A COMPACT HIGH-INTENSITY SOURCE
OF 14-MEV NEUTRONS

by

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SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
July, 1954

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ACKNOWLEDGEMENT

Sincere appreciation is expressed to the many persons whose kind assistance made this thesis possible. To Dr. T. S. Gray I extend my most sincere thanks for supervising this thesis and lending many helpful comments. Gratitude is expressed to Dr. Clark Goodman, of the Department of Physics, who supplied me with unceasing encouragement, assistance, and many suggestions. Thanks is expressed to Dr. H. E. Edgerton whose aid in writing this paper is deeply appreciated. My Laboratory Technician, Bernard Gittleman, rendered many hours of fine assistance, including his work on the Beam Analysis Tube, which were invaluable in the accomplishment of this thesis. Kindest regards go to Dr. T. T. Magel for his helpful preparation of targets, and to Mr. Larry Ryan for his many hours of tube construction and willing consultation.
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Submitted to the Department of Electrical Engineering on July 23, 1954, in partial fulfillment of the requirements for the degree of Doctor of Science.

ABSTRACT

A deuterium filled gas tube capable of producing neutrons was developed in this research. The sealed-off tube utilizes an RF ion source for the production of ions which are accelerated by 100 Kv until they strike a tritium or deuterium filled zirconium target. Either 14-Mev or 2.4 Mev neutrons are produced at the tritium or deuterium target, respectively. The ions are accelerated in a single accelerating gap operated in a deuterium pressure range of from 1 to 20 microns. The RF ion source operating at the same pressures, utilizes a single-tube Hartly Oscillator. A tube with the RF source replaced by a filament type ion source also was tried successfully.

In a tube filled with deuterium, the neutron yield for a tritium target is $10^8$ neutrons per second, and $10^6$ neutrons per second for a deuterium target.

The pressure can be controlled in the tube automatically by the use of a zirconium absorber.

As the tube is simple and small, its applications to industrial and medical problems may be analogous to the application of the x-ray tube.

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CHAPTER I

INTRODUCTION

The physicist has available for use in the laboratory convenient sources of $\alpha$-particles, $\beta$-particles, and $\gamma$-rays, as they are emitted from naturally or artificially radioactive elements. There are also weak neutron sources available as a result of the use of the $\alpha$-radioactive elements in conjunction with the light elements. The purpose of this research was to devise a source of high-energy neutrons utilizing a known nuclear reaction. The source was to have high fluxes, be compact, versatile, and suitable for laboratory and geophysical applications.

As this research was sponsored by the Schlumberger Well Surveying Corporation of Ridgefield, Connecticut, as part of their effort to achieve a neutron source having large fluxes for the purpose of well-logging, the reasons for certain specifications set forth in this chapter are self-evident. It is then desirable to utilize components that can be subjected to the severe requirements of well-logging and that can be enclosed in a sonde 3 inches in diameter.

All of the requirements necessary to fulfill this application have not been achieved, but must be subjects of further research; however, a feasible source is described here.
Available Nuclear Reactions

The bombardment of most light elements (\(^{6}\text{Li}\), \(^{4}\text{Be}\), \(^{11}\text{B}\), \(^{19}\text{F}\), \(^{11}\text{Na}\), \(^{12}\text{Mg}\), \(^{23}\text{Al}\)) by high-energy particles will produce neutrons. For example, a portable source of neutrons is made by bombarding \(^{4}\text{Be}\) with the alpha particles of radium. Although this source is commonly used, it has three disadvantages characteristic of most other neutron sources. First, \(\gamma\)-rays are emitted, as well as neutrons. Second, the number of neutrons produced is limited since only about one neutron is produced for every 5000 \(\alpha\)-particles, and large amounts of radium are difficult to obtain and handle. Third, the energies of the neutrons emitted vary over a wide range (energies up to 13 Mev maximum, with a peak intensity at 4.8 Mev).

Neutron sources using the light elements bombarded by artificially-produced, high-speed charged particles have the advantage that they can be easily turned on and off, but have the disadvantage that usually large accelerating voltages and complex equipment are needed (Van de Graaff generator, cyclotron, etc.). These accelerators are now commercially available but are relatively expensive and very bulky. For example, neutrons can be produced by bombarding the heavy isotopes of hydrogen with relatively low-energy charged particles. If the accelerated particles used are deuterons (\(^{2}\text{H}\)), neutrons result from the bombardment of either deuterium, \(^{2}\text{H}\), or tritium, \(^{3}\text{H}\). The nuclear reactions are as follows:

\[
(D-D): \quad \text{H}^2 + \text{H}^2 \rightarrow \text{He}^3 + \text{n}^1 \quad (2.48 \text{ Mev neutron}).
\]

\[
(D-T): \quad \text{H}^2 + \text{H}^2 \rightarrow \text{He}^4 + \text{n}^1 \quad (14.0 \text{ Mev neutron}).
\]
The maximum of the \( (D-T) \) cross-section occurs for an energy of about 108 KeV, and in the \( (D-D) \) reaction the energy for optimum yield is above one MeV\(^1,2,3 \). For energies less than 600 KeV, these two reactions are more productive than any other known reactions. The \( (D-T) \) reaction seems to be the most easily adaptable to a small accelerator because of the low energy needed for the accelerated particles. No gamma-rays are produced in these reactions. The relative yields of the \( (D-D) \) reaction and the \( (D-T) \) reaction are shown in Figure 1\(^4,5 \), using an ice target. The cross-sections for these reactions for energies less than 110 KeV are shown in Figure 2. Although tritium is expensive, it is not prohibitive for most applications. Summarizing, the reaction, \( H^3(d,n)He^4 \), has the following advantages:

1. Only low accelerating potential is required for high neutron yields.
2. No \( \gamma \)-radiation is produced, and thus there are no shielding problems.
3. Monoenergetic neutrons are produced.
4. High-energy neutrons are produced (14 MeV).

The present portable sources (i.e. Ra-Be sources, one curie, or \( 1.5 \times 10^7 \) neutrons per second) have low intensities compared with that theoretically available utilizing the \( (D-T) \) reaction with reasonable ion currents (approximately 6.6 curies per \( \mu \)a of \( D^+ \) ions, or about \( 10^8 \) neutrons per second per \( \mu \)a for a heavy ice target).
Figure 1  Thick Target Yields Calculated from Yields for Heavy Ice Target D$_2$O

Deuteron Ion Energy (Kilovolts)
Figure 2 Cross Sections for (D-D) and (D-T) Reactions
Typical Neutron Sources

A Canadian patent\textsuperscript{6} describes a neutron source which utilizes the D-D reaction but cannot utilize the D-T reaction. This source consists of a pumped tube in which deuterium is continuously bled through a palladium leak.

Ions are created by a glow discharge between electrodes 2 and 3 (see Figure 3). High negative voltage is periodically applied to the palladium tube (cathode) and the ions formed between electrodes 2 and 3 are accelerated to the palladium tube and bombard the deuterium in the surface of the palladium, producing neutrons. Apparently the pressure is high enough to cause complete breakdown inside the tube during the pulse. Because of this breakdown, neutrons probably can be produced only for short times at the peak voltage of the pulses; thus, it may be difficult to produce reasonable durations of the high-voltage pulses making the average neutron output small. The tube has the disadvantage that the glass envelope must be pumped continuously and the palladium tube heated to allow the deuterium to be bled slowly into the envelope in order to maintain the correct operating pressure. The tube might be used for bombarding tritium with deuterium if the gas bled through the palladium leak is a mixture of deuterium and tritium. This technique would be prohibitively expensive if the tube were not sealed-off in some way to prevent the loss of tritium. A possible means of sealing-off this tube is discussed in Appendix A.

One of the earliest neutron generators using the D-D reaction was reported in 1937 by Bouwers\textsuperscript{7}. The ion source was rather impractical,
Figure 3 Salisbury Neutron Source Tube
as it operated with 50 kV and $2 \times 10^{-3}$ mm. Hg pressure, supplying a total ion current of approximately 600 microamps and approximately 30 per cent monatomic ions. It was operated with a pumped accelerating section much as the Van de Graaff generators of today.

Later the same year, Penning and Moubis of the same laboratory constructed a neutron source tube operating at a constant pressure throughout. Using a magnetic field with a P.I.G. type ion source a neutron yield of $2.9 \times 10^5$ neutrons/sec. was produced at 65 kV, using a zirconium-deuterium target with a target current of 40 microamperes at a pressure of $6 \times 10^{-4}$ in the tube. The neutrons were measured by means of the activation of a rhodium plate using the 44-second half-life isotope. This neutron yield is below that obtained using an ice target by at least a factor of 100. (This reference was not discovered until late in this research.)

The Neutron Source Developed In This Research

Because of the proposed fields of application of this neutron-producing tube, the physical size of the source should be made as small as possible. Because of the high voltage needed, it is probable that most of the volume will be associated with the high-voltage supply. The achievement of such a supply will not be discussed in this thesis as the main field of research was for a suitable sealed-off neutron source tube.

It is evident that in order to obtain a small and simple neutron source, a vacuum system used for continuous pumping would introduce tre-
mendous complications and have excessive physical size. A sealed-off tube would provide a valuable solution to this difficulty. A satisfactory sealed-off tube should have the following characteristics:

1. The physical size should be small.

2. The power required for its operation, other than the beam power, should be small (preferably less than 100 watts).

3. The nature of the ions produced by the ion source should be predominantly monatomic.

4. A method of cooling the target should be provided such that a beam current of 100 microamperes at 100 Kv (10 watts) can be maintained.

5. It should be simple, rugged and long-lived.

If the above requirements are met, a neutron source with the approximate following specifications might be achieved:

1. Small size (3 inch diameter, 6 ft. long including the voltage source).

2. Controllable neutron flux, from zero to full output. Monoenergetic neutrons (14 Mev for D-T reaction and 2.5 Mev for D-D reaction).

3. Neutron yields up to $5 \times 10^9$ neutrons/second with D-T and $10^7$ neutrons/second with D-D.

4. Easily shielded x-ray emission and no gamma-ray emission.

5. Small power input
   a. 40 watts high voltage supply output power
   b. 100 watts ion source
   c. 20 watts pressure control
      Total: 160 watts

6. Life-time >100 hours.
In this research, a neutron source meeting many of these specifications was developed providing a versatile and convenient tube having many applications. Because of the controllability and simplicity of the source, it will be quite valuable for use in neutron therapy experiments. The absence of $\gamma$-rays and the fact that it can be turned off is advantageous in these experiments also. If neutron therapy proves to be useful, such a tube as the one described here might become widely used in a manner similar to the x-ray tube of today.

Industrial neutron radiography should be practical and become common because of the simplicity and cost of this device. If this type of source became commercially available, many new commercial applications would become apparent, particularly since pulsed operation of the tube is possible. Many laboratory experiments will become feasible to the ordinary research worker that are impossible now. In the field of process control, a high yield neutron source might be utilized to produce radioactive tracer elements for the control of processes. It should also aid the chemist in his experimental use of tracer elements. The present neutron source has the potentialities of fulfilling the strict requirements of neutron well-logging applications.

The success of this source depended upon the idea of operating the ion source and the accelerating gap at the same pressure in a sealed-off unit. During the later part of the research it was found that Penning and Moubis had operated a tube that had the same pressure throughout. Apparently since 1937 this idea was left with no further development. The author has operated such a tube with both an RF and a filament type
ion source. The next three chapters discuss the problems of the ion source, the target and of sealing-off the tube. The final tube and its control element developed here is described in Chapters V and VI.
CHAPTER II

ION SOURCES

From the general description of the problem in Chapter I, some of the desirable characteristics of a source of deuterium ions are apparent. If one can continuously flow through the source a supply of deuterium and maintain low enough pressure in the accelerating section of the tube by continuous pumping, an ion source working at a high pressure might be used. As the original purpose of this research was to achieve a sealed-off tube, an ion source was sought such that both ion source and accelerating gap could be maintained at the same low pressure.

Because of the difficulties of operating the ion source at high voltage and the target at ground potential in the restricted space available, the target is operated at negative high voltage. If a pumping lead is connected to the accelerating section of the tube and the ion source tested at ground potential, breakdown difficulties arise because of the pumping lead. This difficulty was experienced in several of the early tests and breakdown occurred between the high-voltage target and the vacuum system through the pyrex pumping lead. Thus the accelerating section of the tube must be pumped through the ion source.

The accelerating gap pressure should be maintained small for insulating large accelerating voltages, yet large enough so that the ion source is capable of producing sufficient current at this small pressure.
J. B. Trump made measurements of breakdown in vacuum for high voltages between a stainless steel ball 1" in diameter and a 2" steel disk. It is interesting to note that while the gradient for breakdown increases with electrode spacing the voltage supported increases. For an electrode spacing of 6.5 cm. (2.6 in.) the breakdown voltage is 650 Kv. See Figure 4. The paper did not give the vacuum pressure of the type of gas involved but the author states that it was at an air pressure of $10^{-4}$ mm. Hg or less.

Figure 4 Breakdown Voltages and Gradients between 1" Stainless Steel Ball and 2" Steel Disk in Vacuum.
According to the curve of probability of ionization of different gases, the ability of the electron to ionize hydrogen is much less than nitrogen (see Figure 5) so that the breakdown strength in hydrogen should be much higher than in air. As all of these ionization probability curves decrease with increasing energy, this effect of gas ionization by electrons becomes quite small at high energies.

In an accelerating gap, the ionization of the residual gases by high-energy positive ions is larger than the ionization by electrons. An \(\alpha\)-particle has a specific ionization of about 3000 ion pairs per mm. of air at N.T.P. for an energy of 100 keV \((2.2 \times 10^8\) cm./sec). The ionization of the deuteron is approximately one-fourth the ionization of the \(\alpha\)-particle, or 0.1 ion pairs per cm. at 0.01 mm. pressure. Assuming that there are no non-ionizing collisions of importance, the mean-free-path is 10 cm. while for the electron of these energies it may be one-hundred times greater.

A more important criterion which determines breakdown is the secondary emission ratios of the electrodes. At the anode the number of metallic ions produced by impinging secondary electrons is less than \(5 \times 10^{-4}\) for steel electrodes according to Trump. This is small compared to the ratio at the cathode. Some interesting secondary emission ratios were obtained by Webster, et al. For monatomic ions the secondary electron emission ratio up to 200 Kv lies between 2 and 4. For diatomic ions the ratio rises to 10 at 200 Kv. Breakdown will occur if the secondary electron emission ratio \((A)\), times the ratio of positive ions formed by these secondary electrons going to the anode \((B)\), exceeds one.
Fig. 5. Curves showing the number $N$ of ionizing collisions made per cm path through gas at 0.01 mm pressure at 25°C.
For breakdown $AB > 1$.

$A = \text{ratio of electrons emitted to ions impinging on the cathode}$

$B = \text{ratio of ions produced in gas and at anode to electrons leaving the cathode}$

Breakdown is also determined by the nature of the high voltage circuit impedance. To insure good breakdown characteristics a resistor of several megohms was used in series with the high voltage target cathode. The function of this resistor is to extinguish discharges as they are initiated.

Because of the high secondary emission ratio expected for the target, it was assumed that breakdown difficulties would be encountered if pressures much above 1 micron were used. Professor Trump suggested that even pressures above 0.1 micron might give trouble. Thus it was expected that the ion source would have to operate around a pressure of 1 micron.

