm²,

$$S_t = 2 \cdot 10^{14} \text{ n/s}.$$

Assuming a detector surface of $20 \times 80 = 1600$ cm², and a detector efficiency of 10%, an integral count rate of 228 counts/s is obtained. A total of 600 000 counts can be gathered in 3000 s, or in less than one hour the fast part of spectrum can be measured. The low energy part of the spectrum can be measured 20 times faster.

The very low energy part of the spectrum can be measured by either choosing larger detector opening times, or measuring at shorter flight paths, i.e. $L = 10$ m.

Since a chopper assembly with two rotors is needed, shorter pulses may be obtained by dephasing the rotor slits, at the cost of decreasing the chopper transmission. With a shorter pulse, the same energy resolution and count-rates are obtained at smaller distances, i.e., a pulse of 150 ns with $L = 50$ m is

TABLE II RESOLUTION AND INTENSITIES FOR THE SPECTRUM MEASUREMENTS OF T-O-F.

	E (MeV)	$\Delta t_c = 600 \text{ ns}^+$			$\Delta t_d = 60 \text{ ns}^+$		
		$L = 200 \text{ m}$	ΔE_{eff} (MeV)	I (n/cm ² s)	$L = 50 \text{ m}$	ΔE_{eff} (MeV)	(n/cm ² s)
Source Neutrons ----- S = 10 ¹⁵ n/s	14						
Tailored spectrum S = 2.10 ¹⁴ n/s ----- $\phi(E)$ (1 MeV) [*]							
8.53 x 10 ⁻²	13	3.89	0.389	4.75 x 10 ⁻²			
4.96 x 10 ⁻²	8.7	2.13	0.213	1.51 x 10 ⁻²	8.53	0.853	0.97
0.18	1.	0.083	8.3 x 10 ⁻³	2.14 x 10 ⁻³	0.332	0.032	0.116
0.493	0.1	2.63 x 10 ⁻³		1.86 x 10 ⁻³	10.5 x 10 ⁻³	1.05 x 10 ⁻³	1.18 x 10 ⁻²
0.630	15 x 10 ⁻³	1.52 x 10 ⁻⁴		1.34 x 10 ⁻⁴	6.11 x 10 ⁻⁴		8.81 x 10 ⁻³
0.928	2 x 10 ⁻³	7.43 x 10 ⁻⁶		9.87 x 10 ⁻⁶	2.97 x 10 ⁻⁵		6.31 x 10 ⁻⁴
0.356	100 x 10 ⁻⁶				3.32 x 10 ⁻⁷		2.71 x 10 ⁻⁶
0.032	14 x 10 ⁻⁶				1.74 x 10 ⁻⁸		
Integral S x $\int_0^\infty \phi(E) dE$				1.43			22.9
		$\Delta t_c = 600 \text{ ns}$			$\Delta t_d = 600 \text{ ns}$		

$$^* \int_0^\infty \phi(E) dE = 1.$$

⁺Data above dotted line apply to $\Delta t_c = 600 \text{ ns}$ and $\Delta t_d = 60 \text{ ns}$.

Data below dotted line apply to $\Delta t_c = \Delta t_d = 600 \text{ ns}$.

equivalent to a pulse of 600 ns with $L = 200$ m. Whether this is possible depends on the chopper and synchronization stability.

The transmission of the closed chopper between the pulses must be 10^{-4} to ensure a signal to background ratio of more than 50; this means a few percent background counts. By choosing an optimal distance for each energy range, the whole spectrum is measured in about 100 μ s after each pulse. With 14-MeV neutrons, 50 cm of iron give a pure transmission of $T_B = e^{-0.22 \times 50} = 1.6 \times 10^{-5}$. The real transmission has to be calculated by Monte Carlo technique and may be estimated to be about 10^{-4} for 50 cm of iron.

The fast chopper assembly will have a preliner, two rotors of 40 cm by 25 cm, and an afterliner. Figure 4 gives a schematic view of the chopper assembly. The slitted surface will be about 10 cm by 10 cm with one slit every 2 mm each with an effective slit width of 0.3 mm.

