CONF-791102--12 (Abst)

NEUTRON SHIELD ANALYSIS AND DESIGN FOR THE PDX FUSION FACILITY

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SUMMARY

The PDX (Poloidal Divertor Experiment) tokamak will be the first magnetic fusion device to produce intense neutron fields requiring substantial biological shielding. Injection of deuterium beams into deuterium plasmas is expected to generate up to at least 10^{15} 2.45-MeV neutrons per pulse and 5.0×10^{12} - 14.1 MeV neutrons per pulse. The experimental program requires 1000 pulses per year without occupancy restrictions in the control room. Limits for radiation exposure of operating personnel in the control room were set at 1 Rem/yr for the combined neutron and gamma radiation dose. The limit for public exposure at the closest site boundary (150 meters) was set at 10 milli-Rem/yr.

The basic component of the biological shield for PDX is an existing 81 cm thick high-density concrete shielding wall surrounding the machine. The principal additional shielding requirement is a roof shield over the machine to reduce air-scattered skyshine dose into the PDX control room and to the site boundary. The roof shield is designed in removable sections on a steel support structure permitting overhead crane access to major PDX components.

After analysis of a number of alternate concepts, a roof shield consisting of 50 cm of water in polyethylene tanks was selected to meet design objectives of effectiveness, weight, removability, and cost. The controlling factor on water thickness in the tanks is the gamma ray skyshine dose at the site boundary. Additional shield doors, thin walls, and plugs are required to satisfy the control room radiation requirement.

INTRODUCTION

Designing shielding for an existing structure such as the PDX building is more difficult in one sense because the options are usually limited relative to modifying the existing structure to suit the priorities of the shielder. In confrontations with the experimentors, the shielders priorities receive a low rating. On the other hand, with an existing facility, the problem areas are usually well-defined and there are consequently fewer surprises in store for the shielder in the final stages of construction modifications.

To satisfy the PDX experimental program requirements, the capability to conduct up to 1000 pulses per year is desired. The annual yields for 2.45 MeV and 14.1 MeV neutrons will be 10^{18} and 5×10^{15} respectively. PDX is located in the same building as the PLT (Princeton Large Torus) and some pre-existing shielding walls were already in place prior to these studies as is indicated in Figure 1. The PDX machine is located near the center of the room with the midplane of the torus approximately 1.5 meter above the level of the machine floor. The environmental roof over the building is not shown in Figure 1 since it has essentially no shielding value.

Figure 1. Cutaway View of PDX Existing Shielding Wall

The first floor is 30.5 cm of ordinary concrete with a large number of hatches and penetrations permitting access to the machine by system utilities located in the basement. These hatches and penetrations permit neutron streaming paths whereby first flight neutrons can scatter off the concrete basement floor, under the 81 cm shielding wall, into the PDX control room to the west side of the machine. Three doorways permitting personnel access to the machine room will require heavy shielding doors to block neutrons scattering off the concrete shielding wall and neutron capture gamma-rays from the concrete. A roof shield over the machine room is required to reduce both neutron and neutron capture gamma-ray skyshine reflection into the control room and to the site boundary 150 meters from the torus. Additional shielding reinforcement is required on the west shielding wall facing the PDX control room to reduce total radiation dose to personnel in the control room to 1 Rem/yr.

SHIELD ANALYSIS

Two considerations complicate the design of an acceptable roof shield for PDX. Foundation loadings are near maximum limits already due to the 81 cm high density concrete shielding wall surrounding the machine room and access to the PDX machine and auxilliary equipment is required for the 30-ton capacity overhead crane, which will travel above the shielding roof. These two considerations require a roof shield that minimizes weight and is designed in moveable sections so that the overhead crane can lift PDX components over the concrete shielding wall for transport to designated maintenance locations. Pre-stressed concrete roof sections would be too heavy and clumsy to move around. A dome shield over the PDX machine itself would require shielding skirts dropped from the dome which would interfere with diagnostic access to the torus. The roof shield design selected to satisfy these requirements consists of water in polyethylene tanks 63 inches by 96 inches supported on a steel structural framework which covers the PDX machine room. Each tank can be drained by a portable overhead sump pump to permit ease of removability whenever portions of the roof shield are dismantled.

