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DESIGN OF A CRYOGENIC DEUTERIUM GAS TARGET FOR NEUTRON THERAPY

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Summary

A cryogenic deuterium gas target operating at 80°K and 10 atm pressure has been designed for use with a small cyclotron; the D(d,n) reaction is used to produce a neutron beam suitable for radiation therapy. The target is cooled by circulation of the gas in a closed loop between the target and an external heat exchanger immersed in liquid nitrogen.

Introduction

Several clinical trials are under way in which the possible advantages of neutrons for radiotherapy are being investigated. Most neutron beams currently in use for this purpose are produced by bombardment of thick beryllium targets with deuterons or protons from accelerators located in physics laboratories. These accelerators are being used because of the high bombarding energies for deuterons (≥20 MeV) or protons (≥35 MeV) required to produce a neutron beam that is suitable for radiation therapy with a beryllium target. If neutron therapy is to become widely available, the accelerators needed for the production of neutron beams must be located in hospitals.

The minimum clinical requirements for a hospital-based neutron therapy facility have been outlined recently.[1] These requirements state that the beam must be easily available for therapy, preferably not fixed in one direction, and of sufficient intensity and penetration to permit treatment techniques similar to those used with conventional cobalt-60 units. The last two conditions are met reasonably well if the average energy of the neutron beam is at least 8 MeV and the output is at least 25 rad/min at a distance of one meter from the target. This distance is dictated by the amount of shielding required for the production of a well-collimated beam.

A neutron beam with output and penetration sufficient for radiotherapy can be produced with an 8 MeV deuteron beam from a small cyclotron if a thick deuterium target is used. We have carried out dose measurements[2] by using the 8.3 MeV deuteron beam from the Franklin McLean Memorial Research Institute (FMI) cyclotron with a low-power totally stopping deuterium gas target. The observed dose rate for a 10 x 10 cm^2 field at one meter is 0.17 rad/min-μA. The dose in tissue reaches a maximum value at about 1.5 mm from the entrance and is attenuated to 50% at a depth of about 10 cm. These measurements were extended to higher bombarding energies and it was observed that at 10 and 12 MeV the penetration in tissue is not increased; only the neutron output increases. This is in agreement with our calculations which show that the average neutron energy does not change significantly as the bombarding energy is increased from 8 to 12 MeV, and that the total neutron yield increases roughly as the third power of the bombarding energy.

Deuterium gas targets capable of generating high-intensity neutron beams are still in the developmental stage. The two difficulties encountered are (1) the confinement of the pressurized gas in a vessel which has a thin window with an adequate lifetime for routine use and (2) removal of the beam power dissipated in the gas. A deuterium gas target is presently in use with the 10.6 MeV deuteron beam at the German Cancer Research Center (DKFZ) in Heidelberg.[3,4] This target is 30 cm long and is operated at a pressure of 11 atm. The gas is separated from the vacuum system by a 0.0005 in. thick Havar** foil. The target has been operated at beam currents up to 70 μA. The 0.77 kW of beam power dissipated in the gas is removed by water cooling of the gas chamber. Experience with this target indicates that it is reasonable to expect a lifetime for the Havar foil of as much as 1000 μAh.[5] Information available so far is insufficient to allow predictions whether this design would be adequate for the 1.2 kW power dissipation necessary for a therapy beam with 8.3 MeV deuterons.

Conceptual Design

The basic requirements set for the design of a deuterium target to be used with the 8.3 MeV deuteron beam from the 30" cyclotron of the FMI are as follows:

1. The 8.3 MeV deuteron beam must be completely stopped in the gas.

2. There must be provisions for dissipation of a maximum power of 1.5 kW in the gas under controlled temperature and pressure conditions. This value is associated with a projected maximum deuteron beam current of 180 μA.

3. The overall dimensions of the target volume should be sufficiently small to permit good geometrical beam definition at one meter by use of a 65 cm long collimator, as well as adequate local shielding of the neutron beam.

4. In addition, safety, reliability, simplicity, and cost of operation must be considered.

Of the two possibilities of operating a gas target at room temperature with water cooling or at liquid nitrogen temperature with cryogenic cooling, the second offers two distinct advantages. The increased density of the cold gas makes it possible to reduce the target dimensions, and the lower temperature increases the tensile strength of the Havar foil. A third possibility,

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**Havar, a cobalt-base alloy of high tensile strength, supplied by Precision Metals Div. of Hamilton Watch Co., Lancaster, Pennsylvania.

