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PRELIMINARY RADIATION CRITERIA AND NUCLEAR ANALYSIS FOR ETF

by

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GENERAL ATOMIC COMPANY

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GENERAL ATOMIC COMPANY

PRELIMINARY RADIATION CRITERIA AND NUCLEAR ANALYSIS FOR ETF*

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Preliminary biological and materials radiation dose criteria for the Engineering Test Facility are described and tabulated. In keeping with the ETF Mission Statement, a key biological dose criterion is a 24-hour shutdown dose rate of 2 mrem/hr on the surface of the outboard bulk shield. Materials dose criteria, which primarily govern the inboard shield design, include 10^9 rads exposure limit to epoxy insulation, 3×10^{-4} dpa damage to the TF coil copper stabilizer, and a total nuclear heating rate of 5 kW in the inboard TF coils. Nuclear analysis performed during FY 80 was directed primarily at the inboard and outboard bulk shielding, and at radiation streaming in the neutral beam drift ducts. Inboard and outboard shield thicknesses to achieve the biological and materials radiation criteria are 75 cm inboard and 125 cm outboard, the configuration consisting of alternating layers of stainless steel and borated water. The outboard shield also includes a 5 cm layer of lead. NBI duct streaming analyses performed by ORNL and LASL will play a key role in the design of the duct and NBI shielding in FY 81. The NBI aluminum cryopanel nuclear heating rate during the heating cycle is about 1 milliwatt/cm^3, which is far less than the permissible limit.

Introduction

An important initial step in any shield design is the establishment of radiation criteria, i.e., the material and biological dose and dose rate limits outside the shield. In the case of fission power reactors, many of these radiation criteria have been standardized, and documented in various regulatory codes, guides, and handbooks. The fusion industry is young enough, however, to allow considerable flexibility in the choice of radiation criteria until more design, construction, and operating experience is acquired.

In the case of the Engineering Test Facility (ETF), now in the preconceptual design phase, the matter of setting radiation criteria is a cooperative effort on the part of several participating organizations. The nuclear analysis effort itself is being carried out by General Atomic with support from LASL and ORNL. Safety issues are the responsibility of INEL, including public radiation safety. Radiation limits on components are specified by the magnetic and electrical designers, namely MIT, PPPL, and GE.

It should be emphasized that radiation criteria selected in the preconceptual design phase of a novel device such as ETF can change almost on a day-to-day basis. An initial "guesstimate" of material and biological limits must be made at the outset to permit a first cut at the design of the bulk shield, the dimensions of which greatly influence the configuration of the rest of the device. Even though numerous iterations on shield thickness, composition, and arrangement can be anticipated, a start must be made so that the design of the plasma chamber, TF- and PF-coils, neutral beam system, and overall structure can be initiated.

This paper will primarily address the bases for the selection of ETF radiation criteria, but will also cover some of the initial bulk shield calculations and the influence of radiation criteria on the outboard shield configuration.

Biological Dose Criteria

The ETF Mission Statement[1] greatly influences the outboard bulk shield and component shielding design by specifying as a design goal "to allow hands-on maintenance external to the toroidal field coil shield." This objective is consistent with INTOR's guidelines "that radiation shielding of the penetrations must be adequate to the adoption of a partially remote maintenance plan which is based upon personnel entering the reactor hall for certain ex-reactor maintenance operations. Outboard of the shielding, numerous operations may be performed 'hands-on'."[2]

If contact maintenance is assumed for ETF, that is, relatively unlimited access to the

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tokamak building after shutdown, then personnel dose and dose rate criteria can be modeled after: (1) NRC/DOE guidelines, (2) nuclear fission plant practice, and (3) parameters already established for other fusion devices such as TFTR and INTOR.

NRC guidelines are delineated principally in 10CFR20 and Regulatory Guide 8.8. The latter is directed mainly at light-water power reactors and specifies that occupational exposures be "as low as reasonably achievable" (ALARA). The Code of Federal Regulations 10CFR20 specifies 1.25 rem/quarter for radiation workers, but is in the process of being revised to incorporate ALARA principles.[3]

DOE radiation guidelines are given in Chapter XI of the Department of Energy Environmental Safety and Health Manual, where it is stated that radiation worker exposure in controlled areas must not exceed 5 rem/year. However, this limit is subject to the provisions of ALARA guidelines, which specify that "onsite personnel exposure levels less than one-fifth of the permissible dose equivalent limits prescribed in this chapter should be used as a design objective."

Current fission plant design practice is also to limit worker exposure to one-fifth of 10CFR20 regulations, namely, 1 rem/year or approximately 0.5 mrem/hour for continuous 40 hour work weeks. Usually, continuous access to radiation areas is not required, in which cases higher general dose rates are permissible. Collectively, LWR plants are experiencing about 500 person-rem per unit-year accumulative occupational exposure, which NRC considers excessive.

