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CHARACTERISTICS OF ROTATING TARGET NEUTRON SOURCE AND ITS USE IN RADIATION EFFECTS STUDIES

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ABSTRACT

The Rotating Target Neutron Source (RTNS) at Lawrence Livermore Laboratory is currently the most intense source of DT fusion neutrons available for the study of radiation effects in materials. This paper will present a brief description of the machine, outline the history of its development and discuss its performance characteristics and its application to CTR materials research.

DESCRIPTION OF MACHINE

The RTNS consists basically of an ion source, a deuteron accelerator and a rotating tritium-containing target [1-4] (Fig. 1). The ion source is of the duoplasmatron type. The beam from the source is magnetically analyzed and atomic deuterium ions are accelerated to 400 keV by an electrode stack of conventional design which is powered by an Insulated Core Transformer (Fig. 2). The deuteron beam is bent down into a concrete-shielded target room so that the actual source of neutrons is located near the center of a cubical room 12 meters on a side.

The deuteron beam passes through a water-cooled collimator which has a 16-mm diameter aperture (Fig. 3). The beam impinges on a rotating target. The target is made of a copper - 0.15% zirconium alloy (Amzirc), 1 mm thick, which is hydroformed into the shape of a spherical surface. The inside of the target is vapor plated with a layer of titanium about 5 mg/cm^2 thick. (The range of 400 keV deuterons in Ti is about 1.6 mg/cm^2.) Tritium is occluded in the Ti to an average concentration of about 1.2 tritium atoms per Ti atom. (This is done by the Isotopes Division of Oak Ridge National Laboratory.) The target rotates at 1100 rpm while the deuteron beam is held fixed, so that the actual source of neutrons which is about 1 cm in diameter is fixed in space. In addition to the fast axial rotation of the target, there is provision for rocking it up and down about the pivot point shown on Fig. 3 so that the deuteron beam may strike the target over a range of target

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radii. In current operation, however, we normally leave the beam at a fixed radius until the neutron output decreases significantly (several hours) and then move to a new band, rather than oscillating the target continuously.

The target is cooled on the back side by a turbulent water layer 0.3 mm thick which is confined by a stationary stainless steel water spreader. The water is collected by a thin stainless steel catch cage and recirculated (Fig. 4). Since the catch cage moves up and down as different radii on the target are used, a thin stainless steel marker plate is mounted immediately behind the catch cage. This plate is stationary and its crossmarks show the fixed location of the neutron source. Samples are placed immediately behind the marker plate, and are mounted on clamps or tripods.

In order to reduce radiation leakage through the roof of the target room, a water tank, 1.2 m x 2.4 m x 0.6 m, is placed 0.4 m above the target (Fig. 5). The effect of this tank on the fast neutron spectrum at a sample placed close to the target is small because of the rapid decrease of flux with distance from the target and because of the long mean free path of the primary neutrons in water.

DEVELOPMENT OF THE RTNS

The RTNS was originally developed to obtain nuclear cross section data. It was first described in 1967 [1]. At that time, a fresh target produced 2×10^{12} n/sec with a target current of 8 mA. The output decreased to approximately half this value in 50 hours of operation. With the growing interest in CTR materials studies and biomedical applications, efforts have been made to increase the neutron output. In 1973, a new high voltage power supply and a new ion source were installed. These modifications resulted in larger target currents. The largest current that has been used to date is 22 mA, and the largest neutron output so far observed is 6×10^{12} n/sec. In order to increase the target life at the higher beam currents, the 150 mm diameter target described in 1967 has been replaced by a 230 mm diameter target, and care is taken to avoid the use of a too sharply focussed beam. In typical runs with 15 mA target current the yield decreases from 4×10^{12} n/sec to 3.4×10^{12} n/sec in 100 hours of operation [4].

CHARACTERISTICS OF SOURCE

Variation of Flux with Position

If the neutrons originated at a point, the flux would drop off inversely as the square of the distance. However, the actual source of neutrons is a spot about 1 cm in diameter. If one assumes, as is approximately the case, that the neutron emission is isotropic in the laboratory reference system, and that the source is a disc of radius a, the flux on axis is given by

$$\phi = \frac{Y}{4\pi a^2} \ln \left[1 + \left(\frac{a}{z}\right)^2\right] ,$$

where z is the distance from the center of the disc, and Y is the total neutron source strength in n/sec. Figure 6 shows the flux as a function of z as calculated from this relationship for a = 5 mm and Y = 3×10^{12} n/sec. This curve has been confirmed by foil activation measurements. For comparison, the dashed curve shows the variation of flux with distance calculated for a point source. It is evident that close to the source the behavior is significantly different from that for a point source.