An example of such a rotor is described in the SORA Scientific Experimental Program:¹²

"Fast Neutron Chopper Fig. 4.2-10

"The fast neutron chopper of the DMF/C2H-experiment has a beam-like rotor rotating about a vertical axis. Since the rotor is not shaped like a symmetrical gyroscope, it must be supported between bearings in order to avoid dynamic instabilities. All rotating parts run in a vacuum. The motor stator and ball bearings are surrounded by water jackets for cooling purposes. The heat generated in the motor rotor is evacuated by cooling its shaft. Oil enters at the upper end of a blind bore-hole and is centrifuged out through three radial holes bored at the blind end. Emergency bearings provide a measure of security in the event of a motor shaft failure.

"The rotor is shown in Fig. 4.2-11. It snugly encloses the two chopping inserts which are placed in its longitudinal openings. The inserts are schematically represented in Fig. 4.2-12. They consist of a package of partially slotted Ni-plates, clamped together by electron-beam welded cover plates. The longitudinal stresses can be withstood by these plates. The slots are not full-length: crosspieces are left during fabrication to prevent transverse bending of the longitudinal walls and transmit the loads to the lateral cover-plates, i.e., to the rotor.

"The fabrication of the Ni-plates will most probably give rise to some problems, since the width of the slits is small (0.1 mm at the narrowest point,

0.5 mm at the widest). At the moment, electroforming is the process envisaged.

"The design data of the fast chopper are:

rotational speed:	$n = 12000 \text{ rpm}$
peripheral speed:	$u = 250 \text{ m/s}$
rotor material:	maraging steel
weight of the rotor:	$G \approx 280 \text{ kg}$
stored energy:	$E \approx 0,4 \cdot 10^6 \text{ mkg} = 1.1 \text{ kWh}$
max longitudinal stress:	$\sigma_l \approx 30 \text{ kg/mm}^2$
max transverse stress	$\sigma_t \approx 30 \text{ kg/mm}^2$
max bending stress:	$\sigma_b \approx 40 \text{ kg/mm}^2$
motor power:	$N = 2 \text{ kW}$ "

In our case two such rotors would have to rotate synchronously.

Fig. 10. Response function of the detector for different time channels with $\Delta t_d < \Delta t_c$.

Fig. 4/2-10. DMF/C2H fast chopper.

Fig. 4/2-12. DMF/C2H fast chopper inserts. (Units: mm)

APPENDIX B

NEEDS FOR CROSS SECTIONS IN THE MFE FIELD

The conclusions of the "Magnetic Fusion Energy Blanket and Shield Workshop" held in 1976⁶ concerning neutronic problems, are as follows:

1. From the "Study Session on Materials...", p. 23,
"Dimensional and stoichiometric transmutation studies on candidate materials such as Li_2O and Pb_3Li_7 are needed,"

2. From the "Study Session on Neutronics," p. 37
"It is clear that with present data and codes, a viable final blanket/shield neutronic design is not possible," and

3. From the "Study Session on Neutronics," p. 38:
"Specific experiments to confirm EPR blanket/shield material choices, were assigned top priority among integral experiments. A final verification of the design will, however, require an actual mock-up. Very simple, clean integral experiments are essential for establishing a long-term basis for confidence in some nuclear data. Top priority should be given to principal EPR materials, but some effort must be devoted to identifying long-range results for DEMO.

3.1 "It was generally agreed that, although the data needs of the CTR program are vast, the measurement request from this group should be kept to a bare minimum in order to have maximum effect. Accordingly, only the few most obvious needs were addressed. In all cases, experimental data at additional incident neutron energies would be welcome.