Some other unusual requirements for the neutron source are necessary for drill-hole applications. The life-time of the sealed-off tube is dependent upon the deterioration of ion source parts, thus a source which does not sputter is desirable. Because of the target life-time considerations, the normally desirable feature of focusing is now not required — in fact, it is preferable that a very diffuse beam strike the target to prevent local heating and sputtering and thus prolong the life of the target. It is also desirable that the ion source require very little power.

Separation of the different mass components of the beam cannot easily be made in such a small tube, hence it is desirable to produce and accel-
erate only monatomic ions \((D_1^+\))\). If diatomic ions \((D_2^+\)) are produced predominantly by the ion source the effective beam current (atoms) is doubled but each atom has only one-half the accelerating energy. This decreases the thick-target yield for a tritium ice target for 100 KeV accelerating voltage from about \(1.2 \times 10^8\) to \(2.4 \times 10^7\) neutrons/sec/\(\mu\)a. (factor of 5); for 50 KeV accelerating voltage from \(1.2 \times 10^7\) to \(1.2 \times 10^6\) neutrons/sec/\(\mu\)a (factor of 10). See Figure 1 in Chapter I.

If there is a small surface layer on the target which contains no tritium, the yield will be cut greatly. If the source is to produce large neutron fluxes and if one is limited to 100 Kev acceleration voltage, the ions should be largely monatomic. If diatomic ions predominate the current used must be increased by a large factor to compensate for the tremendously decreased yield, thus making a greater heat dissipation problem in the target. As the secondary emission ratio is probably larger for diatomic ions, cooling problems produced by secondary electrons become more difficult.

Because monatomic ions are so important, an RF ion source was immediately utilized as this type is noted for its high monatomic yield. It was expected that it would require considerable input power, as the RF power coupled to the ions is a small percentage of the total power input to the class-C oscillator. To increase this efficiency it might be possible to use the historic "spark-transmitter" oscillator as shown in Figure 6. Also, because of the construction of the RF ion source, it is difficult to defocus the ion beam. In spite of these difficulties the RF ion source was chosen first because of its high monatomic yield.
Various authors report good results from RF sources and these are discussed in Appendix B. A summary of the pertinent operating features of RF ion sources given by these authors is as follows:

1. Complete absence of all unnecessary metal parts in the ion chamber is essential for high monatomic yields.

2. Optimum pressures range from 15 to 40 microns.

3. Quite large powers are required for large monatomic yield. (300 - 500 watts)

4. Percentage of monatomic ions depends on cleanliness of tube, purity of gas, and time of operation.

5. Percentage of monatomic ions can be approximated with hydrogen by color of discharge (Red - higher than 50%; Pink - less than 50%).
6. Magnetic fields are not particularly helpful.

7. Starting the discharge is sometimes difficult. It may be started by raising the pressure, or with a sparker.

8. Aluminum extracting electrodes prevent sputtering.

9. Low pressures produce less percentage of monatomic ions and ion sources are never operated below 5 microns.

Low Pressure RF Discharge Phenomena

The use of RF ion sources at a few microns is not discussed in the literature, as the normal requirements for an ion source permit their use at higher pressure and thus make large currents easily obtainable. In this application, however, it was felt that low pressure must be used so that the voltage breakdown requirement of the accelerating gap could be met.

As RF discharges are possible at relatively low-voltage gradients at low pressures (1 micron), and direct voltage breakdown does not occur until large gradients are reached, some explanation of the mechanism of breakdown is given in Appendix C. (The author has been able to maintain discharges at pressures as low as 0.1 micron.)

Gill and Von Engle have made measurements on the breakdown of various gases at pressures between 1 and 8 microns as a function of frequency. In this range of pressure the glass walls of the discharge become the important factor causing breakdown. As the mean-free-path for the electron in this range of pressure is several times larger than the
ion chamber, cumulative buildup of ions and electrons in the volume, by
collision of free electrons with gas molecules, is insufficient to pro-
duce breakdown. In other words, the Townsend coefficient in the gas is
much less than unity because of the long mean-free-path; and, therefore,
it is necessary for the glass walls to supply the cumulative supply of
electrons necessary to produce the discharge.

From the relations derived in Appendix C it follows that breakdown
occurs more easily with larger discharge chamber dimensions and even for
lower frequencies. An effect added to the one caused by the secondary
emission of the electrons is obviously one of increased path length in
the larger chamber. It is thus desirable to make the chamber as large
as possible.

When the discharge container is made of soft glass instead of pyrex,
the gradient necessary for breakdown is decreased by 30%. This can be
explained by the fact that soft glass has a larger secondary emission
ratio. See Figure 7. A soft glass tube is impractical; however, a pyrex
tube having a soft glass insert might improve the monatomic ratio in the
discharge.

The RF ion sources used in the experimental tubes have been operated
over a range of frequency of 10 to 150 Mc. The operation of the sources
at any frequency for large input powers (>100 watts) caused considerable
heating of the glass because of the electron and ion bombardment. Experi-
mentally the optimum operation seemed to be about 25 Mc where a 2¾" dia-
meter tube approximately 6" long breaks down easily.
Cold cathode discharge ion sources are discussed frequently in the literature, but the monatomic yields reported are usually less than 20%. Some typical sources are discussed in Appendix D. It would seem that the possibility of the favorable operating pressure regions and the low power consumption of the hot and cold cathode discharges would force the application of this type of source to the desired sealed-off neutron tube. However, the achievement of large mona-
tomic percentages from RF sources at relatively low power, enticed the author to test the tube as a unit at various pressures to determine whether it was possible to make monatomic ions with an RF source at a pressure low enough to permit 100 Kv acceleration voltages to be used across the accelerating gap simultaneously. The first two tubes tested, as described in Appendix G, indicated that it was possible to operate a sealed-off tube in this manner; however, large monatomic yields were not achieved. In the last experimental tubes, as described in Chapter V, high monatomic yields were achieved. This was made possible because high-voltages across the accelerating gap were maintained at pressures as high as 10 - 15 microns.
CHAPTER III

TARGETS

A most important factor in the achievement of large neutron fluxes, using the D-T reaction, is the fabrication of the tritium target. There are two reasons for using a tritium target instead of a deuterium target. First, if a deuterium target is used, the accelerating voltage or the target current must be increased to give the same yield as that of a tritium target. The accelerator voltage per neutron must be increased by a factor of $3/2$, and the ion current by a factor of $3$ to $6$. Second, because of the difficulty of handling tritium and its costliness, as well as the possible health hazard, it is advantageous to fill the tube with inexpensive deuterium.

Tritium targets have been made in various forms, but most of these are impracticable for the present application. Pure tritium gas, at various pressures, separated from the accelerator's vacuum system by a thin membrane, can be used as a standard target when the accelerating particles have high energy ($>1$ Mev). With $100$ Kv accelerating potentials, this type of gas target cannot be used because of the window thickness necessary to support the pressures. Solid T$_2$O targets are also impractical, because of the difficulty of maintaining the target at freezing temperatures.
The formation of tritides, deuterides, or hydrides with various metals such as uranium, zirconium, titanium, tantalum, lithium, etc., makes possible the retention of tritium in a useful manner. Uranium hydride is not useful in this application as it has a hydrogen vapor pressure of about $10^{-3}$ mm. Hg at room temperature. Zirconium, on the other hand, can be heated to 450°C in a vacuum without loss of tritium, according to reference 13.

In the latter part of the research, difficulties were encountered in producing the theoretical neutron yield, and depletion of the tritium from the target was suspected. A Gieger counter made by Victoreen Instrument Company, called the Thyrode 1B85, was sealed into a vacuum chamber together with a newly made tritium target placed 3\(\frac{1}{8}\) inches from the tube. Counting rates at atmospheric pressure and at high vacuum (5 \(\times\) $10^{-6}$ mm.) were taken. The counting rate in vacuum was 14.5\% higher than at atmospheric pressure. The target was heated in vacuum to a temperature of 150°C for a period of fourteen hours and the counting rates both at atmospheric pressure and in vacuum remained unchanged. It was found that tubes could be sealed-off if they were baked only at 150°C so that this test was not carried to higher temperatures.

Techniques Used In Making Tungsten-Backed Zirconium-Tritium Targets

Zirconium possesses the disadvantage of becoming brittle and may be reduced to powder if the hydrogen content is too high (ZrH\(_2\)). If a metal
with fairly high melting point is used as a backing for the zirconium, the loss of mechanical strength is no longer troublesome. Tungsten is normally used but aluminum and beryllium also have been used successfully.

As zirconium is a good getter - it takes up oxygen and nitrogen readily when heated - all sources of contamination must be excluded from the vacuum system used in making targets. The tungsten backing must, therefore, be cleaned and outgassed by heating in a vacuum to about 2400°C. The surface of the tungsten has been previously polished.

Two methods have been used to place the zirconium on the tungsten. Melting a small foil of zirconium on a tungsten disk in vacuum has not proved to be as successful as the evaporation technique now in general use. By supporting zirconium wire on a heated tungsten ribbon, very thin uniform coats of zirconium can be evaporated. If an additional heater is first used to evaporate zirconium on the walls of the vacuum chamber so that the residual gases (N₂, O₂, and CO₂) are captured on the walls, the target is not contaminated during evaporation onto the tungsten. Thicknesses of 10 μg/cm² up to 500 μg/cm² have been obtained in this manner.

The target is inserted into a small volume chamber and pumped to 10⁻⁵ mm. Hg or better, with a vacuum system containing no oil. Very small amounts of oil contamination impede the absorption of tritium. A liquid-nitrogen trap is used. The tritium is stored in uranium which may be heated in the same vacuum system. In this way the chamber can be filled with about 1 mm. pressure of tritium. Targets can be made with quite low tritium gas pressures, and usually must be because of the small quantities
generally available. The target is heated to a dull red and cooled slowly for about 15 minutes. The maximum tritium that can be absorbed practically is a ratio of tritium atoms to zirconium atoms of about 1:1.5 and usually a ratio of about 1:1 is obtained. The theoretical limit is $\text{ZrT}_2$.

During the process of making tritium targets, it was observed that zirconium absorbed a considerable amount of tritium at room temperature. This fact indicates that targets may be made without heating the zirconium to cause absorption.

It is possible that, as in the case of uranium, the vapor pressure of tritium over zirconium is sufficiently high so that a layer of tritium near the surface escapes. This would be a serious obstacle in the achievement of large neutron fluxes. Data on vapor pressures in zirconium are as yet unavailable.

To achieve maximum yield from a zirconium target its thickness should exceed the penetration of the ions. As the stopping power for zirconium is greater than that of oxygen, a theoretical yield determination was made for thick zirconium targets so that they might be compared to yields from thick ice targets. See Appendix E.

If a zirconium target is 0.5 mg./cm.$^2$ thick, the yield for a $\text{ZrT}_1$ target is compared with the yield for a $\text{T}_2\text{O}$ target as calculated from data by Bretscher, et. al. in the following table:

---

*Dr. T. T. Magel, of M.I.T. Research Laboratories, lets the target cool quickly.*
<table>
<thead>
<tr>
<th>Deuterium Energy Kev</th>
<th>Calculated yield of zirconium target ZrT$_1$ neutrons/sec/µA</th>
<th>Calculated yield from thick ice target (T$_2$O) neutron/sec/µA</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>6.5 x 10$^7$</td>
<td>1.3 x 10$^8$</td>
</tr>
<tr>
<td>80</td>
<td>3.5 x 10$^7$</td>
<td>7 x 10$^7$</td>
</tr>
<tr>
<td>60</td>
<td>1.20 x 10$^7$</td>
<td>3 x 10$^7$</td>
</tr>
</tbody>
</table>

On examining the stopping power for various metals (see Figure E-8), yield differences for various target materials could change the total yield only by a factor of about 2.5, assuming the same number of tritium atoms per atom of target material. Although other materials may have desirable advantages, after titanium was tried and found to be almost identical with zirconium targets, it was thought unprofitable to try other materials. This, however, would be an interesting subject for further research.

**Target Properties**

From Figure E-11, it is seen that a target thickness of 0.5 mg./cm.$^2$ (0.8 micron zirconium thickness) is sufficient to produce the maximum yield from a target with 100 Kv deuterons. Thus a typical target ZrT$_1$ having 0.5 mg/cm.$^2$ of zirconium has the following properties:
Diameter of Zirconium = 0.75 in.
Area = 2.85 cm.²
Mass Zr = 1.42 mg.
Moles Zr = 1.55 x 10⁻⁵
Moles tritium (T₂) = 7.8 x 10⁻⁶ (for ZrT₁, average target)
Tritium decay rate = 1.72 x 10¹⁰ disintegrations/sec.
Curies tritium = 0.462
Volume tritium
1 atmosphere = 0.175 c.c.
5 microns = 2650 c.c.

Experimenteres cited previously, indicate that after a few hours of operation the neutron yield drops to about fifty per cent. They usually suggest that this is due to carbon collection or some other unknown conditions of the target surface. To avoid this, it is recommended that no oil be used in the vacuum system. To determine the effects of bombardment upon the targets the radioactive properties of the tritium was used by making an autoradiograph using bare x-ray film placed against the target for about 15 seconds for 1 curie/cm.² target strength. Some typical autoradiographs of the targets used in this work are shown in Figure 8.

The original uniformity of the tritium distribution may be determined from densitometer measurements on the film. After the targets have been bombarded, lighter spots on the film may be attributed either to
Target Bombarded by RF Ion Source
3/4 inch diameter Hole in Extracting Electrode

New Target

Figure 8  Autoradiographs
"gunk" collection or tritium depletion. If the activity is sampled over the target area by means of an x-ray sensitive counter that excludes $\beta$-particles (18 Kev), the difference between loss of tritium and "gunk" that may have been deposited can be determined as the "gunk" will not stop the x-rays. This is also accomplished by using something to stop the $\beta$-particles and taking an autoradiograph of the x-rays only.

Radioactive film measurements to determine the tritium content of targets that have been bombarded heavily is subject to error because of the neutron-induced activity of the zirconium. ($\text{Zr}^{95}$ has a half-life of 65 days.)

**Build-Up In Targets**

If we assume that the target has the thickness of 0.8 microns (100 Kev thick) and that the ratio of the zirconium to tritium atoms is 1:1, there are $4.4 \times 10^{22}$ atoms per c.c. in the zirconium. The rate of deposition of deuterium atoms in zirconium can be calculated for various beam areas and currents. For a beam area of .04 square centimeters it takes $2 \times 10^4$ seconds for a 1 microampere beam to deposit enough deuterium to make a 1:1 ratio of Zr to tritium atoms. For a 100 microampere beam this would be only 200 seconds. If, however, the 100 microampere beam area were increased to 2.85 square centimeters it would take a little over four hours to build-up the same target. Thus it seems practical that a good target could be produced in
a sealed-off tube if D-D neutrons are desired, as .175 c.c.'s at N.T.P. of deuterium are required to fill the target. This can be easily obtained from a zirconium filament sealed in the tube and filled with deuterium. The same is true for tritium targets.

**Build-Up Of Deuterium In Tritium Targets**

As has been shown above, a tritium target 0.8 microns thick could be filled in 3 hours with a 100 μa beam with deuterium if each impinging deuterium atom displaced a tritium atom. This is highly improbable but certainly some tritium would be displaced by deuterium. If all the tritium were to escape into the tube it would fill a typical tube with 1520 c.c. volume to 87 microns pressure of tritium. The zirconium filament then must absorb this excess of tritium and thus tritium ions would be formed and accelerated and again become imbedded in the target. As it takes only .02 c.c.'s of deuterium at N.T.P. to fill this tube to 10 microns pressure, an equilibrium might be reached in which approximately half of the ions accelerated would be tritium. Thus the yield would drop only to about fifty percent.

