Radioactivity in the Light Ion Fusion Target Development Facility

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RADIOACTIVITY IN THE LIGHT ION FUSION TARGET DEVELOPMENT FACILITY

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ABSTRACT

Radioactivity and biological dose calculations have been performed for the target chamber of the Target Development Facility (TDF). Two conventional shield designs are considered. One has the target chamber submerged 3 m from the surface of a borated water pool, the other has the chamber surrounded by approximately 250 cm of concrete. The first wall materials, Al-6061 and 2-1/4 Cr-1 Mo steel and the ion beam targets, one made from BeO_2 and W and the other from CH_2 and Au, are investigated. Shielding designs are presented that reduce the dose from each of these choices of shield, first wall and target material to acceptable levels.

INTRODUCTION

The light ion beam fusion target development facility (TDF) is an experimental facility proposed to verify the feasibility of using light ion beams to initiate thermonuclear burn within fusion targets. It is intended to test approximately ten to twelve 50-800 MJ fusion targets per day over a period of five years (~ 15000 shots over its lifetime). This large number of high yield shots causes the TDF to be one of the first inertial confinement fusion experiment where radioactivity induced by fusion neutrons could represent a significant biological hazard which would require some form of radiation shield. Therefore, the preliminary design of the facility has the target explosion chamber submerged in a borated water pool below the operating floor as shown in Fig. 1. Because the water shield might be lowered for periodic maintenance either in the chamber's interior or exterior and because workers performing this maintenance may be required to come in close contact with the first wall, it is very important to determine the biological doses the workers would be receiving near the target chamber. As an alternative to the borated water pool shield, a design where the target chamber has been enclosed within concrete as shown in Fig. 2, has also been investigated. Calculations of radioactivity induced in Al-6061 and 2-1/4 Cr-1 Mo steel walls and in target materials have been done. The resultant biological dose of the accumulated radioactive target debris and first wall structure has been computed. These results represent improvements on early calculations[1] which did not consider the effects of the activated target debris and which contained some inaccuracies.

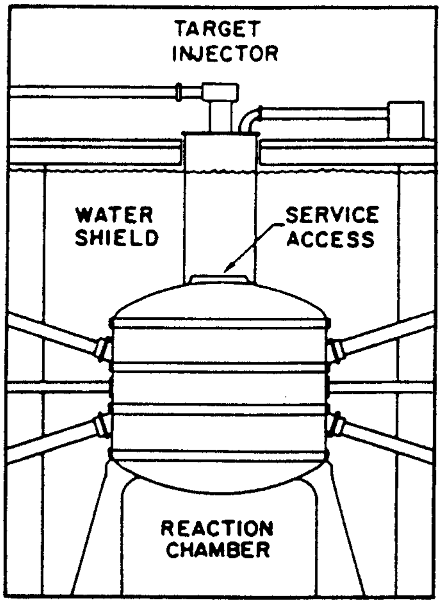

Fig. 1. TDF target chamber with water shield.

METHOD OF SOLUTION

The transport of neutrons and gamma photons, both in the burning target and throughout the facility is performed with the one-dimensional discrete ordinates code ANISN. A combined RSIC DLC-41B/VITAMIN-C and DLC-60/MACKLIB-IV 25 neutron-21 gamma group cross section library containing P_3 Legendre expansions of the scattering cross sections is used in the calculations. The cylindrically shaped

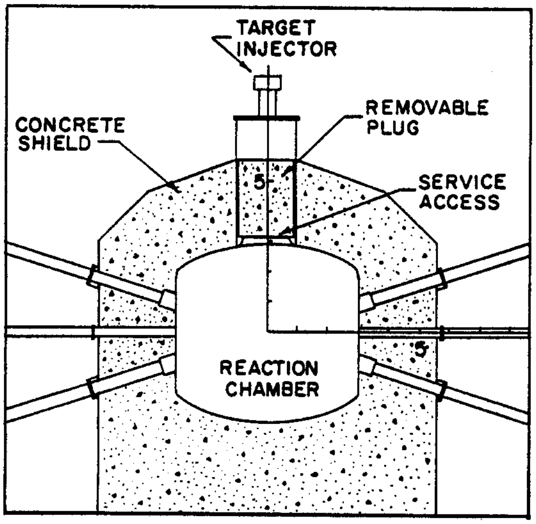

Fig. 2. TDF target chamber with concrete shield

target chamber is approximated by spherical geometry and hence the results represent conditions at the midplane of the chamber. The target chamber has an inner radius of 3.0 meters while the first wall is 3.5 cm thick for ferritic steel and 14.8 cm thick for aluminum. The first wall thickness has been determined through fatigue lifetime analysis.[2] A 3.0 m thick water shield having a boron content of 2000 wppm is assumed for the water pool design. The alternative design has the target chamber enclosed by a concrete shield containing a boron frites-barytes concrete,[3] 95% vol., and a carbon steel (C1020), 5% vol., as concrete reinforcement.

