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SAFETY REPORT FOR A NON-MEDICAL ACCELERATOR FACILITY AT THE SUDBURY NEUTRINO OBSERVATORY.

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1. INTRODUCTION

1.1 General Description

This report describes a facility for calibrating the Sudbury Neutrino Observatory [SNO] detector. The SNO detector is a large detector of neutrinos from the sun and other astrophysical sources. It is being constructed at the 6800 ft deep level of INCO's Creighton mine outside Sudbury, Ontario in order to shield against the cosmic radiation present at the surface of the earth. It will consist of 1000 tonnes of heavy water, contained in a 12 m diameter transparent acrylic vessel. Cerenkov radiation from neutrino interactions in the heavy water will be observed by some 9600 photo multiplier [PMT] tubes mounted on a 16 m diameter geodesic support structure. The acrylic vessel and PMT support structure will be immersed in approximately 8000 tonnes of ultra-pure light water, which will act as a radioactivity shield from trace Uranium and Thorium decay chain elements in the surrounding norite rock. The detector is being built inside a 22 m diameter, 30 m high, barrel shaped cavern which has been blasted at the end of an extended drift at the 6800 ft level of the mine. Drifts surrounding the cavern have been walled, cleaned, and isolated from the rest of the mine, so that an "underground [UG] laboratory" with better than class 10000 clean room conditions now exists at the site.

A commercial deuterium-tritium [DT] neutron generator will be located inside a so-called "neutron pit", about 50 m away from the center of the detector cavern inside this UG laboratory. 14-MeV neutrons from this generator will be used to produce short lived radioactivities. The radioactivities will be rapidly transported to a decay chamber inside the heavy water of the detector by fast gas flow in a flexible capillary tube. Events in the detector in coincidence with triggers from the decay chamber will be used to calibrate the SNO detector's gain, linearity and efficiency. The "calibration sources" thus produced will be: (a) $^{16}N(t_{1/2} = 7.1$ s, 6.13 MeV γ-rays) made by $^{16}O(n,p)$ using pure O_2 gas as both target and transport gas, (b) ^{8}Li ($t_{1/2} = 0.84$ s, 13-MeV endpoint energy β's) via the $^{11}B(n,\alpha)$ reaction on a solid target with the recoils being collected and transported on aerosol particles in a Helium gas stream, and (c) ^{17}N ($t_{1/2} = 4.4$ s, β-delayed neutron emitter) made by $^{17}O(n,p)$, using enriched $^{17}O_2$ gas as target and carrier in a closed flow loop. This closed loop is required because $^{17}O_2$ is too expensive to vent. The DT generator will be switched on (infrequently) only on those occasions when a calibration run is being performed. The generator is expected to operate at an output level of 10^7 to 10^8 neutrons per second, in order to produce the above activities in the range of 1 to 100 Bq.

We plan to acquire a sealed tube DT generator, Model A320L made by MF Physics Corp. of Colorado Springs, Colorado, U.S.A. This is the laboratory version of their A320P borehole pulsed neutron generator. It has a nominal output of 1 x 10^8 neutron per second, and is warrantied for 500 hours at a minimum of 7 x 10^7 ns^{-1}. It is a turn-key device with factory training and installation services. We shall be end-users of this device, and will return the entire generator to the factory for repairs, replacement and disposal.

1.2 Identification of Owner, agents and contractors

The device will be owned by:

The United States Government, through a grant to:
The University of Pennsylvania, Philadelphia, Pennsylvania, U.S.A.
Dr. Gene Beier, Professor of Physics.

It will be licensed and operated in Canada by:

The Sudbury Neutrino Observatory Institute
Department of Physics
Stirling Hall, Queen's University
Kingston, Ontario K7L 9N6

It will be operated on INCO property at Creighton Mine, Lively, Ontario

The manufacturer and supplier of the DT generator tube, instrument and control system is MF Physics Corporation of Colorado Springs, Colorado, USA. All major servicing and disposal of the instrument will also be carried out by MF Physics in the USA.

1.3 Use of the facility.

The DT generator facility will be used to produce short-lived radioactivities for calibrating the SNO detector. The activities will be produced in a small gas target chamber surrounding the generator tube, and will be transported by fast gas flow (a few std. litre per minute [slm]) in capillary tubing to a decay chamber located inside the sensitive volume of the SNO detector. After a further time delay, the return gas flow will be either recirculated or diluted and flushed by directly exhausting it into the 1000 cfm laboratory air exhaust duct immediately above the pit.