The flux also decreases rapidly in the lateral direction for samples placed close to the target. Figure 7 shows this variation calculated for three values of the axial distance [5]. For a specimen placed 4 mm from the source, the flux decreases to half its on-axis value at a lateral distance of about 6.5 mm. The flux drop-off shown in this figure may not represent the actual conditions in a given run, but we believe that it is a conservative guide. The figure shows that it is possible to keep the dose uniform to within 15% for a sample of diameter (2r) 6 mm and thickness 0.5 mm placed 4 mm from the source.

Figure 7 shows the importance of knowing accurately the location of the center of the neutron source. Since the deuteron beam collimator only assures that all the neutrons are produced inside a circle of diameter 16 mm, a tuning monitor is used to ascertain that the effective center of the neutron source remains fixed in space. This monitor consists of a neutron detector which views the source through a narrow collimator.

Flux and Fluence Performance

The flux at a sample that is to be irradiated depends on several factors: The neutron source strength, the effective size of the deuteron beam, the size of the sample, the spacing between the neutron source and the sample, and the sample alignment. The fluence that can be obtained depends, in addition, on the length of the irradiation, the variation of source strength with time, and the maintenance of accurate beam positioning.

The highest measured value of the flux averaged over an extended run is 1.4×10^{12} n/cm^2-sec. This was obtained for a sample 5 mm x 5 mm x 0.13 mm irradiated at 20° C for a beam time of 33 hours. Typical values of the average flux during extended runs range between 5×10^{11} and 1.2×10^{12} n/cm^2-sec.

The large variation in these numbers is due primarily to variation in performance of different targets. Efforts are underway to determine the important factors affecting target performance and to improve quality control.

Energy Spectrum

The energy of a neutron resulting from a deuterium-tritium reaction depends on the energy of the incident deuteron and the angle between the path of the deuteron and the path of the emitted neutron [6]. The most important factors which give rise to a spread in neutron energy are:

(1) The energy of the deuterons varies from 400 keV to zero as they are stopped in the target.

(2) When samples are placed close to the target to obtain high flux, so that the separation between target and sample is small compared to their lateral dimension, the neutrons can strike the sample from a range of angles.

The first of these factors produces in the forward direction a range of neutron energies from 14.0 to 15.6 MeV, with a mean value of 15.0 MeV [7]. If a 1 cm diameter sample is placed as close to the source as possible, the mean energy of the neutrons at the sample is about 14.8 MeV. This value is based on calculations and corroborated by measurements by Heinrich and Dudey [8].

The mean neutron energy may vary slightly from target to target and as tritium is lost from the target, since the energy distribution of the neutrons depends on the tritium distribution in the target.

The neutron spectrum is also affected by scattering in material near the target, including the samples and associated equipment.

APPLICATION TO CTR MATERIALS RESEARCH - USERS' REQUIREMENTS

In the course of performing radiation effects studies on materials at the RTNS for over 40 experimenters during the past [illegible] 1/2 years, we have gained a great deal of experience with users' requirements. The main ones are the following:

Flux and Fluence

We have already discussed flux and fluence values and uniformity. Although there are plans to construct a more intense neutron source of similar design, the present machine has sufficient intensity to make possible several types of experiments. Table I is a list of those already performed. An example of an effect that occurs at low neutron fluence is the observation of an increase in the yield strength of copper at a fluence of 10^{16} n/cm^2. The yield strength more than doubled at a fluence of 3 x 10^{17} n/cm^2 during room temperature irradiation at the RTNS. It is possible to place several samples at different distances from the target in order to obtain a range of fluences during the same run. We have irradiated as many as 80 samples simultaneously.

Neutron Spectrum

Compared to other radiation sources used in materials research the RTNS neutron spectrum is narrow. When effects observed at the RTNS are compared with observations with fission reactor neutrons, the uncertainties in spectrum and fluences are considerably greater for the latter.

Irradiation Volume

Although the volume over which the flux is fairly uniform is small for the RTNS, it has proven to be adequate for many experiments, including studies of bulk mechanical properties, where the results have been very reproducible. Use of small samples also reduces the amount of radioactivity produced, and facilitates handling and shipping. Samples can usually be handled with bare hands after a few weeks of decay.

Sample Positioning

Accurate location of the sample relative to the neutron source is essential for maximum flux, as already pointed out. At the RTNS, the deuteron beam collimator and the marker plate are aligned using optically projected crosshairs. The tuning monitor collimator is aligned using a mechanical jig. The final sample alignment is performed by autoradiography: Either the sample itself or a copper foil with a hole in the center for reference is given a short irradiation (3-5 minutes) using the tuning monitor. An autoradiograph is then made using a Polaroid film pack. This requires about a 1-minute exposure. The position of the spot relative to the sample outline (or the hole in the copper foil) shows the quality of alignment directly. It is then simple to move the sample so as to correct any deviation. The tuning monitor is used throughout the main irradiation. With this technique we have usually been able to keep the sample centered to within about 1 mm on the neutron source.