**Targets Incorporated In Final Experimental Tubes**

Zirconium targets with deuterium or tritium were used throughout the experiments in this research. When the neutron yields achievable were
found to be smaller than expected, titanium targets were tried. Titanium evaporates more readily when melted on the surface of a tungsten filament than does zirconium. The first titanium target prepared did not have a smooth layer but was deposited in bumps and patches on the tungsten backing. No explanation is evident for this type of deposition. The second target tried had a more uniform coat, but was not as nearly uniform as the zirconium had been. Neutron yields achieved with a titanium target with 0.81 mg./sq. cm. of titanium (TiT₁₅) were almost identical with that of the zirconium target of 0.9 mg./sq. cm. (ZrT₁₁).
CHAPTER IV

PRESSURE CONTROL

The success of these tubes depends entirely upon the feasibility of sealing them off and controlling their pressure during operation. The operation is critical with respect to slight residual contaminants since they alter the operating characteristics of the ion source and perhaps decrease the breakdown strength of the accelerating section of the tube. Hence, extreme care in cleaning and baking of the tube is necessary. Zirconium getters offer an excellent solution to these pressure control problems.

Some Properties Of Zirconium

As mentioned in Chapter III, zirconium is an excellent getter for hydrogen and thus provides a simple and practical means of storing deuterium and controlling the pressure in a sealed-off tube. It is theoretically possible to store in a 10-inch length of .025-inch diameter zirconium wire, about 360 c.c.'s of hydrogen at N.T.P. for the saturation value. As mentioned in Chapter III, the hydrogen may be released again if the zirconium is heated.
According to Fast and Haass\textsuperscript{17, 16}, hydrogen is soluble in zirconium up to ZrH\textsubscript{1.95}, however, disabsorption occurs when the pressure is lowered. According to the experiment reported in Chapter III, no appreciable loss of tritium was noted for tritium targets placed in vacuum and heated to temperatures of 150°C, and other authors indicate no loss of hydrogen up to 450°C.

Some typical reaction curves are given by Gilbransen and Andrew\textsuperscript{13} for oxygen, nitrogen, and hydrogen as shown in Figure 9. The absorption of oxygen is dependent on the thickness of the oxide layer as it is formed; however, the absorption of nitrogen appeared from the data to be similar to that of oxygen but may be different since the nitride is soluble in the metal at the reacting temperatures. The rate of absorption of nitrogen is nearly independent of pressure from 0.15 to 7.6 centimeters. However, the absorption of hydrogen in zirconium is quite pressure dependent. Hydrogen is apparently dissolved in the metal to form a compound or stable complex. The 300°C curve for hydrogen corresponds to the compound ratio of ZrH\textsubscript{.216} after two hours. The oxide is soluble at the high temperatures and the oxide film may be removed by heating; however, on cooling in a vacuum a film will form again. Since the oxide is not reducible the surface must be abraded to restore a zirconium surface. In the case of nitrogen, the nitride dissolves in the metal and after a certain time clean metal will be exposed. The nitride reaction is very sensitive to traces of oxygen and hydrogen in the gas. Since oxygen and hydrogen react much more quickly than the nitrogen it is difficult to use a zirconium filament as a getter for nitrogen in sealed tubes. Water vapor
Figure 9 Pressure Control Circuit
is normally present providing a source of both hydrogen and oxygen. The zirconium will release hydrogen but not oxygen or nitrogen if it is heated. Thus if a filament is heated slowly there is an apparent equilibrium temperature at which the hydrogen pressure remains constant in a closed vessel. Such an equilibrium curve is shown in Figure F-12.

Early in this research a simple experiment was performed to test the practicability of using zirconium filaments to control pressure in a sealed-off tube. A vacuum system containing a zirconium filament tube, an ion gauge, a cold trap, and a neutron source tube was sealed from the pump by means of a stopcock. After evacuation, the deuterium pressure was controlled by heating and cooling of a simple zirconium filament constructed with approximately eight turns of one-eighth inch diameter helix. This filament was operated at approximately 5 watts having a resistance of 0.5 ohm. To test the life of this system a simple electronic pressure controlling device was constructed using the ion gauge to give a pressure signal. See Figure 9. The ion current from the gauge collector supplied the signal to the grid of a 6SH7. A variable resistor in the grid circuit provided the possibility of selecting various regulating pressures. This signal controlled the load on a series transformer T₁ so that the heating of the zirconium filament varied inversely with the pressure. A more simple circuit for controlling the pressure may be designed eliminating one tube (6B4G) and transformer by using a saturable-core transformer as suggested by Overbeck\textsuperscript{16}.

The deuterium pressure could be regulated by this automatic system for 10 to 12 hours with no apparent change in regulating characteristics.
Figure 10 Absorption of Gases in Zirconium
over a range of pressures from 0.8 to 16 microns. The liquid-nitrogen trap makes this experiment unrealistic. However, only water vapor and other volatile gases can be removed by this trap. As zirconium is a getter for water vapor as well as oxygen and nitrogen, the cold trap was replaced by a white hot zirconium filament. Hot zirconium has the ability to decompose water vapor, thus absorbing at high temperatures the resulting oxygen present in the tube. The hydrogen thus liberated can be absorbed only when the filament is cooled. Using a white hot zirconium filament, control was maintained for a few hours.

The partial success of these preliminary experiments did show that a solution to the pressure control problem is possible. Many zirconium filament tubes were constructed and utilized. Some of the typical experimental results obtained are discussed in Appendices F and G. The present filaments are constructed by wrapping the .025 inch zirconium wire around .015 inch tungsten hairpin filaments, and the zirconium is heated indirectly by the filament which gives support to the zirconium. Without the tungsten support the zirconium filament would change shape so badly that it would touch the glass envelope or short itself. There is danger of melting the tungsten filament because the zirconium forms a eutectic with it at 1550°C which is below the melting point of either metal.

The Pressure Regulation System

Chapter VI describes the unit which was constructed to control the neutron tube. An electronic pressure control device for the tube was
incorporated in the unit. As it is desirable to monitor the pressure while the automatic control is functioning, a slightly more complex circuit was used. See Figure 11. Using the ion collector current for both pressure reading and control, the pressure can be read on the $10^{-4}$ mm. scale of the D.P.I. gauge.

The pressure regulative system may be represented in block diagram form, as shown in Figure 12. Block A ($K_p$) represents the ion gauge converting pressure $P$ into a current proportional to it. This current produces a voltage $E$ which is compared to a reference in the difference amplifier shown as a summing device. The magnetic amplifier Block B ($K_1$) produces an a-c output voltage that is approximately proportional to the input voltage. Although the temperature of the filament is not proportional to the output voltage, a linear constant ($K_2$) of proportionality will be assumed between the temperature and the output of the amplifier for incremental quantities. One of the important time-constants of the system is produced by the thermal capacitance of the zirconium filament and is designated as $\tau_1$ in Block C.

According to Figure F-12, the pressure is a complex function of the temperature of the filament. Again, to make stability calculations, it will be assumed that the pressure is a linear function ($K_T$) of the equilibrium temperature for incremental changes. The equilibrium pressure and thus $K_T$ varies inversely with the concentration of deuterium in the zirconium. Another time constant of the system is produced by the time delay in filling the volume of the system. This time constant is dependent on $K_p$ and the volume of the system. As the rate of pressure increase
Figure 11  Automatic Pressure Control Circuit
Figure 12A Block Diagram of Pressure Regulator

Figure 12B Simplified Block Diagram of Pressure Regulator.
depends on the pressure and thus the temperature, it will be assumed that the rate of pressure change depends upon the difference between the actual and equilibrium temperatures. Thus, if there is no difference in the two temperatures there will be no pressure change as indicated in the block diagram. As the pressure change is proportional to the integral of the rate, an integrator is provided in Block D. The block diagram applies only to incremental quantities. Statically there is a temperature and pressure corresponding to a reference voltage $E_{\text{ref}}$.

The stability of the system may be determined by solving for the transfer function $\frac{P}{E_{\text{ref}}}$. First simplify the diagram by solving for $P/T$.

$$\frac{P}{T} = \frac{K_v}{s + K_v K_T}$$

The system now reduces to Figure 12B. Solving for the transfer function:

$$\frac{P}{E_{\text{ref}}} = \frac{K_1 K_2 K_v}{s^2 \gamma_1 + s(K_T K_v \gamma_1 + 1) + (K_T K_v + K_P K_1 K_2 K_v)}$$

As we have assumed that the amplifier has no time delay in comparison with the thermal time delay of the filament, the system is one of second order. This means that the system is stable as the coefficients are positive; however, it may be greatly under-damped. Because of the difficulty in finding the constants of the system which have to do with the heating of the filament and the rate of hydrogen absorbed and given off by the filament, no computation has been made of the damping coefficient. From
observations of the system using the circuit of Figure 11, the damping coefficient may be as low as 0.4 as a few small overshoots take place. The period of these oscillations was about one or two seconds. The system seemed quite stable when disturbances of any kind were introduced.

This same system can be used for control of the pressure in a tube when a palladium leak is used. It should be applicable to the method of sealing off tubes as described in Appendix A.

When a palladium leak was substituted for the heated zirconium filament and the system was pumped continuously, the pressure could be controlled quite well by the circuit of Figure 9. However, when the new circuit, Figure 11, having more gain was used the system became erratically oscillatory, and caused a sinusoidal pressure variation of about 4 microns having a natural period of about 10 seconds. These oscillations most probably arose because of the additional thermal time constant introduced by the palladium leak. The heater has thermal capacity and cooling conductance from the gas. The palladium tube, which is heated by radiation and conduction of the gas also has thermal capacitance. The electric circuit analog of the thermal system of a palladium leak is shown in Figure 13.

The transfer function of the analog is of second order and this additional time constant requires that the loop gain of the overall system be much smaller than before in order to preserve stability. However, it is probably not necessary to have large gains in order to maintain the pressure sufficiently constant.
Four tubes have been successfully sealed-off and operated. The first three are described in Appendix G. The fourth tube is identical with the one described in Chapter V. This tube was sealed off without baking it in an oven. The tube was operated for a sufficient time to outgas the ion source and then sealed off with the zirconium filament filled with an excessive amount of deuterium. The tube was sealed off at $10^{-5}$ mm. and
then the pressure was increased to 10 microns where the tube was operated. The zirconium filament was unable to reduce the pressure below several microns but by use of a barium-filled iron-wire getter the pressure was reduced to less than 0.1 microns. Again the pressure was controlled by the zirconium filament and the tube operated successfully, but soon the barium getter absorbed all the available deuterium and the pressure became too low for operation of the tube. A multi-filament barium getter that could flash controlled small amounts of barium on the glass wall can be used to renew tubes by cleaning out all gases evolved during operation. The tube may be refilled with deuterium from the zirconium filament. The pressure control in sealed-off tubes by zirconium is adequate if proper care in vacuum techniques is taken; however, the addition of a barium getter makes the problem easier.
Chapter V

The Neutron Source Tube

At the beginning of this research the first two experimental tubes constructed utilized the RF ion source, see Appendix G. These tubes were quite successful but were thought to require too much power for the operation of the ion source. Although the problem of secondary electrons emitted from the target was unsolved, the next few tubes were constructed using a filament ion source described in Appendices G and H. The first of these was quite successful, and a yield of $5 \times 10^7$ neutrons/seconds was obtained with an ion current of 40 $\mu$A at 100 kV. This yield was considered low at that time, compared to the theoretical yield; however, several other experimental tubes using filament type ion sources were tested with no better results. It was then assumed that while most of the difficulties in obtaining neutron yields rose from the target it would be of considerable advantage to utilize ion sources with high monatomic ratios.

RF ion source tubes having ion chambers like the one shown in Figures 15b and G-29 were constructed. Characteristics of this ion source are discussed in Appendix G. A series of three sealed-off tubes was tested using this ion source, see Appendix G. Successively larger extracting holes were used in these sources to spread the beam. When the hole became
as large as $\frac{1}{2}$ inch in diameter and the beam was spread fairly well, adequate control of the magnitude of the beam current was no longer possible. It was then thought that the addition of a third electrode between the exit hole and the target could be inserted so as to shield the high voltage electrostatic field from the ion source exit hole thereby regaining control of the beam current. A simple grid structure was placed in the tube and a successful test was made giving simultaneous beam current control with nine small beams. This arrangement is pictured in Figure G-34.

An improvement was made in the grid structure by increasing the number of small holes, effectively spreading the beam. Present tubes have a slightly different hole-electrode construction than the experimental tubes, as shown in Figure 14. With this structure 29 small beams are possible covering a circular area $\frac{1}{4}$ inch in diameter, exactly that of the target. During the search for a means of controlling the beam current another device was tried for decreasing the secondary emission current from the target. A cylindrical electrode electrically insulated from the target was mounted by means of a teflon ring as pictured in Figure 15b. If the cylinder is placed at a negative potential with respect to the target, secondary electrons having energies less than this potential will be repelled and returned to the target. The cylinder is maintained negative by means of the voltage drop in the 5 megohm resistor, see Figure 16. The current flowing in the resistor is the sum of the target ion current and the secondary electrons emitted having energies greater than the voltage drop. Thus, if the secondary emission increases, the retarding potential automatically increases producing some degree of self-regulation. As there are still many secondary electrons
Figure 14  Comparison of Hole-Electrode Structures

Figure 15a  Neutron Source Tube Mounting
Neutron Source Tube

Fig. 15b
returned from the target or being formed by the beam, the effectiveness of this suppressor is not accurately known, but is believed to have decreased the secondary electron current by a factor of 2. The final tubes constructed with both of these improvements are shown in Figure 15.

It was found necessary to put a resistor in series with the grid 800-volt power supply to prevent discharge between the press leads behind the grid. The action of the positive potential applied to the grid is to repel the ions from the ion source. Electrons from the ion source are attracted to the grid and about 0.5 ma. of electron current flows to the grid when there is no probe voltage applied. As the probe voltage increases this current decreases and then reverses. If the plasma potential in the RF source is increased by means of the probe, the ions gain enough energy to overcome the repelling potential of the grid and some hit the grid and others escape into the accelerating gap. Thus the ion current may be almost completely cut-off, and can be turned on and off as quickly as the potential is placed upon the probe. This should enable modulation, either pulse or sinusoidal, of the neutron output of the tube. (This method of spreading the beam is applicable to other types of ion sources as well.)