The benefit of using a DT generator is that it is a switchable, controlled, safe and relatively inexpensive source of high energy (14-MeV) neutrons. This source has enough neutron energy and intensity to produce a number of short-lived radio-activities which will be very useful for calibrating the SNO detector.

The expected output of the DT generator is 10^7 to 10^8 neutrons per second, with the output controlled as needed, and monitored by a plastic scintillator fast neutron monitoring device. The facility will produce radioactivities with half-lives of 0.84 to 13 seconds, transported by a gas stream flowing in capillary tubing. After flowing through the decay chamber, where the decays of these activities will be used for detector calibration, the return gas stream, with negligible remaining entrained activity, will be exhausted directly into the main laboratory air exhaust duct.

Potentially, the facility may be used for other low-level neutron activations. These may include activating a NaI detector to be used as a ^{24}Na ($t_{1/2}$ = 15 h) calibration source in SNO, and Fe and/or Al foil activations for calibrating the fast neutron monitor detector.

1.4 Material Incorporated by reference

1) MODEL A-320 NEUTRON GENERATOR MANUAL – MF Physics Corp.

2) Colorado Department of Health RADIOACTIVE MATERIALS LICENCE for MF Physics Corp.

3) Plan Drawings of the SNO Underground Laboratory showing location of the DT generator "neutron pit", and acrylic vessel neck and deck areas. Drawing Numbers 17-702-B-6223-2, 17-702-6223-8, and 17-702-B-6204-1.

4) D-T Neutron Source Shielding for the Sudbury Neutrino Observatory – G. B. Wilkin,AECL Report RTB-TN-057, SNO-STR-95-030.

5) N-16 Releases from SNO – R. D. Graham, AECL Memo EP-C95-032.

6) Scientific and Technical Reports:

a) ^{16}N : A Calibration Source for SNO – B. Sur, E. D. Earle, E. Gaudette and R. Deal A.E.C.L., Chalk River Laboratories SNO-STR-93-04.

b) ^{8}Li: A β Calibration Source for SNO - B. Sur, E. D. Earle, V. T. Koslowsky, E. Hagberg, M. Watson, E. Gaudette, and R. Deal, A.E.C.L. Chalk River Laboratories,(*in preparation*).

c) ^{17}N: A Tagged Neutron Calibration Source for SNO - E. B. Norman and B. Sur, SNO-STR-94-037.

7) Drawing of Shielding blocks for the DT generator housing in the SNO underground laboratory - Drawing No.17-702-E-7125, (*in revision*).

8) Safety Considerations for the Health Physics Neutron Generator - W. G. Cross & H. Ing, CRNL-1412.

2. SITE

The DT generator facility will be located in the SNO underground laboratory at the 6800 ft. level of INCO's Creighton mine. This level is reached by the number 9 shaft of the mine.

Item 3 of section 1.4 lists drawings showing the general layout of the DT generator location and the rest of the underground laboratory. The laboratory is situated at the end of a ~1 mile drift at the 6800 ft level of INCO's Creighton mine. Access to the laboratory is restricted to authorized personnel. The entry is constantly monitored because all entering personnel have to undergo an elaborate cleaning procedure in order to not compromise the class 10000 clean room conditions inside the entire laboratory. The "neutron pit" shielding will be such that personnel can safely stand right beside it during operation, although it is expected of-course that such a situation will not arise. This shielding is shown in the drawings in item 7 of Section 1.4.

Access to the 6800 ft level drift is normally via the main cage which runs in the No. 9 shaft at Creighton. In the case of emergencies, the UG laboratory has its own "refuge station", with air seal, and fresh air supply.

Initial Commissioning site:

Because of the lack of access to machining and electronics support facilities underground, it is proposed to initially set up the DT generator and the target, decay chambers and gas flow apparatus at Chalk River Laboratories in the DT generator facility of the Health Physics Branch in Building 513. This large laboratory facility has already been licensed for operating DT generators with outputs of 10^{10} and 10^{13} neutrons per second.

Details of the safety considerations for this site may be found in report CRNL-1412 (Item 8 in section 1.4). The control electronics of the SNO neutron generator would be interlocked with the access doors of the shielded room and the controls would be placed in the existing control room of the CRL facility. The existing warning lights and bells would also be operable. It is appreciated that permission to perform this initial commissioning at CRL must be obtained from the AECL Accelerator Safety Committee.

These tests are anticipated to take less than 20 hours of DT generator ON time and a total period of 1 to 2 weeks. The benefit of these tests will be the complete test and tune up of the DT generator operation, and the gas flow systems and electronics in a convenient laboratory environment.