Dosimetry

For most experiments, the samples are sandwiched between two niobium foils, and the fluence is calculated from the results of gamma ray counting of $^{92}Nb^{m}$ and the record of dose delivery as a function of time as measured with a proton recoil telescope. We estimate that the fluence can be determined to within $\pm$ 7.5% overall uncertainty by this technique.

Temperature

Temperature control requires the use of furnaces and cryostats. The challenge in designing these for use at the RTNS is to keep the sample as close as possible to the neutron source while keeping its temperature at the desired value, which may be much higher or lower than that of the water catch cage.

For high temperatures, we have sealed the samples inside a platinum capsule, which is heated from the back by a spot heater. This consists essentially of a tungsten-quartz-iodide light bulb inside an ellipsoidal reflector. The bulb is mounted at one focus of the ellipsoid, and the capsule at the other. Temperature is monitored with thermocouples spotwelded to the capsule, and control is maintained by regulating the current to the bulb. A small thickness (about 1 mm) of insulation is used between the capsule and the back of the water catch cage. This device has been used at temperatures from room temperature to above 800° C, and is able to control the temperature within $\pm$ 5° C during long irradiations. The flux achieved on the sample is generally about a factor of 3 to 4 lower than in room temperature irradiations, because of the thickness of the capsule and insulation.

For cryogenic measurements of electrical resistivity, we have modified a conventional cold finger type liquid helium dewar so that the sample is located about 12 mm from the neutron source while submerged in liquid helium.

The sample holder is rotated by a small motor as in a rotisserie in order to equalize the fluence on all parts of the sample. The first use of this apparatus is planned in July 1975.

For cryogenic measurements of neutron effects on the critical current of superconductors we are planning to use a liquid helium transfer line refrigerator. In this device, liquid helium is continually evaporated through an orifice on the cold finger. Because the device will operate in any orientation, it is possible to position the cold finger with its axis colinear with the deuteron beam rather than perpendicular to it as with the conventional dewar. Since a circular end plate is not subject to collapse due to buckling under vacuum loads as is a cylindrical wall, it is possible to use thinner structural material and thereby to place the sample closer to the neutron source. With this device, we hope to locate the sample within 8 mm of the source, while holding it at liquid helium temperature. Nuclear heating is negligible with the RTNS as compared with fission reactors primarily because of the much lower gamma ray flux.

Environment

It is necessary to maintain ultra-high vacuum around the samples for certain types of experiments, in particular, surface studies and high temperature irradiation of refractory metals. Three groups of experimenters have so far performed surface studies at the RTNS. All have used dynamic vacuum systems employing vac-ion pumps. As with furnaces and cryostats, the key problem is to keep the sample close to the neutron source for maximum flux. This has been achieved using thin end plates on the vacuum chambers. It is possible to locate the sample within about 6 mm of the neutron source by this method. A small increase in pressure is observed when the neutron source is turned on, probably due primarily to radiation-enhanced outgassing, as well as (n,p) and (n,α) reactions.

For high temperature irradiation of refractory metals, we have used the sealed Pt capsules mentioned above. They are designed to have a minimum amount of dead space inside, and are evacuated and sealed by electron beam welding. The resulting static vacuum reduces oxygen and nitrogen contamination to a minimum.

In situ creep testing will require a dynamic ultra high vacuum system with provision for loading the sample, measuring its strain, and controlling the temperature. This apparatus has not yet been built.

In Situ Monitoring

Many radiation effects experiments involve remote monitoring and control of parameters such as pressure, temperature, mechanical loads, and voltages or currents. For this purpose provisions are made to make connections through the concrete shielding to a room adjacent to the target room, where experimenters can set up instrumentation outside the radiation field.

Radioactive Materials Storage and Handling

The amount of radioactivity generated by the RTNS is small for two reasons: First, the volume over which the flux is appreciable is small because of the very localized nature of the source and its relatively small source strength by reactor standards. Second, the largest cross sections for activation in the 14-15 MeV region are only of the order of 1 barn. These conditions are much different from those with fission reactors, for example, where the high flux region may be measured in cubic meters and the cross sections may be hundreds of barns or more. As a result of these factors it has normally been possible to enter the target room to remove samples only a few hours after long irradiations. Samples are handled with tongs or on the end of rods, and stored in a small lead cask until they can be shipped, usually within two weeks. Activated apparatus is stored against the walls of the target room until the activity decays sufficiently that it can be removed.

Access

It is essential that users have ready access to the machine. We have attempted to accomplish this by maintaining flexible scheduling and combining several samples on the same run where possible. We have usually been able to keep the turnaround time below two months from the time samples are received to the time they are shipped back to the experimenters.