With respect to other fusion plant designs, the TFTR onsite radiation design objective is <1 rem in a controlled area,[4] which is in accord with DOE guidelines. The INTOR design[2] divides workers into Class A, who might receive 1.5 rem/yr, and Class B, who would receive less than 0.5 rem/yr. INTOR earlier selected 2 or 20 person-rem as their annual cumulative exposure limit, but later increased the figure to 200 person-rem. In view of the fact that British gas-cooled reactors are experiencing 20 to 30 person-rem per year,[5] it seems reasonable to at least emulate this goal for ETF, which, after all, may be the forerunner to a DEMO fusion plant.

After consideration of the foregoing, provisional biological dose criteria were established for ETF as shown in Table 1.

The general dose rate criterion of 2 mrem/hr can be further evaluated in the light of expected downtime for ETF. The availability goal of 25% implies an annual downtime of 270 days, possibly apportioned as shown in Table 2.

TABLE 1
PROVISIONAL ETF BIOLOGICAL DOSE CRITERIA

ITEM	CRITERION	JUSTIFICATION
GENERAL DOSE RATE IN TOKAMAK BUILDING AFTER SHUTDOWN	2 mrem/hr 24 HOURS AFTER SHUTDOWN	TAKES INTO ACCOUNT THAT ETF IS SHUT DOWN ~75% OF THE YEAR AND DOSE RATE DROPS OFF WITH TIME.
DOSE RATE AT EXTREMITIES (HANDS) FOR CONTACT MAINTENANCE	10 mrem/hr	IT IS EXPECTED THAT LOCALIZED PORTIONS OF SOME COMPONENTS WILL EXCEED 2 mrem/hr.
HIGHLY LOCALIZED STREAMING DOSE RATE(s)	100 mrem/hr	ACCEPTABLE ONLY IF OVER AREAS WHICH ARE SMALL IN COMPARISON WITH WHOLE BODY AREA.
GASEOUS ACTIVITY IN TEST CELL	<0.2 MPC	IS CONSISTENT WITH ALARA (i.e., ONE-FIFTH OF 10CFR20). CORRESPONDS TO 1 μCi/m^3 TRITIUM.
CUMULATIVE PERSONNEL EXPOSURE PER YEAR	20 PERSON-REM	SUBSTANTIALLY LOWER THAN MOST FISSION PLANTS.
BIOLOGICAL HAZARD POTENTIAL (RADIOACTIVITY INVENTORY)	NOT A CONSTRAINT	RADIOACTIVITY INVENTORY IN ONE-OF-A-KIND TEST DEVICE IS NOT CONSIDERED LIMITING.

TABLE 2
DOWNTIME DISTRIBUTION

LENGTH OF DOWNTIME	NO. PER YEAR	ACTIVITIES	TOTAL MANHOURS IN BUILDING
1 DAY OR LESS	100	NO CONTACT MAINTENANCE	0
3 DAYS	20	MINOR ADJUSTMENTS	4,000
1 WEEK	10	INSTRUMENTATION AND DIAGNOSTIC REPAIRS; MINOR REPAIRS	10,000
2 WEEKS	4	MODULE CHANGEOUTS; MINOR REPAIRS	8,000
2 MONTHS	0.5	TORUS SECTOR REPLACEMENT; INBOARD MAGNET ANNEAL; NBI REPLACEMENT; DIVERTOR COIL REPLACEMENT; MODULE CHANGEOUTS	10,000
			32,000

Dose rate calculations to be discussed later indicate that if the shutdown dose rate is 2 mrem/hr at 1 day, it continues dropping with time to a level of $\sim$1 mrem/hr at 2 days. This reduction should be taken into account for all downtimes longer than 2 days. Another factor which should be accounted for is location in the building - if the dose rate between the outboard bulk shield and the outboard TF-coil is 2 mrem/hr, it will be much lower in remote locations in the building. Perhaps an average reduction factor of 2 is appropriate. The resulting accumulated annual exposure is 16 person-rem, which conforms to the criteria proposed in Table 1.

Material Dose Criteria

A continuing survey of expert opinion and experimental results on radiation effects shows some rather wide ranges for the key parameters. The important radiation effects will be discussed in order - insulation damage, TF-coil resistivity increase, and nuclear heating.

Insulation Damage

G10 or an equivalent epoxy-fiberglas electrical insulation is proposed for the ETF toroidal field coils. In this application, maintenance of insulating properties and compressive strength is essential. The critical location is in the inboard TF coils on the midplane, closest to the inboard shield. The radiation criterion needed is maximum exposure in rad (or gray), in a neutron and gamma spectrum characteristic of the ETF inboard region.

The excellent testing program performed on epoxy insulation by Coltman et al.[6] measured radiation effects at cryogenic temperatures up to an exposure of 10^{10} rads, but in an environment where 97% of the damage was contributed by gamma radiation (as contrasted with the ETF inboard region where at least 50% may be neutron damage - an entirely different damage mechanism).

