14 MeV d,t Sources

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I. INTRODUCTION

Among the neutron producing reactions the reaction of ^{2}H with ^{3}H, the D-T reaction, has by far the largest cross section. It reaches 5 b at a deuteron bombarding energy of 105 keV. This large cross section at a low bombarding energy has made the D-T reaction the most widely used reaction for applications in which a compact intense neutron source is needed. Usually deuterons of energy between 100 and 400 keV are stopped in a metallic target in which tritium has been absorbed. Much effort has gone into the design of targets that will provide a strong neutron source over a long time. Target performance is also strongly influenced by the energy, composition, and spatial current distribution of the bombarding deuteron beam. Ref. 1, which is concerned with the use of neutron generators for activation analysis, describes D-T generators, as well as their operation and their hazards, in much more detail than the present account.

II. THE DT REACTION

(a) Neutron Yield and Energy Distribution

The cross section for the reaction $^{2}H + ^{3}H \rightarrow ^{4}He + n + 17.59$ MeV is plotted against laboratory deuteron energy in Fig. 1. This figure is based on the measurements of references (2), (3) and (4) and is taken from reference (5).

According to reference (6), for bombarding energies below 400 keV the angular distribution of the emitted neutrons is nearly isotropic in the center-of-mass system, but the laboratory differential cross sections in the forward direction are about 26% higher than in the backward direction at a deuteron bombarding energy of 400 keV.

The center-of-mass motion introduces a substantial variation of the energy of the emitted neutrons even at fairly low bombarding energies. The energy of the neutrons in the center-of-mass system is 14.1 MeV. In the laboratory system the neutron energy varies from 14.8 MeV at 0° to 13.4 MeV at 180° for a deuteron bombarding energy of 100 keV, and from 15.6 MeV to 12.9 MeV at a deuteron energy of 400 keV.

In the use of the D-T reaction for neutron generators the deuterons are usually stopped in a thick target. In that case the neutron yield and spectrum depend on the distribution of the tritium in the target. A good freshly prepared target has a uniform distribution of tritium throughout the interior of the metal, but as the bombardment of the target proceeds, tritium is removed from the metal at differing rates depending on depth, so that the energy distribution of the emitted neutrons may change with time. There are variations in the number of tritium atoms per metal atom in targets manufactured by different suppliers and even in targets manufactured by the same supplier. In addition, the tritium concentration varies with the time the target has been in use. Calculations of neutron yield sometimes assume an atomic ratio of tritium to metal of unity throughout the target (7) although some calculations (5) assuming atomic ratios from 0.2 to 2.0 have also been published. Calculated yields depend not only on the assumed atomic ratios and a knowledge of the reaction cross section but also on the stopping powers, and the stopping powers of the metals are not very well known for low-energy ions.

Because of the large peak in the cross section at a deuteron energy of 100 keV, the thick-target neutron yield rises rapidly with deuteron energy as shown in Fig. 1; it increases eightfold from 50 keV to 100 keV, doubles between 100 and 150 keV, and increases another 50% between

150 keV and 240 keV. At higher energies the yield increases more slowly, only by about 40% when the 240 keV deuteron energy is doubled.

In reference (7) neutron spectra from thick targets are calculated. The spectra have a pronounced peak at the neutron energy corresponding to a bombarding energy somewhat above 100 keV. For neutrons emitted in the forward direction, the average neutron energy increases from 14.1 to 14.8 MeV as the deuteron energy increases to 200 keV, and increases more slowly above a bombarding energy of 200 keV reaching 15.0 MeV around 500 keV. Although these neutron-energy variations are small, some neutron cross sections vary rapidly in this energy region so that in many uses care must be taken to specify the neutron energy more definitely than "14 MeV", although 14 MeV is close to the average neutron energy if the direction of observation is near 95° or if neutrons emitted in all directions are used.

The yields plotted in Fig. 1 and the quoted neutron energies refer to the bombardment of the target by deuterium atomic ions. If singly charged diatomic deuterium ions are used, the bombarding energy should be divided by two and the yield should be multiplied by two. If the reaction is reversed, i.e., if tritons bombard a deuterium target, the reaction cross section is the same as that for deuterons of 2/3 the triton energy. On the other hand, the thick target yield for the reverse reaction cannot be obtained simply. Calculations of thick target yields for the reaction of tritons on deuterons are given in reference (5). Just above 200 keV bombarding energy the yield curve for triton projectiles crosses that for deuterons. In some generators a mixture of deuterium and tritium ions bombards the target. 150-keV tritons produce about two-thirds the neutron yield of 150-keV deuterons. When a mixed beam of equal numbers of deuterium and tritium ions bombards a target containing equal numbers of deuterium and tritium ions, only half the collisions are between deuterons and tritons. In this case, for a bombarding energy of 150 keV on a Ti target, the yield of neutrons is about 40% of that expected from a deuteron beam on a tritium target. At the same time the reactions of deuterons with deuterons will produce a small number of neutrons of lower energy. The yield produced by 150-keV deuterons on deuterium is only 0.4% of the yield from deuterons on tritium and hence will contribute less than 0.5% to the total yield. The deuteron beam will also embed deuterium in pure tritium targets. The contribution of neutrons from the reaction of deuterons on deuterons increases as tritium is lost from the target during bombardment. Whether this contribution is appreciable depends on how long the target is used and whether the beam has components other than atomic deuterons.

Although mixed-beam sources usually use equal amounts of deuterium and tritium, this mixture does not necessarily produce the largest number of neutrons per unit incident charge, but no systematic study of the dependence of source strength on isotopic composition of the beam appears to be available.

(b) Charged-particle Energy and Current Requirements

In most commercially available DT neutron generators hydrogen ions are accelerated to 150 kV. This voltage is determined by the availability of compact, simple, and inexpensive high-voltage power supplies at ratings up to 150 kV. Although there are some D-T generators that operate at higher voltage, these are used only in applications that require very high neutron source strengths.

As shown in Fig. 1, 150 keV is above the energy of the peak in the cross section and is well up on the thick-target yield curve. In most D-T generators the ion beam is not analyzed and contains a substantial fraction of diatomic and, in many cases, triatomic deuterium ions. Their energy is substantially below the peak in the cross section. Hence they contribute little to the neutron yield but contribute to the target deterioration.

Deuterium ion currents in most commercially available D-T generators are in the range of 1-5 mA. According to Fig. 1, 1 mA of 150 keV deuterons produces about 1.5×10^{11} n/s. Such a high yield is expected only for a fresh tritium target bombarded by an atomic beam. The presence of other ion species, the fact that many commercially available tritium targets have a lower atomic ratio than the value 1.6 assumed in Fig. 1, and that targets often deteriorate rapidly with ion bombardment, result in considerably lower yields in most generators. Some generators use sealed tubes rather than evacuated acceleration tubes. In these units the yield is much lower for a given tube current. Typical neutron source strengths available from compact D-T generators are of the order of 10^{11} n/s.

For yields much above 10^{11} n/s more elaborate systems are needed. Neutron yields may be increased by using higher energy projectiles. As the energy is raised much above 150 keV, the neutron yield per incident beam power decreases. Since heat removal from the target limits the beam current, there is little advantage in increasing the acceleration voltage very much. The highest operating voltage of high-intensity D-T generators is at present 500 kV.

The highest ion currents that have been actually used in D-T generators are near 0.5 A (8), but currents as high as 1 A have been proposed (9). The highest power that has been dissipated in the target is about 80 kW (8) to achieve a neutron source strength of 8 × 10^{12} n/s. Proposals for more intense neutron sources contemplate a power dissipation of 150 kW in a solid target (10) and 300 kW in a gas target (9) for neutron source strengths of 10^{14} n/s and 10^{15} n/s, respectively.

III. APPLICATIONS

(a) Microscopic Cross Section Measurements

As soon as solid tritiated targets had been developed, D-T generators served as neutron sources for the measurement of microscopic cross sections for neutrons of energy near 14 MeV. The D-T reaction provides a unique intense source of monoenergetic neutrons above the region around 3 MeV which had been explored with D-D neutrons. At first the interest in measuring 14 MeV neutron cross sections was primarily to gain knowledge in fundamental nuclear physics. More recently 14 MeV cross sections have become important to the design of fusion reactors.

The earliest measurements of microscopic neutron cross sections with D-T generators were investigations of the angular distribution of 14-MeV neutrons scattered by protons (11), deuterons (12), and tritons (13), and measurements of the total cross sections (14) of the elements from H to U.

The high neutron intensities available from more recently built D-T generators have made possible the detection, identification and energy determination of charged particles emitted in reactions, even in cases where the emission cross section is small (15).

(b) Integral Experiments

Although a knowledge of microscopic cross sections is in principle sufficient to calculate the transport of neutrons through matter in bulk, the information about the spectra of secondary neutrons and gamma rays is often not sufficiently complete for calculating the total dose behind a thick shield or the transport of neutrons in the thick blankets of fusion reactors. Integral experiments serve to supplement and verify microscopic data. D-T generators have been useful for performing such experiments with 14-MeV neutrons, particularly by the "Pulsed Sphere" experiments (16). In these experiments a pulsed deuteron beam produces a pulse of 14-MeV neutrons about 1.5 ns long at the center of a sphere made of the material to be studied. The radius of the sphere is several mean free paths for 14-MeV neutrons. The spectrum of neutrons emanating from the sphere is measured by observing the times of arrival of the neutrons at a detector about 10 m from the neutron source. In addition, spectra of gamma rays produced in the sphere may be measured with a gamma ray spectrometer.

