Dose Rate Calculations for a Light Ion Beam Fusion Laboratory Microfusion Facility

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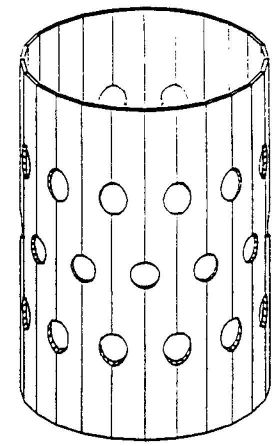
Abstract

A preliminary study of the target chamber design for a light ion beam driven Laboratory Microfusion Facility (LMF) has been performed. The LMF will explode fusion targets with yields between 10 and 1000 MJ over a period of 30 years inside a 1.5 m radius chamber. Activation analysis has been performed for the target chamber and the resulting dose rates calculated. The calculations were performed for three different chamber wall materials: the ferritic steel 2 1/4 Cr-1 Mo, the Al-6061-T6 alloy and a low activation modified Al-5083 alloy. The target chamber is submerged in a borated water pool for neutron shielding. The detailed pulsing schedule has been modeled in the activation calculations. The aluminum chambers result in contact dose rate levels much lower than those from the steel chamber in the period between one week and five years after shutdown. However, except for the Al-5083 chamber, one still has to wait several years for the contact dose rate to drop to tolerable levels. Limiting access for maintenance to distances greater than 1 m from the chamber allows maintenance to start in a few days after shutdown if the borated water remains in place. If the borated water is drained out after shutdown, maintenance for the aluminum chambers can start after two weeks.

Introduction

The Laboratory Microfusion Facility (LMF) is a proposed inertial confinement fusion (ICF) experiment designed to contain target fusion reaction yields between 10 and 1000 MJ. This corresponds to the production of up to 3.6 x 10^{20} (14.1 MeV) D-T neutrons per shot. Based on 500 shots per year, the facility is expected to accumulate approximately 15,000 shots over a thirty year time period. The level of induced radioactivity produced from the interaction between the high energy neutrons and surrounding materials is of a great concern to the facility designers. The level of contact dose in the vicinity of the target chamber plays an important role in the process of selecting the target chamber wall material.

In this paper one ferritic steel alloy (2 1/4 Cr-1 Mo), and two aluminum alloys (Al-6061-T6 and low activation Al-5083) were considered as candidate materials for the target chamber wall. The chamber consists of a capped cylindrical shell 1.5 m in radius and 4.5 m in length [1] (Fig. 1). The chamber wall thickness differed with the different materials used. A chamber wall made of ferritic steel or aluminum had a thickness of 3 or 6 cm, respectively. A thinner steel wall is used because of the relatively good fatigue life characteristics of 2 1/4 Cr-1 Mo steel. The inner surface of the chamber wall is protected by a 2 cm thick graphite (H-451) liner. In all cases a 1 cm thick sheet of boral (a B_4C-Al mixture) is placed on the outer surface of the wall. The target chamber is submerged in a borated water pool for neutron shielding. The borated water contains boric acid (H_3BO_3) at a concentration of 5 g/100 cm^3. The boron in both the borated water and boral is enriched to 90% ^{10}B for enhanced thermal neutron absorption.



Radius: 1.5 m
Length: 4.5 m
No. of Beam Ports: 36
Beam Port Radius: 18.0 cm

Figure 1. LMF chamber design.

Calculational Procedure

Neutron transport calculations have been performed for the LMF chamber using the one-dimensional discrete ordinates neutron transport code ONEDANT [2] together with the Los Alamos National Laboratory (LANL) MATXS5 [3] cross section data library processed from the ENDF/B-V evaluated files. The standard LANL 30 neutron-12 gamma group structure was used and the calculations were performed using the $P_3 - S_8$ approximation. The problem has been modeled in spherical geometry with a point source at the center of the 1.5 m radius chamber. The energy spectrum of the neutrons emitted from the HIBALL target [4] was used to represent the source for the chamber calculations. The results were normalized to the average target yield of 200 MJ which corresponds to 7.1 x 10^{19} D-T fusions per shot. It should be pointed out that since shots of different yields are to be used in LMF, knowledge of the operational schedule before shutdown is essential for proper estimation of the dose after shutdown. The worst case conditions can be assessed by renormalizing the results to 1000 MJ assuming that the high yield shots will take place right before shutdown.