3. ACCELERATOR TECHNICAL SPECIFICATIONS.

All the material for sections 3.1, 3.2, 3.3 and 3.4 are documented in the " MODEL A-320 NEUTRON GENERATOR MANUAL" which is incorporated as item 1 of section 1.4 in this report.

4. FACILITY

The "neutron pit" is shown schematically in figure 1. It was made by blasting a roughly 5 ft. by 6 ft. by 6.5 ft. deep cavity in the floor of the main drift during excavation of the laboratory. The hole was subsequently back-filled with compacted gravel around two concrete sewer pipes, 4 ft and 1.5 ft in diameter, and 6.5 ft deep. The smaller diameter pit is being used as a sump to drain water from laboratory cleaning and mine operations. We propose to install a 0.25" thick water proof liner, made of either polyethylene or polyurethane (Urylon™) in the 4 ft diameter pit. The pit will then be filled with "doughnut" shaped, close fitting concrete shielding blocks, leaving an opening in the middle to take a 10" diameter PVC or steel pipe. The DT generator, and target chambers will be located in this hole as shown in figure 1. A 4" by 4" conduit in the upper surface of the topmost doughnut will carry the DT generator cable as well as gas circulation lines and cables for the fast neutron flux monitor, and other pressure or position monitors as needed. This conduit will have a bend in it to reduce neutron streaming, and its opening will be directed towards the laboratory wall, looking into solid rock. Access to the 10" diameter hole and the DT generator will be restricted by a concrete cap, roughly 3 ft in diameter and 2 ft tall. To permit safe operation, the DT generator control will be interlocked by two switches in series, one at the cap-doughnut interface, and the other in the positioning block at the bottom of the pit. This will ensure that the DT generator can be turned on only if it is positioned inside the hole, and the cap is closed.

Flow diagrams for the ^{16}N, ^{17}N and ^{8}Li gas transport calibration sources are given in figures 2, 3 and 4. Gas cylinders, gas flow control "boards", pumps, as well as the DT generator control console and other electronics will be located in the area immediately adjacent to the "neutron pit". Proof-of-principle tests of the radio-isotope production and processing are reported in item 6 of section 1.4.

5. ANALYSES OF RADIATION HAZARDS AND SAFETY FEATURES

5.1 Source of Radiation Hazards

5.1.1 Radiation

The shielding configuration has been designed such that the dose rate at the outer surfaces of the shielding are 0.1 mrem per hour or less. These calculations are shown in the document "D-T Neutron Source Shielding for the Sudbury Neutrino Observatory" incorporated as item 4 in section 1.4 of this report.

Prompt radiation inside the shielding is produced by the neutron generator tube in the form of 14 MeV neutrons at the rate of between 10^7 and 10^8 neutrons per second and X-rays at less than 0.15 mSv/hr.

Activation of shielding and DT generator components will produce negligible radiation fields outside the shielding. Experience with such a device by the manufacturer has shown that production of long-lived radioactivities in the instrument by activation is negligible.

5.1.2 Radioactivity

The DT sealed tube contains less than 3 Ci of Tritium total. This is immobilized in the solid Titanium target inside the tube.

The oxygen in the air surrounding the probe, inside the shielding can be activated by the (n,p) reaction to produce 7.1 s ^{16}N. This activity produces 10 MeV β's with a 23% branch, 4 MeV β's and 6.1 MeV γ's with a 68% branch and 3 MeV β's and 7 MeV γ's with a 5% branch. The total activity inside the 10" diameter well, produced with a 35 milli-barn cross-section is expected to be 500 Bq. This activity will be present only when the DT generator is producing 14 MeV neutrons.

For the ^{16}N and ^{17}N calibration source systems, the target chamber is an annulus fitted around the DT probe, with maximum inside diameter 5.25 inches and length 4.25 inches, operated at a maximum oxygen gas pressure of 75 psiA (5 bar). With the generator running at its peak of 10^8 neutrons per second, it will produce 3850 atoms s^{-1} of ^{16}N when operated with pure $^{16}O_2$ gas, and 2772 atoms s^{-1} of ^{17}N with 90% enriched $^{17}O_2$ gas. With a maximum anticipated gas flow of 200 std cc s^{-1} (12 s.l.m.), if the gas outlet tube were opened immediately outside the shielding, it would expel 895 ^{16}N or 437 ^{17}N atoms s^{-1} into the atmosphere. These isotopes, however, have a half-life of only 7 s and 4.2 s respectively. Under the above assumptions, the "calibration source" in a 500 cc decay chamber operated at 1 bar pressure (residence time =2.5 s), after transport over 70 m of 2.5 mm ID capillary (transit time = 5.2 s) would have an activity of 106 Bq for ^{16}N, or 55 Bq for ^{17}N with $^{16}O_2$ and 90% $^{17}O_2$ gas flows respectively. After returning in a 70 m long, 5 mm diameter tube (transit time = 6.9 s), the exhaust will consist of 222 atoms per second of ^{16}N, or 43 atoms per second of ^{17}N. The exhaust may be vented in the case of ^{16}N (i.e. ordinary O_2 gas) or the gas may be recirculated in both cases. Along the 2.5 mm ID transport capillary in the above circumstances, the average activity along the tube will be 3.2 Bq m^{-1} in the case of ^{16}N, or 3.8 Bq m^{-1} for ^{17}N. In the return line, the average activity will be 3.6 Bq m^{-1} for ^{16}N or 1.9 Bq m^{-1} for ^{17}N These numbers represent the maximum possible activaties under system operation.