Although ordinary water is an excellent material to attenuate 2.5 MeV neutrons, it is a poor shielding material for 14.1 MeV neutrons and marginal for concrete neutron capture gamma-rays. The concrete capture gamma-rays originate in the concrete shielding wall and in the concrete floors below the PDX machine. In addition to these gammas, a 2.2 MeV gamma-ray results from hydrogen neutron capture in the water roof shield. Borating the water with boric acid equivalent to 5000 parts per million natural boron results in the production of 0.476 MeV capture gamma-rays in the shield from boron-10 instead of the 2.2 MeV gammas from hydrogen capture. The boron capture gamma-rays are softer and are self-attenuated by the water more easily. Borating 15 inches of water results in a reduction of the gamma-ray skyshine dose in the control room by a factor of 2 compared with unborated water, but has no effect on the capture gamma-rays from the concrete floors which leak through the roof. Borated water presents corrosion problems for the pumps, valves and piping used to fill and drain the tanks and its effect is reduced due to the large component of concrete gammas incident on the roof. Twenty inches of unborated water produces the same gamma skyshine dose at the site boundary (150 meters) as fifteen inches of borated water. Using 50 cm (20 inches) of unborated water, only 3 percent of the skyshine dose at the site boundary is due to neutrons which survive the roof shield. The neutron and gamma-ray skyshine dose in the control room is small compared with the direct dose leaking through the 81 cm concrete shielding wall in front of the control room. The very restrictive requirement of 10 milli-Rem/yr total dose at the closest site boundary due to PDX is only 15 percent of the natural background radiation in the vicinity of Princeton, N. J. and is the controlling factor for the 50 cm thickness of the water roof shield.

The source of 14 MeV neutrons at the torus is a factor of 200 less than the 2.5 MeV source. The lower attenuation of 14 MeV neutrons in water is such that the skyshine dose at 150 meters is about half of the 2.5 MeV neutron dose. Capture gamma-rays in the roof due to 14 MeV neutrons are negligible relative to the 2.5 MeV gammas.

Figure 2.

Modeling for the Skyshine Problem

The geometry for the skyshine problem relative to the roof and the torus is indicated in Figure 2. The neutron source is a ring at the midplane of the torus with a radius of 127 cm. The skyshine dose into the control room and to the site boundary for each thickness of roof shield considered can be solved economically in 3 steps.

A. The total neutron and capture gamma-ray source in each energy group leaking from the roof shield is obtained from an ANISN[6] one-dimensional slab transport calculation using a homogeneous source of 2.5 MeV and 14.1 MeV neutrons below the roof. The concrete floors are modeled below the homogeneous source which lies in a vacuum. Forty-five neutron energy groups and sixteen neutron capture gamma-ray groups were used in the ANISN calculation and the neutron and gamma-ray cross sections were taken from the Bugle library[1]. The concrete capture gamma-rays which stream back-up to the roof are thus included as part of the gamma-ray leakage from the roof along with the hydrogen capture gammas which originate in the roof.

B. Given the exact total leakage of neutrons in each energy group from step A, the radial distribution of the neutron leakage current from the roof is given by the equations developed in Reference 2. The neutron skyshine dose to the control room and site boundary was calculated for the 45 energy groups of the leakage source distribution by a random walk problem with the RAFFLE Monte Carlo code[3] using cylindrical symmetry for the PDX building, source and shielding walls. The air mass above PDX was taken to have the density at sea level for 60 percent humidity.

C. The gamma-ray skyshine dose was obtained from a modified QAD point kernel code[4] using the total photon leakage current in each energy group calculated in step A. This integrated total leakage current was modeled as a point source for each of 16 energy groups at a point on the roof above the axis of the torus. The point source restriction is a requirement for this code and represents a significant approximation only for the gamma skyshine dose into the control room. At 150 meters, the point source approximation for the roof source is excellent.

In steps B and C, the angular distribution of the leakage neutrons and photons was taken to be isotropic in the half plane above the roof. From the results of the ANISN calculations, the angular distribution of leakage neutrons and photons peaks in a direction normal to the roof in the highest energy groups. The isotropic assumption for leakage particles is conservative in these calculations since particles emitted parallel to the roof contribute proportionately higher to the dose at ground level than those emitted normal to the roof.