In another experiment,[7] a series of compression fatigue tests was performed on G10 after irradiation to 10^{11} rads gamma radiation and 10^{19} n/cm^2 > 0.1 MeV, but at room temperature and 77 K rather than 4 K. The sample discs were much thinner than contemplated in TF coil design, namely, 0.5 mm. All samples survived the test satisfactorily, but applicability to ETF conditions is questionable.

The lack of experimental data for actual ETF conditions has led MIT to recommend a 10^9 rad limit for G10 insulation,[8] whereas ORNL points out that the material has been proven only to 2×10^8 rads.[9]

It is clear that further irradiation experiments are called for, including not only G10 but some other promising radiation resistant insulators such as Kapton.

TF Coil Resistivity Increase

The radiation induced resistivity increase in the TF-coil copper stabilizer should probably be limited to 25% of that of the pre-irradiated matrix (including magnetoresistivity).[8] Other recommendations in the literature range from 10% increase to doubling the resistance.[2] Periodic annealing is usually prescribed to restore conductivity, but as pointed out by Abdou and others, it may take two to three months to cool down the magnet from room temperature to 4 K.

The initial resistivity of the copper stabilizer is about 10^{-9} Ω-m. A 25% increase amounts to 2.5×10^{-10} Ω-m, corresponding to a neutron fluence of about 5×10^{17} n/cm^2 or 2.5×10^{-4} dpa (based on 5×10^{-22} dpa per unit fluence).

Nuclear Heating

Control of nuclear heating in the dewars and TF-coils usually follows automatically from control of radiation exposure. However, in those cases where heating may be the dominant factor, economic tradeoff studies are required to ascertain the proper limit.

Radiation effects constraints currently in force for the ETF design are listed in Table 3, along with some estimates of equivalent calculable quantities.

Preliminary Nuclear Anaylsis

Background

The general neutronics concerns for the ETF design are discussed and illustrated in another paper at this meeting,[11] and will not be repeated here. The selection of ETF bulk shield materials and configuration is also covered elsewhere, particularly with respect to the inboard shield[12] where it is shown that a 75-cm-thick configuration of stainless steel and borated water will control radiation levels to meet the materials dose criteria of Table 3. Therefore, this paper will focus on the nuclear analysis associated with the outboard shield. As already pointed out, the design of the outboard shield is dictated by the permissible shutdown gamma dose rate for contact maintenance. Of course, the same criterion applies to outboard duct shielding and component shielding as well.

Geometry - Outboard Shield

An overall view of ETF showing shielding concerns is provided in Ref. 11. Figure 1 of this paper illustrates the bulk shield and TF-coils, and shows typical shutdown dose points.

TABLE 3
PROVISIONAL ETF RADIATION EFFECTS CRITERIA

ITEM	CRITERION	EQUIVALENT QUANTITIES	JUSTIFICATION
DOSE TO EPOXY/FIBERGLAS INSULATION (G10 OR EQUIVALENT)	10^9 RADS COMBINED NEUTRON AND GAMMA	NEUTRON DAMAGE FUNCTION NOT KNOWN FOR EPOXY. 1 RAD $\cong 2 \times 10^{18}$ GAMMA MeV/cm^2	REF. 8
DAMAGE TO TF-COIL COPPER STABILIZER	$\sim 3 \times 10^{-4}$ dpa	$\Delta\rho \cong 3 \times 10^{-10}\ \Omega$-m $\phi t \cong 5 \times 10^{17}$ n/cm^2	FOR 25% RESISTIVITY INCREASE
HEATING RATE IN INBOARD TF-COILS	5 kW	INITIAL VOLUMETRIC HEATING RATE $\cong 2$ mW/cm^3; GAMMA FLUX $\cong 7 \times 10^{10}$ MeV/cm^2–sec	REF. 8
HEATING RATE IN NBI CRYOPANELS	<250 mW/cm^3 IN SS316	GAMMA FLUX $\cong 8 \times 10^{12}$ MeV/cm^2–sec	REF. 10
TRITIUM PRODUCTION IN BORATED WATER	MUST BE LESS THAN TRITIUM DIFFUSION INTO WATER		
AFTERHEAT	NOT A CONSTRAINT		FIRST WALL AFTERHEAT <1 W/cm^3
RADIOACTIVITY	SEE TABLE 1, SHUTDOWN DOSE RATE		BHP NOT CONSIDERED A CRITERION FOR ONE-OF-A-KIND MACHINE

As discussed in Ref. 12, the preconceptual design of the bulk shield consists of alternating layers of 316 stainless steel and borated water with the thickness and spacings chosen so as to minimize the external dpa rate to copper. The one-dimensional model used for calculational purposes is shown in Fig. 2.

Analytical Approach

For scoping and preconceptual design purposes, one-dimensional discrete-ordinates methods were deemed adequate for neutron and gamma flux calculations. The ANISN code with 25-neutron-group, 21-gamma-group DLC-41 cross sections was utilized on the CRAY computer at Livermore.