For the ^{8}Li calibration source system, a 10 mg cm^{-2} thick solid target of 97% enriched ^{11}B powder in a 10% polyethylene binding matrix will be adhered to the inner wall of the annular target chamber. The activities produced will be 0.84 s ^{8}Li with a cross-section of 30 mb, and 13.8 s ^{11}Be with a cross-section of 5 mb. ^{8}Li is a pure β-emitter with 13 MeV end-point energy, while ^{11}Be has β's with 11 MeV end-point energy, and a

35.5% branch of 2 MeV γ-rays. A 10 cm long cylindrical target foil will build up activities of 1372 Bq and 229 Bq of ^{8}Li and ^{11}Be respectively with the DT generator producing 10^{8} n s^{-1}.. It has been experimentally verified (Ref. 6(b) in section 1.4) that the yield of recoil atoms entrained on aerosol (NaCl) particles borne by a He gas stream through the target chamber is only 3 x 10^{-7} of ^{8}Li atoms per incident neutron, and that of ^{11}Be is 2 x 10^{-8} per neutron. Thus for aerosol laden He gas flow of 200 std. cc s^{-1} through a target chamber of outer radius 1.65", operated at 2.5 bar absolute pressure, the outlet capillary would expel 4.8 atoms per second of ^{8}Li and 1.3 atoms per second of ^{11}Be into the atmosphere if opened immediately outside the neutron pit. After transit through a 70 m long, 2.5 mm ID capillary (transit time = 2.57 s), the delivered rate of activity into the decay chamber will be 0.6 s^{-1} of ^{8}Li and 1.2 s^{-1} of ^{11}Be. Calculations indicate that the ^{8}Li delivery rate can be doubled by adjusting the position of the target chamber with respect to the DT neutron source. The calibration "source strength" for a 500 cc decay chamber operating at 0.5 bar pressure under the above circumstances will be 0.6 s^{-1} of ^{8}Li and 0.07 s^{-1} of ^{11}Be. After a return path of 70 m through a 5 mm ID (0.25" OD) line at 0.5 bar pressure (transit time = 3.43 s), the ^{8}Li atoms will essentially all have decayed, while the ^{11}Be activity will still be at 1 s^{-1}. This residual activity will be immobilized by catching the aerosol particles in a particle filter, before venting the He gas stream into the laboratory air exhaust. The He gas itself is not expected to be activated. There may be a build-up of residual recoil activity in the aerosol capturing particle filter from activation products of the Stainless Steel target chamber. This build-up will be monitored. It is not expected to exceed a few 10's of Bq after a full day of running. The average activity in the target to decay chamber capillary will be 0.1 Bq m^{-1} of ^{8}Li and 0.002 Bq m^{-1} of ^{11}Be. The average activity in the return line will be 0.003 Bq m^{-1} of ^{11}Be. All the above calculations are at the maximum rated DT neutron generation rate of 10^{8} n s^{-1}.

Schedule quantities for unlisted radioisotopes is 1 μCi, see Atomic Energy Control regulations Schedule 1. Noble gases, e.g. Xenon, present no internal hazard and have an external hazard DAC of around 10^{6} Bq m^{-3}, see IAEA Safety Series #9. The concentrations of radioisotopes expected, during the operation of this facility and even during a malfunction which causes the radioactive gases to be emitted into the room at the source, are below these values. A calculation using conservative scenarios (item 5 of section 1.4) confirms that the radiation hazards associated with the radioactive gases in this facility are negligible.