(c) Activation Analysis

Qualitative and quantitative determinations of chemical elements by measuring radioactivity induced by neutrons has in many cases advantages over the methods of conventional analytical chemistry. Activation analysis permits the detection of elements in very low concentrations or in very small samples with good accuracy. Although activation analysis is most frequently performed with the thermal neutrons from a reactor, there are advantages in using a D-T generator (1). It is possible to slow down the D-T neutrons and use the slow neutrons for activation analysis, but the intensity is much lower than that available from a reactor. For nuclides which have a large activation cross section for slow neutrons, the intensity of slow neutrons from a D-T generator may, however, be adequate.

The principal use of D-T generators in activation analysis is for the detection of elements that do not produce readily observable activities with slow neutron irradiation. Activation with 14-MeV neutrons is particularly useful for the determination of some of the light elements, such as nitrogen and oxygen (1) (17).

Activation analysis with DT generators has included the determination of oxygen in steel and other metals; the determination of oxygen, silicon, and aluminum content of rocks; analysis of coal and coal derivatives (18); foods by the determination of nitrogen (19); the determination of fluorine, sodium, and selenium in water; and the detection of explosives through their nitrogen content.

(d) Safeguards

Safeguards refers to the measurement and analysis of fissile materials. The presence of fissile materials in a container can be ascertained by irradiating the container with neutrons which will induce fissions in the fissile material. Since secondary neutrons are produced in the fission process, the detection of these neutrons can serve to give quantitative information about the fissile material that is present (20). Prompt neutrons from fission can be identified by observing coincidences, because more than one prompt neutron is usually emitted in each fission process, and delayed neutrons can be observed after the neutron source has been turned off (21). Radioactive neutron sources are most frequently used for the safeguards application because of their simplicity and reliability. There are, however, advantages to the use of DT generators provided that they are reliable and, for many applications, easily portable. DT generators can produce much higher source strengths than radioactive sources, they can be easily turned on and off, a feature of great importance for delayed neutron counting, and DT generators do not emit neutrons unless they are turned on which simplifies their transportation. Sealed-tube DT generators are likely to be widely used for safeguards applications in the future.

A quite different use of D-T generators for safeguards is in the lead slowing-down spectrometer (22). In this method a burst of DT neutrons is produced at the center of a large lead block which serves to slow down the neutrons gradually. At a given time after the initial burst the neutrons will have a fairly well defined average energy. The observation of the time at which fission neutrons from a sample placed inside the lead block arrive at a neutron detector permits the quantitative determination of fissile nuclides in the sample because different fissile nuclides have fission resonances at different energies. This method can be used on spent fuel elements that are intense sources of γ-rays because the lead is an effective shield between the sample and the detector.

(e) Geophysics

The development of sealed tubes of small diameter for DT generators has made it possible to produce 14-MeV neutrons in bore holes. When these neutrons interact with the material in the neighborhood of the borehole, secondary radiation is produced that can yield information about the composition of the surrounding material.

Exploration for uranium ore is a particularly promising application of "Bore hole configured" sealed tubes. The presence of uranium can be ascertained as in the safeguards application either by the detection of prompt fission neutrons or by the detection of delayed neutrons (23). In this application prompt neutrons are, however, not detected directly by coincidence counting, but their effect on the time dependence of the arrival of slow neutrons returning to the bore hole is observed (24). Most of the fissions are induced by neutrons that have been slowed in the material surrounding the bore hole. The prompt neutrons produced in these fissions are in turn slowed and therefore arrive much later than the neutrons from the original burst. Neutrons from the initial burst disappear within 10 μs, while the slowed fission neutrons arrive for several hundred microseconds after the burst (25). Exploration for other ores or oil with DT generators can use the techniques of activation analysis by the observation of characteristic γ-rays after a neutron pulse or by measurement of the time dependence of the returning neutrons or gamma rays (26). The rate at which the neutrons are slowed down is very sensitive to the presence of hydrogen in the surrounding formation.

(f) Radiation Damage

An important consideration in the design of fusion reactors is the choice of the material for the first wall of the reactor, the wall that is nearest the region in which the thermonuclear reactions occur. Present designs of fusion reactors are based on the DT reaction so that the first wall is bombarded by a DT neutron flux of a density of the order of 10^{14} cm^{-2} s^{-1}. How long the first wall can be subjected to this bombardment without losing its mechanical integrity determines how long the reactor can be operated without major overhaul and hence how feasible the reactor is for power generation (27). Hence investigations of the radiation damage caused by 14-MeV neutrons are vital to fusion reactor technology (28).

Neutrons of lower energy produce fewer transmutations than 14-MeV neutrons so that radiation damage studies with fission neutrons do not give adequate information. On the other hand, it is very difficult to design a DT generator that will produce the required flux density, i.e., more than 10^{14} cm^{-2} s^{-1}. The only way in which high flux densities can be obtained is to make the neutron source very small and to place a small sample very close to the source, but even with this arrangement the required flux density has not yet been achieved. Studies of radiation damage with 14-MeV neutrons are the application that has by far the most severe requirements for DT generators.

(g) Radiation Therapy and Radiobiology

At present clinical trials are in progress to find out whether or not radiotherapy with neutrons has advantages over the conventional radiotherapy with photons (28). Neutron sources for radiotherapy should produce neutrons of average energy above 10 MeV to provide sufficient penetration through tissue. They should provide at least 5×10^{11} neutrons per second and per steradian so that treatment times can be limited to 5-10 minutes. In addition, the source should permit isocentric mounting, i.e., permit the source to move around the treatment volume. DT generators are the cheapest source of high-energy neutrons and can be easily isocentrically mounted. Until a few years ago DT generators did not provide adequate intensity, but recently DT generators have been developed that may have adequate source strength. Their cost is likely to be very much lower than that of cyclotrons that are at present the only other available appropriate neutron source. Cost is a particularly important factor, should neutron therapy become a widely adopted modality.

In part because of the application in therapy and in part because of the interest in radiation protection, many radiobiological experiments have been performed with 14-MeV neutrons using either standard or high intensity DT generators. An important advantage of DT generators over other neutron sources that produce neutrons of comparable energy is that DT generators do not produce gamma rays which have a much lower biological effectiveness.

D-T generators have also been used for total body in vivo neutron activation analysis (29,30). For this application with a neutron source strength of the order 5×10^{10} n/s, irradiations lasting about one minute produce satisfactory signals. The interest is primarily in the determination of N, but also of P, Mg, and Cl.

IV. CHARGED-PARTICLE ACCELERATION

Accelerators of ions consist of a source in which the gas is ionized and from which ions are extracted through an aperture into a region at lower pressure where they are accelerated. Most D-T generators consist of such an ion source and a straight acceleration tube across which a D.C. potential difference is applied. In some compact D-T generators the ion source and the acceleration tube are not as clearly separated and may be at the same gas pressure. In this type of tube ions are accelerated in a low-pressure gas discharge. The present discussion will treat first the traditional accelerators which produce a beam of particles and will describe some of the sealed tubes in a later section.

(a) Ion Source

The same types of ion sources that are used in other accelerators are used in D-T generators (1). Radiofrequency sources are preferred over Penning sources in low current generators because they produce a larger fraction (~ 90%) of atomic ions. The output of the R.F. source decreases with use and after several hundred hours of operation the bottle which contains the plasma must be replaced. High frequency oscillators are preferred to reduce modulation of the extracted ion beam.

Some sealed-off neutron generator tubes use radiofrequency sources (such as some of the tubes manufactured by Marconi Avionics in England) while others use Penning sources (such as other tubes manufactured by Marconi Avionics and those produced by Philips in the Netherlands). Other sealed-off tubes (such as some tubes manufactured by Kaman Nuclear) use occluded gas sources in which a spark discharge releases occluded deuterium (or tritium) from the cathode. These sources also produce nearly 90% monatomic ions.

For high-intensity generators duoplasmatron ion sources are most frequently used (8, 31, 32). Duoplasmatron sources permit extraction of total beam currents of up to 150-200 mA (9,32), but have been less successful for obtaining well-focused beams of monatomic ions of more than about 50 mA. This limitation has been overcome by the multiple aperture source developed by Osher and Hamilton (33) which has been reported (10) to produce a well-focused beam of 150 mA of monatomic ions.

(b) Acceleration Tube

Since the voltage across the tube of a D-T generator is usually below 200 kV and only in some high-intensity sources as high as 500 kV, the design of the acceleration tube offers no great problem. Some use a single gap (32), others as many as 18 gaps (34). In high-current accelerators defocusing by space charge effects can be reduced by using a high gradient and few electrodes, while the use of more electrodes reduces the possibility of electrical breakdown, especially if the gas pressure in the tube is high. Electrodes have been made out of aluminum, stainless steel, and molybdenum. Often provisions, such as biased electrodes, are made to prevent secondary electrons ejected by positive ions, from being accelerated towards the high voltage terminal.

While the details of the design of the acceleration tube are usually not important at ion currents up to a few mA, considerable care has to be exercised when currents of many mA are desired in a well-focused beam. The design of an appropriate electrode system is discussed in ref. (10).

(c) Voltage Supply

The type of high-voltage supply needed for a D-T generator depends on whether or not the beam is analyzed after acceleration or transported over a long distance through a system of lenses. Beam analysis and transport require good voltage stability and low ripple to assure a stable beam. Most D-T generators do not have beam analysis, and all accelerated particles hit the target. For this type of generator many types of commercially available high-voltage supplies are satisfactory, provided the current is below 50 mA and the voltage below 300 kV. For higher currents and voltages, and for generators that use an analyzed beam, more specialized voltage supplies are needed. The Livermore high-intensity generator built in 1967 (35) uses an Insulated Core Transformer (ICT) manufactured by the High Voltage Engineering Corporation. Such supplies are available with voltages up to 500 kV and current ratings up to 200 mA. They have adequate voltage stability and low enough ripple to produce a stable beam after deflection in a magnetic field. ICT systems can also be used to provide power for the ion source at high voltage.