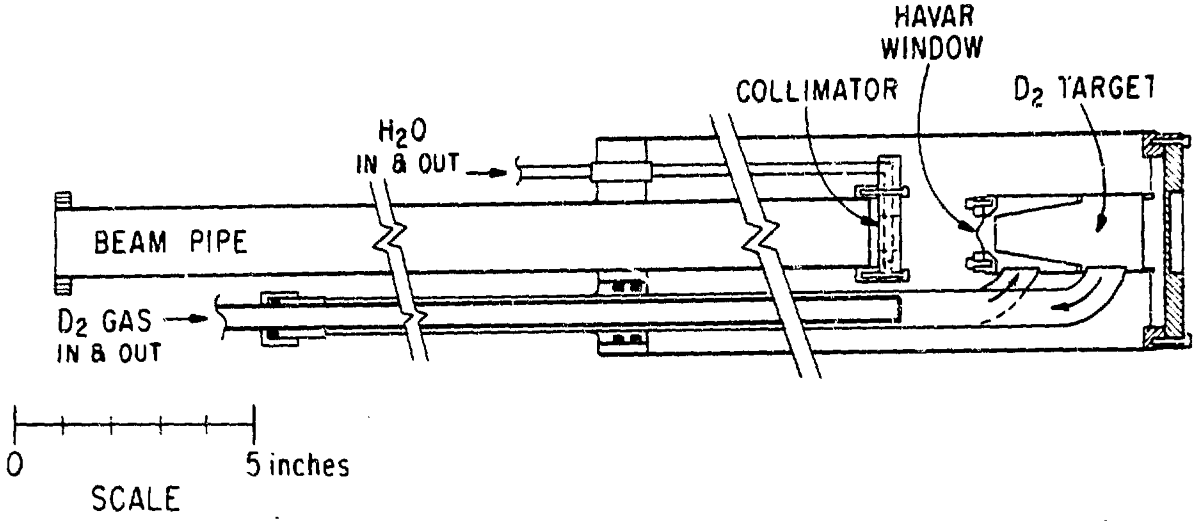

Figure 1. Cross-section of the cryogenic deuterium gas target dewar.

that of using a closed system consisting of a liquid deuterium target coupled to a liquefier in which heat is removed by boiling of the liquid deuterium, is not practical due to the high power requirement.

A cryogenic system in which the heat is removed by boiling of liquid nitrogen is the choice for the present design. The problem of transmitting the 1.5 kW of power to the liquid nitrogen is handled by circulation of the deuterium gas in a closed loop through a heat exchanger. A compact target is achieved by operation at high gas pressure and by keeping the heat exchanger removed from the target. The design goal for the temperature rise in the target under normal operation is set at 10°C above liquid nitrogen temperature. With the system operating under pressure regulation at 10 atm and between 77° and 87°K, the target length can be as small as 7.5 cm.

A critical part of the target is the thin foil separating the gas from the vacuum system. It is important that energy loss in the foil be kept to the lowest possible value. Besides the static stress on the foil, one has to consider radiation damage and local heating. The latter can be controlled if the cold circulating gas entering the target vessel is made to impinge directly on the foil. Radiation damage is expected to reduce the tensile strength of the foil material. The extent of the damage can only be judged by experience; in any event, provisions must be made for rapid foil replacement and for recovery of the deuterium gas in case of foil rupture.

Target Dewar

The cryogenic gas target is shown in fig. 1. The target design represents a compromise between the requirements of small physical size, to permit good collimation of the neutron beam, and the thinnest possible entrance window. The target vessel consists of a stainless steel cell 4 cm in diameter and 7.5 cm long. The deuteron beam enters the cell through a 0.0005 in. thick Havar foil window held in place by a teflon O-ring. Cold deuterium gas is circulated from the heat exchanger to the target through 5/8 in. diameter vacuum-insulated lines. The gas enters the target vessel and is blown past the window as an annular jet by the conical partition and exits at the back of the target vessel. A water-cooled, gold-faced collimator at the end of the beam line prevents the deuteron beam from striking the frame of the target window. The collimator is electrically insulated, so that the beam current striking the collimator can be monitored when the beam is tuned.

The target vessel is contained within an evacuated chamber which forms a dewar designed to fit into the 5 in. diameter opening in the target shield and is connected to the 1-1/2 in. beam line from the cyclotron. The target vessel can be removed for window replacement by removal of the back plate from the dewar vessel; the two deuterium lines are disconnected at the O-ring-sealed coupling, and the entire target assembly is removed through the neutron collimator opening.