For the activation calculation the DKR computer code was employed. DKR computes activity levels and gamma photon sources for selected time periods after shutdown from the scalar flux distribution within the fusion target and the facility provided by ANISN. The decay data library used is DCDLIB which contains radioactivity data from ENDF/B-IV, the Table of Isotopes and the ACTL library.

For a comparison between the target debris and first wall material dose rates, the target debris from each pulse during a 1 year operation span was accumulated onto the interior surface of the first wall. The radioactive decay between each pulse and accumulation of the debris was computed by a small computer code which treats the target debris radioactivity produced by each pulse as a delta function in time. The pulse sequence is assumed to be 12 shots a day for 5 days a week for 52 weeks a year which amounts to 3120 shots/yr. The target debris gamma photons from each target were then transported through each of the first wall materials and the target dose rate computed.

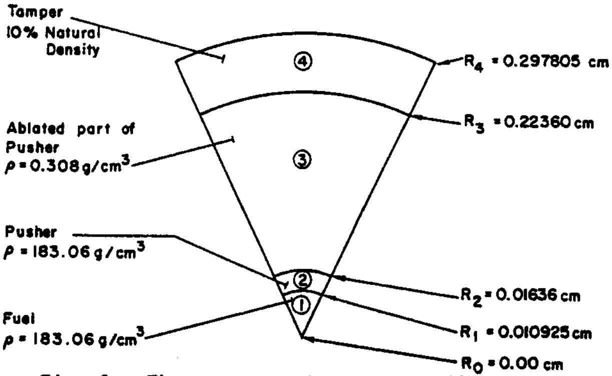

Fig. 3. The compressed target configuration used for the neutronic and radioactivity calculations.

TARGET ACTIVATION ANALYSIS

When considering the effects of radioactive target debris, two ion beam targets were analyzed. Both are based upon a target design published by Bangerter and Meeker.[4] The targets are composed of a 1 mg DT region surrounded by a BeO_2 pusher and a W-tamper or a CH_2-pusher with an Au tamper. The compressed target configuration used for the neutron transport and neutron activation calculations is shown in Fig. 3. A 30% fuel burnup fraction was assumed, giving approximately 100 MJ of released fusion energy with 71 MJ of that being in neutrons. The activation results presented are for one ignited target.

The results of the BeO_2-W target constituents are shown in Fig. 4. The formation of ${}^{6}_{2}He$ ($t_{1/2} = 0.810$ s) and ${}^{16}_{7}N$ ($t_{1/2} = 7.10$ s) in the target leads to the very high initial activity of 3.3×10^5 curies which decays to the level of 0.3 curies after approximately 2 minutes. For times greater than 3 minutes, the activity is due to the radioactive isotopes formed by neutron interactions with the W isotopes. The activity of the unburned tritium (dashed line) is shown for comparison.

For the CH_2-Au target constituents (Fig. 5), ${}^{6}_{2}He$ is also responsible for the high initial activity of the target. The remaining activity is from radioactive isotopes formed by neutron interaction on ${}^{197}_{79}Au$. The unburned tritium activity is shown for comparison.

CHAMBER FIRST WALL ANALYSIS

The neutrons emanating from the target are considered as sources for the first wall neutron transport calculation. The energy spectrum of the source neutron has a large peak at 14.1 MeV due to the uncollided flux of neutrons escaping the ignited target. This amounts to 70.75% of the released neutrons. There is also some local