A typical curve showing the control characteristics of the probe voltage is shown in Figure 17. The ion current to the target was measured with zero volts applied to the target circuit so that almost no accelerating potential appeared between the target and grid. The beam currents thus measured are free from secondary electron errors. In contrast to this excellent control of the probe, the grid voltage has very poor control of the target current.
Figure 16  Schematic Diagram of Neutron Tube Circuit
Figure 17  Control Characteristics of the Probe

Pressure - 10 microns
Oscillator Plate Power - 130 watts
Grid Voltage - 800 volts

Beam Current (microamperes)

Probe Voltage (Volts)
Some anomalous results have been obtained using this tube. It is indicated by Webster, et. al., that the secondary emission ratio for diatomic hydrogen ions at 100 Kv is at least twice that of monatomic hydrogen ions striking steel. It might be assumed that this is true for the target materials. As is shown in Appendix A, the increased monatomic percentage for an RF ion source operating at higher pressures and higher input powers is increased by a factor of 3 or 4. Thus it would seem because of the change in secondary emission ratio and ion mass composition that the neutron yield should increase rapidly for increasing pressures and RF oscillator input power, if the target current and voltage are maintained constant. This, however, has not proved to be the case. As shown in Figure 18, the neutrons produced per microampere of target current (including secondary electrons) is fairly constant over a range of 13 to 120 watts oscillator power. This is also true over a range of 5 - 15 microns for an oscillator input power of about 100 watts. Tremendous change in the color of the discharge occurs for both cases indicating that like changes take place in the ion mass composition. No explanation has been found for this anomaly.

It was thought, perhaps, that the use of a titanium target would produce a greater neutron yield since it was reported that titanium retains the tritium better than zirconium. A target was prepared by the same techniques used with zirconium. The titanium, however, did not evaporate uniformly onto the tungsten. Many bumps were produced. The absorption of this target was approximately TiT1.5. The amount of titanium used would give a uniform surface thickness of 0.61 mg./cm.².
Figure 18 Neutron Yield Dependence on Oscillator Power
Since the lumps were quite large, the thickness over much of the area must have been quite a bit less. The yield for this titanium target was approximately one-half that of the best zirconium target and the yield curve for a 300 microampere target current is plotted in Figure 19.

The data of Figures 17 and 18 indicate that a secondary emission ratio of approximately 20 is possible. Thus for a 300 microampere target current only 15 microamperes is ion current. The predicted yield from Figure 19 then would be about $10^8$ neutrons/second at 100 Kv for 15 microamperes of deuterons. This yield is less than that theoretically predicted by about a factor of 7. The reason for this discrepancy is unknown but probably could be explained if an analyzed beam could be used. Similar difficulties have been encountered by Peck and Eubank19. In a pumped accelerator using a high yield monatomic ion source they achieved a neutron yield of approximately $3 \times 10^9$ neutrons per milliampere at 120 Kev. This yield is also a large factor below the theoretical yield.

The maximum voltage at which these tubes may be operated has not been determined as the available high voltage source could not be used safely above 80 Kv. It is possible that this tube could be operated at considerably more than 100 Kv and eventually should be tested to determine the over-voltage rating. When operated at these higher voltages a neutron yield of $10^8$ neutrons/second probably can be achieved for extended periods of time. In the future as improved techniques for target manufacture and tube seal-off procedures are made, considerable increase in neutron yields will be achieved.
Figure 19  Thick Titanium Target Neutron Yield for a Target Current of 300 Microamperes
CHAPTER VI

TUBE CONTROL UNIT

During the course of these experiments a unit was built for the control and housing of the neutron producing tube. This unit is constructed so that it can be used for testing new well-logging procedures utilizing 14 Mev neutrons. It is a laboratory unit containing a small vacuum system and all the controls necessary for the operation of the tube. The vacuum system was included in case it was later found impossible or impractical to use and maintain sealed-off neutron tubes. The tube is housed in a 5 3/8" i.d. steel pipe, four feet below the bottom of the control equipment. The entire equipment is movable by means of a small chain hoist so that the pipe can be lowered into a test hole with the control equipment and vacuum system remaining above ground. The high voltage for the target is supplied through a coaxial cable from an external power supply.

The control unit consists of four parts:

1. The ion gauge control used to measure the pressure in either the sealed-off or pumped tube

2. The automatic pressure control as shown in Figure 11

3. The vacuum system shown in Figure 20, containing:
   a. Fore pump (25 micron limit)
   b. Pyrani gauge measuring fore pump pressure
   c. Single stage mercury diffusion pump requiring water cooling
   d. Deuterium storage bottle for palladium leak
Figure 20 Vacuum System
4. The main control unit (circuit shown in Figure 21) containing:
   a. Deuterium pressure control for either zirconium filament or palladium leak
   b. Vacuum system controls
   c. RF oscillator controls
   d. Probe voltage supply control
   e. Grid voltage supply control

Figure 22 shows a picture of this unit with the eight foot steel pipe attached.

Typical Operating Procedures

1. After a sealed-off tube has been lowered into the pipe by means of the high voltage cable and the control wires are connected, the pressure is read on the ion gauge and adjusted by the deuterium pressure control.

2. If the pressure is correct the RF oscillator filament and plate power may be turned on. This simultaneously applies the positive "grid" voltage if the switch on the front panel marked "grid" is on.

3. After the pressure is adjusted and the discharge becomes normal the target high voltage may be turned on.

4. The beam current may be "brought-up" by means of the probe voltage control.

If it is desired to use the automatic pressure control, the switch on the main control unit should be thrown to automatic only after the
FIGURE 21 MAIN CONTROL UNIT SCHEMATIC DIAGRAM
Figure 22 Main Control Unit
pressure control unit has been turned on and allowed to warm up. Correct pressure should be obtainable by means of the pressure control adjustment.

No provisions are made to measure the neutron yield or the target current as this equipment should be supplied by the user for his special application. These should be available for safe operation of the unit. As the x-ray hazard is serious, the tube should not be operated outside its casing at high voltages without proper precautions. Methods of measuring neutron yields used in this research are discussed in Appendix I.

If the tube is not sealed-off and the vacuum system of the unit is used, the oscillator tube assembly must be lowered into the steel pipe with a glass pumping lead sufficient in length to be connected to the vacuum system. After the tube is evacuated for an hour and a pressure of $10^{-4}$ mm. is achieved the RF oscillator should be operated at a pressure of about 10 microns for a long enough period to out-gas the tube and achieve a pressure of less than $5 \times 10^{-6}$ mm. The operating procedure is the same as has been previously outlined for a sealed-off tube with the exception that a palladium leak and a supply of deuterium must be used.
CHAPTER VII

SUGGESTIONS FOR FUTURE WORK
AND IMPROVEMENTS ON THE TUBE

As the main technical difficulty with the tubes designed and constructed to date is the excessive power required by the secondary electrons, which dissipate their energy in the part of the ion source structure they strike, their elimination from the beam would be highly desirable. This secondary emission ratio is high (possibly 20) so that not only is the power from the high voltage source excessive, but cooling of the grid structure of the tube is desirable. Although to date the abundance of secondary electrons has not produced breakdown difficulties up to 20 microns pressure, it is conceivable that at higher voltages than are available ( >90 Kv) breakdown will be troublesome.

One method of decreasing the secondary emission ratio might be to mount the target at a 45° angle to the beam so that the high energy secondaries will be more likely to hit the walls of a catcher. This might also have the advantage of spreading the beam over a wider target area but would accentuate any surface conditions of the target such as tritium depletion and "gunk" deposits. Increasing the available suppressor voltage might be helpful but probably not sufficient.
A cross magnetic field at the target supplied by a permanent magnet also connected to the target high voltage supply might also be very useful in conjunction with the suppressor cup now being used. This was not tried because of the time necessary to build a non-magnetic target structure which is difficult because of the kovar seal. The cross magnetic field has been tried. It was found that no metal at ground potential could be tolerated next to the glass and adjacent to the target. This also makes the mounting of a permanent magnet difficult if it must be maintained at high voltages.

The grid can be cooled if a tube is made utilizing a kovar cylinder sealed in the center of the tube if the grid has good thermal and electrical contact with the kovar. The aluminum extracting electrode can be supported from the grid by fired lava insulators and a connection can be made to it in a manner similar to Figure 15b.

Although the target is now cooled by oil, heat transmission might be improved by making the backing material of thin copper. If a connector insulated for high voltage could be found, so that it is no longer necessary to use oil to prevent breakdown, the target backing could be made of a large piece of copper to provide sufficient cooling.

The diameter of the tube probably can be reduced to 1/2 inches, but the length should remain the same for proper operation. The RF source will lose efficiency but probably will be still adequate. As the diameter is decreased the problem of breakdown may be difficult to solve without the use of oil. Breakdown seems to occur readily between the target assembly and outer container through the wall of the tube.
The construction of the present tube requires an expert glass blower. The tube is so made that it can be easily cracked apart and experimental changes made. All leads come out the ends of the tube in order to minimize the over-all diameter. The tube is fragile and an improved design is necessary for drill hole applications.
APPENDIX A

A SEALED-OFF TUBE THAT IS PUMPED

The Salisbury neutron source tube might be sealed-off with a mixture of deuterium and tritium if a diffusion pump is used, see Figure A-1. The temperature of the palladium leak could be adjusted so that the proper pressure inside the tube could be maintained. The diffusion pump might

![Diagram of a sealed-off tube with labels: Salisbury Source, Palladium Leak, Diffusion Pump, 10^-3 - 10^-2 mm pressure, 0.1 to 0.2 mm pressure]

Figure A-1 Method of Sealing off Palladium
Tube Type Neutron Source
maintain a pressure of 10 microns in the discharge tube and 0.2 mm. pressure inside the palladium cathode tube. The disadvantage of this arrangement is that the source mounting cannot be changed easily to other physical orientations because of the liquid in the diffusion pump. This same method might be applied to any type of sealed-off tube.
APPENDIX B

RF ION SOURCES

It was reported by P. C. Thonneman\textsuperscript{20} that an ion current of 10 ma. was achieved at a pressure of 1 micron by using a two-turn RF coil around a spherical two liter flask operating at 5 meters (60 Mc). This paper was one of the first describing an RF ion source and no similar sources successfully operating at this low pressure have been reported. Other workers have reported on sources operating at pressures between 14 and 30 microns and in this range were able to achieve substantial ion currents.

The Rutherglen and Cole\textsuperscript{21} RF ion source was excited at 100 megacycles with 30 watts of RF power by means of 2 metal rings spaced two inches apart on a $\frac{1}{2}$ inch diameter pyrex tube. With an axial magnetic field (300 gauss) they were able to increase the monatomic yield from 6\% to 60\% and produced a 400 microampere beam at 15 microns pressure.

R. N. Hall\textsuperscript{22}, operating at high pressures (60 microns) in a small pyrex or quartz discharge tube using 60 watts of RF power at 460 megacycles, produced a beam current of 400 microamperes having 60\% monatomic ions. This source utilized an axial magnetic field.

Thonnemann\textsuperscript{23}, in 1949, achieved a 50\% monatomic beam for a current of 500 microamperes using 250 watts of RF power at 15 megacycles.

Thonnemann, et al.\textsuperscript{24}, later achieved monatomic beams of 72\% at 13 microns
and up to 89% at 25 microns. They state that very little improvement was obtained when operating at 20 megacycles from a magnetic field and the monatomic percentage did not change appreciably.

Goodwin\textsuperscript{25}, using 200 watts of RF power at 27 megacycles, achieved a 92% monatomic beam of 600 microamperes. About 12 microns pressure was used in a 1 inch diameter pyrex envelope. He reported that no discharge was obtainable below about 3 microns pressure.

A rather remarkable source is reported by Eubank, et al.\textsuperscript{26}, which yields 15 milliamperes with a 80% - 90% monatomic yield. Credit is given to J. Symonds, University of Birmingham, England, for the original design of this source. 300 watts of RF power, including the oscillator coil power, is used at about 20 Mc in a pressure range between 30 - 50 microns which gives a collision frequency of the electrons and atoms of the order of the oscillator frequency and the electron mean-free-path of the order of the tube dimension. The tube was 2\!\frac{1}{2} inches in diameter and 9 inches long.

A summary of the characteristics of the several ion sources reported above, are tabulated as follows:

<table>
<thead>
<tr>
<th>Author</th>
<th>Date</th>
<th>Freq.</th>
<th>RF Power</th>
<th>Dimensions</th>
<th>Ion Current</th>
<th>% Atomic Yield</th>
<th>Pressure</th>
<th>Mag. Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thonemann</td>
<td>1946</td>
<td>50Mc</td>
<td>-</td>
<td>12 cm</td>
<td>10 ma</td>
<td>?</td>
<td>1 micron</td>
<td>no</td>
</tr>
<tr>
<td>Ruthergarten-Cole</td>
<td>1947</td>
<td>100 Mc</td>
<td>30w</td>
<td>1!\frac{1}{2}&quot; tube</td>
<td>400 \muA</td>
<td>60</td>
<td>15 micron</td>
<td>300</td>
</tr>
<tr>
<td>Hall</td>
<td>1948</td>
<td>460 Mc</td>
<td>60w</td>
<td>1&quot; diam.</td>
<td>400 \muA</td>
<td>60</td>
<td>60 micron</td>
<td>yes</td>
</tr>
<tr>
<td>Thonemann</td>
<td>1949</td>
<td>15 Mc</td>
<td>250w</td>
<td>10 cm</td>
<td>500 \muA</td>
<td>89</td>
<td>25 micron</td>
<td>no</td>
</tr>
<tr>
<td>Goodwin</td>
<td>1952</td>
<td>27 Mc</td>
<td>200w</td>
<td>1&quot; diam.</td>
<td>600 \muA</td>
<td>92</td>
<td>12 micron</td>
<td>no</td>
</tr>
<tr>
<td>Eubank</td>
<td>1953</td>
<td>20 Mc</td>
<td>300w</td>
<td>2!\frac{1}{2}&quot; diam</td>
<td>15 ma</td>
<td>80-90</td>
<td>30-50mic</td>
<td>no</td>
</tr>
</tbody>
</table>
APPENDIX C

RF BREAKDOWN CHARACTERISTICS

An analysis of breakdown at low pressures in a glass container by a radio frequency field was made by Gill and Von Engle\textsuperscript{12}. The pressure for which this analysis is made is low enough so that the mean-free-path is several times larger than the container. This is true for pressures up to about 10 microns in hydrogen and for containers about 20 cm. long.

A typical curve of the breakdown-gradient vs. wavelength of the applied field is shown in Figure C-2. Below a certain frequency there is apparently no breakdown for reasonable gradients. This critical frequency is the frequency below which electron multiplication by secondary emission from the glass walls no longer takes place. If a secondary emitted electron is accelerated from one glass wall to the other glass wall by a sinusoidal field so that the electron leaves with velocity $v_0$ at time $t = \Phi/\omega$ and arrives at the other wall at the end of a half-cycle, emitting secondary electrons, an increased number may in turn be accelerated during the succeeding half-cycle.

If the secondary emission ratio is greater than unity for glass walls, this multiplication of electrons increases with limit theoretically, or until the rate of loss of electrons is equal to the rate of production.
Starting field strength as a function of wave-length for flat-ended cylindrical tubes of 3 and 6 cm. length with axes parallel to the electric field, filled with pure hydrogen at a pressure of $1 \times 10^{-3}$ mm. Hg.

Starting field strength as a function of wave-length in spherical bulbs of 6 and 17-6 cm. diameter filled with mercury vapour ($p = 1 \mu$; temp. 18°C).