Havar is used for the window because of its high tensile strength which, for the unannealed sheet, is 260,000 psi. After annealing, this is increased to 330,000 psi. An attempt was made to preform the Havar into a hemispherical shape that would fit the window opening, in order to give the window greater strength. This approach failed because the Havar fractured before it took on any deformation.

Since the performance of Havar at liquid nitrogen temperatures was unknown, destructive tests were made on several samples of annealed sheets 0.0005 in. thick. A test jig with a 3/4 in. diameter window opening was prepared, with the edge of the window carefully rounded. Tests at room temperature were run with nitrogen from a high-pressure bottle. For the low-temperature tests, the jig was immersed in a vessel containing liquid nitrogen and the window was pressurized slowly with nitrogen gas. The accumulation of liquid nitrogen in the high-pressure space behind the window insured that the entire window was at the boiling temperature of nitrogen, 77°K. At room temperature, the 0.0005 in. annealed Havar in a 3/4 in. diameter window burst at a pressure of 220 psi. At 77°K, the bursting pressure was 320 psi. an increase of 45%. At room temperature, the foil fractured into small pieces when it failed; at liquid nitrogen temperature, it failed at the center, the point of highest stress, and from this point split radially into a number of pie-shaped segments. The segments remained attached to the unbroken annular ring under the pressure seal. This response is taken to indicate that the alloy is not only stronger, but also more ductile at low temperatures.

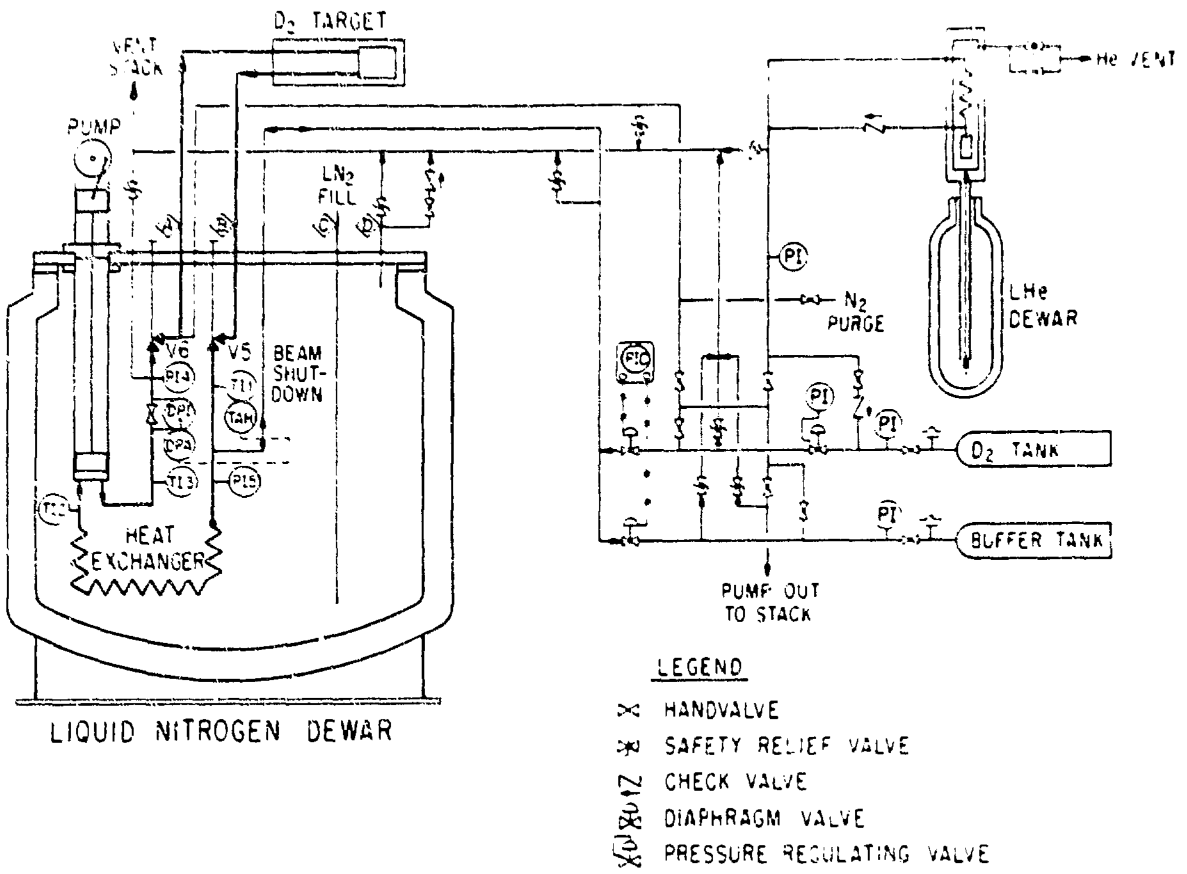

Figure 2. Schematic diagram of the gas handling system.