The radial distribution of leakage neutrons from the roof in step B above as a function of the radius R from the axis of the torus for a single source neutron below the roof was

$$j(R) = \frac{1}{4\pi^2} \int_0^{\pi} \frac{\sin\alpha \, \ell^{-\Sigma_1 \ell}}{(\ell+r)^2} \, d\phi \qquad (1)$$

Equation (1) is the uncollided leakage current derived for a ring source representation of the torus[2] where each point in the ring source contributes to the leakage current j(R) from the roof shield. The geometric parameters in Equation (1) are defined in Reference 2. Equation (1) yields a flatter distribution for the neutron leakage from the roof than a point source at the midplane on the axis of the torus. The macroscopic cross section Σ_1 is the total cross section of the shield for the source energy. The source group distribution falls off with increasing radius R due to the increasing slant thickness of the roof for source neutrons incident on the at an angle α relative to the normal to the roof. If one assumes the separability of the spatial and energy dependence of the leakage current from the roof, the source normalized leakage current in each energy group g is

$$S_g(R) = N J_g \, j(R) \qquad (2)$$

where

$$N = \frac{S}{2\pi \int_{roof} j(R) R dR} \qquad (3)$$

and S is the number of source neutrons per pulse in the torus. The denominator of Equation (3) was integrated numerically for the ring source uncollided current given by Equation (1). J_g in Equation (2) is the total leakage current in energy group g from the slab ANISN calculation using a homogeneous source of a single neutron below the roof. The spatial distribution in each energy group then exhibits the same shape as the first flight neutrons from the source. This is a reasonable result since the first flight neutrons at any radius R contribute to the slowing down source for neutrons at each lower energy.

J_g is the energy dependent normalization factor for Equation (2). This one-dimensional slab leakage current in each group g is an exact result using a uniform distribution of source neutrons below the roof because the integrated leakage current is independent of the source distribution below the roof as long as the source lies in a vacuum. This hypothesis is proved in

Reference 2 for first flight source neutrons. The one-dimensional slab transport calculation with a uniform source distribution below the roof correctly integrates all attenuation paths through the roof shield at each energy E. For the uniform source normalized to a single neutron, the neutron current emerging from the slab is just the probability per source neutron of leaking from an infinite slab. One additional advantage of this model is that the concrete floors below the torus can be modeled correctly in slab geometry and the concrete neutron capture gammas emerging from the roof shield are likewise correctly integrated. This is an important consideration for a water roof shield since the higher energy concrete gammas contribute significantly to the skyshine dose[2].

The Monte Carlo neutron skyshine problem using the source distribution for 45 energy groups given by Equation (1), sampled 70,000 source histories from isotropic angular distributions in the half-plane above the roof shield. 70,000 source histories produces statistics at the site boundary of ± 10 percent for 2.5 MeV source neutrons using a track length estimator for the neutron flux[3]. Five percent steel by volume was placed at the height of the PDX environmental roof homogenized into a 30 cm thickness to represent roof steel over the area of the roof. The neutron skyshine dose into the control room was increased 20 percent relative to no roof steel included; therefore, 5 percent by volume environmental roof steel was included in all neutron skyshine calculations.

The leakage capture gamma-ray distribution at the top of the roof shield is a flatter distribution[2] then the neutron distribution due to the fact that the gamma-rays are born isotropically in the shield and the intensity emerging from the roof at a radius R depends only on the neutron current density incident on the bottom of the roof at radius R. The integrated leakage over an infinite roof is again given exactly in the coupled neutron-photon slab transport problem for a uniform neutron source distribution below the roof. The point kernel transport calculation for the photon skyshine[4] over 16 photon energy groups uses a point source representation for the integrated leakage at the top of the roof shield. This approximation is negligible for the skyshine at 150 meters, but is more serious for skyshine into the PDX control room near the source. Since the photon skyshine dose to the control room is only a small part of the total dose, this approximation will not have a significant effect on the results.

The total skyshine dose determined by the above methods is given at two locations in Table I for two different roof designs. The first is for 0.381 meter (15 inches) of water borated to 5000 parts per million (PPM) with natural boron and the second is for 0.483 meter (20 inches) of unborated water.

TABLE I

TOTAL SKYSHINE DOSE TO CONTROL ROOM AND SITE BOUNDARY

Dose Point	.381 m Borated Water 5000 PPM	.483 m Water No Boron
	Ray Dose (mR/pulse)	
Control Room	.058	.058
150 m	.0073	.0073
	Neutron Dose (mR/pulse)	
Control Room	.040	.0045
150 m	.0016	.0002
	Total Dose (mR/pulse)	
Control Room	.098	.062
150 m	.0089	.0075

In Table I, the 0.483-meter thickness of unborated water was chosen to yield the same gamma-ray skyshine dose as 0.381 meter of borated H_2O. The contributions of both 2.5 and 14.1 MeV neutrons to the neutron skyshine dose has been summed. The capture gammas from 14.1 MeV neutrons are negligible.