Referring to Fig. 1, the trial shield thickness of 1.2 m is small compared with the major radius of 5.4 m, implying that the correction for toroidal curvature should be modest. The 1-D problem could be run in a cylindrical geometry representing a poloidal inside radius of 2 m, but the D-shaped torus is only approximately represented by a circle. It was finally decided to run ANISN initially in slab geometry with the P_3S_{16} approximation, and adjust the external flux levels by a double $1/R$ correction, at least for shield scoping studies. Later, either a cylindrical 1-D discrete-ordinates calculation could be made, or, preferably, a two-dimensional treatment employing DOT or TRIDENT.

A subsequent calculation of shutdown gamma dose rates can also be performed using ANISN, but the PATH gamma shielding code[13] was preferred for three reasons: (1) the cross section set available for ANISN has insufficient photon energy groups below 1 MeV; (2) the calculation using ANISN would be limited to one dimension; and (3) the various sources of shutdown gammas could be individually identified only by making numerous ANISN runs.

Outboard Shield Results - Operating

There are numerous quantities of interest relative to the outboard shield during operation, such as the neutron flux level and spectrum at various locations. Figure 3 shows the absolute spectra both in the first wall and at the outside surface of the shield. Figure 4 depicts the dpa and gas generation rates in the first 30 cm of the first wall/shield. The dpa cross sections for 316 SS are from Ref. 14; the helium and hydrogen generation rates are assumed to be equivalent to the total (n,α) and

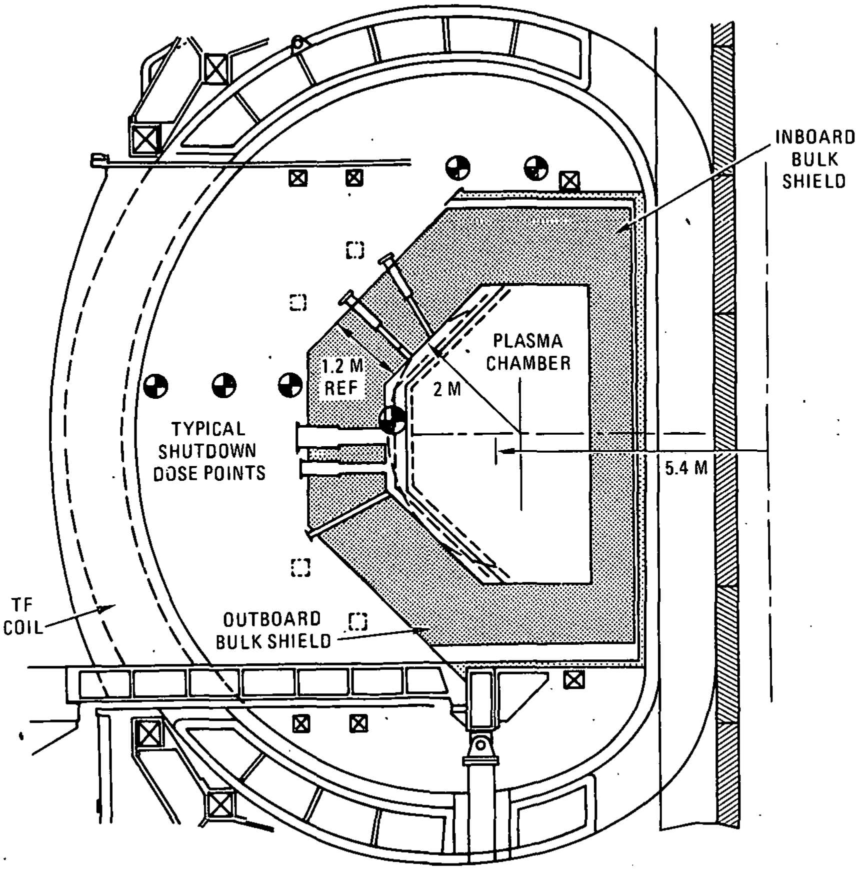

Fig. 1. ETF bulk shield geometry.