Figure C-2
If a glass tube of length d has a field \( E \sin \omega t \) applied between the ends, the acceleration of a free electron is:

\[ \ddot{x} = \frac{Ee}{m} \sin \omega t. \]

Integrating, the velocity of the electron is:

\[ \dot{x} = -\frac{Ee}{\omega m} \cos \omega t + K. \]

If we assume that this electron leaves the glass wall with initial velocity \( v_0 \) at time \( t = \phi/\omega \), the velocity of this electron as a function of time may be written

\[ \dot{x} = -\frac{Ee}{\omega m} \cos \omega t + (v_0 + \frac{Ee}{\omega m} \cos \phi). \]
Integrating again we find the displacement with respect to time:

\[ x = -\frac{B e}{\omega \epsilon_m} \sin \omega t + (v_0 + \frac{B e}{\omega m} \cos \phi) t + K'. \quad \text{(Eq. 1)} \]

If the electron leaves the glass surface at \( t = \phi/\omega \) \((x = 0)\) then:

\[ x(t) = -\frac{B e}{\omega \epsilon_m} \sin \omega t + \frac{B e}{\epsilon_m} \sin \phi + (v_0 + \frac{B e}{\omega m} \cos \phi) (t - \phi/\omega). \]

The distance traveled at the end of the half cycle \((t = \phi/\omega + \pi)\) is:

\[ x_f = \frac{2B e}{\omega \epsilon_m} \sin \pi/\omega \left( v_0 + \frac{B e}{\omega m} \cos \phi \right) \]

and the velocity at the end of the half cycle is:

\[ v_f + v_0 + \frac{2B e}{\omega m} \cos \phi. \]

Putting these equations in a little different form by substituting

\[ k = \frac{v_f}{v_0}, \]
then

\[ v_f = \frac{k}{k-1} \left( \frac{2E}{\omega m} \cos \phi \right) \]

and

\[ x_f = d = \left( \frac{k+1}{k-1} \cos \phi + 2 \sin \phi \right) \frac{eE}{m\omega^2} \]  
\[ \text{(Eq. 2)} \]

If \( \omega \) is replaced by wavelength \( \lambda \), the simplified relations are

\[ E \lambda \cos \phi = v_f \times \text{constant} \]

and

\[ \left( \frac{k+1}{k-1} \cos \phi + \frac{2 \sin \phi}{\pi} \right) E \lambda^2 = d \times \text{constant} \]

It can be shown from these two equations that the relation between \( E \) and \( \lambda \) is of the sixth-degree. If various values of \( \phi \) and a value of \( k \) are assumed, relative values of \( E \) and \( \lambda \) may be computed. For \( k = 10 \) these values are plotted in Figure C-4. This curve is very similar to the experimental curve which is shown in Figure C-2. However, the rise in the curve at small wavelengths is too steep and the curve does not exhibit a cut-off wavelength. Lack of a cut-off wavelength can be attributed to the fact that \( x(t) \) has negative values for negative values of \( \phi \) when \( k \) is small. Thus, the electron is lost to the discharge by being returned to the glass wall at a velocity too small to cause secondary emission. This is illustrated in Figure C-5. If we make the turning point of the elec-
Figure C-4 Calculated Breakdown Strength vs. Wavelength (arbitrary units)

Figure C-5 Illustrating Long Wavelength Limit
tron, as shown in Figure 20, such that at \( t = \phi/\omega \), \( x = 0 \) and \( \dot{x} = 0 \), then the dependence of \( \phi' \) and \( k \) for this cut-off wavelength can be shown to be:

\[
k = \frac{v_f}{v_o} = \frac{\cos \phi' + \cos \phi}{\cos \phi' - \cos \phi}
\]

The following table shows the limiting values of \( \phi \) and the relative cut-off wavelength for various values of \( k \).

<table>
<thead>
<tr>
<th>( k )</th>
<th>( \text{limiting } \phi )</th>
<th>( \text{Relative cut-off } \lambda (\phi = 0) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>42</td>
<td>20</td>
<td>1.28</td>
</tr>
<tr>
<td>19.2</td>
<td>30</td>
<td>1.48</td>
</tr>
<tr>
<td>9.8</td>
<td>40</td>
<td>1.74</td>
</tr>
<tr>
<td>5.8</td>
<td>50</td>
<td>2.16</td>
</tr>
<tr>
<td>3.7</td>
<td>60</td>
<td>2.75</td>
</tr>
</tbody>
</table>

It should be noticed that breakdown occurs over a broad band if \( v_f/v_o \) is small, which is in accordance with the experimental results. It is interesting to note from these expressions the effect of the dimensions of the tube on breakdown. We note that

\[
v_f \text{ is proportional to } E \lambda
\]

and

\[
d \text{ is proportional to } E \lambda^2
\]
approximately, for fixed angle $\phi$. Thus, $E$ may be scaled down by a factor $1/n$ and $\lambda$ increased by a factor $n$, for the same $v_f$ and $\phi$ if $d$ is increased by a factor $n$. Thus one sees that with the larger tube dimensions, breakdown occurs more easily even for a lower frequency. It is then desirable to make the discharge chamber as large as is possible so that it is easy to obtain and maintain a discharge, thus lowering the cut-off frequency.

If data from the experimental curve shown in Figure C-2 are used to check the validity of Equations (2) by assuming $\phi = 0$ when $\lambda = 9$ meters thus giving a value of

$$\frac{\lambda_{\text{cut-off}}}{\lambda(\phi = 0)} = \frac{24}{9} = 2.7$$

then $k = 3.7$ from the above table. At $\lambda = 9$ meters the breakdown gradient is 25 volts per centimeter giving a computed value of $d = 5.8$ cm., $v_f = 93$ electron volts, and $v_0 = 7$ electron volts. This compares favorably with the actual $d$ of the container of 6 cm., and the electron velocities seem quite reasonable. An approximate formula for the cut-off wavelength of applied field in terms of the dimension $d$ is $\lambda = 4d$, where $\lambda$ is in meters and $d$ in centimeters.

While operation of an ion source just above the cut-off frequency is possible, it has been found experimentally that increasing the dimension of the tube and the RF voltage applied produces a more stable ion source with greatly increased monatomic yields. If the small initial velocity is neglected and we assume $\phi = 0$ one may solve equation (1) for the
frequency at which the electrons have half-cycle transit time between the ends of the tube. This is

\[ f = \frac{\sqrt{\pi}}{2 \pi} \frac{\varepsilon}{m} \frac{\sqrt{v}}{d} = 1.18 \times 10^5 \times \frac{\sqrt{v}}{d} \]

where

- \( v \) is the applied voltage to the discharge chamber
- \( d \) is the length of the chamber in meters.

Thus it would take a little less than the voltage computed by the above formula to cause breakdown at the \( \Phi = 0 \) point on the curve. See Figure C-2.

According to the approximate formula for a \( 2\frac{1}{8} \) inch diameter tube 4 inches long, the breakdown voltage is:

\[ v = \frac{(f d)^2}{1.4 \times 10^{10}} = 300 \text{ volts} \]

This value agrees fairly well with experimental values, however, about twice this value is sometimes needed to cause breakdown before the tube is thoroughly cleaned by a discharge.
Penning and Moubis\textsuperscript{27}, in 1939, used for their sealed-off neutron-producing tube, a cold cathode discharge ion source commonly known as a P.I.G. source (Chapter I). A cold cathode discharge was maintained with 4 - 15 kV supply potential in series with a 0.4 - 4 megohm resistor using a field of 400 oersteds. The actual beam at the target was only 40 microamperes produced by a total input power to the ion source of 1.2 watts. Ion currents of 300 microamperes at a pressure of $6 \times 10^{-4}$ were produced in which 90\% were diatomic.

In 1947, Lorrain\textsuperscript{28} showed that a strong discharge could be maintained at $10^{-3}$ mm. pressure and 300 volts between magnesium electrodes. See Figure D-6. With the ion source operating at the pressure range shown in Figure D-7 and a discharge current of 30 milliamperes at approximately 300 volts in a magnetic field of 780 gauss, the percentages of the different ion masses are shown for two sizes of anodes. The relatively low percentages of monatomic ions are typical of these sources when operated with pure hydrogen. Proton percentages of as high as 40\% may be obtained by the addition of oxygen and water vapor.

For the application considered here, proton percentages of only 10\% seem rather poor and the introduction of fixed concentrations of foreign gases into a sealed-off tube seems impractical.
Another cold cathode source reported by Stone⁹⁹, of the London Branch of the Office of Naval Research, has the following ratings: 600 microampere beam current with 15 - 30% monatomic ions at a pressure of 2 x 10⁻⁶. A 550 gauss field was used and 16 watts power was required.

The cold cathode type of ion source fulfills the requirement of low power; but the requirements of long life, high proton yield, and a non-focused beam are not fulfilled. Similar results can be obtained using hot cathodes with oscillating electron beams constrained by magnetic fields.
**Figure 5.** Percentage composition of the ion beam as a function of the pressure, with pure hydrogen. The gauge pressures shown are higher than the true pressures by a factor of about 3. Magnetic induction, 780 gauss; discharge current, 30 ma. Anode length, 26 mm.; anode diameter, 13 mm.

**Figure 6.** Percentage composition of the ion beam as a function of the pressure, with pure hydrogen. Magnetic induction, 780 gauss; discharge current, 30 ma. Anode length, 60 mm.; anode diameter, 20 mm.
Bailey, et al. 30, was able to achieve high monatomic yields in a hot filament type oscillating-electron-beam ion source. The actual pressure in the ion chamber was unknown but was probably around 10 microns. With a power consumption of over 800 watts, including the magnetic field, a proton percentage of approximately 80% was achieved using a magnetic field of 1000 gauss. These results with those obtained by others would seem to indicate that high proton percentages can be achieved only when large amounts of power are utilized.
APPENDIX E

TARGET THICKNESS AND THEORETICAL NEUTRON YIELD

The stopping power of protons for a few metals has been experimentally determined by Warshaw\textsuperscript{31, 32}. The curve, as shown in Figure E-8 has been extended for energies less than 20 KeV for gold and silver by the use of the following formula derived by Fermi\textsuperscript{33}:

\[
\frac{dE}{dx} = \frac{4}{3} \frac{E}{v_t^2} \log_e \left( \frac{\frac{137}{c} v_m}{v} \right) \text{ Kev/cm}
\]

(1)

where

\( t_0 \) is a collection of constants = \( 4.42 \times 10^{-14} \) sec.

\( v_m \) is the maximum velocity of valence electrons of target material.

\( v \) is proton velocity cm/sec.

\( E \) is proton energy Kev

According to Conner, et al.\textsuperscript{14}, the stopping power for Zr-T targets is 100 KeV/mg./cm.\textsuperscript{2} at a deuteron energy of 50 KeV. This almost identically coincides with the stopping power of copper as given by Warshaw. Thus, if we assume the stopping power of Zr-T targets to be the same as copper, we can compute the yield for thick targets.
Figure E-6  Stopping Power Curves
The reciprocal of the stopping power curve is plotted in Figure E-9 using the equation

\[ \frac{dx}{dE} = kE^{-k} \quad (2) \]

where

\[ k = 2.27 \times 10^{-15} \]

E is in Kev

for deuteron energies less than 40 Kev and using experimental points above this energy. Integrating this reciprocal curve, the range-energy curve can be computed, see Figure E-10. Superposed upon this curve is the reaction cross-section as given by Bonner and Arnold, et al. Using the curves of Figure E-10, the reaction cross-section \( \sigma \) may be plotted against deuteron penetration into the target for various energies, as shown in Figure E-11. The neutron yield per microampere may then be computed by integrating the area under the curve using the equation

\[ Y \text{ (neutrons/sec/\( \mu \)A)} = N_I n_T \int_0^X \sigma(x) \, dx \quad (3) \]

where

\[ N_I = \text{ions per microampere} \]

\[ n_T = \text{tritium atoms per c.c. assumed equal to } \text{thorium atoms per c.c.} \]

\[ x = \text{penetration in mg./cm}^2 \]

\[ \sigma = \text{cross-section in barns} \]
Figure E-9 Stopping Power Curve and Its Reciprocal (Copper)
Figure E-10  Deuteron Range in Copper and D-T Cross Section Curve
Figure E-11 Cross Section of Reaction vs. Penetration Distance of Deuteron
Using the above formula, the following theoretical yields are predicted:

<table>
<thead>
<tr>
<th>E</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 Kev</td>
<td>6.5 x 10^7 neutrons/sec/μa</td>
</tr>
<tr>
<td>80 Kev</td>
<td>3.5 x 10^7 neutrons/sec/μa</td>
</tr>
<tr>
<td>60 Kev</td>
<td>1.28 x 10^7 neutrons/sec/μa</td>
</tr>
</tbody>
</table>

This predicted yield is less by a factor of two than that calculated from the experimental results of Bretscher and French\(^4\) using deuterium ice as a target. If the tritium concentration in the zirconium target was assumed to be ZrT\(_2\), then a yield of 1.3 x 10^8 neutrons/sec/μa would be achieved. These results were derived using the cross-section data of Arnold, et al.\(^3\).

Normally, the cross-section curve is derived from experimental thick target neutron yield curves and stopping power curves for the target materials. As experimental stopping power curves for proton energies less than 100 Kev have not been taken for metals, the theoretical curve as in Equation (1) must be used when metal hydride targets are used. Thus the preceding computed theoretical yields with zirconium targets are based on questionable stopping power data.

Bretscher, et al.\(^5\), from some experimental works referred to in their article, derived a theoretical curve for stopping power of D\(_2\)O for the energy range below 100 Kev and use this in the evaluation of \(D(D_n)He^3\) reaction cross-section. (Stopping power for 50 Kev protons is 720 Kev/mg./cm.\(^2\).)
Cross-section curves can be computed as follows: Let $\Delta E$ be an incremental energy taken at any energy $E$ (ev) on the total yield curve, and $\frac{dE}{dx}$ be the stopping power at this energy given in ev/atoms/cm.$^2$. Thus the incremental distance traveled at the energy $E$ is:

$$\frac{\Delta E}{\frac{dE}{dx}} \text{ (atoms/cm.}^2\text{)}.$$

Let $\Delta Y$ be the corresponding increment in the neutron yield at the assumed energy $E$ per bombarding deuterium atom. Hence, the cross-section in barns is

$$\sigma = \frac{\Delta Y}{\Delta E} \cdot \frac{dE}{dx} \times 10^{24} \text{ barns.} \quad (4)$$

It is possible, by inverting Equation (4) to compute the stopping power for unknown target materials from thick target yields and known cross-section data. Inverting the equation and solving for stopping power:

$$\frac{dE}{dx} = \frac{\sigma \cdot \Delta E}{\Delta Y} \times 10^{-24} \text{ ev/atom/cm.}^2$$
APPENDIX F

LOW PRESSURE CONTROL EXPERIMENT

As pressure control by zirconium is not discussed in the literature for pressures less than a few microns, the following experiment was performed to determine the action of zirconium at low hydrogen pressures. Two zirconium filament tubes and an ion gauge were sealed off, one filament being partially filled with hydrogen. Two filaments, one 8 inches the other 16 inches long, were wound in helices and supported by tungsten supports.

The tubes and ion gauge were baked for several hours at 450°C. The filaments were heated slowly to a white heat until no more gas was evolved. The 16 inch filament was partially filled with deuterium by filling the system to a pressure of 20 microns and cooling the filament slowly. The palladium leak used to fill the system was heated long enough so that the contaminant gases evolved by heating were pumped off, before the filament was deuterided. By cooling at this pressure enough deuterium was stored to fill the system to several microns after the cut-off was completed.

The tubes were then pumped and baked at 200°C and then were sealed off. At the time the seal-off was made considerable gas was evolved from heating the glass constriction. At seal-off time the pressure had
risen to $5 \times 10^{-6}$ mm. After several hours the gettering action of the ion gauge pumped the system to $3 \times 10^{-7}$ mm.