Occasional activations of pure ^{27}Al and ^{56}Fe foils will take place to cross-calibrate the fast neutron flux monitor. The activities produced will be less than 100 Bq each of 15 h ^{24}Na or 2.6 h ^{56}Mn respectively. The thermalised component of the neutron flux inside the shielding may be used to activate a small NaI detector. This will produce less than 1000 Bq of ^{24}Na and about 10000 Bq of 25 minute ^{128}I activity sealed inside the encapsulated NaI detector. After allowing several hours for the ^{128}I to decay away, the activated detector will be withdrawn from the neutron pit and inserted as a ^{24}Na calibration source into the SNO detector.

5.2 Area Designation

The shielding is being designed so that the dose rate at its outer surfaces does not exceed 0.1 mrem h^{-1} for full neutron output from the generator. If this condition is found to be true during comissioning surveys, then there will no exclusion areas as such. However, for the sake of general awareness, there shall be a visual indication of a rotating light located on the shielding to indicate that the DT generator is on.

5.3 Shielding Design and Calculations

The DT generator tube will be located close to the bottom of the existing 4 ft wide, 6.5 ft deep neutron pit. A schematic drawing of the neutron pit design, including shielding is shown in figure 1. The shielding material chosen is ordinary grade concrete because of its low maintenance and familiarity. The shielding is achieved by doughnut shaped, pre-cast concrete blocks. The main issues are the thickness of the proposed cap, and the effect of neutron streaming through the cable access duct.

The shielding calculations have been performed by a fully three dimensional Monte-Carlo neutron transport method. The detailed report of the calculation is attached (Item 4 of section 1.4). The conclusion is that with (a) concrete doughnuts with a 10" diameter central hole and (b) a 3 ft diameter by 2 ft thick concrete cap, the neutron plus gamma radiation dose anywhere on the surface is less than 0.1 mrem h^{-1} except at the opening of the cable access duct, where it is 0.27 mrem h^{-1}. In practice this duct will be angled to further reduce neutron streaming. The opening of this duct will be directed towards the laboratory wall, looking into solid rock. If neccessary, further shielding material will be used to reduce this field to 0.1 mrem h-1 .

Since the generator will operate infrequently and personnel will not normally be within 1 m of the pit, the annual dose on any individual will not exceed a few mrem.

5.4 Radiation Warning Systems

The primary interlock system will consist of two switches in series, one between the cap and the topmost block of the concrete shielding, and the other between the bottom of the DT generator and the positioning block in the bottom of the pit. These switches will be hardwired to the interlock on the control console of the DT generator. They will allow power to the control and drive electronics only if the generator is in place inside the neutron pit and the shielding cap is in place.

During commissioning neutron and beta-gamma dose rate meters will be on hand to monitor any unexpected radiation outside the shield when the generator is operating. It is expected that during operation a neutron monitor will not be required but an alarmed beta-gamma meter will be located next to the shielding cap to alert the operators of any extraordinary, unaccounted radiation levels above background.

The fast neutron flux from the generator will be monitored by scaling pulses above a preset threshold from a 2" x 2" plastic scintillator detector coupled to a photo-multiplier tube, located inside the shielding, close to the DT tube.

A water detector will be used to check for the presence of any water inside the neutron pit. This will be similar to the "beetles" used to check and alarm for heavy water leaks in the electrolysis plant at CRL. They are designed and built at CRL.

Gas pressures and flow rates in the gas transport calibration systems will be monitored both before and during DT generator operation.

The control console voltage, current and pulse rate and width information, dose rate meters, neutron flux monitor, water detector and gas pressure and flow rate monitor outputs will be fed into the main laboratory Controls, Monitoring and Alarms (CMA) computer system, as well as a stand-alone "calibration computer" acquisition, control and monitoring system. Limits of safe operation will be pre-set on one or both of these systems, so that appropriate shut-downs or operator alarms occur when these limits are breached.

For the gas flow systems, the whole system will be pressurized, sealed and monitored for pressure drops to ensure leak-tightness. Any leaks will be located and fixed before any irradiation can begin. The pressures and flow rates will be adjusted and stabilized, and limits on these parameters will be set on the above mentioned computer control systems before the DT generator is switched on.

Removal of the shielding cap, if required, will be delayed at least 30 minutes after the DT generator is switched off, to allow any short-lived induced activities to decay away. The housing of the generator and any components which require servicing or replacement will be surveyed on contact by a beta-gamma dose rate meter before handling.

The procedures for start-up and pit opening will be written down, and a checklist will be signed off and recorded in the operating log before any of these operations.

5.5 Radiation Damage to Components

No significant radiation damage is expected.