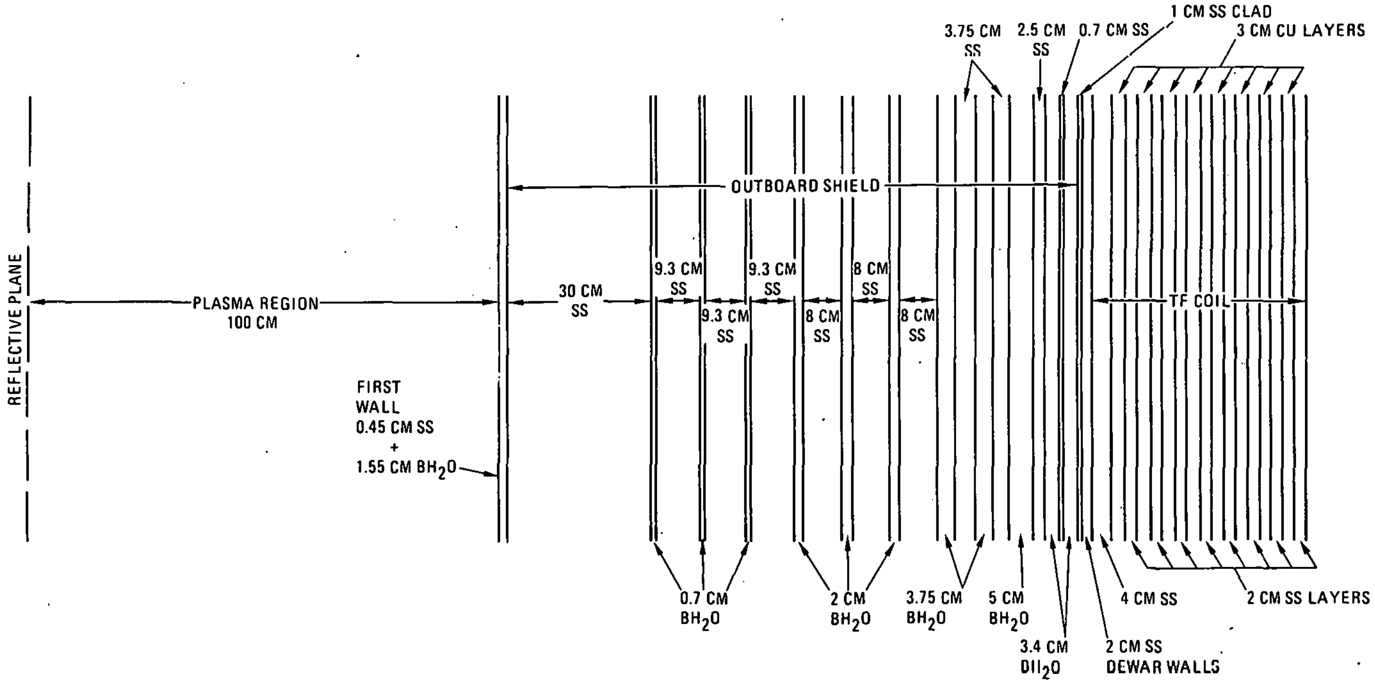

Fig. 2. Calculational model of outboard shield.

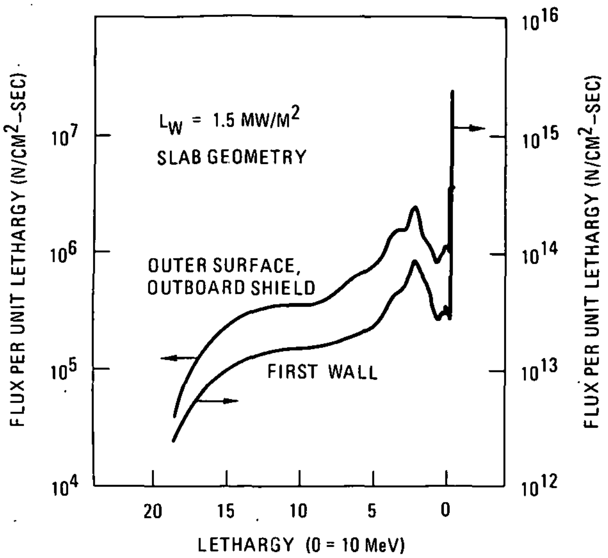

Fig. 3. Absolute neutron spectra in first wall and outside of outboard shield.

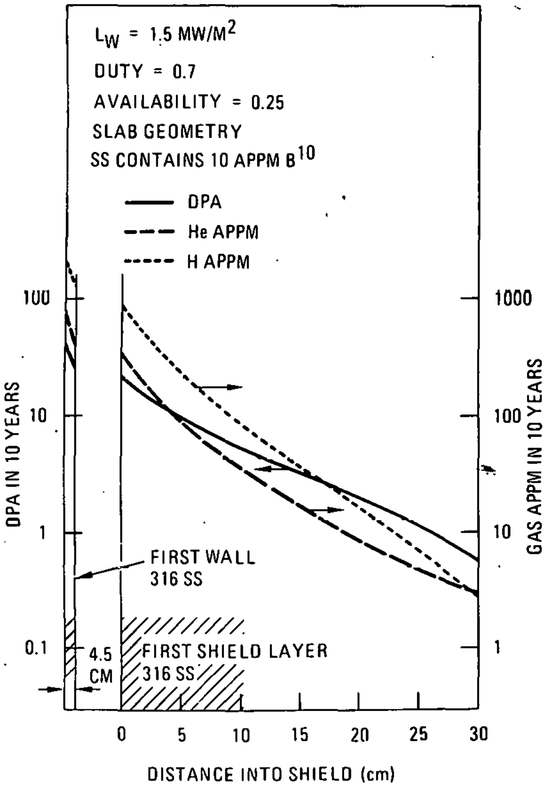

Fig. 4. Stainless steel dpa and gas generation in outboard shield.