The filament containing the deuterium was heated slowly so that an equilibrium pressure reading could be taken. See Figure F-12. The pressure did not return as low as it had been originally, because the walls had adsorbed a great deal. As evidence of this assumption the filament was flashed and the pressure went down to $3 \times 10^{-6}$ mm. The gas in the volume was pumped out quickly but in a few minutes the gas from the walls brought the pressure back to $10^{-5}$ mm. If the filament that had not been filled was flashed the pressure was reduced to $10^{-7}$ mm.

The anomalous behavior of these zirconium filaments at low temperatures and low pressures, shown in Figure F-12, can probably be disregarded. The fact that the pressure did not return to its original low value is similar to what happens in normal vacuum procedure. If gas is admitted to a system, considerable pumping time is required to return it to its original low pressure. As the zirconium filaments are not high-speed pumping devices, considerable residual gas may remain on the walls after cooling. This is especially true when an RF discharge is produced, as the gas molecules are driven into the surface of the glass walls. Upon turning off the discharge and then cooling the zirconium filament the pressure will temporarily go down. After a few minutes the pressure will rise again, sometimes to several microns, but the deuterium can be absorbed again by the same zirconium filament or another, as was stated above.
Figure F-12 Experimental Zirconium Filament vs. Pressure Equilibrium Curve
Upon connecting the filament containing the deuterium to the automatic regulator previously described, the pressure could be regulated over a range of at least 0.8 to 16 microns. After 24 hours of continuous automatic operation the pressure decreased only a few percent.

To try to simulate conditions of an RF discharge in a tube whose pressure is to be controlled in this manner, a spark vacuum-leak tester was applied to the glass envelope with no apparent adverse effects. Since this experiment did not require a cold trap, it was expected that these same techniques could be used to control the pressure in a neutron tube using an RF ion source.
First Experimental Tubes

The first tube was designed using an RF ion source and an ion accelerating gap, both operated at the same pressure. See Figures G-13 and G-14. After evacuating the tube to $10^{-5}$ mm. Hg. it was filled with hydrogen to a pressure that was thought to be approximately 2 microns, but after the test on this tube was completed it was found to be 20 microns because of improper markings on the McLeod gauge. Because of the large aluminum parts it was difficult to maintain this pressure for any length of time even after the tube was baked for several hours at 500°C.

During the short operating times of this tube it was possible to test the feasibility of the tube with considerable success. Although the RF oscillator was inefficient (see Figure G-15) it did produce an adequate number of ions at low pressures. An 829B oscillator tube was operating at approximately 150 megacycles supplied with 700 volts plate at 150 ma or 105 watts. The color of the discharge produced was never at any time extremely red, indicating that the monatomic ion percentage was not the best possible.
Figure G-13 First Tube

Scale: one-half size

Figure G-14 First Tube Experimental Setup
It was noticed that with probe voltage applied it was impossible to start the RF discharge, however, no difficulty was experienced in starting the discharge with the probe voltage zero. It could be increased to several thousand volts but if made higher than approximately 7000 volts the discharge would be extinguished. As the target voltage was increased above 20 Kvp the hole-electrode current decreased to approximately 10 microamperes and the probe and target currents were almost equal. The apparent current to the hole-electrode was the sum of the secondary electrons returning from the target and the ions arriving from the RF discharge. The secondary emission ratio for ions bombarding different metals is not known, but has been obtained by E. W. Webster, et al.\(^{11}\), for steel, using both monatomic and diatomic hydrogen ions. The secondary emission ratio for steel is approximately 7 for monatomic ions and 3 for diatomic ions for 100 Kvp energies. Using these values of secondary emission ratios the actual target ion current may be as low as 25 microamperes or as high as 50 microamperes for 200 microamperes measured at the aluminum target.

Some typical values for tube voltages and current are as follows:

<table>
<thead>
<tr>
<th>Target supply voltage</th>
<th>75 Kvp</th>
<th>65 Kvp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target current</td>
<td>400 µa</td>
<td>200 µa</td>
</tr>
<tr>
<td>Probe voltage</td>
<td>6000 volts</td>
<td>2000 volts</td>
</tr>
<tr>
<td>Hole-electrode current</td>
<td>zero</td>
<td>zero</td>
</tr>
<tr>
<td>Probe current</td>
<td>400 µa</td>
<td>200 µa</td>
</tr>
<tr>
<td>Pressure of hydrogen in microns</td>
<td>up to 20</td>
<td>up to 20</td>
</tr>
</tbody>
</table>
Figure G-15  First Oscillator

Figure G-16  First High Voltage Supply
Although the vacuum techniques were poor and prolonged tests could not be made, this first tube illustrated the feasibility of the RF ion source and a single accelerating gap operating together at identical pressures in a sealed-off tube.

The picture, Figure G-14, shows the x-ray high-voltage supply lead in the foreground entering the oil bath in which a filter and the high-voltage end of the tube were immersed. An aluminum shield was placed at ground potential separating the field of the RF ion source from the accelerating gap section of the tube so that the RF field was prevented from ionizing the gas in the accelerating gap. A high-voltage probe immersed in the oil was used in conjunction with a Volt-Ohmyst to measure the accelerating voltage. Figure G-16 shows the electrical circuit of the high voltage power supply for obtaining and filtering the accelerating voltage. A McLeod gauge was used to measure pressure in the tube.

In order to utilize an available tritium target, the target electrode was made in the form of an annular ring in which the 15/16 inch tungsten disk target could be inserted so as to cover the sharp edges of the disk. See Figure G-17. The hole-electrode design was changed so as to defocus the spot; however, the spot diameter (about 1/8 inch) was still the same as in the first tube.

The deuterium was bled into the ion source and evacuated from the tube on the other side of the hole-electrode in the accelerating section to insure purity of the deuterium. Although it was eventually desirable to have electrodes of other materials because of the problem of outgassing, this tube again had aluminum electrodes and a dummy target of aluminum.
Figure G-17  Second Experimental Tube
Tests were conducted on this tube and its operation was similar to the first tube. The deuterium was bled in through a heated palladium tube at a slow rate and the pressure was maintained constant at one or two microns, according to a Philips Ion Gauge calibrated for deuterium by a McLeod Gauge. The RF ion source seemed to start more easily than it did in the first tube. An unstable operation prevailed in the ion chamber when the probe voltage was applied. The instability was evidenced by the glow jumping around. This instability was not present in the first tube, but the second tube was operated at a much lower pressure.

In construction, the mounting for the target was left with several sharp points behind the target, thus limiting the target voltage to about 50 Kv. The tube was "cracked off" and the points rounded off and there were no more breakdowns up to 80 Kv.

The tube was operated for fifteen minutes at about three microns of deuterium with a target current of 200 microamperes and a voltage of approximately 80 Kv. With the use of a BF₃ counter in paraffin, a neutron flux of approximately $10^5$ neutrons/second was produced by embedding deuterium in the aluminum target. See Appendix I for a description of the neutron measurement techniques.

After this short period of operation, it was noticed that a small shattered place appeared in the side of the glass wall of the ion chamber. This was explained by the fact that the secondary electrons emitted by the target came back through the hole-electrode and were focused on the glass wall. A small permanent magnet was used experi-
mentally to deflect this electron beam from the probe and then it formed a hot-spot on the side of the tube. The focused secondary electron beam will cause the tube to crack within a few minutes wherever the beam strikes.

**Tubes Using Filament Type Ion Source**

As the power required in these first experimental tubes to make sufficient ions with an RF ion source is larger than is desired for operation in a "drill hole" another type of ion source was tried in spite of the expected low monatomic yield.

A tube was constructed using an ion gauge type of ion source using an oscillating electron-beam as shown in Figure G-16. Aluminum electrodes were used in the high voltage gap as in the first two tubes. A .010 inch tungsten filament and 0.005 inch tungsten grids were used in the ion source. The spacing of the high voltage aluminum electrodes was increased in this tube to 1\(\text{\(\frac{3}{4}\)}\) inches. It was thought that this resulted in better high voltage breakdown characteristics than was obtained in tubes No. 1 and 2. High breakdown strength was maintained by using a cross magnetic field of between 100 and 200 gauss at the target. It was necessary to place the permanent magnet at the target potential to prevent breakdown between the target and magnet. Voltages above 50,000 volts produced unstable operation without the use of the cross magnetic field; however, 100 kilovolts could be successfully maintained with cross magnetic field at a pressure of 0.58 microns ion gauge reading and a target current of 40 microamperes.
Figure G-18 First Filament Type Ion Source Tube
It was intended that the ion source be used with an axial magnetic field to increase the path length of the electrons. The gauge constant of the ion source with the field applied was over 200 and without the field was slightly over 20. Gauge constant is a measure of ions produced per unit electron emission current and is defined here as $K$ in the equation:

$$K = \frac{i_+}{i_-}$$

where

$p$ = pressure in mm. of Hg

$i_+$ = the ion current delivered to hole-electrode and target

$i_-$ = electron emission current of the filament

However, use of this axial magnetic field with high voltage applied to the accelerating section of the tube caused a cold cathode discharge to form between the target and hole-electrode. Thus the magnetic field cannot be used with this tube as there is no way to shield the accelerating gap from the magnetic field of the ion source.

The tube was first baked at 350°C and then operated using a dummy aluminum target. Correct deuterium pressure was maintained inside the tube by continued pumping and heating of a palladium leak. Using the aluminum target, a yield of $10^5$ neutrons per second at 87 kilovolts and 40 microamperes target current was obtained from the D-D reaction produced by the deuterium driven into the target.
A thick tritium target which had been used six months before was obtained from Dr. Goodman. The tritium containing area was a quarter-inch diameter spot on the 15/16 inch diameter tungsten disk. As the hole in the hole-electrode was \( \frac{3}{4} \) inch in diameter, the fraction of ions striking the sensitive area could have been rather small. The target was considered to be very poor because of the amount of tritium it contained and because it was dirty and should have been cleaned, but no acceptable method of cleaning off the oxide coat is known. The target was made by melting a spot of zirconium on a tungsten backing. However, a maximum neutron yield of approximately \( 5 \times 10^7 \) neutrons per second was achieved. The yield curve of Figure G-19 agrees in shape with the yield curves given in the literature.

The neutron yield at 87 Kv target voltage varied linearly over a small range of pressure. See Figure G-20. This condition does not continue indefinitely because as the pressure is increased above approximately 1.5 microns the neutron yield per microampere decreases, although the target current varies linearly with the pressure. See Figures G-21 and G-22. As the tritium target is not cooled, the break in the curve of Figure G-22 possibly shows that tritium was lost from the target by heating. Another explanation might be that the number of diatomic ions hitting the target decreased and the triatomic ions increased, as indicated in Figure D-7. As the target current was constant, the secondary emission ratio at the target might have increased so that the actual beam of ions decreased.
Pressure 0.58 microns gage
Target current 40 μa
Emission 10 ma

Figure G-19 Neutron Yield vs. Target Voltage (Zirconium-Tritium Target)
Figure G-20 Neutron Yield vs. Pressure

Figure G-21 Target Current vs. Pressure (52 kv)

Figure G-22 Neutron Output Efficiency vs. Pressure
It was noticed that the target current was a function of the target voltage for constant pressure and filament emission. See Figure G-23. This is probably because of the penetration of the accelerating field up into the ion source as well as the increasing secondary electron emission from the target. At low acceleration voltage the cross magnetic field at the target causes the knee in the curve by deflecting the beam so that it misses the target.

The neutron yield, as achieved with this tube, is smaller by a factor of 8 than is theoretically possible if the beam is assumed to be 100% diatomic and the target has a secondary emission ratio of 3. This low secondary emission ratio is assumed as a cross magnetic field was used at the target. Thus it would seem that the target was faulty and new targets were ordered.

In the meantime, several new geometries for the filament type of ion source were tried. Because of the desirability of utilizing a magnetic field with the filament type of ion source much effort was expended in the attempt to make a tube with a magnetic shield between the ion source and the accelerating field. It was hoped that it might be possible not only to increase the ion current but also the monatomic yield. Several attempts were made by various glass blowers to seal simultaneously #7052 glass tubing to the opposite sides of a thick kovar disk (.050 inch). The kovar warped so badly in one case that the glass was broken. Mr. Ryan* was able to make a seal with only a slight

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*Ryan, Velluto, and Anderson, Glass Blowers, 145 Main Street, Cambridge, Massachusetts.
Figure G-23 Effect of Target Voltage on Ion Current (constant emission and pressure)
symmetrical curvature of the plate but as the seal was being completed the glass slipped out of the lathe and twisted hopelessly. After this unsuccessful attempt it was decided that a 2\(\frac{1}{2}\) inch diameter shallow Kovar cup might be used instead of the disk and be sealed to glass as shown in Figure G-24. Two successful magnetic partitions or hole-electrodes were made and incorporated in tubes. At this time various new designs were tried for a filament type ion source similar to the one made previously. In these the dimensions of the grids and their spacing was decreased and a socket in the back side of the tube was made for the insertion of a magnet. The magnetic path was to be closed around the outside of the tube through the Kovar as shown in Figure G-24. Although these tubes produced about 100 microamperes of target current the magnetic field was completely ineffective. (The geometry made it difficult to obtain sufficient axial fluxes.)

Typical operating conditions for the tube are tabulated below:

<table>
<thead>
<tr>
<th>Electrode No.</th>
<th>Potential</th>
<th>Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>-500</td>
<td>-500</td>
</tr>
<tr>
<td>#2</td>
<td>+500</td>
<td>0</td>
</tr>
<tr>
<td>#3</td>
<td>-500</td>
<td>+500</td>
</tr>
<tr>
<td>#4</td>
<td>-500</td>
<td>-500</td>
</tr>
<tr>
<td>Hole-electrode</td>
<td>+500</td>
<td>+500</td>
</tr>
<tr>
<td>Reflector</td>
<td>-500</td>
<td>+500</td>
</tr>
</tbody>
</table>

| Target current        | 90 \(\mu\)a | 100 \(\mu\)a |
| Emission current      | 20 \(\mu\)a from #1 and #4 | 20 \(\mu\)a from #1 and #2 |

(Potential in volts)
Figure G-24 Experimental Tube
It was found that by omitting electrodes #1 and #2 and the reflector that as many ions could be produced by using only electrodes number #3 and #4 so that the tube was reconstructed with the socket for the magnet very close to the grids. A piece of mica was suspended between electrode number 3 and the glass socket so that returning secondary electrons would not heat the glass tube. This ion source was not much more effective in producing ions than the previous one. The electrode spacing was much too short and the magnetic field obtainable too small to increase the path length of the electron sufficiently.

A thin target similar to one used at high voltages (\( > 1 \text{ MeV} \)) was bombarded in this tube assuming that the zirconium thickness was sufficient to stop 100 Kev deuterons. After achieving a yield of only \( 4.5 \times 10^6 \) neutrons per second with about 95 microamperes target current, thick target calculations were made. It was found that these targets were only \( 0.080 \text{ mg./cm.}^2 \) thick and that they should be approximately \( 0.500 \text{ mg./cm.}^2 \) thick to stop a 100 Kev deuteron. However, this difficulty with the targets was not realized until another ion source with a tungsten filament had been tried. Another ion source design that was tested was taken from one suggested by J. Kistemaker\(^{34}\). See Figure G-25.