DIRECT DOSE THROUGH 81 cm CONCRETE WALL

At 150 meters, the 127 cm plasma radius of the torus represents a close approximation to a point source and a one-dimensional spherical annulus approximation for the 81 cm high density shielding wall was used to calculate the coupled neutron photon direct dose through the wall into the control room and to the site boundary[2]. Since the skyshine dose from the roof shield was calculated separately, a vacuum was assumed outside of the shielding wall so that the skyshine dose would not be calculated again due to the spherical symmetry condition with the associated scatter reinforcement from a spherical air mass. The spherical annulus representation of the shielding wall is conservative for dose points in the PDX control room. This is because the spherical annulus always presents the minimum thickness to radius vectors from the source whereas radius vectors through a slab shielding wall intercept increasing slant thicknesses in a vertical or horizontal plane. The direct dose due to both 2.5 MeV and 14.1 MeV neutrons was determined using the ANISN coupled neutron-photon Bugle[1] cross section library for 45 neutron energy groups and 16 photon groups. The results are presented in Table II using Princeton specifications for the constituents of the concrete mix.

TABLE II

TOTAL NEUTRON-PHOTON DIRECT DOSE (mRem/pulse)

		14.1 MeV Source	2.5 MeV Source	Total
Control Room	Neutrons	.058	2.744	2.802
	Gammas	.005	.565	.570
	Total	.063	3.309	3.372
150 Meters	Neutrons	1.42-4*	6.66-3	6.80-3
	Gammas	1.30-5	1.54-3	1.55-3
	Total	1.55-4	8.20-3	8.36-3

*1.42-4 is 1.42×10^{-4}

3.372 mR/pulse in the control room exceeds the acceptable design dose of 1 mR/pulse for radiation workers. Three inches of polyethylene or water on the inside surface of the control room shielding wall is sufficient to reduce the combined dose in the control room to 0.7 mR/pulse with the resulting direct dose to 150 meters through the control room of 1.1×10^{-3} mR/pulse. Table III lists the calculated values for the three principal mechanisms of radiation leakage into the control room at 150 meters for the 50 cm water roof shield.

TABLE III

DOSE AT CONTROL POINTS (mR/pulse)

	PDX Control Room (9 cm Water on Wall)	Site Boundary 150 Meters (No Water on Wall)
Direct Dose	0.7	0.0085 (maximum)
Basement Scatter	<0.15	---
Skyshine	0.1	0.0075
Total	0.95	0.0165

The direct dose to the site boundary in Table III is along the normal radius vector from the torus to the wall without additional shielding on the wall.

Basement Shine to PDX Control Room

In Table III, the contribution to the radiation dose in the control room from single scattered neutrons off the basement floor was determined to be < 0.15 mR/pulse. Figure 2 indicates the geometry whereby neutrons on first flight from the torus can scatter off the basement concrete floor, under the 81 cm concrete shielding wall, to the PDX control room. The torus is partially shielded by the 30.5 cm concrete first floor. A large number of hatches and utility ports penetrate the first floor under the torus permitting unshielded first flight streaming paths through the concrete floor to the basement[2]. Only two of the hatches permit single-scatter reflection under the shielding wall to the control room. The 2.5 MeV neutron scattered dose to the control room was calculated using Equation (4).

$$D = K\alpha \int_A \frac{\phi_{INC} \cos^{2/3}\theta_0 \cos\theta \, \ell^{-\Sigma Z}}{\rho^2} dA \qquad (4)$$

where $\phi_{INC} = \frac{S}{4\pi r^2}$

α is the single scatter albedo for flat concrete surfaces taken from the albedo data of French & Wells[5] and was evaluated as 0.11 per steradian for 2.5 MeV neutrons. The parameters in Equation (4) are defined in Reference 2. The dose D was evaluated at the center of the control room and the integration in Equation (4) is over the single-scatter area on the basement floor under the 81 cm shielding wall. This area was divided into 8 discrete segments[2] whereby Equation (4) could be evaluated by a desk calculator. Dose attenuation through the various concrete floor thicknesses Z was determined from curves generated by ANISN[1] for ordinary concrete slabs. The radiation level due to the largest first floor hatch was 2 mR/pulse near the entrance to the control room. With this hatch plugged, the scattered dose is ∿0.15 mR/pulse. The dose with all hatches plugged is 0.022 mR/pulse. Only the largest hatch will be plugged with concrete because necessary electrical bus lines pass through the other ports.