(n,p) reaction rates in 316 SS respectively. Finally, Fig. 5 shows the nuclear heating rates (neutron and gamma) through the shield. Energy multiplication in the first wall/outboard shield is calculated to be 1.33. The operating biological dose outside the shield is 500 rem/hr, of which 425 rem/hr is from neutrons (at 1.5 MW/m^2 wall loading with a geometry correction factor of 2).

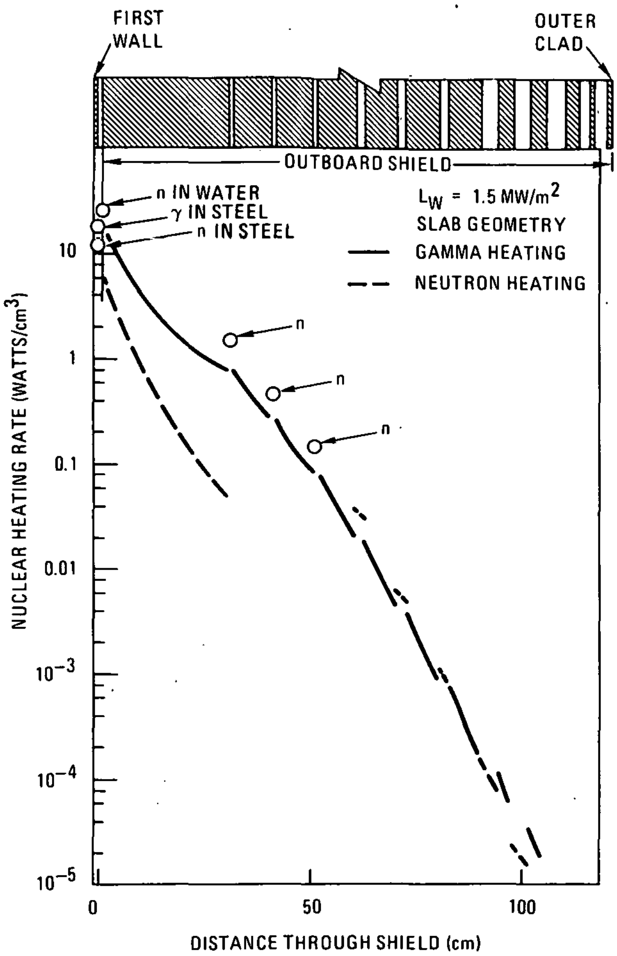

Fig. 5. Nuclear heating in outboard shield.

Outboard Shield Results – Shutdown

ANISN can be instructed to calculate any number of reaction rates in nuclides of interest. Of concern from the standpoint of shutdown dose rates are the troublesome photon emitters listed in Table 4.

At equilibrium (i.e., extended operation at 100% load factor) the radionuclide decay rate equals the reaction rate. After conversion to curies, the activity inventories with relatively short half lives (Mn56, Cu64) must be must multiplied by the duty factor. Nuclides with long half lives (Co58, Co60) must be multiplied by the availability (25%) as well. The finite plant life must also be taken into account in the case of Co60. The resulting induced activities in the outboard ETF shield and TF coils are shown in Fig. 6 (without geometry correction).

TABLE 4
HALF LIVES AND EMISSIONS OF TROUBLESOME ACTIVATION PRODUCTS

RADIO-NUCLIDE	HALF LIFE	ORIGIN	PHOTON EMISSION
Mn54	312 d	Fe54(n,p)	0.83 MeV 100%
Mn56	2.58 h	Mn55(n,γ) Fe56(n,p)	0.85 MeV 100% 1.81 28% 2.11 14%
Co58	70.8 d	Ni58(n,p)	0.81 MeV 100%
Co60	5.27 y	Co59(n,γ) Ni60(n,p) Cu63 (n,α)	1.17 MeV 100% 1.33 100%
Cu64	12.7 h	Cu63(n,γ)	0.51 MeV 38% 1.35 0.6%

PATH calculations were then made utilizing the volume sources of Fig. 6 as input. The 12 hour shutdown dose rate outside the shield was found to be excessive at approximately 30 mrem/hr. Increasing the shutdown time to 24 hours reduces this dose rate by one-third. Replacing the 316 SS with 201 SS in the outer half of the shield, the dewar walls, and the TF-coil structure further reduces the dose rate by a factor of two (because of the reduced nickel content of 201 SS). Finally, addition of 5 cm of lead to the outside of the outboard shield provides another reduction factor of 4. The net result is the achievement of a shutdown dose rate of 2.5 mrem/hr at 24 hours, comprised of the radionuclides shown in Fig. 7.