The electrons emitted by the filament are repelled by the reflector and attracted by the cylinder whose potential is 400 - 700 volts positive with respect to the filament. The electrons, constrained by an axial magnetic field, are accelerated into the field free region inside of the cylinder and continued through to the grid on the opposite side where they are repelled. After repeated excursions the electron is
Figure G-25 Filament Type Ion Sources
collected by the cylinder or it has an ionizing collision with a deuterium molecule. Thus the efficiency of ionization is enhanced by the increased path length of the electrons.

There are approximately 0.003 ionizing collisions per centimeter path for the electrons at one micron. Thus 10 ma. of emission should produce at least 0.8 ma. of ions if the electron makes five paths through the anode before being collected. Without a magnetic field the ion current is less than this, and with a magnetic field of 150 gauss the ion current is approximately 1.2 ma. Many ions are lost by incorrect focusing and at least half of the ions are accelerated in the reverse direction so a beam current of about 300 microamperes was achieved with a magnetic field.

Two tubes were made having this design. In the first tube the target current achieved was only about 0.3 per cent of the electron emission current at 1 micron pressure without a magnetic field. A second tube was made larger to give a greater path length for the electrons. Because of the increased size in the second tube, the ionization efficiency was doubled. The target current measured from the first tube was approximately 100 microamperes for a filament emission of 20 milliamperes at approximately 3 microns. As this ion source was first put in a simple glass envelope without the magnetic shield partition, it was considered worthwhile to test it without the use of a magnetic field.

A neutron yield of approximately $2 \times 10^6$ neutrons/second was achieved at 80 Kv of which 12\% were neutrons produced by the D-D reaction. This was determined by the use of photographic plates in which proton
recoil tracks were counted. Proton tracks of lengths greater than 100 microns were produced by 14 Mev neutrons and tracks that were 40 microns or less in the forward direction, were from D-D neutrons.

At this time the targets still were assumed to be thick. Also the target current of 60 microamperes was made up of a large number of secondary electrons. The actual yield is difficult to compare with what is theoretically expected. It was suspected that diatomic ions predominated, and later when the ion beam was analyzed this was shown to be the case. See Appendix H. It was also suspected that layers of "gunk" were deposited on the target by means of the acceleration of contaminate ions. These ions may be produced by the sputtering of the reflector electrode or filament by the high energy secondary electrons or ions produced in the source. Possibly the tritium was depleted by sputtering of the target by the ion beam as the target was darkened.

In the second tube constructed with the filament type ion source, no observance of a "gunk" layer was made with a 100 microampere beam on a stainless steel backing using 50 kilovolts accelerating voltage and operating for several hours. Thus, since darkening only occurs with zirconium, sputtering of the target may be important. Consequently, what was thought to be "gunk" may have been only a discoloration and, therefore, the use of the filament type ion source still may be advantageous.
RF Ion Source Tubes

The RF ion source tube was chosen to be used in the first model of the neutron generator in spite of the relative simplicity of the filament type ion source. It was hoped that the monatomic yield would be appreciable in the RF source even at low pressures. As the power required for the oscillator was large a filament-type ion source was sought. With the failure to achieve neutron fluxes of over $10^8$ neutrons per second with these tubes, another RF ion source tube was built using an oscillator of greater efficiency and also one that would fit in a 5 inch diameter pipe.

As the problem of the returning secondary electrons was still present, an attempt was made to suppress them at the target by means of a cross magnetic field. A permanent magnet was mounted outside the tube electrically connected to the target, and a non-magnetic stainless steel catcher cylinder mounted on the target. However, the electrons escaped from the cylinder and were bent to the side wall of the tube. Instead of suppressing the secondary electrons, a piece of vycor was mounted in the ion source for the electrons to hit in order to protect the glass. This has proved quite successful. The power dissipated in the target is proportional to the ion current and the secondary electron current dissipates its energy in the vycor plate and hole-electrode. For a total target current of 200 microamperes at 50 kilovolts the temperature of the target did not rise above 100°C even without the use of cooling oil. This indicates that there is a very high secondary emission ratio.
A sketch of this ion source is shown in Figure G-29 and a picture of the assembly in Figure 15a. Additional information is given on this ion source in Appendix H.

The RF oscillator used for the tube uses an 807 in a Hartley circuit. See Figure G-26. Later an 814 was substituted for the 807, the screen resistor changed to 50 K, and the choke changed to a single 44 μh choke. The d-c input plate power is plotted against the ion current to the target for a pressure of 8 microns and a probe voltage of 1500 volts. The ion current was measured here by letting the target assume a small positive potential with respect to the hole electrode so that the secondary electrons produced would be repelled and a more accurate measure of the ion current might be possible. See Figure G-27. Power delivered to deuterium as a function of the input oscillator power is shown in Figure G-28 for the oscillator using an 814 tube for a pressure of about 10 microns.

Sealed-Off Tube Number One

The first sealed-off tube used an RF ion source having a 5/16 inch ion extraction hole. An ion gauge and a zirconium filament tube were sealed-off with it. The tube was baked at 450°C for several hours and the ion and zirconium filament tube were flamed until the system was pumped to 10^-6 mm. Hg. The RF ion source tube was further cleaned and out-gassed by using a discharge with deuterium at 5 microns pressure in both the ion source cavity and the accelerating gap cavity for approximately one-half hour. During this time the zirconium filament which had
Figure G-26  RF Oscillator

Coil
2\(\frac{3}{4}\)" ID
3" Long
5 Turns
\(\frac{1}{4}\)" Copper tube
Top \(\frac{1}{4}\) Turns from Grid
Pressure - 8 microns
Probe Voltage - 1500 volts
Tube 807

Figure G-27 Ion Beam Current vs. Oscillator Plate Power

Figure G-28 Power Input to Gas vs. Oscillator Input Power
Figure G-29 RF Ion Source
been out-gassed was filled with deuterium by slowly decreasing its temperature from a red heat in the presence of a 5 micron pressure of deuterium. The tubes were flamed and baked at 200° C in order to pump the system to $10^{-6}$ mm. again. The tube was carefully sealed-off while the pressure was observed. During this time out-gassing of the glass constriction caused the pressure to rise to $3 \times 10^{-6}$. When the seal-off was completed the gettering action of the ion gauge caused the pressure to decrease slowly so that in about eighteen hours the pressure had dropped to $4 \times 10^{-7}$ mm. Hg.

The baking of this tube was possible as loss of deuterium was unimportant. It was expected that a good deuterium target could be built up by means of the ion beam. The target contained about a ratio of 40% deuterium to zirconium atoms and was approximately 0.5 mg./cm.$^2$ thick. The zirconium was evaporated on the tungsten backing and appeared to be fairly uniform. This target was used in two previous attempts to produce a sealed-off tube, and thus the target had been baked twice and was considerably discolored by an oxide coat. These two attempts were unsuccessful because of leaks in the metal target holder.

The day following the seal-off the zirconium filament was heated and the tube was filled to 3 microns pressure. The zirconium filament was cooled but the pressure would not return to below 1/10 micron. However, the RF discharge observed in the ion chamber appeared to be normally pink and thus it was believed that the purity of deuterium was good. The target end of the tube was lowered in oil and high voltage was applied to the target. Neutron yields were measured at various voltages and are tabulated for a gauge pressure of 0.8 microns:
<table>
<thead>
<tr>
<th>Target Voltage</th>
<th>Target Current</th>
<th>Neutrons/second</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 Kv</td>
<td>160 μA</td>
<td>$2.5 \times 10^4$</td>
</tr>
<tr>
<td>60 Kv</td>
<td>175 μA</td>
<td>$5.6 \times 10^4$</td>
</tr>
<tr>
<td>70 Kv</td>
<td>200 μA</td>
<td>$1.6 \times 10^5$</td>
</tr>
<tr>
<td>80 Kv</td>
<td>250 μA</td>
<td>$2.2 \times 10^5$</td>
</tr>
</tbody>
</table>

It was noticed that secondary electrons were apparently hitting the glass walls between the target and hole-electrode and that 80,000 volts could not be supported long without breakdown. The glass walls of the tube may assume any potential readily because they are non-conductors. If it is assumed that they operate at ground or a slightly negative potential they attract secondary electrons from the target assembly. To alleviate this problem an aluminum toroidal shield, directly outside of the tube beside the target, was electrically connected to the target, thus changing the electrostatic field between the target and hole-electrode so that all secondary electrons were returned to the hole-electrode. This prevented the type of breakdown previously observed, but breakdown was still observed in a different manner at 80,000 volts. Using a mirror to watch the tube at close range it was observed that a hot spot was produced in the glass wall near the target at a flaw in the glass envelope. Upon examination of this flaw it appeared to be a crack on the inner wall of about one-half inch long, from which electrons were apparently emitted by field emission. Thus the glass between the target and hole-electrode should be free from air bubbles and seams.
It was desirable to operate the tube long enough to observe its lifetime. The tube was operated four days later at 55 kilovolts and approximately 50 microamperes target current for 16 hours continuously. The yield at first was approximately $0.8 \times 10^5$ neutrons per second, but in fifteen minutes had risen to $1 \times 10^5$ neutrons per second and remained at this rate for seven hours. The equipment was left without care or adjustment for the remaining time and at the end the neutron yield had dropped to a little over $0.5 \times 10^5$ neutrons per second. The oscillator used was the 807 Hartley operating at approximately 300 volts plate and 28 milliams. The tube was sealed-off for approximately two weeks and was apparently alright. After this test was completed the zirconium getter was flashed to "white" temperature and cooled and the pressure was momentarily decreased to $5 \times 10^{-5}$ millimeters. It was interesting to observe that in ten minutes time the pressure had returned to about 4 microns because of the release of deuterium from the walls of the ion chamber in which it had been driven. When it was desirable to begin operation with the tube again, it was easy to readjust to the operating pressure of 8 microns.

During the operation of the tube the ion beam was visually observed at various voltages. At 20 kV the ion beam was about one millimeter in diameter at the target and as the voltage was increased it spread to about three millimeters in diameter. Previous experiments on the tube showed that at 6,000 volts on the target the beam was 4 or 5 millimeters in diameter. This could be explained by a focusing action of the hole electrode as shown in Figure G-30. The size of this beam was verified after this long period of operation by means of a clean silvery spot.
(3 mm. in diameter) produced on the surface of the target. Surrounding this spot the surface had been darkened considerably. Had the ion beam been contaminated as was suspected in previous tubes, the spot probably would have appeared black. The explanation of the darkening might be the effect of sputtering zirconium from the spot and depositing it around the "white" spot and on the walls as well. This theory is further supported by the discoloration or darkening of the glass walls between the target and the hole electrode. To reduce this sputtering it was endeavored to increase the beam spot area in succeeding tubes. This sealed-off tube proved to be very stable and did not need automatic control for pressure variations as was expected.
Sealed-Off Tube Number Two

A tube similar to No. 1 was constructed having an RF ion source cavity 1 inch shorter but in other respects being identical to the first. The tube was first baked out at 450°C to prepare it for the insertion of a tritium target as it was thought that a tritium target could not be raised to high temperatures. The tube was pre-baked to remove the gases contained in the volume of the structure. A tritium target was then mounted and sealed into the tube and the tube was pumped immediately to $5 \times 10^{-5}$.

Following a procedure of flaming and degassing of the ion chamber by the RF discharge, and filling the zirconium filament, the tube was sealed-off at $10^{-6}$ mm. The pressure began to rise slowly and by forty-eight hours later it had risen to $3 \times 10^{-4}$. Supposing that the gas accumulated was deuterium, the zirconium filament was heated and a redish hydrogen discharge was obtained after which the tube was pumped out by the zirconium filament. It was noticed, however, that the color of the discharge changed and low pressures could not be obtained again. The next day the discharge color from the residual gases, obtained without use of the zirconium filament, was green. A rough spectroscopic analysis was made of the light and was found to contain one prominent green band at about 4900 angstroms. The only possible gases which this could have been were chlorine or HCl. It was later found that HCl was used in the cleaning operation of the kovar target assembly and likely had not been washed clean. The unit was cracked open again and pumped for two days and baked at 160°C for about twelve hours. At the end of this bake-out a pressure of $10^{-7}$ mm. was achieved. At this time the tube was filled to 20 microns.
of deuterium and the RF discharge started during which time the zirconium filament was heated again and refilled. It was then found to be quite difficult to pump the tube out to below $10^{-6}$. This was assumed to be the result of the retention of the deuterium by the glass walls of the tube. The tube was then sealed-off again at $10^{-6}$ and this time the pressure did not rise rapidly. In twelve hours the pressure had risen to $2 \times 10^{-5}$.

The sealed-off unit was then mounted in its high voltage oil container and RF oscillator unit and its neutron yield was measured. The RF oscillator was operated at approximately 10 watts input because of the incorrect calibration of a new meter when it was thought that 60 watts was being used. Yield data taken with this tube is shown below. The tube was first run at 50, 60, and 70 Kv with a 300 microampere target current. Assuming the secondary emission ratio for the target to be 7, a 37 microampere beam was used. A yield of $4.2 \times 10^7$ neutrons/second was obtained at 70 Kv and a pressure of approximately 6 microns. Extrapolating this yield curve a yield of approximately $4 \times 10^8$ neutrons/second would have been obtained if 100 kilovolts had been used at this time. However, instead of going to high voltages at first a yield curve was taken beginning at 25 kilovolts. It was noted that during this short period of operation (10 minutes) the yield had dropped by a factor of 2 at the 70 Kv point. It was then decided to run a yield curve vs. time for the target. This is shown in Figure G-31. It was found in a two hour period of operation that the yield dropped almost a factor of 2 when the tube was operated at 70 Kv. It is thought that the drop in yield resulted from excessive spot temperature on the target causing a depletion of tritium from its surface.
<table>
<thead>
<tr>
<th>Target Current (microamperes)</th>
<th>Target Voltage (Kv)</th>
<th>Neutrons per second</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>50</td>
<td>$1 \times 10^7$</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>60</td>
<td>$2 \times 10^7$</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>70</td>
<td>$4.2 \times 10^7$</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>25</td>
<td>$0.6 \times 10^5$</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>30</td>
<td>$1.5 \times 10^5$</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>40</td>
<td>$1.5 \times 10^6$</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>50</td>
<td>$5.5 \times 10^6$</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>60</td>
<td>$1.35 \times 10^7$</td>
<td></td>
</tr>
<tr>
<td>160</td>
<td>70</td>
<td>$1.05 \times 10^7$</td>
<td>Begin 2-hr run</td>
</tr>
<tr>
<td>160</td>
<td>70</td>
<td>$5.5 \times 10^6$</td>
<td>End of 2-hr run</td>
</tr>
<tr>
<td>80</td>
<td>20</td>
<td>$1.1 \times 10^4$</td>
<td>9 days later</td>
</tr>
<tr>
<td>80</td>
<td>40</td>
<td>$1.3 \times 10^5$</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>50</td>
<td>$1.1 \times 10^6$</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>60</td>
<td>$4.0 \times 10^6$</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>80</td>
<td>$1.2 \times 10^7$</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>100</td>
<td>$2.5 \times 10^7$</td>
<td></td>
</tr>
</tbody>
</table>
Figure G-31  Time Test of Sealed-off Tube
The target used in this case was ZrT\textsuperscript{86}. The same small (2 mm. in diameter) shiny spot in the center of the target was not formed as in the case of the deuterium sealed-off tube. It is believed that the spot was less focused than in the former tube because the extracting-electrode was constructed so that the aluminum was 1/8 inch below the surface of the glass plate partition of the ion chamber rather than being flush with this plate. Because of the drop in neutron yield, the defocusing of the beam was considered inadequate and other ways of defocusing were sought.