Substantial shielding doors are required at the northwest doorway entrance to the machine room. Without shielding the dose in the hallway leading to the PDX control room from scattered neutrons off the north shielding wall is estimated from Equation (2) to be 46 mR/pulse[2]. In addition to this, concrete capture gammas from the east shielding wall stream through the doorway to deliver a dose of 1.3 mR/pulse[2]. A shielding door equivalent to 12 inches of polyethylene backed by 2 inches of steel is required to reduce this radiation to 1 mR/pulse.

ROOF SHIELD DESIGN

The roof structure rests on the concrete block shield walls and supports the shielding water tanks. It consists of four (4) 36" wide flange beams running from the north to the south wall, 15" channels on the east and west walls and forty-nine (49) 12" I-beams running east and west between the other members and supporting the tanks either directly or by means of a fiberglass grating All the beams and channels are A-36 structural carbon steel and have a net weight of about 26 tons.

The magnetic field disturbances in the plasma from the structure have been calculated and the maximum effect is less than 1 gauss, which is considered acceptable. The beams and channels are insulated from each other precluding any eddy current problems.

The structure carries a weight of 110.4 lbs/ft^2, or 150 tons total in polyethylene tanks and water. Flame shielding, of an undetermined nature, is estimated to add less than 15T to the total. If the polyethylene tanks are unsuitable, the structure can carry steel tanks filled with water, at a total weight 217 tons, without exceeding its stress of deflection limits.

The structure is designed to maximize machine access. The total height is only 36 inches, the tanks are readily drained and removed and the 12" I-beams may easily be unbolted and removed for access to wider areas. The clearance below the crane bridge is four feet over most of the PDX area, and ten feet over the annex area, allowing access to the PLT machine.

The major assembly problem appears to be bringing the two 50 foot long beams into the PDX area. It is proposed that the beams be brought in through holes in the north wall.

The only instrumentation which will be provided with the roof tanks is a liquid level sensing system. Two independent circuits will be used to monitor the water level in each tank. The two Delaval Gems level switches on each tank will each be connected in a normally open mode in an OR configuration. Actuation of any switch on either circuit will send an interrupt (alarm) signal to the IBM 1800/control room, through optically isolated links. Identification of the specific tank(s) causing the alarm will be performed on the machine floor. Rotary switches will be used to connect indicator lamps sequentially across each level switch.

Three types of material were considered for the roof tanks: stainless steel, carbon steel, and polyethylene. The stainless steel was dropped from consideration due to excessive cost. The four major design concepts which were evaluated are as follows:

The first concept consisted of steel tanks with Hypalon linings and steel tops. The sides of the tanks would be stepped to provide an interlocking system to eliminate gaps. This concept provided a minimum overall height but would be very difficult to disassemble in that as many as nine tanks would need to be removed just to get a specific one out.

The second concept consisted of straight sided steel tanks with Hypalon bladders. The gaps between the tanks would be blocked by slabs of borated polyethylene placed on top of the tanks. This concept produces an overall height of approximately 8" above the 36" steel support beams.

Disassembly would be relatively easy, but, as in the first concept, large amounts of carbon steel would be required.

The third concept was the same as the second one with the exception of the substitution of Hypalon linings and steel tops for the Hypalon bladders. The characteristics of this system are the same as for the second concept and only a minor reduction in cost is realized.

The fourth concept consisted of straight sided, molded polyethylene tanks with fiberglass supports. The gaps between the tanks would be blocked by slabs of borated polyethylene placed on top of the tanks. The overall height of this system is the same as for concepts two and three. However, the disassembly of his system is simpler because the empty tanks weigh about 450 lbs each while the steel tanks would weight up to 300 lbs. In addition, this system costs considerably less than the alternatives.