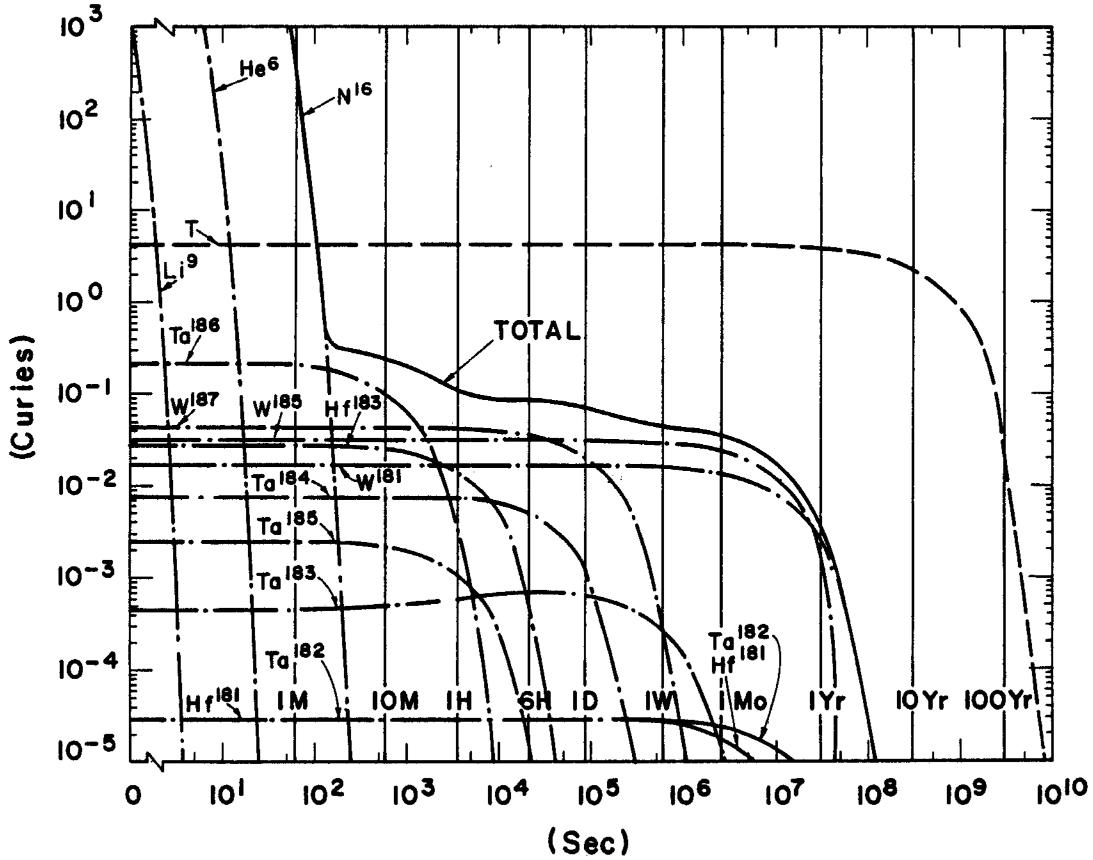

Fig. 4. Isotopic activation versus time for the BeO_2-W target.

peaking of the energy spectrum at 2 and 4 MeV caused by backward elastic scattering of 14.1 MeV neutrons with deuterium and tritium. The low energy continuum spectrum consists of neutrons scattered elastically and inelastically within the target and of neutrons produced from (n,2n) and (n,3n) reactions. For additional information on the determination and shape of the spectrum, consult Refs. 5 and 6. All of the first wall dose rate results are normalized to a target yield of 200 MJ and 3120 shots/yr.

For the borated water pool design, the biological dose rates of the accumulated target debris (BeO_2-W and CH_2-Au targets), the steel chamber and the aluminum chamber have been compared at shutdown, and 1 day, 1 week, 1 month, and 1 year after shutdown. Table I presents the results for the biological dose rates at the inner surface of the first wall upon which the target debris has accumulated. Only the gamma sources of the tamper materials were considered for the target debris. Several points to note are:

1. The dose rate due to the Au debris is higher than that of the W debris through 1 month but then this situation is reversed as the activity of the Au debris decreases rapidly after approximately 3 months (see Fig. 5). The dose rate due to the W debris is down to approximately 2.5 mrem/hr at 1 year after shutdown.
2. The dose rate of the aluminum chamber material is larger than that of the steel up to 1 day after shutdown. After a period of 1 week the dose rate of the steel material exceeds that of aluminum.
3. The dose rate of both chamber materials is seen to be considerably larger than that due to the W debris, whereas the dose rate of the Au debris is comparable to the steel at 1 day and 1 week after shutdown and is seen to be larger than that of the aluminum at one week after shutdown.