The neutron flux obtained from the neutron transport calculations has been used in the activation calculations. The calculations were carried out by using the DKR-ICF [5] computer code with activation cross sections taken from the ACTL [6] library. The neutron transmutation data is given in 46 group structure format. The decay and gamma source data is taken from the table of isotopes with the gamma source data being in 21 group structure format. The radial build used in both of the neutronics and activation calculations is shown in Fig. 2. The calculations have been performed for one year of operation with 500 shots. The pulsing schedule considered here allows for two shots per day which are 6 hours apart with 18 hours between the daily shots. Operating for 5 days a week results in ten shots per week. Therefore, fifty weekly pulse sequences, which are 66 hours apart, are considered in the year. The DKR-ICF code gives the decay gamma source at different times following the final shot in the year. The adjoint dose field is then determined by performing a gamma adjoint calculation using the ONEDANT code with the flux-to-dose conversion factors representing the source at the point where the dose is to be calculated. The decay gamma source and the adjoint dose field are then combined to determine the biological dose rate at different times following shutdown. The contact dose at the outer surface of the boral layer was determined. In this case the borated water remains in place after shutdown. The dose rate was also calculated at a distance of 1 m outside the chamber wall for both cases with and without the borated water shield. Both the composition and trace elements of all materials used in the calculations except for the modified Al-5083 are taken from Ref. 7. The constituents of the low activation Al-5083 [8] are listed in Table 1.

Table 1. Composition of low activation Al-5083 [7].

Element	Weight %
Mg	4.5
Al	94.99
Si	0.5
Fe	0.01

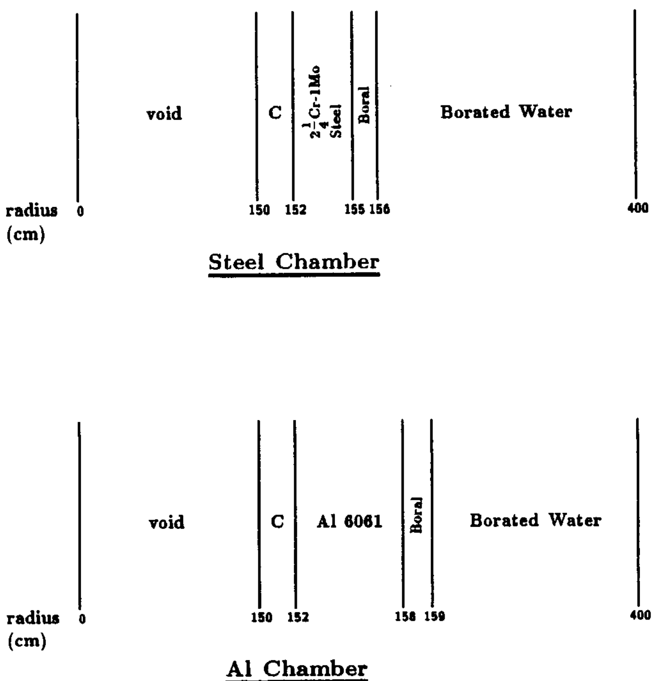


Figure 2. Schematic of the chamber models used in the calculations.

Results

We calculated the different biological dose rates as a function of time following shutdown for the 2 1/4 Cr-1 Mo, Al-6061-T6 and low activation Al-5083 target chambers. Using the DKR-ICF code allows for appropriate modelling of the pulse sequence in ICF chambers. Figure 3 gives a comparison between the dose rates calculated for the steel chamber using the pulse sequence and those obtained by assuming an equivalent steady state operation. Using the steady state operation results in underestimating the dose rate at shutdown by several orders of magnitude with the difference being negligible only after about one week following shutdown. The large difference