5.6 Handling and Confinement of Radioactive Material

No significant long-lived, removable activities are expected to be produced due to normal operation of this facility. All removed components will be surveyed by a beta-gamma radiation monitor. Any components with any detectable radioactivity levels will be bagged, and stored in the on-site radioactive source storage safe for future disposal as low-level radioactive waste.

5.7 Environmental Releases

The only anticipated radioactive releases are expected to consist of very low-level ^{16}N as outlined in section 5.1.2. If the maximum effluent level is measured to be higher than expected during commissioning, then this effluent will also be eliminated by running the system in a closed loop.

6. NON-RADIATION HAZARDS

The generator is contained within a sealed tube, inside a high-pressure "probe" housing containing SF_6 gas. This provides electrical insulation from the 100 KV high voltage developed inside the probe. The HV hazard is minimized by the radiation hazard interlocks, since the physical sources of both are in the same housing. In addition, pressure sensitive cut outs in the HV circuit prevent the instrument from operating if SF6 gas pressure is lost.

The generator is designed for, and is routinely used in extreme conditions of heat, humidity and roughness for oil bore-hole logging. As such the ruggedness of the instrument is an over-design for use in the relatively benign conditions of the underground SNO laboratory.

10. DECOMMISSIONING

10.1 Conceptual Plan for Decommissioning

The DT generator will be returned to MF Physics Corp. for disposal.

The neutron pit will be assayed for induced radioactivity produced over the life of the DT generator. No significant activity levels are anticipated.

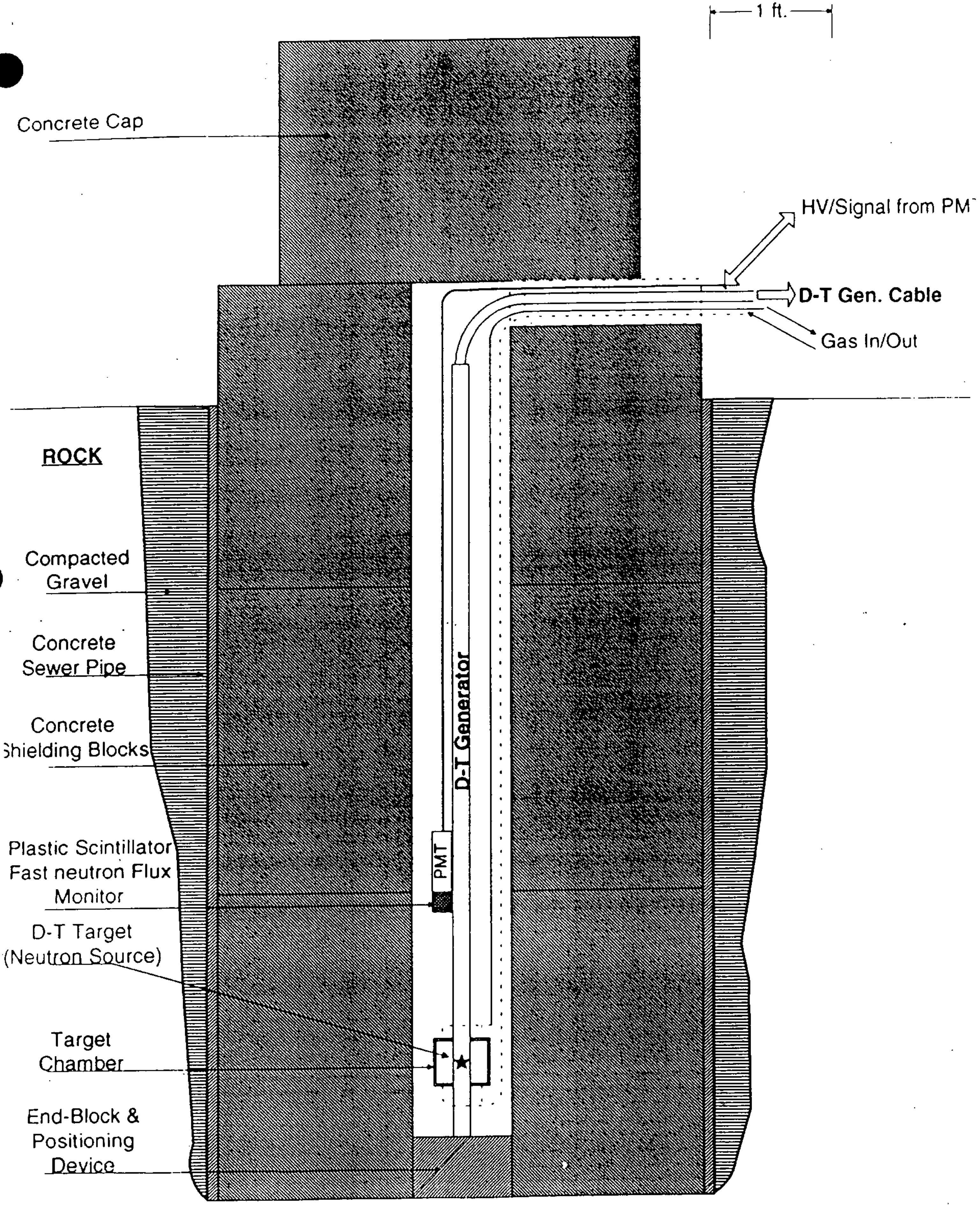
If any activity is found, and it is at an appropriately low level, the pit will be back-filled with cement, and appropriate signs will be posted.