FUTURE PLANS

The RTNS will continue to be used for materials research in the CTR program. Efforts are continuing to improve the performance of the present facility. The following paper [9] describes plans for a new neutron source of similar design as the present RTNS, but which is expected to have an order of magnitude larger source strength. Some of the developments resulting from that work will be incorporated into the present RTNS facility before the new machine becomes operational.

ACKNOWLEDGMENTS

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TABLE I

TYPES OF EXPERIMENTS PERFORMED TO DATE

1. ELECTRON MICROSCOPY
2. MOSSBAUER EFFECT
3. TENSILE TESTS
4. ELECTRICAL RESISTIVITY
5. RATE OF HELIUM PRODUCTION - VACUUM FUSION AND MASS SPECTROSCOPY
6. SPUTTERING AND PARTICLE RELEASE
7. ELECTRON PARAMAGNETIC RESONANCE
8. OPTICAL ABSORPTION
9. THERMAL DECOMPOSITION
10. CRITICAL CURRENT OF SUPERCONDUCTORS

Figure Captions

Fig. 1 Diagram of RTNS Facility.

Fig. 2 RTNS Accelerator.

Fig. 3 Diagram of 230 mm Rotating Target Assembly.

Fig. 4 Rotating Target Assembly in Operating Position.

Fig. 5 Water Tanks in Place above Target.

Fig. 6 Calculated variations of flux with distance on-axis for source strength of 3×10^{12} neutrons/second.

Fig. 7 Calculated variations of flux with distance off-axis of source for three values of separation along axis. The multipliers of the values along the ordinate are shown on the curves.