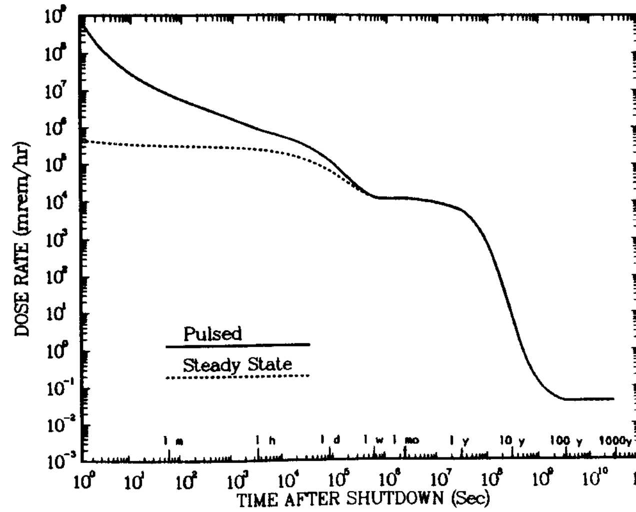


Figure 3. Comparison between pulsed and steady state dose rates at the back of the 2 1/4 Cr-1 Mo steel chamber.

within a short period of time following shutdown is due to the fact that the activity is dominated by short-lived radionuclides whose activities are sensitive to the operational schedule prior to shutdown due to buildup during the on-time with subsequent decay between periods of operation. Notice that the average neutron flux used in the equivalent steady state calculation is lower than that during the on-time preceding shutdown. On the other hand, the long term activity is dominated by long-lived radionuclides whose activity is determined by the total neutron fluence regardless of the temporal variation of the flux.

In both cases of the aluminum walls, the dose rate within the first 10 minutes following shutdown is dominated by ^{26}Na ($T_{1/2}$ = 1.07 s) induced from ^{26}Mg (n, p), ^{27}Mg ($T_{1/2}$ = 9.45 min) produced from ^{26}Mg (n, γ), ^{27}Al (n, p) and ^{30}Si (n, α), ^{28}Al ($T_{1/2}$ = 2.24 min) produced from ^{27}Al (n, γ) and ^{28}Si (n, p), and ^{24}Na ($T_{1/2}$ = 15.02 hr) induced from ^{23}Na (n, γ), ^{24}Mg (n, p) and ^{27}Al (n, α) reactions. ^{24}Na remains the main contributor to the level of dose rate up to a week following shutdown. The dominant radionuclides in the Al-6061-T6 chamber between 1 week and 10 years are ^{54}Mn ($T_{1/2}$ = 313 day) and ^{60}Co ($T_{1/2}$ = 5.27 yr). While ^{54}Mn is produced from both ^{54}Fe (n, p) and ^{55}Mn (n, 2n) reactions, ^{60}Co is mainly induced from the ^{60}Ni (n, p) reaction. ^{26}Al ($T_{1/2}$ = 7.3 $\times$ 10^5 yr) produced from ^{27}Al (n, 2n) is the only major contributor to the dose rate in the same period of time for the low activation Al-5083 wall. At times beyond 10 years after shutdown, the dose rate resulting from any of the two aluminum target chambers is due to ^{26}Al. The dominating radionuclides, except ^{60}Co, are all induced from the constituent elements, namely magnesium, aluminum and silicon in both the aluminum cases, in addition to manganese in the case of the Al-6061-T6 chamber. The radionuclide ^{60}Co is due to the impurity element nickel which is a trace element in both iron (60 wppm) and chromium (3 wppm), which is a constituent element of Al-6061-T6 only.

In the case of the steel chamber, the dose rate in the first few minutes following shutdown is dominated by ^{28}Al, ^{56}Mn ($T_{1/2}$ = 2.6 hr) induced from ^{55}Mn (n, γ) and ^{56}Fe (n, p), and ^{52}V ($T_{1/2}$ = 3.76 min) produced from ^{51}V (n, γ), ^{52}Cr (n, p) and ^{55}Mn (n, α) reactions. The high content of manganese in the 2 1/4 Cr-1 Mo steel chamber, results in ^{56}Mn being the major contributor to the dose rate up to one day. In the period between 1 day and 10 years, as in the case of the Al-6061-T6 chamber ^{54}Mn and ^{60}Co dominate the dose rate produced in the steel chamber. Beyond ten years after shutdown, the dose rate is primarily dominated by radionuclides induced from steel impurities. The two major contributors are ^{94}Nb ($T_{1/2}$ = 20,000 yr) induced from ^{93}Nb (n, γ) and ^{94}Mo (n, p), and ^{93}Mo ($T_{1/2}$ = 3500 yr) produced from ^{92}Mo (n, γ) and ^{94}Mo (n, 2n) reactions.