Another high-voltage power supply that can be used at higher voltage is the Dynaply supply manufactured by Radiation Dynamics. There is at present only one DT neutron generator that uses such a supply (34). This supply is rated at 500 kV and 25 mA, but supplies with ratings of 500 kV and 100 mA and 1.5 MV and 50 mA are also available.

For even higher current ratings air insulated cascade rectifiers manufactured by E. Haefely & Co. (36) have been used. One such system has a 200 kV-300 mA supply (29), another a 400 kV-300 mA supply (10), a third a 200 kV-500 mA supply (37). These supplies are available with regulation of 0.1% and less than 0.5% ripple. A motor generator converts the line frequency to 2 kHz. The rectifiers are Si diodes. Some care has to be taken to shield the rectifiers from the neutrons to avoid radiation damage to the rectifiers.

(d) Beam Analysis and Transport

The purpose of analyzing the ion beam is to prevent deterioration of the target by unwanted species of ions. As will be discussed in a later section, neutron production from solid targets has been observed to decrease very rapidly when the target is bombarded either by a mixture of atomic and molecular ions or by heavy ions. For some types of DT generators target life can be substantially lengthened if only atomic ions hit the target. Magnetic analysis of the beam has been carried out either before (10) or after acceleration of the beam (35). Advantages of analysis before acceleration are that the accelerator and beam transport systems can be optimized for a particular ion species, that no high voltage power is used for the acceleration of unwanted ions, and that there is less problem with stopping of unwanted beams.

Although the neutron source is near the end of the acceleration tube in many D-T generators, there are applications for which it is desirable to transport the beam over a considerable distance. One reason is that for high-intensity sources substantial shielding has to be provided to protect the ion source and associated power supplies and control circuits as well as the main high-voltage power supply from suffering radiation damage from neutron bombardment. In some uses of D-T generators a large amount of experimental equipment has to be placed around the neutron source so that space between the accelerator and the target has to be provided. For example, for a measurement of the attenuation of 14-MeV neutrons in air the neutron source was surrounded by a sphere of 1.7 m radius (38).

The transport of small average currents over long distances poses no problems, but if the currents exceed 50 mA there is a possibility that space charge may defocus the beam. Hence neutralization of space charge is necessary, and the effect of beam crossovers produced by focusing lenses must be considered.

(e) Beam Diagnostics and Current Measurements

When DT generators serve as neutron sources for the study of radiation damage, small samples are often placed very close to the source in order to maximize the neutron flux. For such an irradiation the exact position of the neutron source needs to be known, and the diameter of the source should be as small as is compatible with the power density that the target can withstand. Small changes in the position where the charged particles strike the target and in the profile of the charged-particle beam can change the neutron flux at the sample drastically.

The position of the beam spot on the target can be limited most conveniently with a collimator through which the beam passes. By minimizing the beam that strikes the collimator one can assure that most of the beam strikes the target within a prescribed area. For intense sources that need intense charged-particle beams the collimator requires good cooling. A satisfactory design (31) that limits the beam to a diameter of 1.2 cm consists of 6-mm diameter copper tubing through which water flows. The copper tubing is formed into a collimator by winding it on a tapered mandril. Steel sheet is soldered to the outside to stiffen the tubing.

If samples are placed within a few millimeters of the neutron source, the effective center of the source needs to be more accurately known than the limitation imposed by the collimator. A method that has been used for this purpose is to place a small neutron detector, such as an organic scintillator that observes proton recoils, at about 0.5 m from the source behind a neutron collimator with a small opening, with the axis of the collimator pointing at the desired neutron source position. The charged-particle beam is steered to maximize the response of the scintillator.

Especially if the charged-particle beam passes through focusing lenses, the target spot may have a shape far from circular and a non-uniform intensity distribution. Spots at which the power density is high may result in rapid target deterioration. For low-current accelerators various types of beam profile monitors are available. Usually such monitors have thin wires that oscillate in the beam. At high beam currents the wire would intercept too much power. When a high-current beam strikes the target, enough fluorescent light is given off to make the beam spot visible, and the light intensity increases with beam intensity. Viewing the target with a television camera permits monitoring of the intensity distribution of the neutron source. Care must be taken to prevent source neutrons from striking the camera, since most television cameras are damaged by relatively low neutron fluences. If the target is viewed through a window or with a mirror in the vacuum system, the window or mirror must be protected from secondary particles produced by charged-particle impact.

The neutron source intensity distribution averaged over an irradiation may be monitored by placing a thin foil that is activated by the neutrons, outside the vacuum system next to the target. After the irradiation the foil is placed next to a photographic film. The source distribution can be determined by tracing the photographic negative with a photodensitometer.

Charged-particle beam currents in accelerators are usually measured with an ammeter. The target may be biased positively to suppress secondary electron emission. This conventional method becomes unreliable at beam currents above a few mA because the beam is partially space-charge neutralized and sometimes because of interference by target accessories needed for adequate cooling. Measurement of the temperature rise of the cooling fluid with a thermocouple offers a simple method for current measurement (31). A typical temperature increase of the cooling water is 20°C. Temperature measurement may also be used to determine how much beam hits collimators or other parts of the accelerator or beam transport system.

V. TARGET

The design of a target with a long life time has been the most challenging problem in the design of D-T generators, especially for high-intensity sources. Research and development on targets is active at this writing. Three types of targets have been used: gas targets, metal tritide targets, and targets in which a mixed beam of deuterons and tritons implants the hydrogen isotopes in a metal target.

(a) Gas

For a given deuteron beam current tritium gas will produce the highest neutron yield, since all collisions are between deuterons and tritons. Tritium gas targets have been used in accelerators for a long time for nuclear physics experiments. In such targets the tritium is separated from the accelerator vacuum system by a thin foil through which the charged-particle beam passes. Such foils cannot be used at beam currents much above 10 μA, and hence this type of gas target is limited to very low-intensity D-T generators. Because of the hazards involved in handling tritium gas and the possibility of failure of the foil, solid tritium-containing targets are preferable even for low-intensity sources.

The simplest approach to the design of a tritium gas target without a foil is the use of differential pumping between the target cell and the acceleration tube. One of the earliest suggestions for using a differentially pumped high pressure gas target for a D-T generator was made in 1957 (39), but not necessarily for a very intense neutron source. Because of the hazards of tritium and its high cost, the pumped gas must be recirculated to the target chamber in a closed system. Only one such D-T generator has been described (40). The differential pumping system can maintain only a limited pressure difference for the size of apertures through which the beam enters the gas. The actual system has a beam aperture of 4 mm and a target pressure of 10 Torr. At this pressure the target had to be about 0.5 m long to stop 200-keV deuterons. With this system about 4 mA of 200 keV analyzed deuterons produced about 2×10^{12} n/s. The neutron source strength decreased to about half the initial value in two hours, primarily because of isotopic exchange. Disadvantages of this system are the length of the neutron producing target and the need to handle large quantities of tritium gas; the target contained 150 Ci, while the total inventory was 1 kCi.

In 1967 Lidsky and Colombant (41) proposed the use of a gas target for an ultra-high intensity D-T generator. Because of the large gas requirement for a high pressure gas target the proposal was to bombard a deuterium gas target with a triton beam. The deuterium target in this design is the large density gradient at the sonic line of a free-jet expansion. This idea was taken up a decade later by a group at Los Alamos that proposed to build a D-T generator that would produce 10^{15} n/s (9). The proposal was to produce 1.1 A of 300 keV tritons to be incident on a supersonic (3300 m/s) jet that enters the target region at a temperature of 30-40 K and experiences a 1400 K temperature rise caused by the power dissipation by the beam. 80 g/s of deuterium pass through a 1-cm diameter target region and produce a density of 2×10^{19} deuterium molecules/cm^3. Although a detailed design was developed and testing of components had progressed, the project is at present not active.

A Canadian group (42) has performed experiments on beam heating of high-velocity gas flows to simulate gas-target DT generators. This group has studied systems using subsonic, transonic, and hypersonic flow and has examined advantages and problems of several configurations.

Although gas targets appear to be the only accelerator-based source of D-T neutrons that could produce much more than 10^{14} n/s in a small volume, the technical difficulty of building such sources and their high cost has discouraged their construction. With the exception of the source described at the beginning of this section, all DT generators currently in use or under construction use solid targets.

(b) Metal Tritide

D-T generators were built as soon as tritium became available in appreciable amounts. The first such generator used tritium absorbed in Zr backed by W (43). Later targets in which tritium was absorbed in Sc, Ti, or Eu were developed, and backings of Cu, Mo, Ag, Ta, and Pt have been used. Methods for preparing metal tritide targets, and for cooling them were described in 1960 by Coon (44). This article also describes the behavior of targets during bombardment. The experience was that for bombardment by 250-keV deuterons the neutron yield dropped to half its initial value when 2 C/cm^2 hit the target. Reference (44) describes procedures for assuring that the metal absorbs the tritium and that the tritide adheres to the backing. Users of targets are now less interested in these procedures, since various suppliers sell metal tritide targets for DT generators so that users rarely prepare their own targets.

Suppliers of metal tritide targets include Amersham, Oak Ridge National Laboratory, and United States Radium Corporation. The most widely used targets have Ti layers 0.2 to 4 mg/cm^2 thick backed by a 0.25 mm thick oxygen free high-conductivity copper. Radium Corporation also manufactures targets in which the tritium is absorbed in zirconium, and they provide alternate backings of Mo or W. They quote tritium to titanium atomic ratios between 1.0 and 1.7 but only half this value for Zr. They can manufacture targets of diameters up to 15 cm. Amersham quotes for similar targets as the bombardment during which the neutron output drops to half its initial value 10 C/cm^2. The Isotopes Materials Laboratory of Oak Ridge National Laboratory prepares targets if the requirement cannot be met by commercial suppliers. Oak Ridge can produce targets of diameters between 1 and 50 cm, and thicknesses from micrograms to milligrams per cm^2. The tritium can be absorbed in a variety of metals, and different target backings may be used. Users of targets find wide variations among targets which are manufactured by the same supplier. Sometimes a large quantity of tritium is released when deuterons bombard the target initially, in other samples the neutron output drops unusually rapidly.