Three days later the tube was operated at 100 Kv at a pressure of approximately 2.4 microns, using a 50 microampere beam and the maximum neutron yield was $2.2 \times 10^7$ neutrons/second. When operated this time it was quite noticeable that the zirconium filament had to be heated more in order to obtain the desired pressure. When operated nine days after it was sealed-off, the correct pressure could only be obtained when the filament was almost white hot. A yield curve was taken again and it showed that a partial recovery had taken place and that the yield was as good as when the two hour life test began nine days previous, but that it had not returned to the yield of the first few minutes operation.

It was possible to operate the RF discharge and obtain a yield of $3.7 \times 10^7$ neutrons/second at 98 Kv and 90 microampere beam current when the pressure was as low as 2 microns.

After this period of operation the tube was allowed to lie unused for several days and when the pressure inside was measured again, it was found impossible to heat the zirconium filament sufficiently to obtain more than a few tenths of a micron pressure. It is possible to explain this because
the tritium target in this case was not full and probably absorbed much of the deuterium. Also, some was lost in the walls of the discharge chamber. Zirconium filaments in sealed-off tubes should be filled with deuterium at a higher pressure than 20 microns as was done for this tube, to prevent the depletion of deuterium with use if the targets are not full or if barium getters are used.

Sealed-Off Tube Number Three

Tube No. 1 was broken apart and reconstructed using the same envelope and target assembly, but with a different hole-electrode design. In an effort to achieve a de-focused beam the single hole was replaced by an annular hole constructed as shown in Figure G-32. Construction was made difficult by the necessity of electrically connecting the center of the hole to the outer spinning and covering the connection with glass to shield it from the gas discharge. This was accomplished so that the hole electrode as a unit could be assembled as in previous tubes.

A tritium target was used in this tube having a ZrT ratio of 1:1 or better. The tube was sealed-off at $3 \times 10^{-6}$ mm. pressure but without the extensive care that had been taken with previous tubes. The pressure did rise to $3 \times 10^{-5}$ mm. in about 8 hours. The tube was then operated at 3 - 4 microns pressure of deuterium without the use of a high voltage cooling oil bath up to 50 Kv. A partial yield curve was taken up to 50 Kv at which time the target appeared to get red hot, however, when the heating
persisted after the cooling oil had been added, it was observed that the heating actually took place at the plug of the center hole-electrode. Although there was a sharp rise in pressure when this heating took place, operation of the tube several days later was still possible and the color of the discharge seemed to be better (more reddish than usual). A yield curve was taken using short time operation periods so that the heating of the hole-electrode plug would not be excessive and the tube sustained 100 kV supply voltage at approximately 3 microns pressure. The heating of the hole electrode is caused by the returning accelerated secondary electrons emitted by the target. In the previous tubes these electrons were focused through the hole in the hole-electrode and impinged on the
vycor plate at the top of the ion chamber. This method of defocusing the beam obviously is not practical because of the heating of the center electrode. Cooling of the hole-electrode also seems to be impractical. However, using this tube a total yield of $10^8$ neutrons/second was achieved, which is greater than any previous yield. Typical data are shown below:

<table>
<thead>
<tr>
<th>Target Current (microamperes)</th>
<th>Target Voltage (Kv)</th>
<th>Neutrons per second</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>18</td>
<td>$2.1 \times 10^4$</td>
</tr>
<tr>
<td>120</td>
<td>27</td>
<td>$1.3 \times 10^5$</td>
</tr>
<tr>
<td>140</td>
<td>37</td>
<td>$1 \times 10^6$</td>
</tr>
<tr>
<td>140</td>
<td>46</td>
<td>$4.1 \times 10^6$</td>
</tr>
<tr>
<td>240</td>
<td>54</td>
<td>$9 \times 10^6$</td>
</tr>
<tr>
<td>240</td>
<td>64</td>
<td>$2.1 \times 10^7$</td>
</tr>
<tr>
<td>270</td>
<td>75</td>
<td>$3.1 \times 10^7$</td>
</tr>
<tr>
<td>300</td>
<td>94</td>
<td>$1 \times 10^8$</td>
</tr>
</tbody>
</table>

**Final Experimental Tubes**

Sealed-off tube number three failed because of the heating of the center piece of the hole electrode by the returning secondary electrons. As this tube seemed to be effective in defocusing the spot on the target the center of the hole-electrode was removed entirely leaving an exit hole for the ions of $\frac{3}{8}$ inch diameter. It was feared that the field from
the high voltage target might penetrate through the hole sufficiently to "suck out" all of the plasma and extinguish the RF discharge. This was not the case, however, and a yield curve for a tritium target using extremely large target currents was made. Because of the penetration of the field from the target it was impossible to control the beam current by means of the probe voltage and the current was uncontrollably high. Pertinent data for this yield curve is tabulated below:

<table>
<thead>
<tr>
<th>Target Current (microamperes)</th>
<th>Neutrons per second</th>
<th>Target Voltage (Kv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>550</td>
<td>$5 \times 10^5$</td>
<td>14.6</td>
</tr>
<tr>
<td>670</td>
<td>$2.5 \times 10^6$</td>
<td>21.3</td>
</tr>
<tr>
<td>800</td>
<td>$5 \times 10^6$</td>
<td>27.6</td>
</tr>
<tr>
<td>850</td>
<td>$1.2 \times 10^7$</td>
<td>26.3</td>
</tr>
<tr>
<td>1000</td>
<td>$2.4 \times 10^7$</td>
<td>32.0</td>
</tr>
<tr>
<td>950</td>
<td>$2.34 \times 10^7$</td>
<td>32.5</td>
</tr>
<tr>
<td>950</td>
<td>$5.1 \times 10^7$</td>
<td>42.5</td>
</tr>
<tr>
<td>1000</td>
<td>$6.1 \times 10^7$</td>
<td>72.0</td>
</tr>
</tbody>
</table>

Assuming that the increase in target current with target voltage is directly attributable to increased secondary emission, the neutron yield curve appears to be "headed for" at least $10^{10}$ neutrons per second at 100 Kv. However, the sudden knee in the curve definitely may be attributed to target difficulties. As shown in Figure 8, a depletion of tritium in the target took place over quite an area in the center of the target. This picture, as well as the appearance of the target indicates that the
beam was fairly well defocused but either the target was destroyed by sputtering or by local heating. Using the approximate yield as derived in Appendix E for a zirconium target, out of the 950 microamperes of the target current only about 16 microamperes can be attributed to a monatomic component of beam current from the neutron yield obtained at 40 Kv. If the monatomic percentage is approximately 30% and the triatomic 20%, the ionic beam current would be 53 microamperes giving a secondary emission ratio of approximately 19 for the zirconium target. (This ratio agrees with the ratio indicated in Chapter V.)

As it was impossible to decrease the beam current at high voltages it was felt that some method of shielding the ion exit-hole from the field of the high voltage target was needed. A cylindrical electrode was attached to the hole electrode as shown in Figure G-33. Although somewhat better control was achieved the target current was still over 200 microamperes with 50 Kv applied and the probe voltage zero. In order to gain better control of the beam current at high voltages, a grid structure as shown in Figure G-34 was mounted over the hole-electrode. This additional electrode had an effect similar to the grid of an ordinary triode; that is, by making it positive the target ion current was cut-off completely for low probe voltages. If the probe voltage was increased so that the plasma became more positive than the "grid" the target current increased and could be controlled by the probe voltage. Nine beams were observed coming from the holes in the "grid" but these beams were very sharp, probably less than $\frac{1}{2}$ mm. in diameter. With the probe voltage zero a "grid" current produced by a collection of electrons
Figure G-33 Experimental Hole Electrode and Target Assembly

Figure G-34 Experimental Hole Electrode and Target Assembly

Figure G-35 Test Circuit for Tube
was obtained since the "grid" was positive with respect to the plasma.

As the probe voltage was increased the "grid" current decreased and the target current began to increase as the probe voltage exceeded the "grid" voltage. Some typical operating conditions for the tube are as follows:

<table>
<thead>
<tr>
<th>Target Voltage (Kv)</th>
<th>Target Current (microamps)</th>
<th>Neutrons per second</th>
<th>Pressure (microns)</th>
<th>RF Power (watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>420</td>
<td>$7.4 \times 10^7$</td>
<td>10</td>
<td>96</td>
</tr>
<tr>
<td>80</td>
<td>400</td>
<td>$4.2 \times 10^7$</td>
<td>10</td>
<td>96</td>
</tr>
<tr>
<td>70</td>
<td>300</td>
<td>$1.9 \times 10^7$</td>
<td>10</td>
<td>96</td>
</tr>
<tr>
<td>60</td>
<td>100</td>
<td>$3.4 \times 10^6$</td>
<td>10</td>
<td>96</td>
</tr>
</tbody>
</table>

No effort was made to suppress the secondary electrons in this tube and the target was mounted about 5/8 inch from the "grid" instead of the 2 inch spacing used previously. A target voltage of 100 Kv could be maintained fairly well at 10 microns, however, field emission was noted by quite intense fluorescent spots on the glass walls adjacent to the target. This can be easily remedied if necessary by means of an electrode operating at target voltage outside the tube adjacent to the target as it has been done successfully before. The RF oscillator tube was changed from an 807 to an 814 and an additional 1/2 millihenrie choke as inserted in series with those already there. These chokes were later replaced by a 44 µh choke. This enabled the power to be increased to approximately 140 watts d-c input to the oscillator. The tritium target which had been previously depleted when this tube was operated without the "grid" was
used in these last tests. The nine beams were arranged with one in the center and eight in a \( \frac{3}{4} \) inch diameter circle. As the glass blower was unable to align the target with the "grid", three or four of the beams did not hit the tritium target and the center beam impinged on the depleted part of the target. It was felt at this time that this tube proved to be quite successful and that other tubes with multiple hole "grids" would be successful. The tube as described in Chapter V uses a 29-hole grid.
The analyzer tube was constructed for an approximate determination of the percentages of monatomic, diatomic and triatomic ion yields of both the RF ion source and filament type ion source. The analyzer section of the tube is shown pictorially in Figure H-36. Both ion sources were glass-blown on to this analyzer and both the analyzer section and ion section of the tube were operated at the same pressure. An electro-magnet having a three inch pole-face and an adjustable air gap was used. The stray field from the magnet caused considerable deflection in the ion beam before entering the catcher. Magnetic shielding was, therefore, necessary for both tubes. Both types of ion sources were shielded from the stray field to permit proper operation. As the slit widths were only a sixteenth of an inch, and since the ion beam could not be focused directly into the analyzer slits, quite low collector currents were observable. A volt-ohmyst was used as the collector current microammeter with provisions made to insulate the voltmeter case for 10,000 volts.

Because of the stray field it must be recognized that an appreciable part of the beam missed the analyzer slits and an analysis was made of only the edge of the beam. It must be assumed that the beam is uniform throughout with respect to atomic ratios before the following data can be considered valid.
Figure H-36  Ion Beam Analyzer
There is some question as to the collision cross-section in the residual gas of monatomic and diatomic ions. A monatomic ion has essentially only an effective radius of the nucleus exaggerated by the coulomb field of its positive charge, while the diatomic ion has the atomic radius of a hydrogen atom plus this same coulomb field. If the cross-sections are assumed to be equal then the following beam analysis can be assumed to be valid; however, if diatomic ions are preferentially scattered, the monatomic percentages should be abnormally high. The results, however, are in close agreement with what is expected from these ion sources and thus it is believed that diatomic ions are not preferentially scattered.

A typical curve showing the ion ratios taken at a pressure of 6 microns for the filament type ion source shown in Figure G-25, is shown in Figure H-37. An axial magnetic field was applied to this ion source without increasing the monatomic yield appreciably, see Figure H-38. As it was difficult to shield the magnetic field of the analyzer magnet from the magnetic field of the ion source magnet, it was necessary to use torodial permanent magnets instead of an electro-magnet for the ion source producing a field of approximately 200 gauss. As it was not felt that this source could be useful because of its low monatomic percentages, no stronger magnetic field strength was sought. These results, as obtained by the author’s laboratory assistant, Bernard Gittleman, were certainly in agreement with those of Figure D-7. The mass-three peak was possibly the result of the acceleration of a diatomic ion or mass-four ion which split into a mass-one ion and was bent so as to give an apparent
Pressure 6.0 \mu
Catcher current 130 \mu\text{a} \text{ approx.}

Figure H-37 Analysis of Beam from Oscillating Electron Source (Without Magnetic Field)
Figure H-38 Analysis of Beam from Oscillating Electron Source (With Magnetic Field)
peak. It was suggested that hydrogen could be present, but this seems unlikely as the deuterium is guaranteed to be over 99% pure.

An RF ion source as described in Appendix G, Figure G-29, having a half-inch ion exit hole was mounted on the analyzer. The oscillator of Figure G-26 was used with the 807 tube for RF excitation.

Observing the color of the discharge with this source is a very good indicator as to the percentages of monatomic ions available. The ion percentages are plotted as a function of pressure for five curves similar to Figure H-39. See Figure H-40. A much more useful percentage of monatomic ions is available even at this low oscillator power than in the filament type source. A rough percentage yield curve is plotted against oscillator power input, by using the peak values of the analyzer curve directly as a percentage indication. See Figure H-41. This curve was taken at a pressure of 6 microns. Although these curves are rough, increasing the oscillator power above 50 watts is certainly desirable. As the voltage rating of the 807 had been exceeded, increased power was not available at the time.

As this gives conclusive proof that the ion beams used in the sealed-off tubes were composed of a reasonable percentage of monatomic ions, the explanation for the low neutron yields of these tubes probably does not lie in the ion source.
Figure H-39  Analysis of Beam from R. F. Source

Probe Voltage 1300 volts
Pressure 5 microns
Oscillator Plate Power = 39 watts
Figure H-40 Percentage Ions as a Function of Pressure for R. F. Source
Figure H-41 Percentage Ions as a Function of R. F. Oscillator Power

Pressure 5 microns
APPENDIX I

NEUTRON MEASUREMENTS

Neutron-yield measurements throughout these experiments were made predominantly with the use of a BF$_3$ filled counter surrounded by paraffin. The counter was placed in a one inch diameter hole in a 7 inch diameter 18 inch long cylinder of paraffin covered with cadmium. A cathode follower pre-amplifier is used with an Atomic amplifier (204C) followed by a scaler. A 3000 volt variable regulated power supply was used to supply about 1950 volts to the counter. Usually the counter was mounted so that the neutrons entered the end of the counter.

Checks were made by two different methods on the accuracy of the BF$_3$ counter and it was found to agree with the other measurements within the precision of the readings. The yield was calculated from the proton-recoil track density in a type C-2 Ilford photographic plate using the quoted values for hydrogen content. It was also possible to determine the approximate yield percentages of D-D and D-T neutrons.

A Raychromic Model E-1 fast neutron dosimeter$^{35}$ was also used to check the BF$_3$ counter. The calibration of this instrument was made by Samuel Levin of M.I.T. It checked the readings of the BF$_3$ in the range of 500 neutrons/cm.$^2$/sec. quite well. However, the meter as calibrated by the maker, is less sensitive by a factor of three than its calibration indicates.