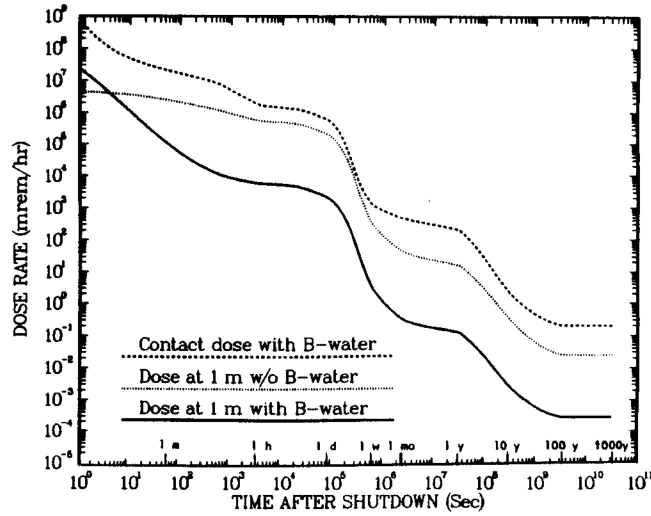


Figure 4. Comparison between dose rates at the back of the Al-6061-T6 chamber and at a distance of 1 m from the chamber.

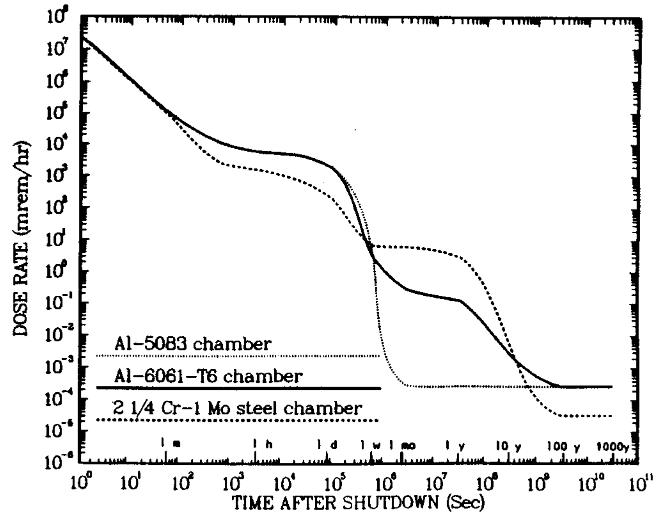


Figure 6. Comparison between dose rates at a distance of 1 m from the chamber with borated water.

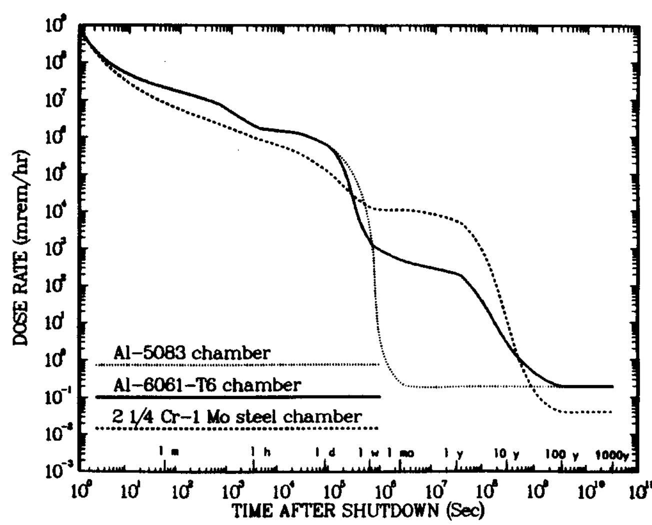


Figure 5. Comparison between contact dose rates behind the chamber.