If the target has a large diameter and has to maintain the pressure difference between the accelerator vacuum and atmospheric pressure, pure copper is not strong enough. Stronger materials that have good heat conductivity and to which Ti adheres well, are copper alloys, such as Amzirk (0.15% Zr in copper) and Glid-Cop (Al_2O_3 in copper).

The earliest users of metal tritide targets realized that the tritium leaves the target at temperatures above 250°C and that the targets had to be cooled by blowing air on the back of the target or by flowing water. Even with good cooling the beam power that could be deposited on a 1 cm^2 spot was about 150 W (44). This restriction combined with the experience that the neutron output decreases to half its value with about 10 C/cm^2 bombardment limited bombarding currents to about 1 mA and neutron source strengths to 2×10^{11} n/s. This source strength would drop to half its initial value in 2-3 h. This remains the performance of commercially available small DT generators that use deuteron beams on tritium targets.

In 1967 Booth (35) developed a rotating target that permitted an order of magnitude increase in neutron source strength and target lifetime. This target effectively increases the target area without increasing the size of the neutron producing area. The original design of this target consists of a 4 mg/cm^2 thick Ti layer vapor plated onto a 1-mm thick Amzirk backing with outside diameter 15 cm. Ti is deposited in a ring 5 cm i.d., 14 cm o.d. About 500 Ci of tritium were absorbed in the Ti. An O-ring seal holds the targets to the end of a 0.5-mm wall thickness cylinder which is attached to the accelerator vacuum system by a rotating seal (45). In order to avoid local heating the target is rotated at 1100 r.p.m. The target forms the end of the accelerator vacuum system. A stationary 0.2 mm thick sheet of stainless steel is placed parallel to the target and leaves a 0.3 mm wide gap. Water is injected at the center of the steel sheet and experiences a strong centrifugal force owing to the rotation of the target. The large velocity gradient between the rotating target and the stationary water spreader produces turbulent water flow and effective cooling. The axis of the rotating target can be moved with respect to the stationary deuteron beam so as to allow the use of different concentric rings on the target without moving the position of the neutron source. When this target was bombarded with 8 mA of 400 keV deuterons, an initial source strength of 2×10^{12} n/s was achieved. The neutron yield dropped to half its initial value in 90 hours, corresponding to about 20 C/cm^2 for the entire target area.

In order to permit operation at higher source strength the 15-cm diameter rotating target was replaced by a 22-cm diameter rotating target (46). With this target 16 mA of 400-keV deuterons produced a source strength of 4 × 10^{12} n/s that decreased 10-20% in 50 hours for a 1-cm diameter neutron source (47).

Further increase of the beam current and source strength required that the rotation speed and/or the diameter of the target be increased. A new rotating target system had to be designed which involved a different type of rotating seal and a different target cooling system. The seal (48) is designed to rotate at 5000 rpm and has been tested up to 10,000 rpm. An air cushion prevents the rotating part from touching the stationary accelerator vacuum system. Two stages of differential pumping maintain the pressure gradient between the air cushion and the accelerator vacuum. A matched pair of ball bearings holds the load of the rotating target. The rotor is driven by an air jet that hits the blades of a turbine wheel.

With larger targets and higher rotation speed the power requirement to overcome the viscous drag caused by external cooling would be excessive. This difficulty was overcome by placing the cooling water inside a sandwich target backing that contained convoluted channels to produce turbulent flow (10) as shown in Fig. 2. The channels are etched into a 1-mm thick sheet of a Cu alloy which is then laminated to a second sheet of the same alloy using a gold diffusing agent. The sandwich is cold-formed to the desired curvature. Cooling water enters and leaves the target through a rotating hub at the center of the target. 22-cm diameter targets of this design have operated at 5000 rpm. Chilled water flows through the targets at a rate of 10 liters/min. 40 mA of 350-keV deuterons have produced a source strength of up to 1.3 × 10^{13} n/s from a 1-cm diameter stationary neutron source. After a typical 70-hour run the source strength decreased to 7×10^{12} n/s. It is expected that considerably higher source strengths can be achieved when targets of similar design, but 50 cm in diameter, become available. Fig. 3 shows this target schematically.

A different type of rotating metal tritide target was developed by Roche (49). The active titanium tritide layer is a ring 15 cm i.d., 25 cm o.d. The target rotates at 3000-4000 rpm inside the vacuum system and is driven by a magnetic field through a stainless steel housing. Cooling is provided by liquid NaK eutectic whose vapor pressure is low enough that it can be placed inside the vacuum chamber. No operating experience with this system has been reported.

(c) Implantation with mixed beams

Although metal tritide has been the most widely used target material for D-T generators, it has serious drawbacks for many applications. The source strength decreases with use at a rate which in some applications is undesirably rapid, and the targets release tritium into the vacuum system, contaminating the vacuum system and, unless special precautions are taken, contaminating the laboratory.

These difficulties can be overcome by building a closed vacuum system and by replenishing the target with a mixed deuterium-tritium beam (44). A great deal of effort has gone into the development of "neutron tubes" that are analogs of "X-ray tubes" and that can simply be plugged into a power supply to form a D-T generator (50).

As was pointed out in I(a), mixed beams on mixed targets produce less than half the neutron yield of monoisotopic beams and targets for the same beam current, even if the target is uniformly loaded. There is, however, no assurance that loading the target by implantation with a fixed-energy beam will result in uniform and optimum distribution of hydrogen isotopes at the target depth where most of the neutrons are produced.

A problem in the design of neutron tubes is that for best operation of the acceleration system the pressure in the ion source should be much higher than in the acceleration tube. Since this is difficult to accomplish, the ion source and the acceleration tube are at the same pressure in most neutron tubes. One of the first useful neutron tubes was described in 1965 (51). It operates at a pressure of 15 mTorr of a mixture of equal amounts of deuterium and tritium. An ion beam of 1 mA is produced in an RF ion source and accelerated by 150 kV. The ions strike a thick erbium metal target 1.5 cm in diameter. This neutron tube produced 10^{10} n/s for over 100 hours. In 1971 the same group reported that they had developed a tube with much higher source strength (52).

General aspects of D-T sources with drive-in targets are discussed in reference (53). Commercially available neutron tubes will be described in Section VI.

(d) Behavior of Solid Targets under Ion Bombardment

The principal problem with solid targets for D-T generators is the decrease in neutron yield with bombardment. Until recently there have been few investigations of the circumstances that determine target deterioration.

The causes of deterioration are somewhat different for metal tritide targets bombarded by deuterium and for mixed beam sources. In mixed-beam sources the same target area is bombarded for a much longer time by high currents so that damage to the metal is likely to be dominant, while for metal tritide targets loss of tritium is the principal cause of decrease of source strength.

Coon (44) reports experiments that show that the deuterium content of zirconium tritide targets that had been subjected to prolonged deuteron bombardment agreed with the deuterium carried by the incident beam. On the other hand, measurements of the tritium release from bombarded targets (31) indicated that only 10-20% as much tritium was given off by a target as was embedded by the deuteron beam.

(i) Simultaneous Bombardment by Different Ion Species

Ion sources produce mixtures of monatomic, diatomic and triatomic hydrogen isotope ions. In most DT generators all three species of ions bombard the target. The molecular ions break up near the surface of the target so that projectiles that induce the neutron producing reactions have not only the full energy,but also energies of half and a third of the full energy. The first evidence that this simultaneous bombardment had an adverse effect on target life was found in 1972 (31). Targets that had the normal neutron yield when bombarded by atomic ions, showed a very large drop in yield after they had been bombarded by diatomic ions for a short time. This effect was explained (31) by the assumption that the deuterons displace tritium at the depth at which the deuterons stop. Since the neutron production is highest a short distance ahead of the end of the range of the deuterons, displacement of tritium at that depth by the half-energy deuterons has a particularly strong effect on yield. This assumption was confirmed experimentally (54) by measuring the deuterium and tritium distribution in a titanium tritide target that had been bombarded for some time by monoenergetic deuterons. The loss of tritium and the build-up of deuterium occurred predominantly near the depth at which the deuterons had stopped. Ormrod (55) has proposed a model to account for these observations.

There is now general agreement that the metal tritide target life is very much longer if the target is bombarded by an analyzed ion beam than if it is bombarded by a mixture of different ions. A different explanation of this phenomenon has, however, been proposed (56) in terms of sputtering and radiation damage caused by heavy ions present in the unanalyzed beam. Although heavy ions reduce target thickness by sputtering, as will be discussed in the next section, this effect is probably less important for tritide targets than for implantation targets which are bombarded with a larger beam for a longer time.

(ii) Sputtering

Since mixed-beam sources do not permit the use of an analyzed beam and require long bombardments at high beam-current densities, the target lifetime is determined primarily by the rate at which the metal-hydride film is sputtered away by the ion beam. This effect has been studied quantitatively at the Sandia Laboratories. Mass spectroscopic analysis of the ion beam (57) showed the presence of less than 1% of impurities, primarily of atomic masses between 12 and 22, but most of the sputtering was due to about 0.02% of Mo ions that originated in a secondary cathode in the ion source. For the ions from this source an average sputter coefficient of 0.02 atoms/ion was measured. After the molybdenum cathode was replaced by a boron nitride cathode, the average sputter coefficient decreased to 0.01 atoms/ion. When 160 mA of 180 kV ions bombarded a 10-μm thick Sc target, about 3 cm in diameter, the copper substrate became visible in about 15 hours with the boron nitride cathode, and in about half this time with the Mo cathode (58). These experiments show the importance of minimizing heavy-metal impurities in the ion beam for mixed-beam sources.