Thus one can conclude that at the inner surface of the chamber, depending on the target material composition, the dose rate due to the accumulated target debris can become comparable to that of the chamber itself. Since a liner on the inside of the chamber wall is being considered for protection of the wall from thermal effects of the target explosion, the condensable

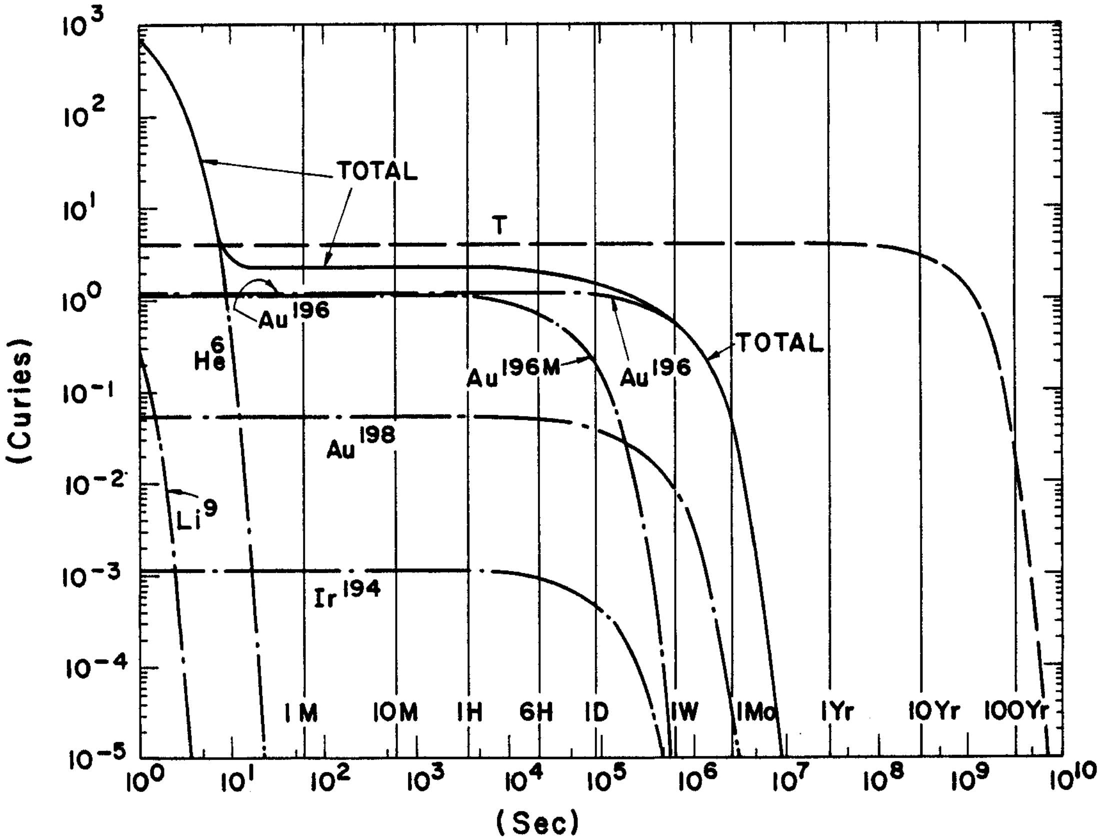

Fig. 5. Isotopic activation versus time for the CH_2-Au target.

Table I. Dose Rate (mrem/hr) At Inner Surface of First Wall

	T = 0	T = 1 day	T = 1 wk	T = 1 mo	T = 1 yr
Aluminum First Wall	6.44×10^6	1.12×10^6	4.26×10^3	2.48×10^3	1.02×10^3
Au (with Al F.W.)	3.05×10^4	2.95×10^4	1.51×10^4	1.08×10^3	5.0×10^{-14}
W (with Al F.W.)	6.25×10^2	1.88×10^2	4.07×10^1	2.42×10^1	2.49
Steel First Wall	8.54×10^5	6.39×10^4	5.96×10^4	5.22×10^4	1.98×10^4
Au (with steel F.W.)	2.72×10^4	2.63×10^4	1.35×10^4	9.57×10^2	4.4×10^{-14}
W (with steel F.W.)	5.84×10^2	1.77×10^2	3.80×10^1	2.33×10^1	2.43

target debris collected on the liner could be periodically removed, thereby reducing the dose rate at the inner surface of the chamber.