3.2 "Priority I recommendations [mainly for EPR (a)]

- a. neutron emission spectra (> 5 angles, $E_n' > 500$ keV)

${}^7\text{Li}_{n,\text{Nem}}$ (θ_n' , E_n') Accuracy = 10%, $E_n = 11, 14$ MeV

${}^{11}\text{B}$ " " " "

- b. gas production

3.3 "Priority II Recommendations (mainly for DEMO)

- a. neutron emission spectra (> 5 angles, $E_n' > 500$ keV)

${}^6\text{Li}$	$\sigma_{n,\text{Nem}}(\theta_n', E_n')$	Accuracy = 10%,	$E_n = 11, 14$ MeV
Al (b)	"	"	"
Mo	"	"	"
Ni	"	"	"
Cr	"	"	"
- b. gas production

Al	$\sigma_{n,\text{xp}}(E_n)$ and $\sigma_{n,\text{x}}(E_n)$	Accuracy = 15%,	$E_n = 14$ MeV
Mo	"	"	"
Ni	"	"	"
Cr	"	"	"

${}^6\text{Li}$ $\sigma_{n,\text{t}}(E_n)$ Accuracy = 15%, $E_n = 1-15$ MeV (a few energies)

3.4 "Priority III Recommendations

- a. neutron emission spectra for Be, Cu, Ti, V, Nb
- b. Gas production cross sections for Be, Cu, Ti, V, Nb
- c. proton and alpha spectrum measurements (b) at $E_n = 14$ MeV for Fe, Ni, Cr
- d. selected measurements on isotopic data (for nuclear heating and activation calculations) for important elements; e.g., Ni, Cr, and Mo."

4. From the "Study Session on Neutronics," p. 50:

"In the course of the considerations of this study group, we developed a number of specific areas, which we request receive special attention in the evaluations of certain materials for version V of ENDF/B. The most important materials have been identified as: iron, nickel, chromium, boron, carbon, copper, beryllium, lithium, and aluminum. Reactions which are frequently not given much attention at high neutron energies, ≤ 15 MeV, have large impacts on DT source neutronic and photonic behavior and it is these reactions which we recommend be given careful evaluation. These are:

$n,2n$	Secondary neutron energies. Two neutron spectra need to be defined with the best estimate of average energies.
n,n'	Discrete level information should be included for low lying levels which lead to small energy loss. Anisotropic

angular distributions for direct reactions are required. Careful attention should be paid to average energies of continuum secondaries, and

n,n'x Particle cross sections are needed. These are especially important for lithium and boron isotopes. Discrete levels should be included if they can be inferred. Secondary neutron and particle energy spectra are important.

"For all of the isotopes of the elements involved, the activation cross-section and radioactive decay chain information is requested. In addition, phase II data testing of evaluated data for these elements is desirable. In particular, integral experiments such as 14-MeV pulsed-sphere neutron-leakage-spectra measurements should be calculated to test these data."

5. From the Study Session in Neutronics, p. 52:

"C. MEASUREMENT NEEDS

"i. ${}^7\text{Li } \sigma_{n,\text{NEM}}(\theta_n, E_n)$ Accuracy = 10% $E_n = 6, 10, 14$ MeV.

Neutron emission spectra are required at 5-10 angles for these three incident neutron energies and preferably at 8 and 12 MeV as well. Spectra of secondary neutrons must go down to a few hundred keV in energy. These data are needed for neutron transport in thick lithium regions.

ii. ${}^7\text{Li } \sigma_{n,n't}(E_n)$ 10% 10, 14 MeV

Tritium production cross section as a function of incident neutron energy needed for tritium breeding calculations.

iii. $\text{C } \sigma_{n,\text{NEM}}(\theta_n, E_n)$ 10% 10, 14 MeV

Neutron emission spectra required at 5-10 angles. An additional measurement at 12 MeV would be useful. Data needed for neutron transport in thick graphite regions. Spectra down to few hundred keV needed.

iv. $\text{C } \sigma_{n,\alpha}(E_n)$ 10% 10, 14 MeV

Gas production cross sections needed for radiation damage studies. Additional energies would be useful.

v. $\text{Fe } \sigma_{n,\text{xp}}(E_n)$ and $\sigma_{n,n\alpha}(E_n)$ 15% 10, 14 MeV.

Same as iv."

6. Further at the Nuclear Cross-Sections and Technology Conference in 1975,⁷ nuclear data needs for fusion reactor design were emphasized by Don Steiner (Oak Ridge), p. 646. "For elastic and non-elastic interactions, secondary γ -ray spectra, activation cross-section, neutron dosimetry by foil activation." The same needs were expressed by S.A.W. Gerstl, D. G. Dudziak, and D. W. Muir (LASL), p. 674.

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