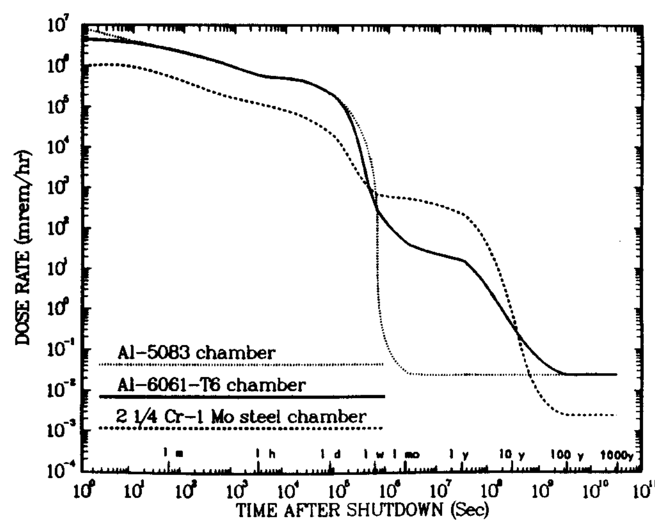


Figure 7. Comparison between dose rates at a distance of 1 m from the chamber without borated water.

Figure 4 compares the contact dose rate at the outer surface of the Al-6061-T6 chamber to the dose rate at 1 m distance from the chamber. It is clear that a reduction in dose rate is achieved by limiting access for maintenance to a distance larger than one meter from the chamber. If the borated water is drained out after shutdown, the dose rate is reduced by a factor of 2-3 in the period between 1 day and 1 week after shutdown and the dose rate will drop below 100 mrem/hr if one waits for only two weeks after shutdown. If the borated water shield is left in place after shutdown much lower dose rates will be obtained at all times except immediately after shutdown due to the ^{16}N ($T_{1/2}$ = 7.1 s) produced from the activation of ^{16}O in the borated water. In this case the dose rate drops to 100 mrem/hr after three days and to only 2.7 mrem/hr in one week following shutdown.

A comparison between the different contact dose rates for the three alloys considered is shown in Fig. 5. The large amount of ^{24}Na produced in both aluminum chamber's results in higher contact dose rates than the steel chamber up to approximately 3 days after shutdown. A significant drop in the aluminum chambers dose rate levels occurs after about one day due to the decay of ^{24}Na. This results in the steel dose being at least an order of magnitude higher than the Al-6061-T6 dose over the period between 1 week and 5 years due to its higher content of ^{54}Mn. The contact dose rate level in the low activation Al-5083 chamber drops to a level which is three orders of magnitude less than the Al-6061-T6 and five orders of magnitude less than the 2 1/4 Cr-1 Mo dose rates within a couple of weeks following shutdown. Such a sharp drop in the dose level is due to the fact that the composition of the modified Al-5083 alloy used in these calculations does not contain most of the major constituent elements or impurities that produce any of the intermediate or long-lived radionuclides. Figures 6 and 7 show comparisons between the different dose rates at a distance one meter from the surface of the target chamber with and without the borated water shield. Note that the results presented in Figures 5 and 6 are based on the assumption that the borated water shield will remain in place after shutdown and therefore represent the biological dose rate a diver would receive at the positions considered.

Table 2 lists the target chamber dose rate results obtained for the three different cases considered. The results show that due to the high level of the contact dose rate, no hands-on maintenance is possible within the first few years if either 2 1/4 Cr-1 Mo or Al-6061-T6 alloys were used as chamber wall materials. Using low activation Al-5083 allows for hands-on maintenance in 2-3 weeks following shutdown.

Table 2. Dose rate (mrem/hr) results for one year operation with 500 shots and average yield of 200 MJ.