It may be possible to perform underwater maintenance with the water shield in place. The dose rate a diver would receive at the outer surface of the target chamber is presented in Table II. Here, as with the dose rate at the inner surface, the target dose rate of the Au debris exceeds that of the W debris until approximately 3 months after shutdown. Also, the dose rate of the aluminum chamber exceeds that of the steel chamber, but after a 1 week period, the steel chamber dose rate is larger. One notices now, however, that the dose rate at the outer surface due to the target debris is considerably lower than that of the chamber materials. This is because the gamma photons due to the effective surface gamma source of the target debris are attenuated as they pass through the chamber wall whereas the gamma photons from the chamber wall are due to volumetric sources.

The dose rate a person would receive standing at the edge of the water shield at shutdown

Table II. Dose Rate (mrem/hr) At Outer Surface of First Wall

	T = 0	T = 1 day	T = 1 wk	T = 1 mo	T = 1 yr
Aluminum First Wall	2.75×10^{6}	3.61×10^{5}	1.29×10^{3}	7.18×10^{2}	2.84×10^{2}
Au (with Al F.W.)	4.84×10^{2}	4.66×10^{2}	2.36×10^{2}	1.66×10^{1}	7.7×10^{-16}
W (with Al F.W.)	1.69×10^{1}	5.32	1.27	9.17×10^{-1}	1.04×10^{-1}
Steel First Wall	6.69×10^{5}	3.82×10^{4}	3.54×10^{4}	2.94×10^{4}	8.90×10^{3}
Au (with steel F.W.)	7.65×10^{2}	7.33×10^{2}	3.68×10^{2}	2.58×10^{1}	1.2×10^{-15}
W (with steel F.W.)	3.21×10^{1}	1.02×10^{1}	2.38	1.78	2.02×10^{-1}

is 10.2 mrem/hr for the aluminum chamber and 20.5 mrem/hr for the steel chamber. One day after shutdown these values are reduced to 0.25 mrem/hr for the aluminum and 1.7×10^{-4} mrem/hr for the steel. The values at shutdown reflect the activity of the water shield, in particular the $^{16}_{7}N$ isotope which has a 7.1 s half-life. After about 10-15 minutes after shutdown the activity of $^{16}_{7}N$ is negligible, therefore the dose rates will be reduced to approximately the values given at 1 day.

The thermal neutron albedo from the borated water shield contributes 9.7% of the dose rate at the aluminum wall outer surface and 54% of the dose rate for the steel wall at 1 day after shutdown of the facility. Thus, the total dose rate can be further reduced by roughly a factor of two by increasing the weight percent boron in the borated water shield or by placement of a boral shield on the outer surface of the wall. This reduction does not offer any qualitative difference in the dose problem at the wall surface; it remains too high for hands on maintenance. An examination of the decay chains given by the DKR code shows that the remaining dose rate component is mainly the result of neutron transmutation reactions above neutron threshold values in the MeV energy range. Hence, to reduce the dose rates significantly, the large component of high energy neutrons would need to be reduced below the neutron interaction threshold values prior to their interaction with the first wall. An ISSEC (Internal Spectral Shifter and Energy Converter) structure placed inside the target chamber would be suited for this purpose and will be investigated in the future.

Since the dose rates at the outer surface of the first wall are considerably higher at 1 day and 1 week after shutdown than is envisioned for routine maintenance of the target chamber, the borated water pool design would need to allow for the drainage of the pool and the assembly of a shadow shield. In particular, access to the ion diodes 1 day after shutdown of the facility is important. Thus, calculations have been performed to compute the lead thickness required to reduce the dose rate to 2.4 mrem/hr. The dose rate within a lead shield as a function of the distance from the outer surface of the steel and aluminum chamber walls is shown in Fig. 6. For the steel chamber wall a thickness of 11.2 cm is required and for the aluminum chamber wall, a thickness of 21 cm.

The alternative TDF design has the target chamber surrounded by a permanent concrete shield. The dose rate within the concrete shield as a function of the distance from the outer surface of the first wall is given in Fig. 7. A concrete thickness of 233 cm for the aluminum chamber and a concrete thickness of 244 cm for the steel chamber are required to reduce the dose rate to 2.4 mrem/hr at shutdown.

Another quantity of interest is the primary dose (defined as the neutron and prompt gamma photon dose received directly from the target explosion) received per shot by a person standing next to the edge of the shield. The total dose values computed range from 2.6×10^{-5} mrem/shot for the aluminum chamber wall with borated water shield to 2.1×10^{-4} mrem/shot for the steel chamber wall with concrete shield. Using our assumption of 3120 shots/yr, the primary dose is seen to be considerably lower than the dose received by the activation of the chamber wall and shield.