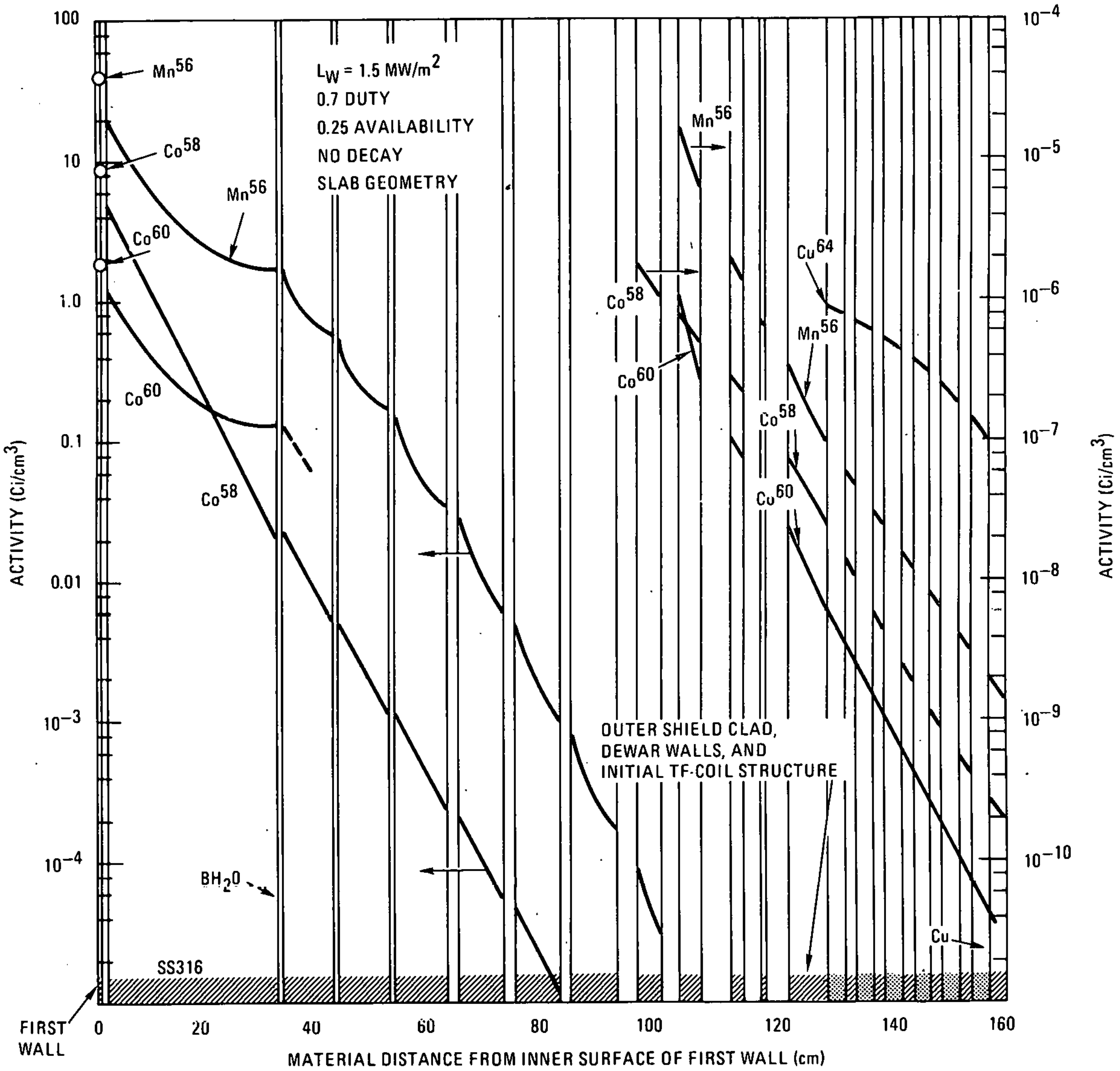

Fig. 6. Saturated induced activities in outboard region.

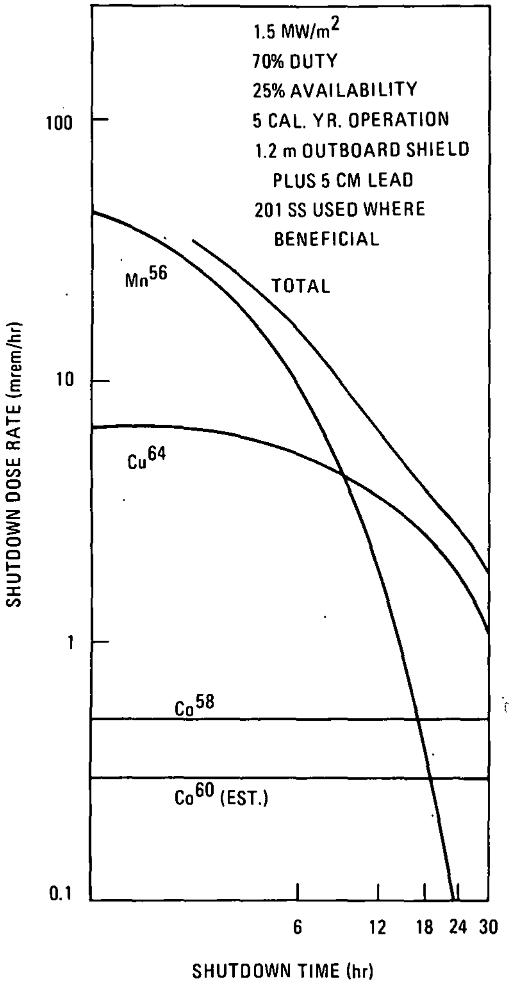

Fig. 7. Shutdown dose rate versus decay time.