The polyethylene tanks are of 1/2" thick high density polyethylene and will be rotation molded. Their overall size was selected to be approximately 63" x 96" and 21" deep, the maximum size that manufacturers have a demonstrated ability to produce. The tanks have 6" wide inner flange at the top for added lateral stiffness and to provide a mounting surface for a separate 1/4" thick top. The top is required to prevent excessive evaporation, spillage of the water, and introduction of foreign objects. The top will include a port for filling/draining, ports for the liquid level sensors, and a fire prevention shield to prevent fires.

Fire resistant fiberglass grating and beams will be used under the tanks to provide continuous support for the tanks. A thin heat shield will be placed between the tanks and the grating to protect the tanks from fire from below.

Fire retardant borated polyethylene slabs (4" wide and 8" deep) are used to block the gaps between the tanks over the area of the machine. When the tanks are empty the gaps will be nominal 1/2" to facilitate installation, but when the tanks are filled the gaps will be greatly reduced by the inherent bulging of the tanks.

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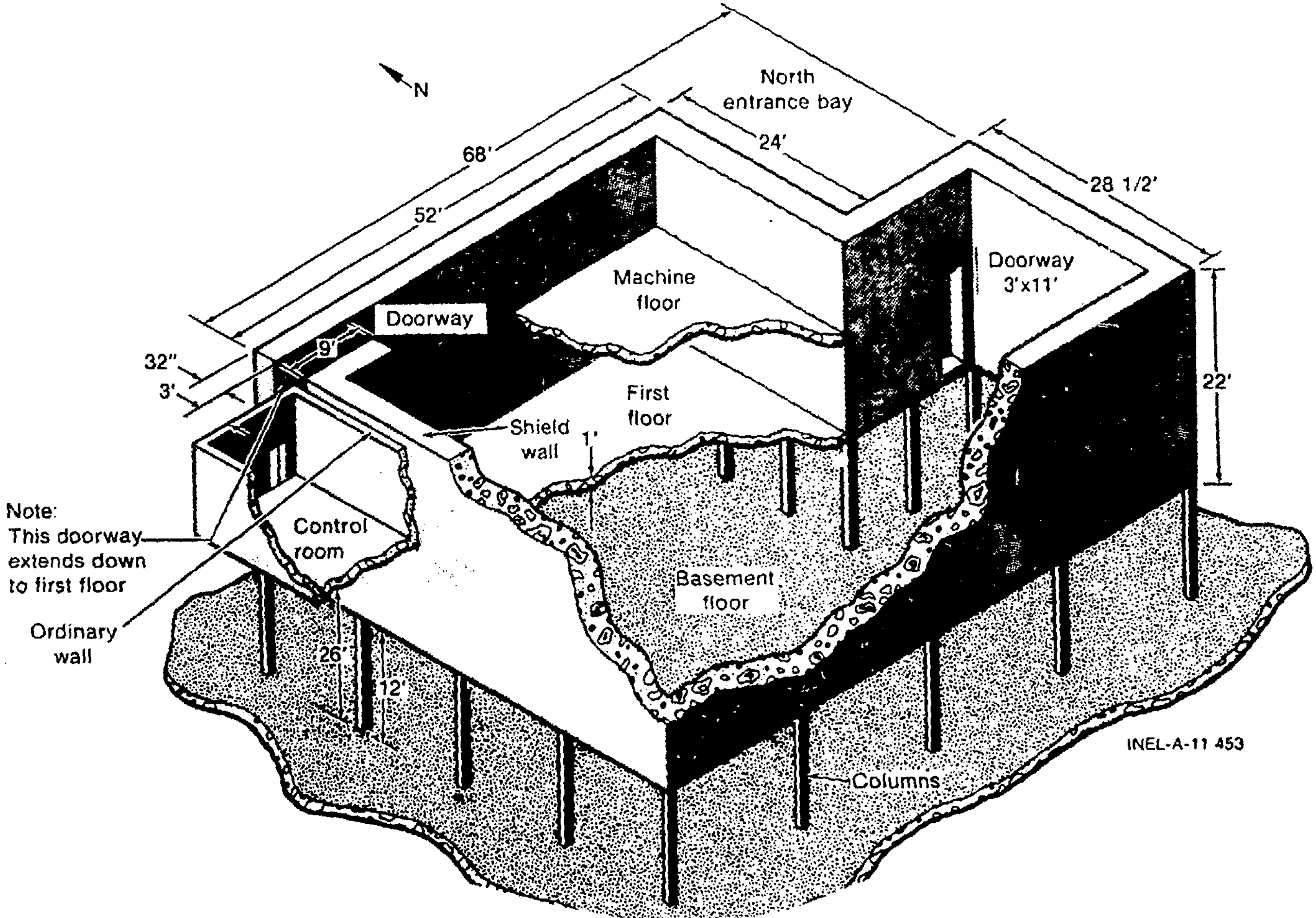
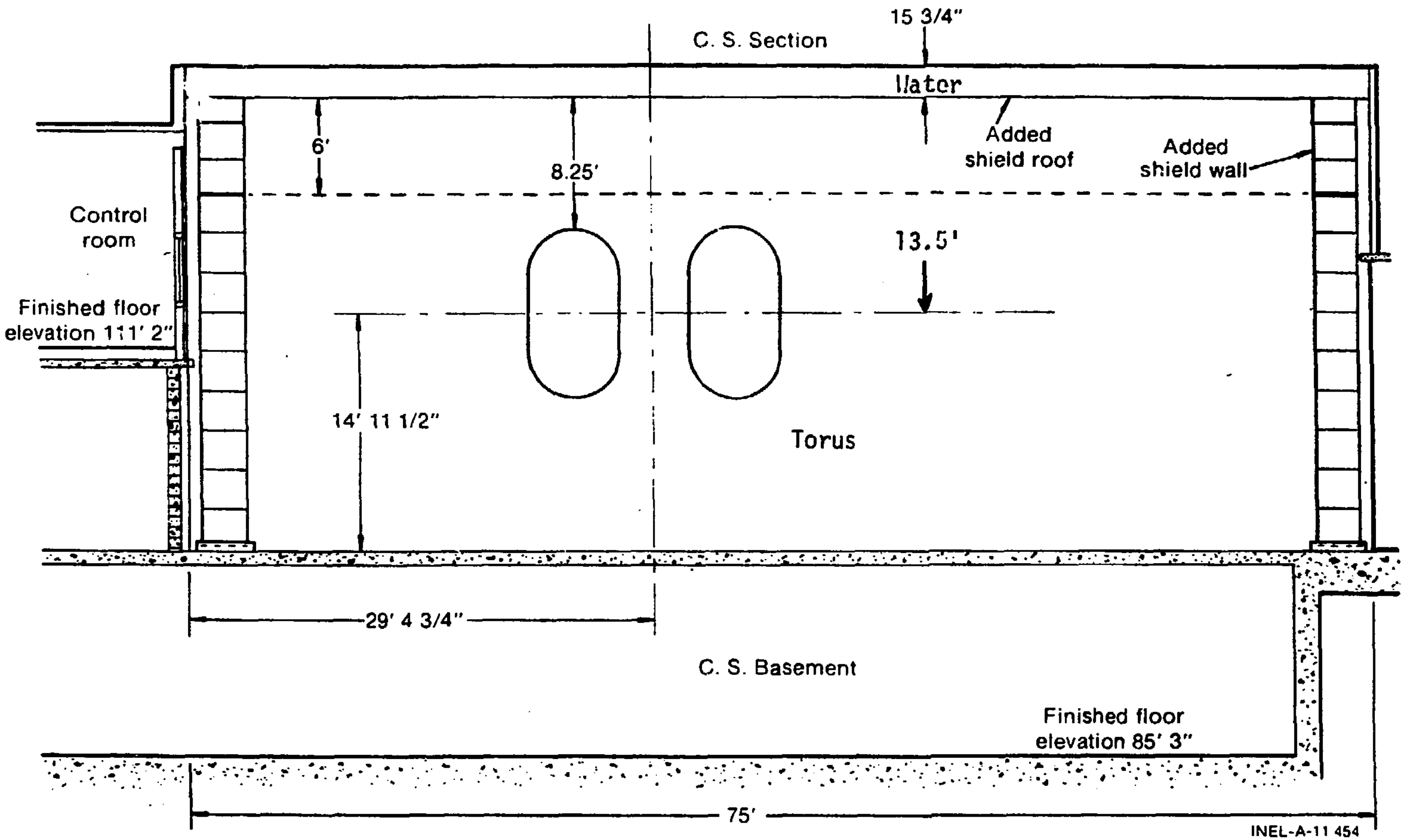


~~Figure 2.1-1.~~ Fig. 1. Cutaway View of PDX Existing Shield Wall.



~~Figure 2.1-3~~. Side View of PDX Torus and Existing Shield Wall.

Fig. 2.