Balancing the desire for a reasonable window safety factor and lifetime, with the smallest allowable energy loss in the window, we decided to use a 0.0005 in. thick, annealed Havar window 2 cm in diameter. This will have an areal density of 10 mg/cm^2 and the energy loss in the window by the 8.1 MeV deuterons is about 0.6 MeV. At 1.5 kW total beam power, 100 watts will be dissipated in the window.

Gas Handling System

Figure 2 is a simplified diagram of the gas handling system. The main features shown are the gas target, heat exchanger dewar, deuterium supply and buffer vessels, and a liquid-helium cryopump for recovery of the gas in the system. During normal operation, the deuterium gas from the target is circulated by a cold pump through a heat exchanger immersed in liquid nitrogen and returned to the target. Pressure (PI) and temperature (TI) indicators installed at the points shown monitor conditions in the circulating gas. Deuterium gas is admitted to the system as needed to maintain operating pressure from a high-pressure supply bottle equipped with a pressure-indicating controller (PIC). This controller will also release gas to the buffer vessel if the pressure increases above a preset value. A differential pressure indicator (DPI) operating in conjunction with a venturi tube monitors the rate of gas flow. Interlocks (DPA) and (TAH) are provided to shut down the beam in case of loss of gas flow or abnormal temperature rise. Safety release valves are provided throughout the system to prevent the development of excessive pressures. These safety release valves and gas vents are connected to a stack for safe disposal of explosive as well as other gases.

The system is filled with deuterium after evacuation of all parts, purging with dry nitrogen gas, and evacuation of the nitrogen. When the target window is being changed, that part of the system can be isolated from the rest by closing of cold valves V5 and V6. These valves are provided with long, thin-walled stems of stainless steel tubing which thermally isolate the warm operating end from the cold seat.

Deuterium gas can be pumped from the target dewar, or from any other part of the system including the buffer tank, by a liquid-helium cryopump. The liquid deuterium will be collected in a vessel of 0.3 liters capacity. On warming, pressure in the vessel can rise to as much as 2,000 psi, and a large part of the deuterium can be returned to the supply bottle. The remainder may be left for the next pumping operation.

Heat Exchanger Dewar

The heat exchanger dewar shown in fig. 3 is a vacuum-jacketed vessel with super-insulation and with a capacity of 180 liters of liquid nitrogen. A coil of 3 copper tubes, 1/2 in. in diameter and 20 ft long, transfer heat from the circulating deuterium gas to liquid nitrogen. Vacuum-insulated transfer lines, pressure and temperature indicating lines, the liquid-nitrogen filling line, nitrogen vent line, and cold valves are all mounted on the header assembly. Nitrogen gas is stratified above the liquid level in the dewar so that the header assembly remains at room temperature.

The deuterium gas circulating pump is also mounted on the heat exchanger dewar and is immersed in liquid nitrogen. The supports for the pump cylinder and the pump rod are constructed of thin-walled stainless steel tubing to provide thermal isolation of the cold pump from the warm dewar header. The piston is sealed with graphite-loaded teflon rings, and the piston rod is sealed with a Garlock packing at the hot end. The space above the piston is connected to the intake line of the pump (not shown in fig. 3) so that both sides of the piston operate at a pressure of 10 atm. The gas above the piston will tend to stratify and isolate the warm dewar header from the pump. Valves are of the poppet type with graphite-loaded teflon guides. The exhaust valve is spring-loaded, and the intake valve is closed by gravity. The bore and stroke are both 3-1/2 in. When operated at 360 rpm, the pump will have a displacement of 3.3 liters/sec.