If no significant activity is found in the concrete shielding blocks, they may be removed and disposed.

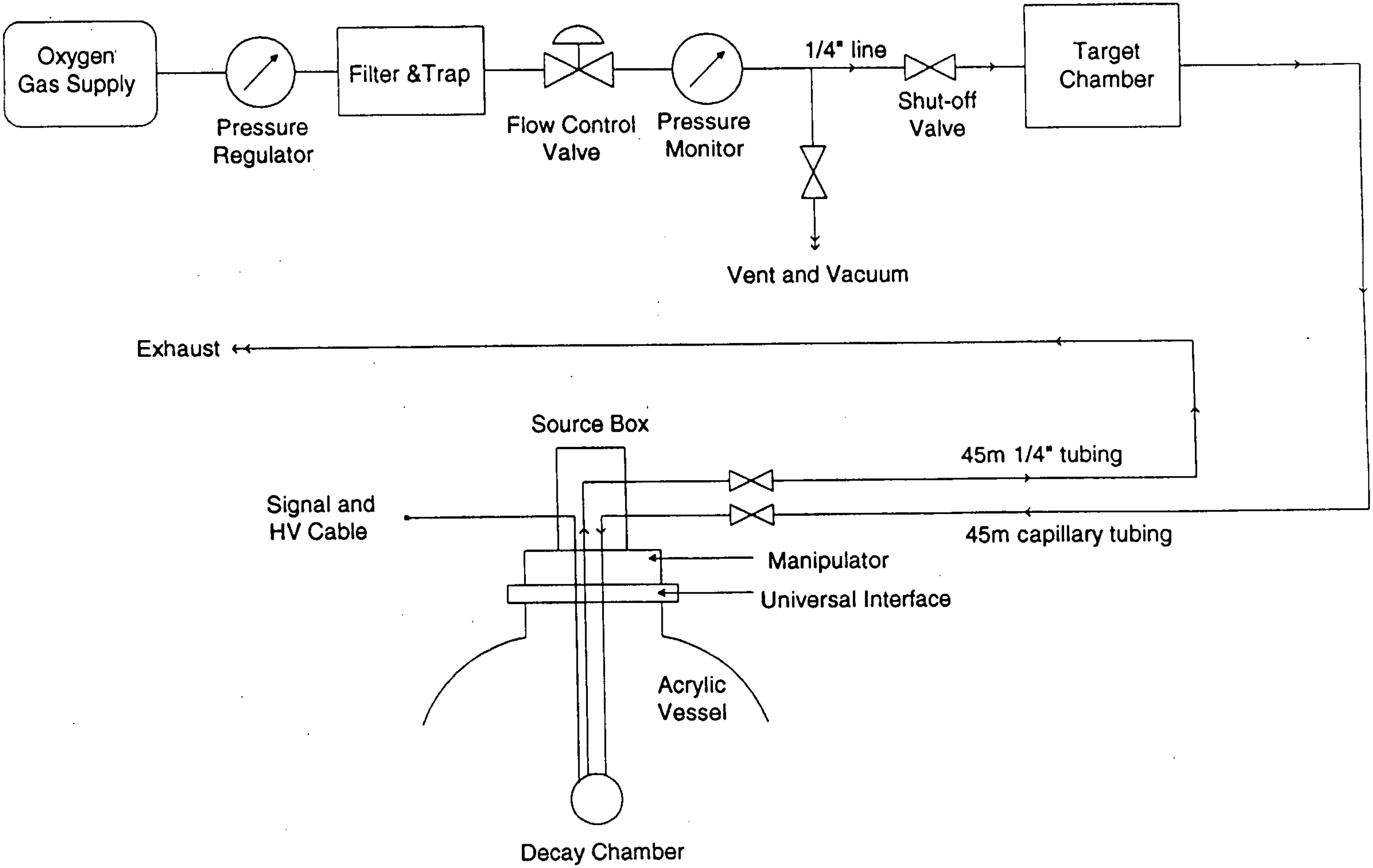
Since the inside of the pit will be routinely monitored during the working life of the facility (approximately 5 years), it is expected that activation levels exceeding those appropriate for backfilling will not be allowed.