(iii) Oxygen Implantation

Since the oxides of Ti and Sc are more stable than the hydrides, oxygen impurities in the unanalyzed ion beam would be expected to affect the ability of the metal to combine with hydrogen in a mixed beam. This effect has been investigated at the Sandia Laboratories in experiments in which ScD_2 targets were bombarded with oxygen ions (59). Near the target surface the deuterium concentration decreased to 25% of its initial value after about 60 mC/cm^2 bombardment. Although the range of the oxygen ions is considerably shorter than that of the hydrogen isotope ions, the decrease in hydrogen concentration occurs at a depth where the neutron production cross section is high. In addition, some inter-diffusion of deuterium and oxygen was observed. The importance of the effect of oxygen implant depends strongly on the rate at which sputtering removes the oxydized surface layer.

(iv) Hydrogen Retention Barriers

There is evidence that the diffusion of hydrogen from a metal hydride target can be reduced by permeation barriers at the target surface. The Sandia group (56) observed an increase of the retention rate of deuterium in wet-hydrogen fired Cu-Be over that in dry-hydrogen fired Cu-Be by a factor of about three, presumably because of the formation of an oxide barrier at the surface. This oxide layer will, however, be sputtered away after extensive bombardment.

(v) Target Cooling

Hydrides of both Sc and Er are stable at temperatures up to 450°C, but hydrogen is given off at temperatures above 450°C. This limits the beam current density that can be used on a metal hydride film deposited on a water-cooled copper backing to about 4 kW/cm^2. Unless the beam optics is very carefully designed, the ion beam will have non-uniform density, usually with the highest current density at the center of the beam, although some systems produce a circular maximum with a minimum at the center. Non-uniform beam densities reduce target life of metal tritide targets and reduce neutron source strength for mixed-beam sources.

(vi) Metal-hydrogen atomic ratios

Commercially available titanium tritide targets usually have a T to Ti atomic ratio of around 1.6. Measurements at Sandia (59) have yielded for Sc and Er targets bombarded by deuterium, D to metal atomic ratios between 0.8 and 1.0 as long as the surface temperature of the target was below 450°C, but the ratio decreased at higher temperature.

VI. COMMERCIALLY PRODUCED D-T GENERATORS

While many D-T generators mentioned in the previous sections were built at the laboratories where they are used, a great variety of D-T generators are commercially produced. This section discusses such D-T generators. For convenience generators that have a neutron source strength below 10^{12} n/s will be referred to as standard generators, while those with higher source strength will be discussed separately under Intense Sources.

Until a few years ago most D-T generators consisted of an accelerator that produces deuterons which bombard a metal tritide target. The relatively short effective life time of the tritium targets and the radiation hazard associated with target changes had led to the development of sealed-tube D-T generators that have now become the most used models.

(a) Standard Sources

(i) Deuteron accelerators

Typical of the generators that employ a deuteron accelerator are those manufactured by Accelerators Inc. In these generators 3.5 mA (90% atomic) of 150-keV unanalyzed deuterons bombard Ti plated on a Cu disk about 4 cm in diameter. About 8 Ci of tritium are absorbed in the target. A source strength of 3.5×10^{11} n/s can be obtained from a new target.

The beams can be pulsed before and after acceleration. Pulse widths of 0.5 to 10^5 μs and repetition rates from 1 to 10^5 Hz are available.

Another system is based on an accelerator built by Texas Nuclear. An analyzed beam of 7 mA of 280 keV deuterons, 2 cm in diameter, bombards a rotating Cu target that contains an annular strip of Ti loaded with 70 Ci of tritium. The generator produces 6×10^{11} n/s with a fresh target. The source strength drops to half its initial value in 15 hours (60).

(ii) Sealed tube generators

Most D-T generators that are currently manufactured use mixed D and T beams in sealed tubes. Such generators are produced by Marconi Avionics and Kaman Sciences. Some are designed for continuous operation with source strengths of several times 10^{11} n/s, while others are intended for pulsed operation with pulse lengths from 10 ns to 0.2 s and repetition rates from 1 Hz to 2×10^5 Hz, typically with an output of 10^8 n/pulse. Voltages applied to the tubes range from 120 to 200 kV. In continuous operation the life time of the tubes depends on operating conditions, but is typically of the order of 100 hours or more, while in pulsed operation 10^5 pulses can be obtained.

Depending on the application and on the required source strength, tubes of a wide range of physical dimensions are available. The dimensions range from tubes with a diameter of less than 6 cm and length 165 cm to canisters 40 cm in diameter and 110 cm long. Fig. 4 shows a photograph of a commercially available neutron tube.

(b) Intense Sources

D-T generators with source strengths of 10^{12} n/s or more that are commercially produced are intended primarily for use in the treatment of malignant disease. For this application there is no need for placing the volume to be irradiated very close to the neutron source. This simplifies the design of the generator. On the other hand, the need to provide "isocentric" mounting, i.e. provisions for rotating the source around the patient or the patient around source, complicate the design.

There is a strong preference for a sealed source for use in hospitals because a pumped accelerator containing tritium involves radiation hazards.

(i) Deuteron Accelerators

The only commercially produced high-intensity D-T generator with a pumped accelerator is in use at the University Hospital at Hamburg-Eppendorf (34,61). This generator consists of an accelerator ("Dynagen") manufactured by Radiation Dynamics, a rotating target supplied by Multivolt, and a collimator-treatment system provided by AEG. With 12 mA of 500 kV unanalyzed deuteron beam the source strength is 3.5×10^{12} n/s. The neutron output drops to half its initial value in about 10 hours of operation, but the life time of the target can be increased by about a factor of three by separating the components of the beam magnetically so that different components hit different parts of the target. This procedure for increasing target life had been suggested earlier by

Cranberg (62).

(ii) Sealed-tube generators

Sealed-tube generators of similar characteristics have been manufactured by Philips and by Marconi Avionics. The latter system was developed by Elliott and has been given the name Hiletron. A Philips generator is in use at the Leeuwenhoek Hospital in Amsterdam, Hiletrons at hospitals in Glasgow and Manchester. Both types of generators have 250 kV power supplies, the Marconi Avionics unit has an ion current of 30 mA incident on an Er target, while the Philips unit has 18 mA incident on a Ti target. In both generators the tube life times have been more than 100 hours (63). Both generators produce 1×10^{12} n/s, a source strength that many radiotherapists consider too low for routine hospital use.

More recently two D-T generators have been developed that use mixed D-T beams in sealed systems and that produce considerably higher intensities.

Schmidt and Dohrmann developed a generator that produces 5×10^{12} n/s in continuous operation (37,64). It consists of a 200 kV accelerator that has a closed 6-liter volume vacuum system. A low pressure discharge in a toroidal ion source produces deuterium and tritium ions in a radial magnetic field. The ions bombard a central conical target that consists of Sc in which a mixture of D and T (500 Ci) has been absorbed. Additional gas is stored in a pressure regulator system so that an operating pressure of 5×10^{-4} Torr can be maintained. This generator is shown schematically in Fig. 5. The region surrounded by the heavy black line is the neutron tube, a photograph of which is presented in Fig. 6.

The ions produce a fairly uniform power density of 600 W/cm^2 on the 50 cm^2 target surface that is water-cooled. About two secondary electrons leave the target for each incident ion so that 60% of the power has to be removed at the ion source where the electrons strike a water-cooled electrode. The life time of the tube depends on the thickness of the Sc layer and on the tritium inventory. The tube is designed to have a life time of 500 hours. The first of these generators was installed in 1976 and has been in clinical use at the German Cancer Research Center in Heidelberg since 1977. Additional units are being installed at hospitals in Zürich and Münster. A fourth unit will be installed in Hamburg, but it will be used for neutron activation analysis.

These generators are manufactured and marketed by Haefely although the tubes were originally built by Schmidt at the Karlsruhe Nuclear Research Center.

A somewhat different approach to the development of a closed-system high-intensity generator has been followed by the Cyclotron Corporation (8). The design of this generator is more similar to a conventional pumped accelerator, in that the ion source which is a duoplasmatron source is at a pressure of 1 Torr while the pressure in the acceleration gap is 10^{-4} Torr. A getter pump maintains this pressure difference. After three hours of operation the gas is transferred from the getter pump into a uranium trap from which it is later released into the ion source. The total inventory is 2000 Ci of tritium and an equal number of deuterium atoms. There are four ion sources that develop a total positive ion current of up to 450 mA. The ions are accelerated in a 1 cm gap by 175 kV. Each of the four ion beams hits twenty seven 3-mm diameter Cr coated Cu tubes through which cooling water flows.

Fig. 7 shows this system schematically. The observed total neutron source strength is 8 × 10^{12} n/s and the expected life time is 500 hours of operation. The tubes can be reconditioned by the manufacturer, presumably by replacement of the target tubes, since the Cr coating will be gradually sputtered away by the incident ions.

Cyclotron Corporation D-T generators are scheduled for installation in Riyadh and at the University of Pennsylvania.

VII. SOURCE STRENGTH, FLUENCE AND DOSE MEASUREMENT

Although the output of a DT generator is usually quoted in terms of its source strength, the quantity that is actually measured is almost always either the flux density at a point, or the time integral of the flux density (called the fluence), or the dose (energy absorbed in a sample per unit mass). At distances large compared with the size of the target, flux density, fluence, and dose depend inversely on the square of the distance from the target. If one wishes to maximize fluence or dose in a sample, the sample is placed as close to the source as possible. In that case knowledge of the source strength is not adequate to determine fluence or dose, but fluence and dose depend also on the physical size of the source and may vary over the sample, so that a measurement of fluence requires a detector smaller than the sample.