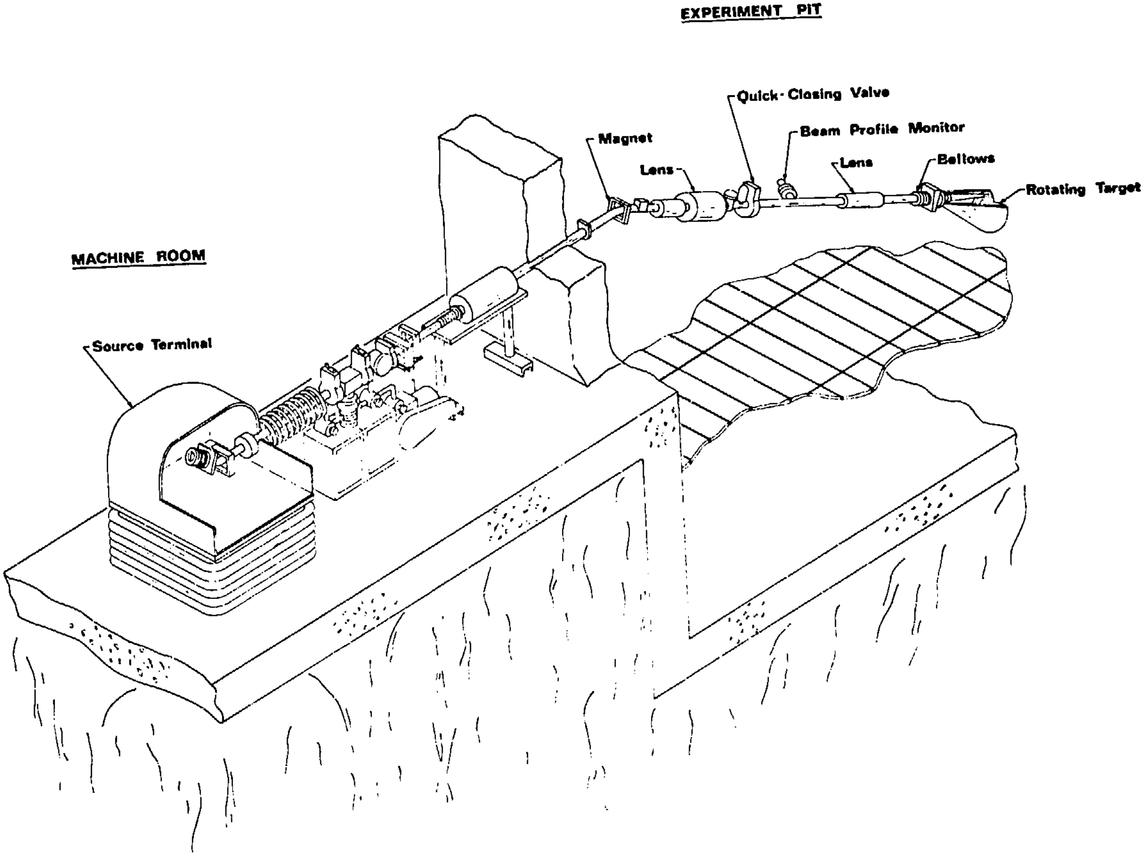
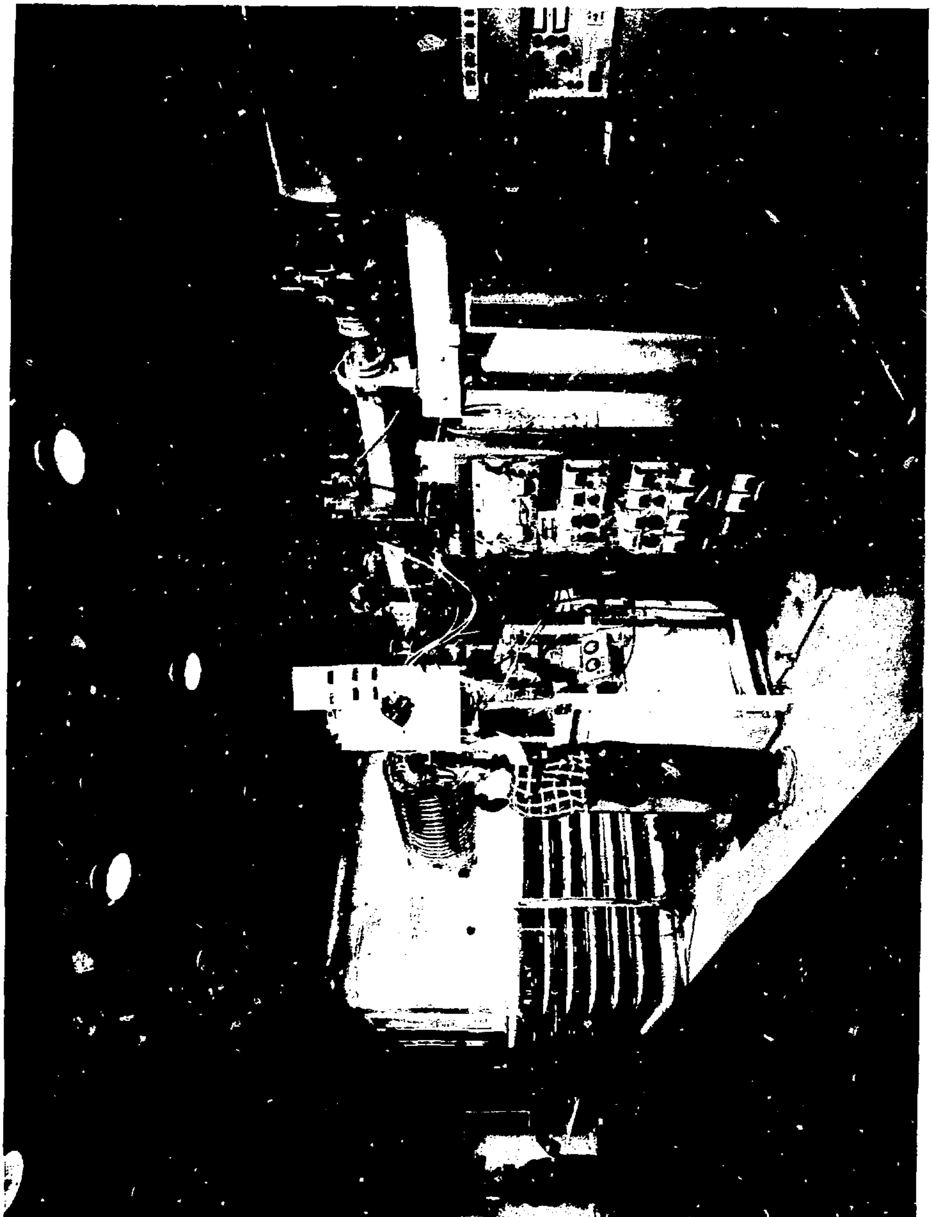
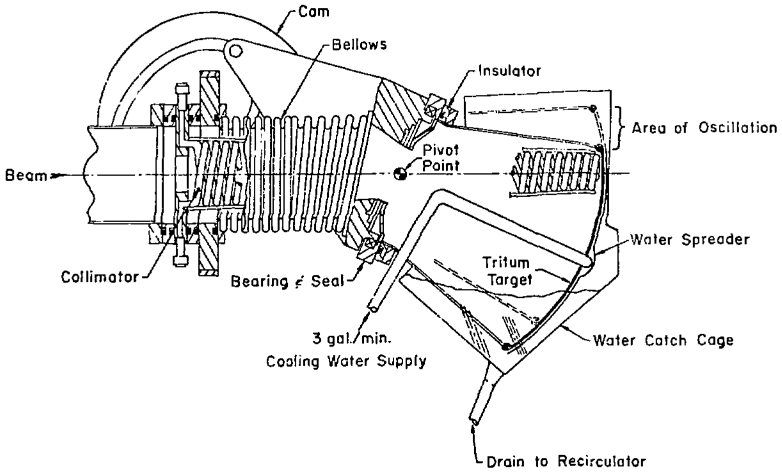