Duct Streaming

Considerable work was performed during FY 80 on radiation streaming through the ETF NBI and vacuum ducts, primarily by Alsmiller's group at ORNL and Dusziak's group at LASL. ORNL evaluated nuclear heating of the NBI cryopanels using a series of codes including DOT 4.2. It can be concluded from this work that the aluminum cryopanel heating rate during the heating cycle will be about 1 milliwatt/cm^3. The work at LASL, reported in another paper at this meeting,[15] utilized the MCNP Monte Carlo code to calculate neutron and gamma streaming down the duct and the resulting surface sources on the duct walls, and then input this information into the TRIDENT 2-D discrete ordinates code to obtain fluxes in the duct shielding.

General Atomic and the ETF Design Center have been considering the use of shield plugs in the NBI ducts, which are open during the heating cycle and closed during the burn. If the heating cycle is 6 seconds, the burn cycle 100 secs, and the average power during heating is 25% of full power, the plug attenuation factor should be on the order of 100 to keep the NBI radiation exposure during the burn less than the exposure during heating. About 30 cm of steel should be adequate. Either a guillotine or a cylindrical shutter could be incorporated, the latter shown in Fig. 8. Detailed analysis of a shutter shield is planned in FY 81.

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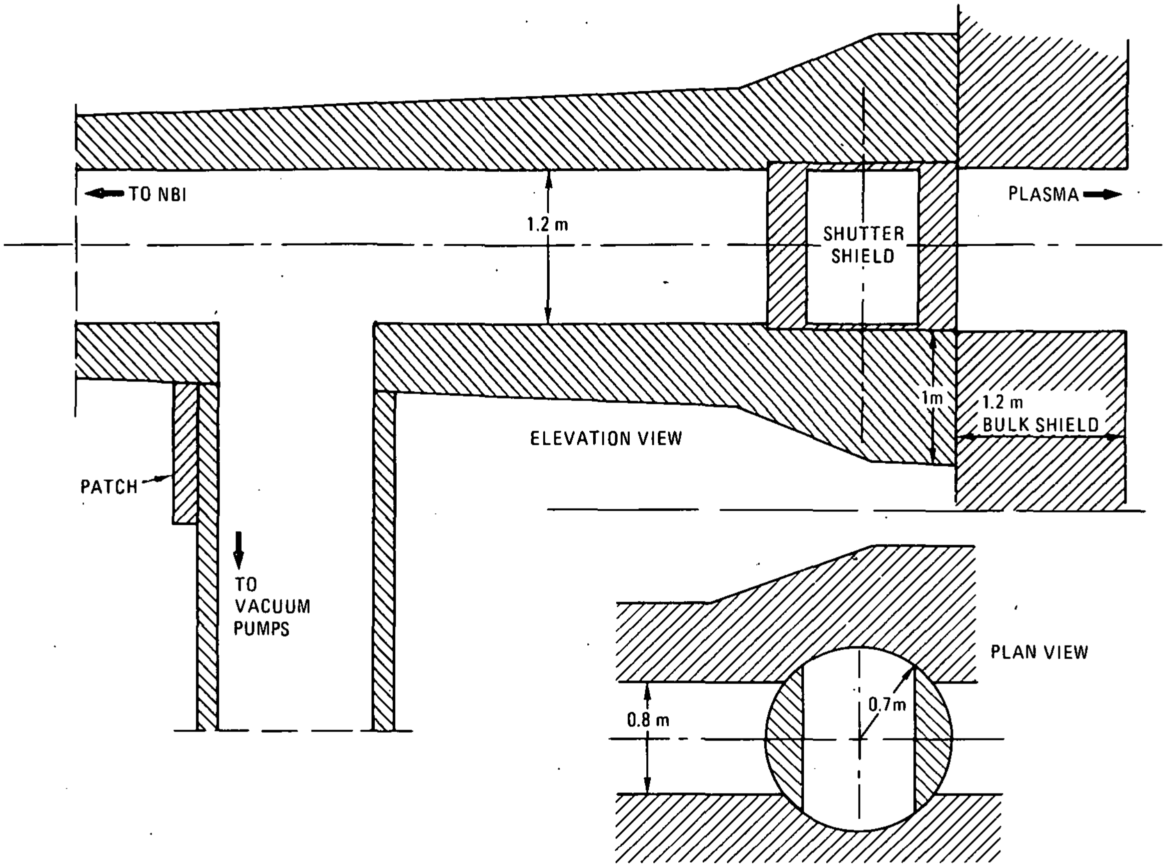

Fig. 8. Duct shielding with shutter shield.

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