For a determination of source strength, fluence is measured far enough from the source that the inverse square law may be expected to hold, but close enough that the background is expected to be small. Source strength is deduced by assuming that the angular distribution is isotropic in the CM system. A correction for attenuation in the target assembly and for background is usually applied.

In DT generators for radiotherapy the source is surrounded by a shield and collimator. Often the source strength that is quoted is based on a measurement outside the collimator. Since there is a substantial amount of inscattering from the walls of the collimator, source strength deduced from such a measurement may be 5-15% high, if no inscattering correction is applied.

(a) Associated Particle Method

The most reliable measurement of the number of neutrons emitted in a given direction involves the counting of the associated alpha particles, since there is one alpha particle produced per neutron and alpha particles can be counted with 100% efficiency. Such a measurement does not assure that all the neutrons from the source will in fact pass through a sample, since some neutrons may have interactions before they reach the sample. Alpha particles may be counted by themselves or in coincidence with the neutron-induced events. Observation of coincidences serves to reduce backgrounds and to define the solid angle within which neutrons are emitted that produce counted events. A cross section measurement with DT neutrons based on the associated particle method without coincidence counting has been reported to have uncertainty of 0.7% (65). This is a measurement of the activation cross section for the $^{27}\mathrm{Al}(n,\alpha)^{24}\mathrm{Na}$ reaction. The quoted uncertainty represents three standard deviations and includes the uncertainty in the fluence determination, the uncertainty in the determination of the induced activity, and the uncertainty in the number of Al atoms. This is probably the highest accuracy quoted for any fast neutron reaction cross section.

A cross section measurement with DT neutrons based on the associated particle method with coincidence counting is the determination of fission cross sections (66). The uncertainty quoted in this measurement is 2%.

(b) Proton Recoils

Observations of proton recoils from the elastic scattering of fast neutrons offer the most reliable fluence determinations, since the neutron-proton total cross section is the most accurately known fast neutron interaction cross section. At 14-MeV deviations from isotropic scattering in the CM system are large enough that the uncertainty in the angular distribution affects the accuracy of the measurement. Observation of proton recoils is unlikely to yield uncertainties as low as the 0.7% claimed for the precise associated particle measurement. On the other hand, proton recoils can measure fluence at the position of the sample, while the associated particles measure neutrons produced at the target.

Proton recoils are usually observed in a counter telescope as described by Johnson (67). A more recently designed counter telescope is described in reference (68).

(c) Dose

For applications in radiotherapy and radiobiology the quantity of principal interest is the dose in tissue, i.e., the energy absorbed per unit mass of tissue. A direct measurement of dose involves the measurement of a very small temperature increase with a microcalorimeter (69). This measurement is difficult so that routine dose measurements are performed either by a determination of fluence or with an ionization chamber (70).

Fluence may be converted to dose in tissue by multiplying by the kerma factor for tissue. Kerma factors for tissue are known quite well around 14 MeV (71), hence dose can be deduced from any fluence measurement.

The most widely used instrument for biomedical work is the tissue equivalent ionization chamber. A commercially available model has a spherical volume of 1 cm^3 and walls made of tissue-equivalent (A-150) plastic. Although for precise measurements tissue equivalent gas should flow through the chamber, measurements with air in the chamber are more convenient and are reliable for 14-MeV neutrons. The chamber is usually calibrated with a γ-ray source in R/nC. For precise measurements a number of corrections have to be applied to the measurement with neutrons, one of them for the fact that the wall material is chosen to be tissue equivalent for γ-rays, but in fact is not quite tissue equivalent for neutrons.

Since the only equipment needed besides the chamber and voltage supply is an electrometer that measures charges in the nC range, the tissue equivalent ionization chamber is very simple to use.

(d) Fluence Monitors

For routine use the absolute fluence determinations by the associated particle method or with a proton recoil telescope are not convenient, nor are they useful for irradiations close to the neutron producing target. There are a number of monitors that are simpler to use. The number of charged particles emitted by a monitor foil during neutron bombardment or the induced radioactivity can be converted to fluence, if the reaction cross section is known. The most easily observable charged particles are fission fragments, and fission counters are convenient monitors.

Induced activities can be observed in very small foils so that variations of fluence over a sample or fluences in small samples can be easily determined. In choosing an activation monitor an important consideration is the half life of the induced activity. The half life should be longer than the time of irradiation, but short enough that a strong activity results. The reaction should have a threshold energy so that slow neutrons do not contribute to the induced activity, but the cross section should depend as little as possible on neutron energy between 14 and 15 MeV and the cross section should be large. Another desired property of the activity is that an easily identified radiation is produced, typically an energetic γ-ray. Reference 72 presents the relevant reactions, the resulting half lives, and the reaction cross sections in the neutron energy range of interest. For this application (n,2n) reactions are most appropriate and the $^{93}\mathrm{Nb}(n,2n)^{92}\mathrm{Nb}^{m}$ reaction produces a particularly useful activity with a 10.2-day half life. The cross section for this reaction is about 0.5 b and does not vary appreciably between 14 and 15 MeV; γ-rays from the decay of $^{92}\mathrm{Nb}^{m}$ have energies around 1 MeV and are easy to count. Other useful reactions are $^{197}\mathrm{Au}(n,2n)^{196}\mathrm{Au}$ and $^{127}\mathrm{I}(n,2n)^{126}\mathrm{I}$. The half-life of $^{196}\mathrm{Au}$ is 6.2 days, the cross section is 2.2 b and varies little with neutron energy, but the presence of the 10-hour $^{196}\mathrm{Au}^{m}$ activity and of the $^{198}\mathrm{Au}$ activity from slow neutrons is somewhat inconvenient. The half life of $^{126}\mathrm{I}$ is 13 days, the cross section is 1.6 b and is also flat, but metal foils are often preferable.

For short irradiations the 15-hour activity from $^{27}\mathrm{Al}(n,\alpha)$ and the 12.8-hour activity from $^{65}\mathrm{Cu}(n,2n)$ have often been used.

The simplicity and reliability of the tissue equivalent ionization chamber have led to the use of this instrument for routine source strength or fluence monitoring. This detector is, however, sensitive to γ-rays and lower energy neutrons so that it must be used with care.

VIII. SUMMARY

With the development of sealed tubes, D-T generators are replacing the conventional α-Be or spontaneous fission neutron sources for routine laboratory and field use. D-T generators have a number of advantages over α-Be and spontaneous fission neutron sources: D-T generators do not emit neutrons unless they are activated, they produce higher intensities, and they can easily be pulsed. Their principal disadvantages are their larger physical size and their lower reliability. On the other hand, D-T generators are smaller and more economical than other accelerator-based neutron sources of the same intensity. Only at the very highest neutron source strengths do other accelerator-based neutron generators outperform D-T generators, and improvements in the design of D-T generators are not likely to change this situation. With increasing experience with sealed-tube D-T generators, their reliability is, however, expected to improve.

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FIGURE CAPTIONS

Fig. 1. The total cross section of the reaction $^{3}H(d,n)^{4}He$, and the total neutron yield of the reaction $^{3}H(d,n)^{4}He$ induced by deuterons stopping in a Ti target for an atomic ratio of tritium to titanium of 1.6. The data are taken from reference (5).

Fig. 2. A section of the etching mask used to produce water-cooling channels within the rotating target. The dark lines are etched into a sheet of copper alloy which is then bonded to another sheet of copper alloy. Cooling water enters and leaves the channels through a central hub (Reference (10)).

Fig. 3. Schematic diagram showing the rotating target for a high intensity neutron source (RTNS-II). The shading represents the portion of the system that rotates, the unshaded parts are stationary (Reference (10)).

Fig. 4. Sealed neutron tube manufactured by Kaman Sciences Corporation for bore-hole exploration. The largest diameter is 5 cm. The black section contains a Penning ion source. The acceleration gap is visible through the glass in the central portion of the tube.

Fig. 5. Schematic diagram of sealed neutron tube and accessories for a high-intensity neutron generator. A mixed beam of deuterons and tritons from a toroidal ion source is focused by magnetic fields onto a conical target at the center (Reference (37)).

FIGURE CAPTIONS (Cont'd)

Fig. 6. Photograph of neutron tube shown schematically in Fig. 5. The tube shown in this figure corresponds to the region surrounded by the heavy black line in Fig. 5.

Fig. 7. Artist's view of sealed neutron generator for a high intensity source manufactured by Cyclotron Corporation (Reference (8)).

Figure 7 is not yet available.