EXPERIMENT PIT
Quick-Closing Valve
Magnet
Beam Profile Monitor
Lens
Lens
Bellows
Rotating Target
MACHINE ROOM
Source Terminal

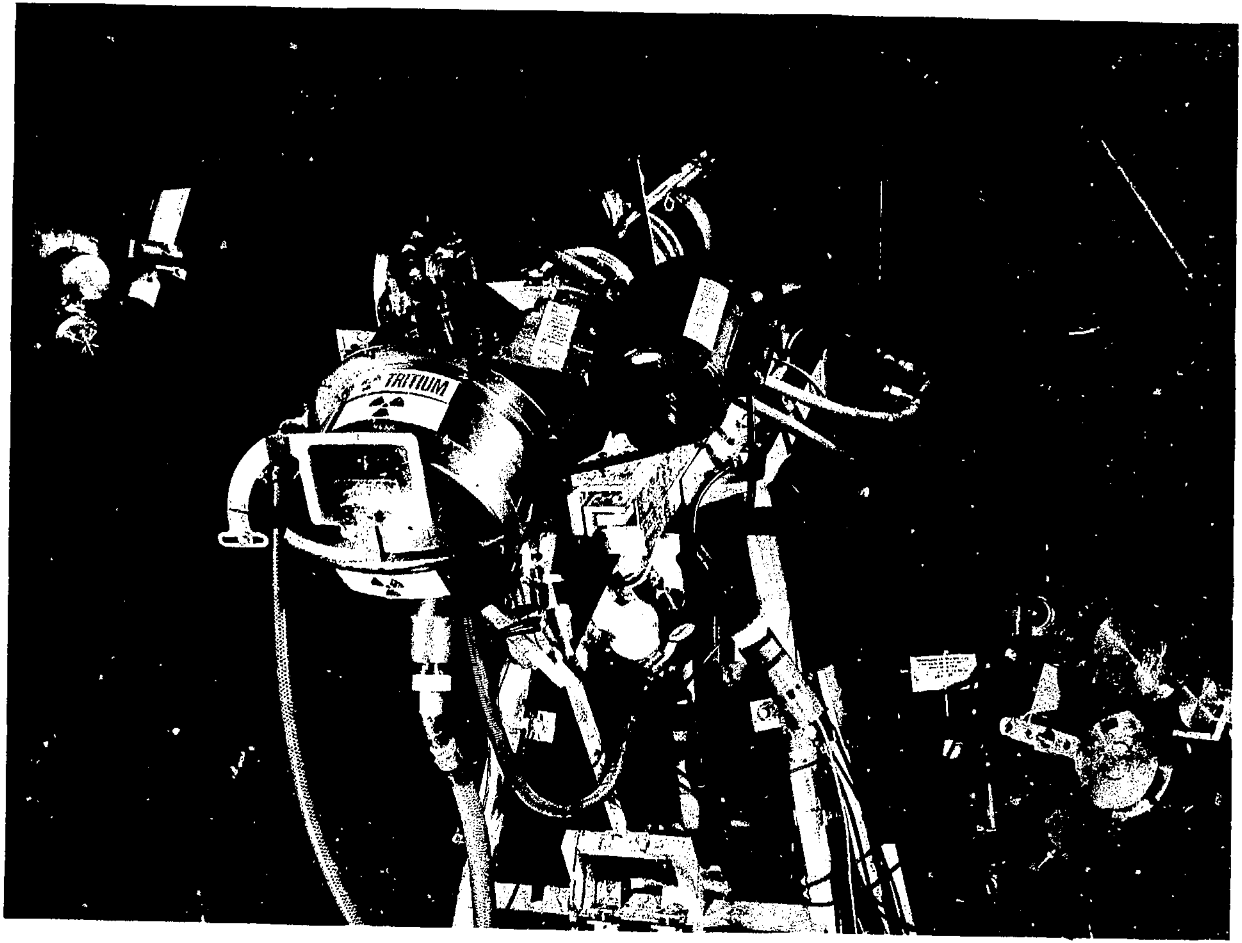
Fig. 1

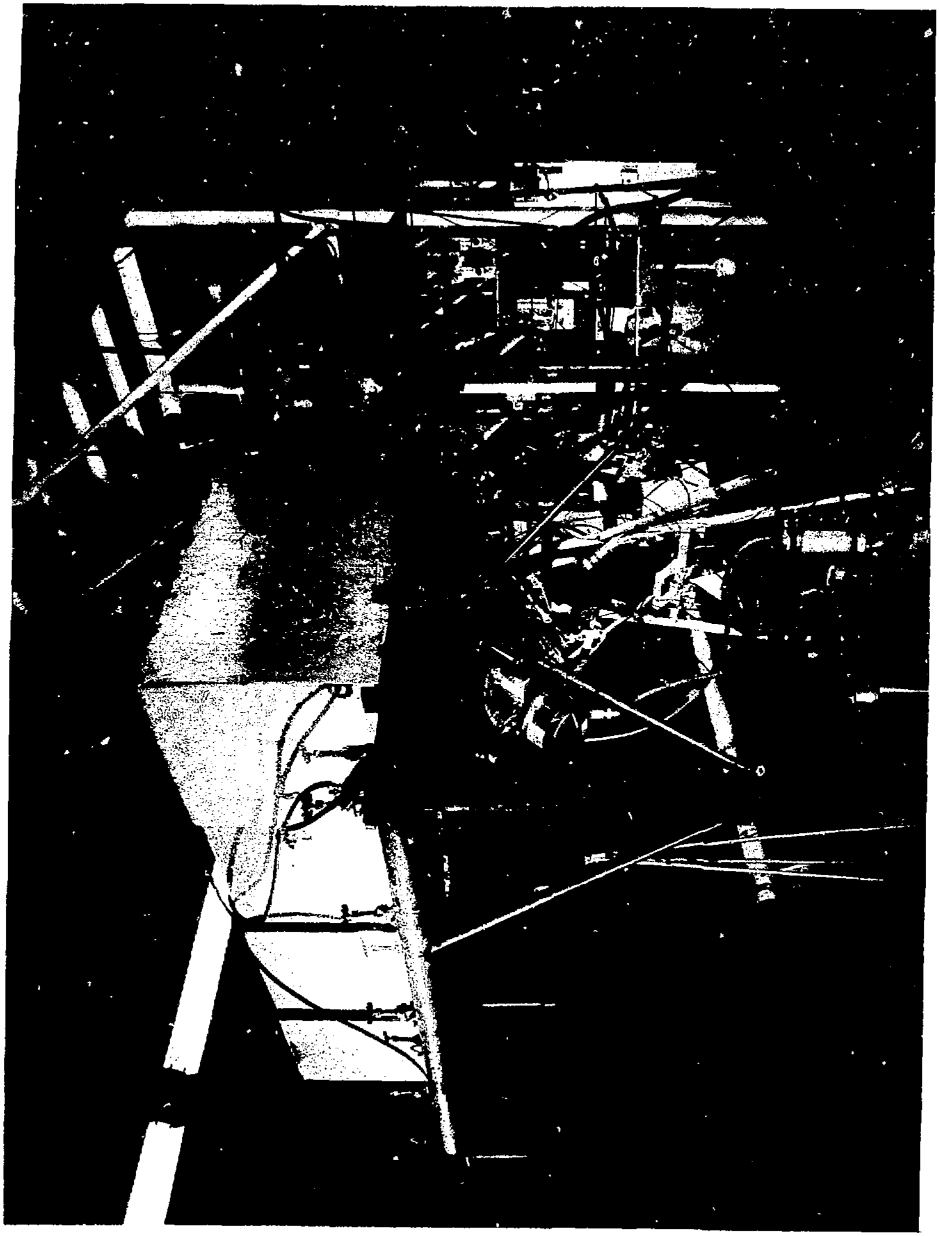




Cam
Bellows
Insulator
Area of Oscillation
Pivot
Point
Beam
Water Spreader
Tritum
Target
Collimator
Bearing & Seal
3 gal./min.
Cooling Water Supply
Water Catch Cage
Drain to Recirculator