List of Figures:

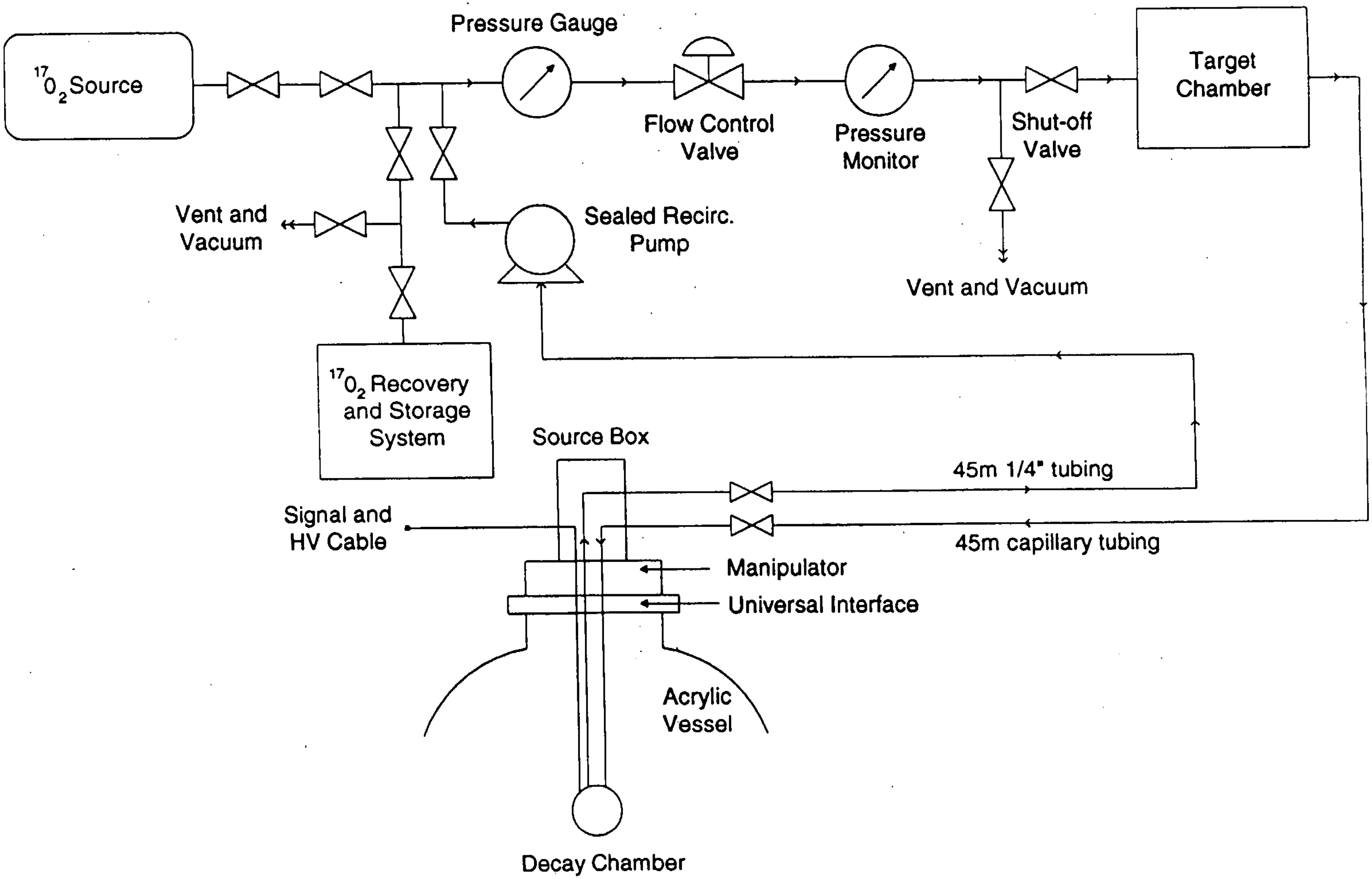
Neutron Pit Schematic



^{16}N Source: Schematic Flow Diagram



^{17}N Tagged Neutron Source: Schematic Flow Diagram



^{8}Li Source: Schematic Flow Diagram