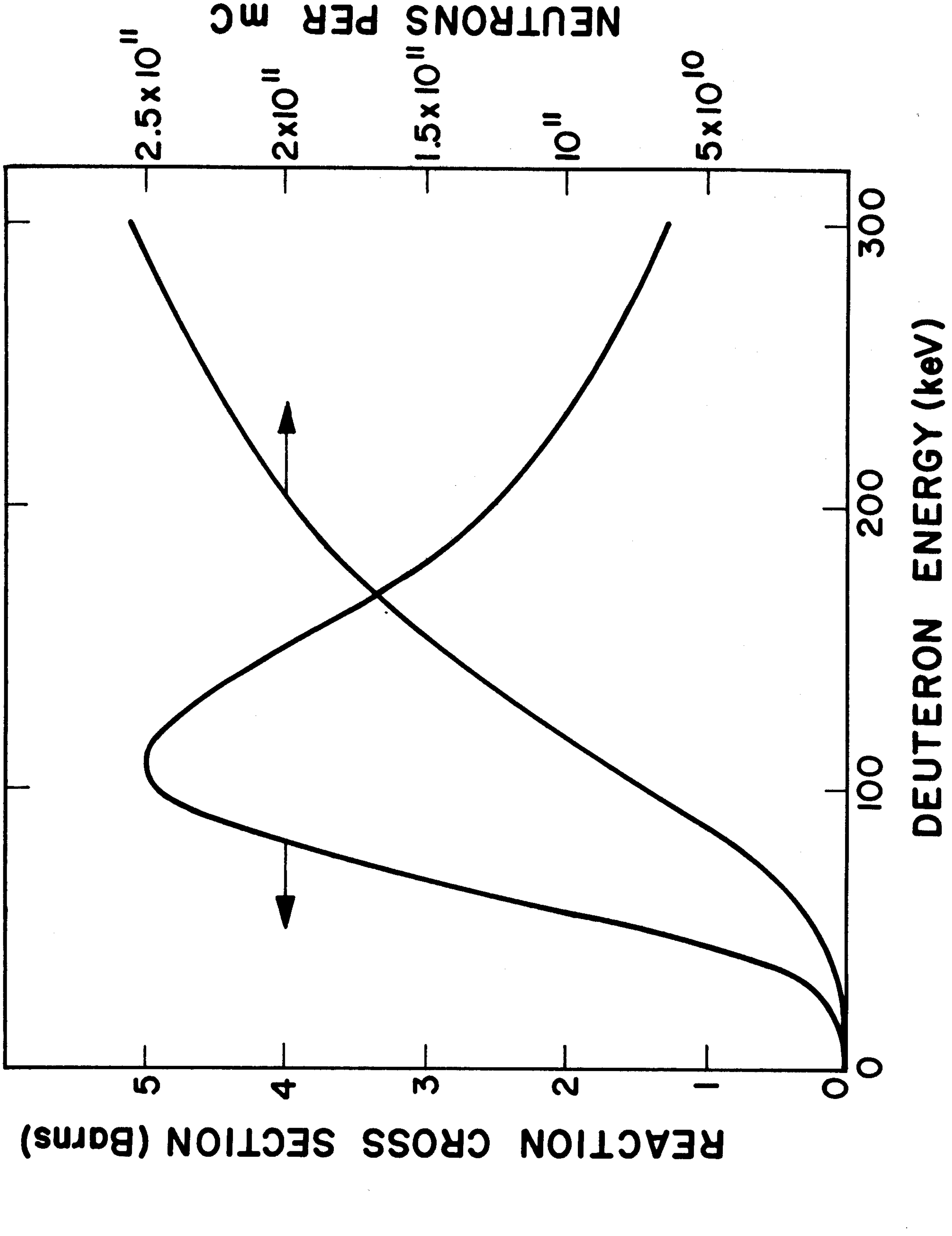
NEUTRONS PER mC
2.5x10^{11}
2x10^{11}
1.5x10^{11}
10^{11}
5x10^{10}
0
100
200
300
DEUTERON ENERGY (keV)
0
1
2
3
4
5
REACTION CROSS SECTION (Barns)

Figure 1

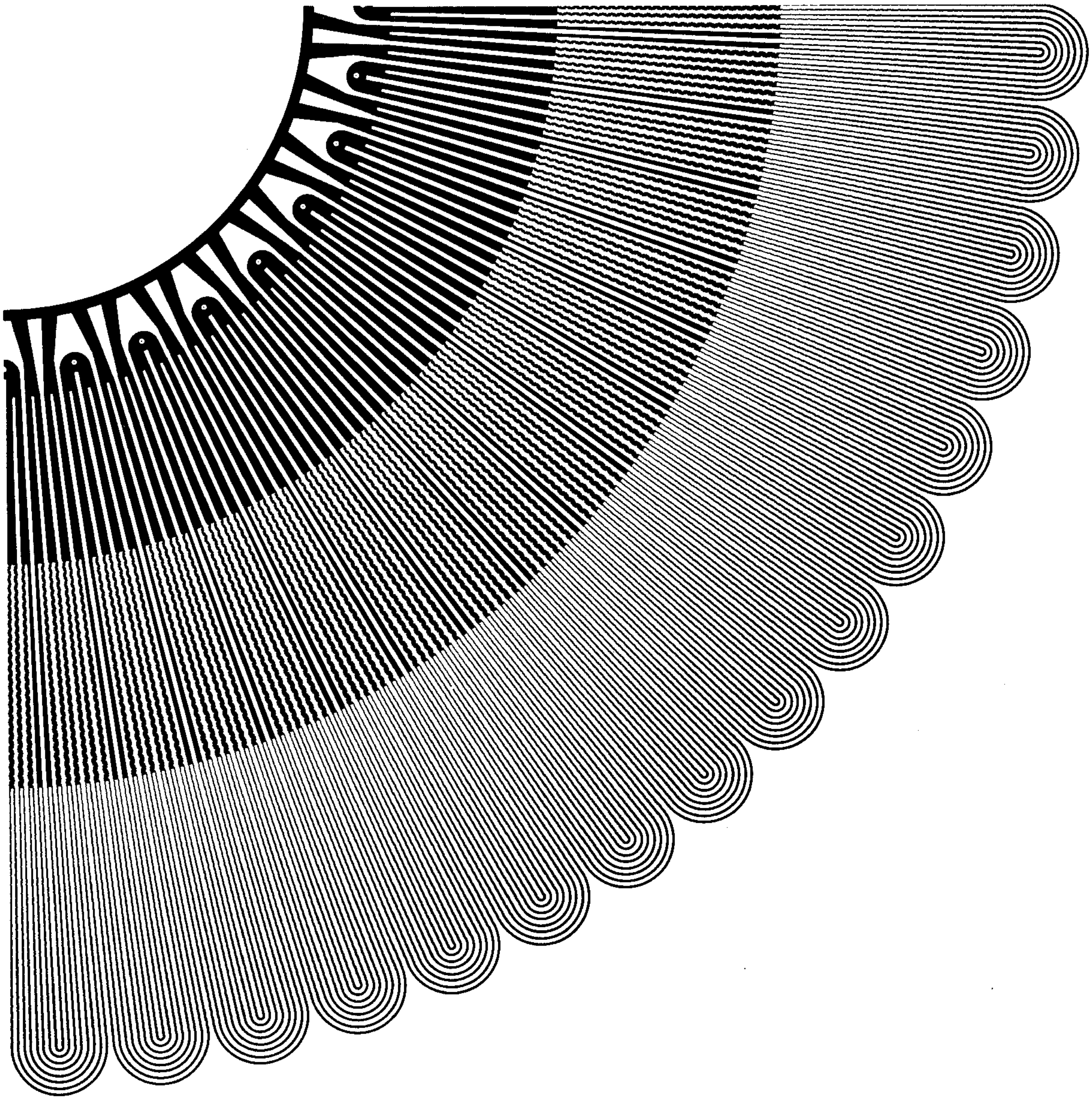

Figure 2

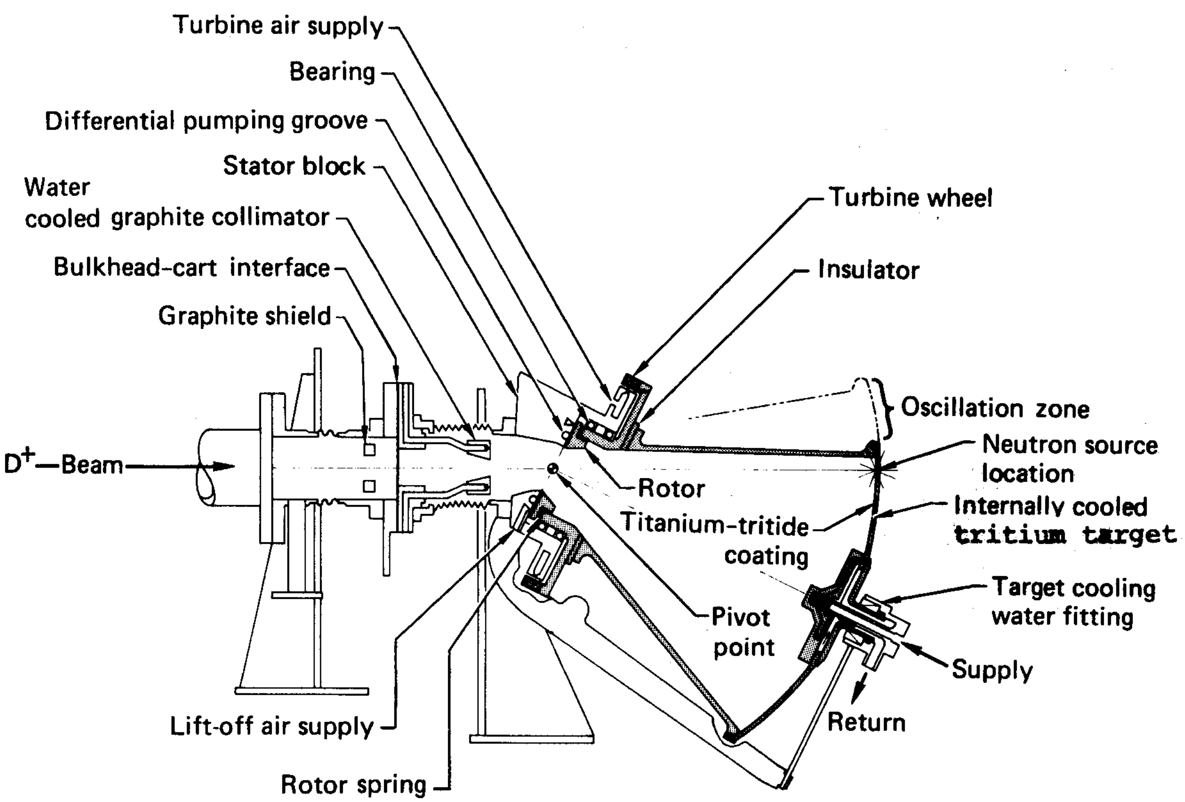
Turbine air supply
Bearing
Differential pumping groove
Stator block
Water cooled graphite collimator
Bulkhead-cart interface
Graphite shield
D+—Beam
Turbine wheel
Insulator
Oscillation zone
Neutron source location
Rotor
Internally cooled tritium target
Titanium-tritide coating
Target cooling water fitting
Pivot point
Supply
Return
Lift-off air supply
Rotor spring