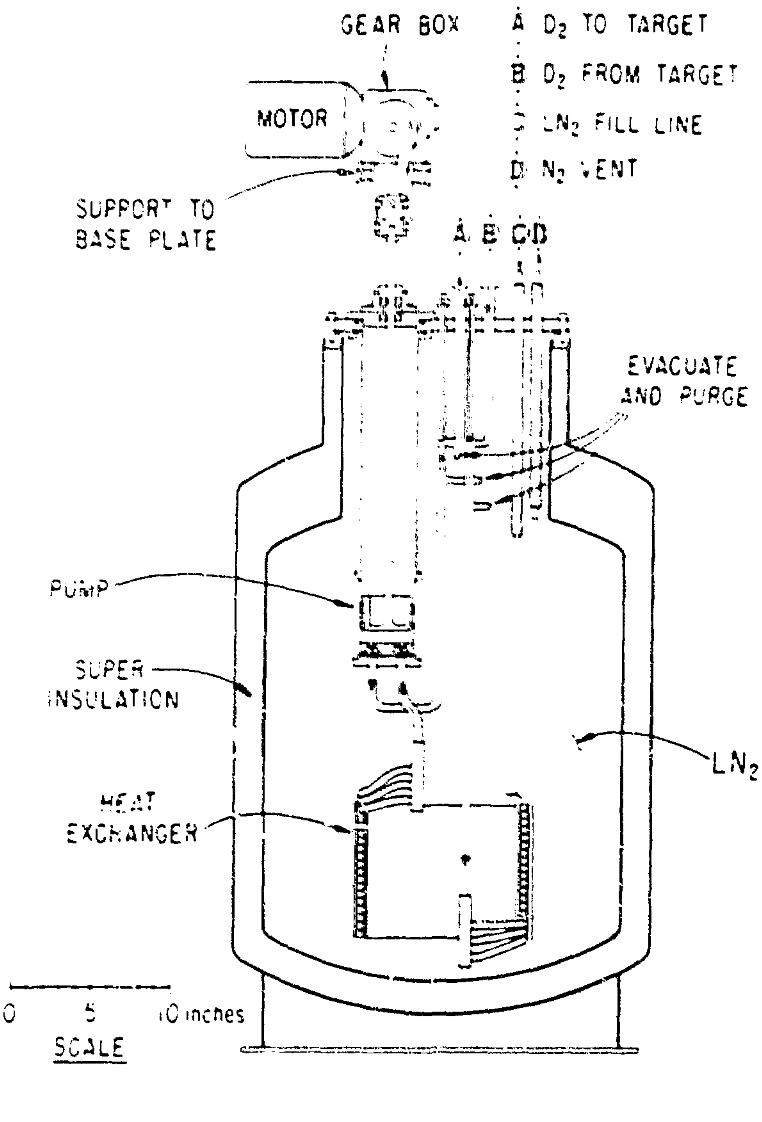

Figure 3. Cross-section of the liquid nitrogen heat exchanger dewar.

Operation

The target vessel is operated at 10 atm. The gas entering the target at 80°K with an enthalpy of 2098 J/mole[6] will leave at 90°K with an enthalpy of 2410 J/mole, a difference of 312 J/mole. Thus, at 1.5 kW dissipation in the target, the deuterium gas must be circulated at a rate of 4.8 mole/sec or 19.4 gm/sec. At the temperature and pressure used, this corresponds to 3.1 liters/sec; therefore, the pump capacity of 3.3 liters/sec at 360 strokes/min should be adequate.

The calculated volume of the gas handling system is 5.8 liters, of which only 0.16 liter is at 300°K; the balance is at 80°K. Thus, the total gas inventory is 195 liters of deuterium at s.t.p. Fast-acting valves will be installed in the beam line to prevent loss of this large inventory of deuterium in case of window rupture. In addition, an adequate buffer volume will be connected to the beam line to prevent the buildup of pressure. It is expected that, in the case of window failure, a substantial fraction of the deuterium can be trapped in the beam-line vacuum system and then be recovered by the liquid-helium cryopump. Operation of the pump to condense all the gas from the system is expected to consume about 0.5 liters of liquid helium.

Heat leaks into the liquid nitrogen dewar from all sources, including the vacuum-jacketed lines under beam-off conditions, are estimated at 15 watts. This will consume about 0.4 liter/hr of liquid nitrogen. With the maximum power dissipation of 1.5 kW in the target, the consumption of liquid nitrogen will be 34 liters/hr. Since the heat exchanger dewar holds 180 liters of liquid nitrogen and an inventory of 104 liters is required for adequate submersion of the heat exchanger coils, 2-1/4 hours of operation are possible. Translated into clinical use, this would be sufficient for about 30 patient treatments, which represents a full day's work on a busy schedule.

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