Fig. 3


TRITIUM



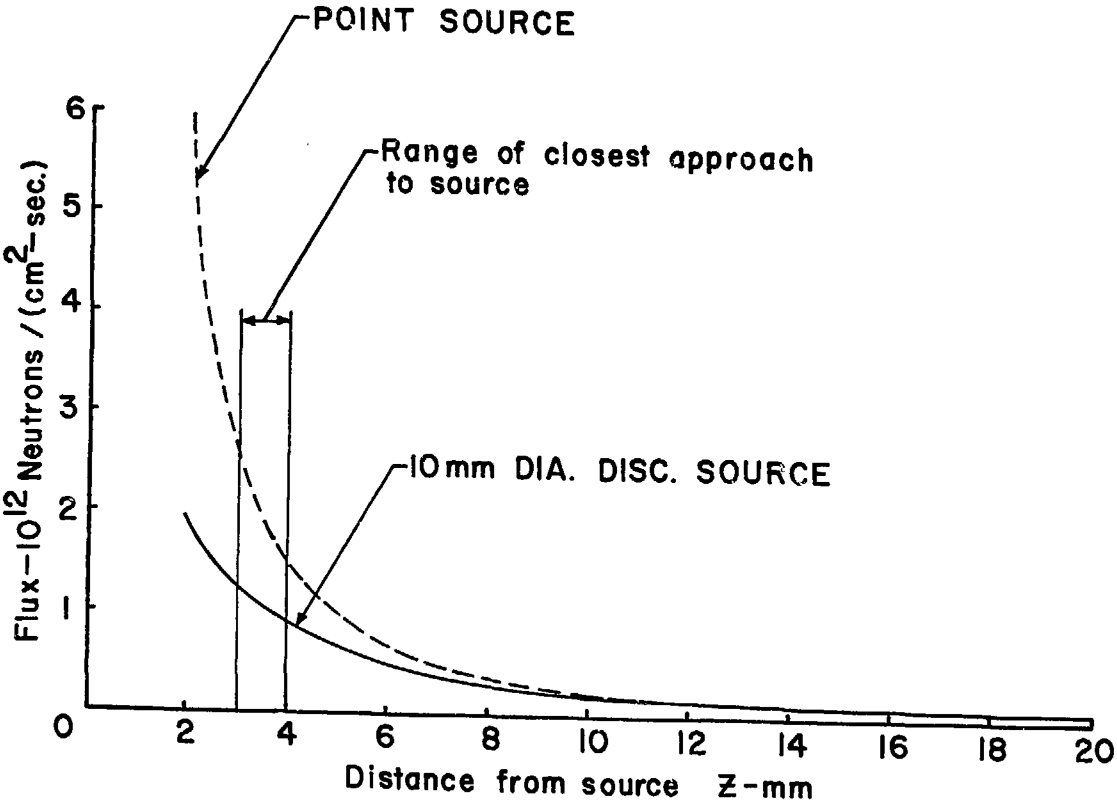
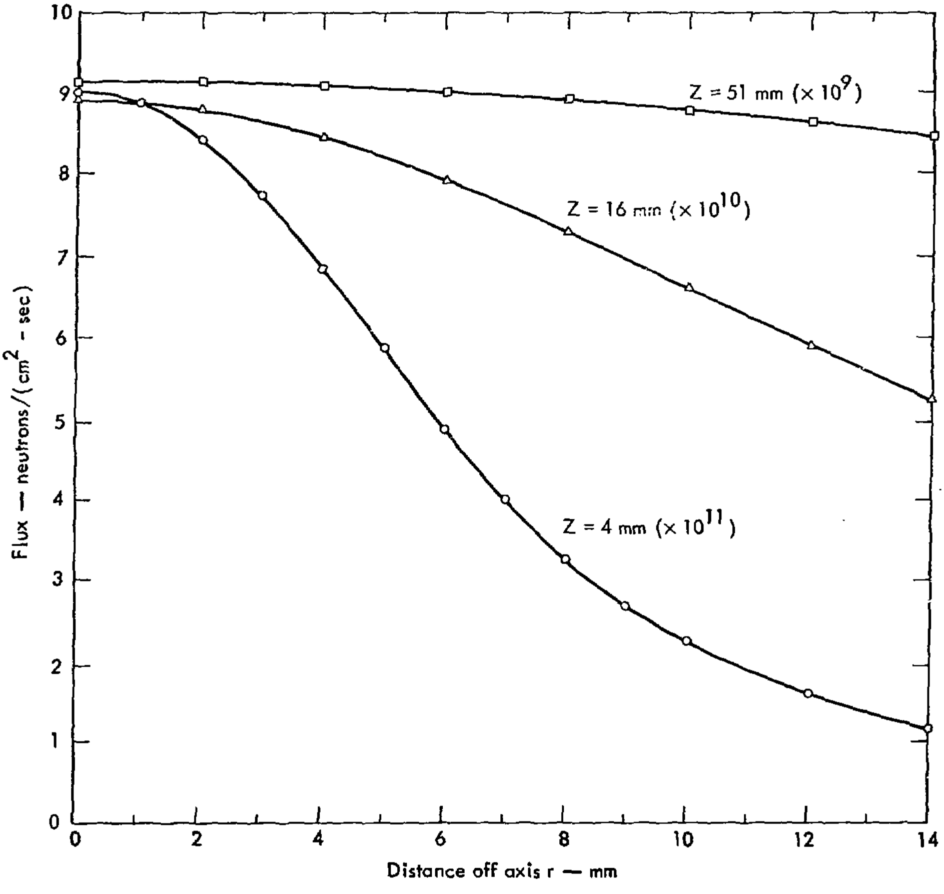

POINT SOURCE
Range of closest approach to source
10 mm DIA. DISC. SOURCE
Flux-10^12 Neutrons /(cm^2-sec.)
0
1
2
3
4
5
6
2
4
6
8
10
12
14
16
18
20
Distance from source Z-mm

Fig. 6



Flux — neutrons/(cm^2 - sec)
Distance off axis r — mm
Z = 51 mm (× 10^9)
Z = 16 mm (× 10^{10})
Z = 4 mm (× 10^{11})

Fig. 7

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