Figure 3

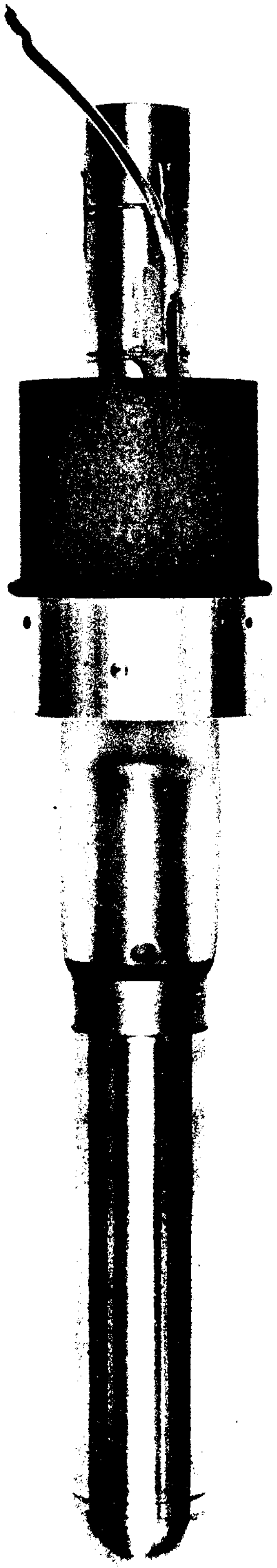

Figure 4

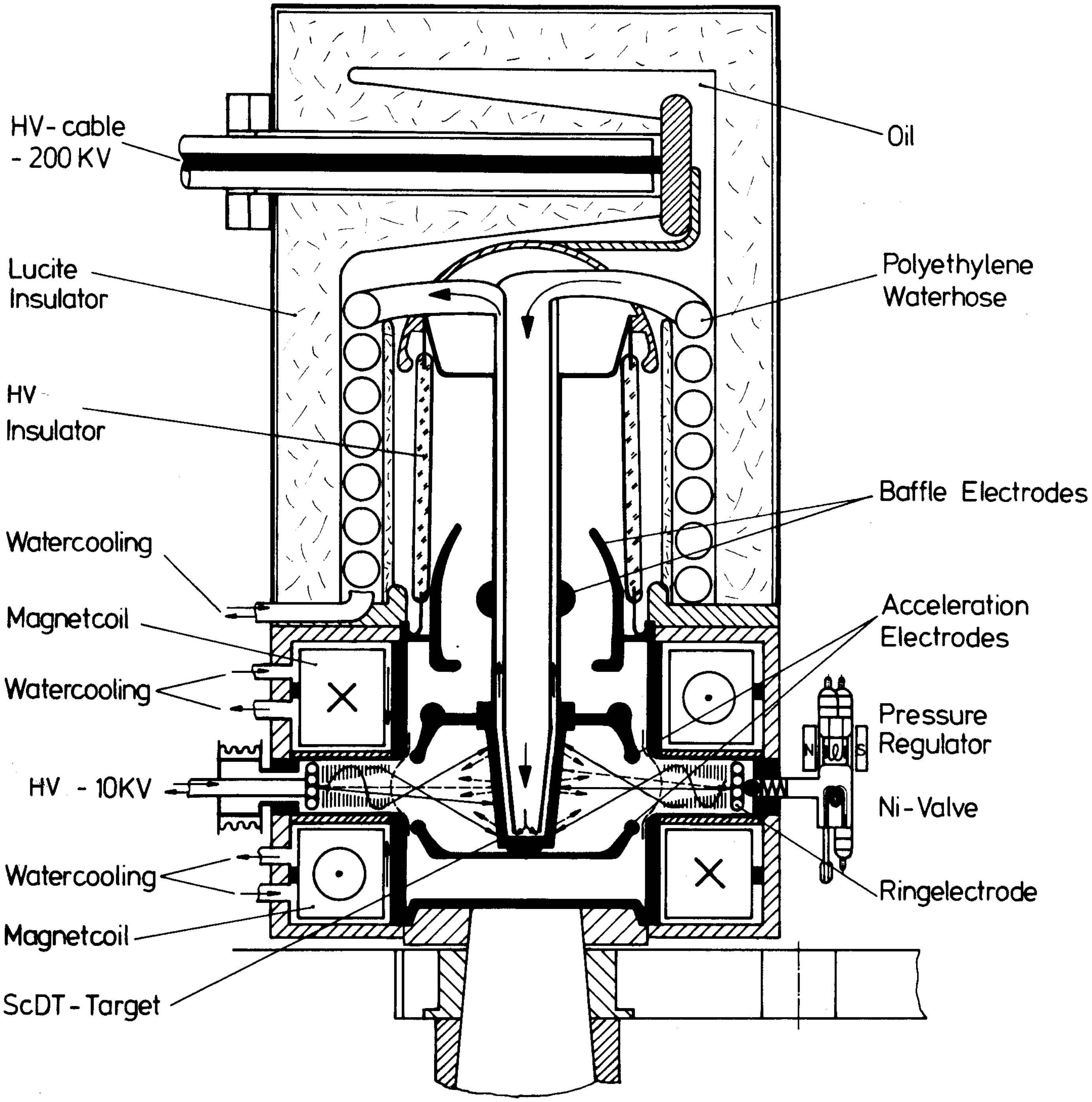

Figure 5 (not in final form)

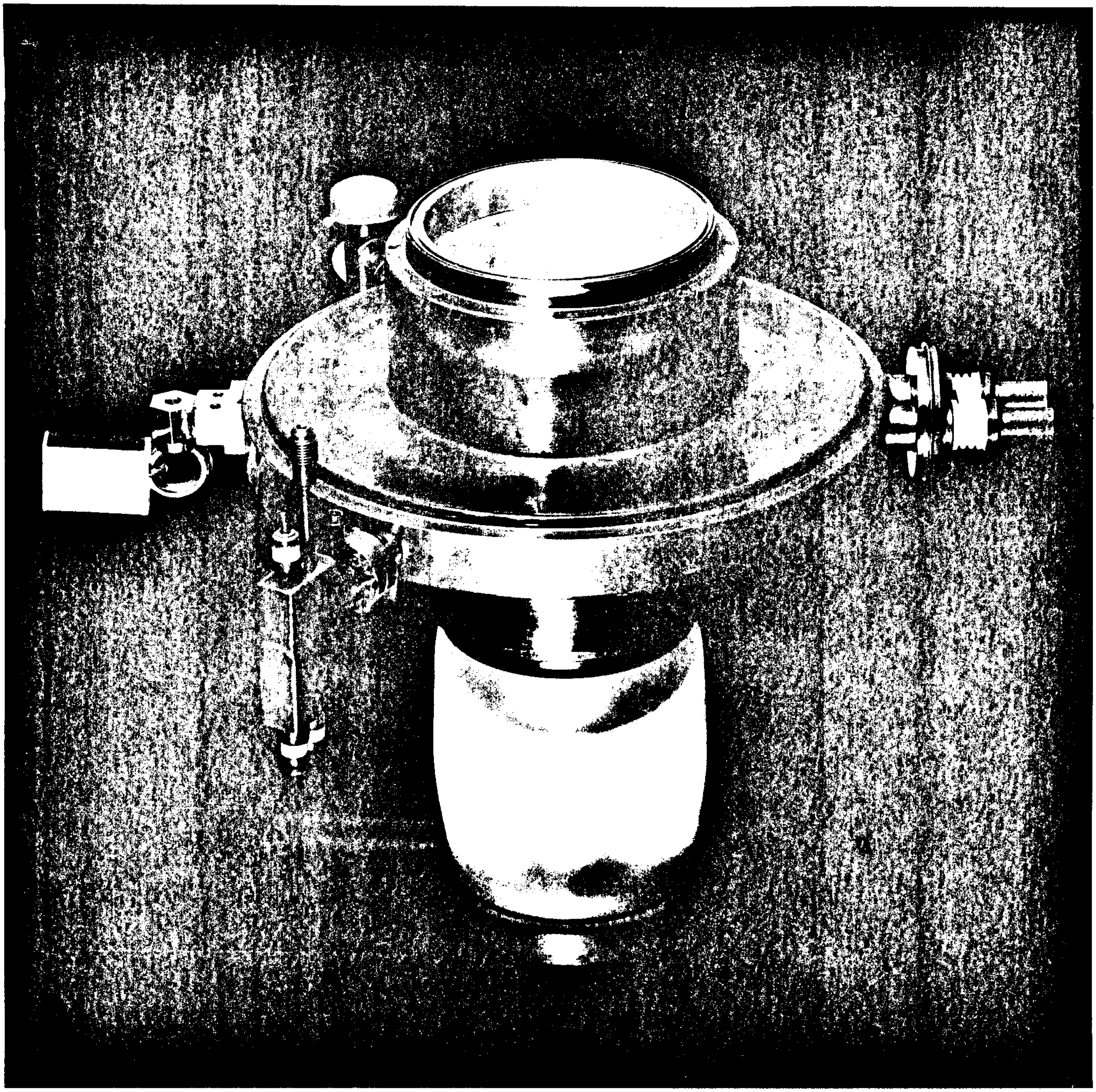

Figure 6