CONCLUSION

Biological dose rates have been determined for the TDF target chamber and accumulated target debris after an operational period of 1 year (3120 shots/yr). It has been shown that at the inner surface of the chamber the dose rate attributed to the target debris can be comparable to the dose rate of the first wall materials depending on the specific target materials used. At the outer surface of the first wall the dose rate attributed to the target debris is lower than that of the first wall. Nevertheless, the dose rate at the outer surface is still larger than is acceptable for routine maintenance of the target chamber. The thickness of lead required for use as a shadow shield 1 day after shutdown of the facility has been calculated to be 11.2 cm for the 2-1/4 Cr-1 Mo steel chamber and 21 cm for the aluminum chamber. This reduces the dose rate to 2.4 mrem/hr. An alternative design using a permanent concrete shield requires 233 cm of concrete for the aluminum

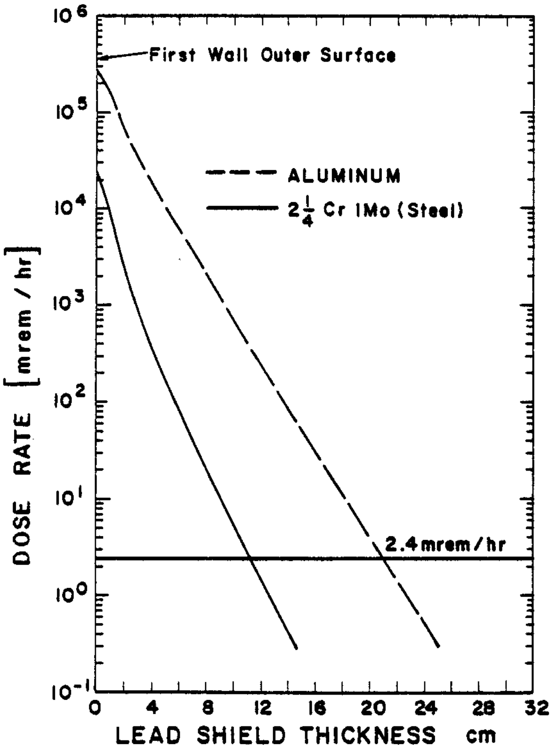

Fig. 6. Thickness of lead shield required to reduce dose rate to 2.4 mrem/hr.

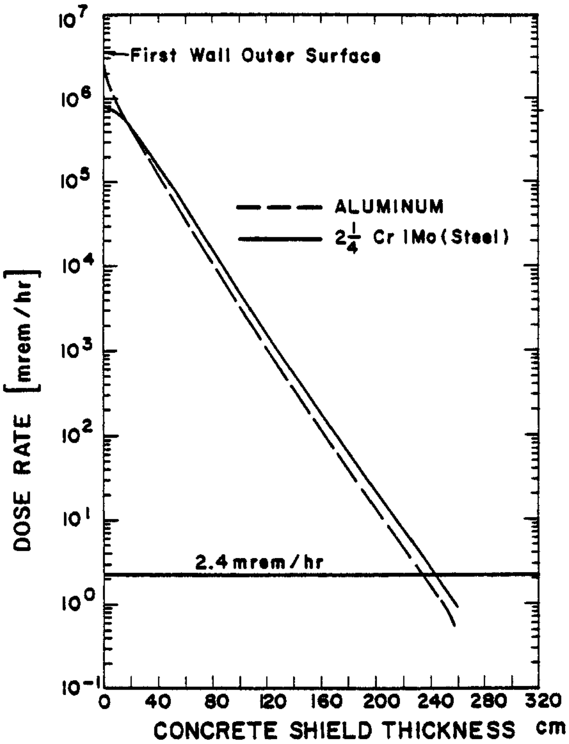

Fig. 7. Thickness of concrete shield required to reduce dose rate to 2.4 mrem/hr.

chamber and 244 cm of concrete for the 2-1/4 Cr-1 Mo steel chamber to reduce the dose rate to 2.4 mrem/hr at shutdown. The primary dose at the edge of the shield received from the target explosion has been found to be considerably lower than that due to the activated chamber wall and shield.

The target activation analysis has shown that the induced radioactivity of the pusher materials decays within 3 minutes after the target explosion and that the activity can essentially be considered as that from the high-Z tamper material.

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