Time After Shutdown	Contact Dose Rate			Dose Rate at 1 m (borated water drained out)			Dose Rate at 1 m (borated water in place)		
	$2\frac{1}{4}$Cr-1Mo Steel	Al-6061-T6	Modified Al-5083	$2\frac{1}{4}$Cr-1Mo Steel	Al-6061-T6	Modified Al-5083	$2\frac{1}{4}$Cr-1Mo Steel	Al-6061-T6	Modified Al-5083
At shutdown	8.51×10^8	8.53×10^8	8.31×10^8	9.35×10^5	4.35×10^6	8.41×10^6	2.36×10^7	2.36×10^7	2.38×10^7
1 min	7.47×10^6	2.01×10^7	1.95×10^7	5.16×10^5	2.43×10^6	2.36×10^6	7.53×10^4	9.39×10^4	9.36×10^4
1 hr	8.5×10^5	1.73×10^6	1.73×10^6	1.11×10^5	5.5×10^5	5.5×10^5	1.5×10^3	5.58×10^3	5.6×10^3
1 day	1.04×10^5	5.4×10^5	5.4×10^5	1.84×10^4	1.84×10^5	1.84×10^5	2.02×10^2	1.88×10^3	1.9×10^3
1 week	1.16×10^4	1.19×10^3	6.95×10^2	6.57×10^2	2.82×10^2	2.37×10^2	6.62	2.7	2.42
1 month	1.07×10^4	4.45×10^2	0.204	5.17×10^2	38.9	2.52×10^{-2}	5.95	0.28	2.81×10^{-4}
1 year	4.95×10^3	1.91×10^2	0.2	2.06×10^2	15.02	2.37×10^{-2}	2.77	0.12	2.74×10^{-4}
10 years	4.66	1.92	0.196	0.407	0.28	2.35×10^{-2}	3.48×10^{-3}	2.31×10^{-3}	2.73×10^{-4}
Time for dose rate <100 mrem/hr	5 yr	1.5 yr	2 wk	3 yr	2 wk	1 wk	3 d	3 d	3 d
Time for dose rate <2.5 mrem/hr	10 yr	7.5 yr	3 wk	8 yr	3 yr	10 d	1 yr	1 wk	1 wk

If hands-on maintenance is limited to a distance greater than 1 m from the chamber, maintenance may start within days for the three alloys if the borated water is kept in place. If the borated water is drained out, maintenance can start after a week for the Al-5083 chamber and two weeks for the Al-6061-T6 chamber. On the other hand, hands-on maintenance for a 2 1/4 Cr-1 Mo steel chamber seems out of reach as the dose rate produced needs several years to cool down to a tolerable level. One should note that the results in Table 2 are given for 500 pulses each having the average yield of 200 MJ. As pointed out before, the dose in the first few days after shutdown is dominated by the short-lived radionuclides ^{24}Na ($T_{1/2}$ = 15.02 hr) for the two aluminum cases and ^{56}Mn ($T_{1/2}$ = 2.6 hr) for the steel case. The activity levels for these nuclides after shutdown are determined only by the last few pulses before shutdown. The yield for these pulses has to be used to give a proper estimate of the dose in the first few days following shutdown. The worst case estimate can be obtained by multiplying the results in the table for $t \leq 1$ day by 5 to account for the possibility of having the last few pulses at a yield of 1000 MJ. On the other hand, after a few days following shutdown, the dose is dominated by the relatively long-lived radionuclides ^{54}Mn ($T_{1/2}$ = 313 day) and ^{60}Co ($T_{1/2}$ = 5.27 yr). All shots during the year operation period will contribute to the activity of these radionuclides. Hence, for a proper estimate of the dose rate in this period, the detailed temporal distribution of the different yield shots is required.

Summary

The LMF target chamber dose rate calculations showed that a target chamber made of an aluminum alloy results in contact dose rate levels much lower than those for a steel target chamber in the period between one week and 5 years after shutdown. However, except for a chamber made of a low activation Al-5083 alloy one still has to wait several years for the contact dose rate to drop to tolerable levels. The biological contact dose rate of a modified Al-5083 chamber drops to an acceptable level within 2-3 weeks following shutdown. Limiting access for maintenance to distances greater than 1 m from the chamber allows maintenance to start in a few days after shutdown if the borated water shield remains in place. If the borated water is drained out, maintenance for the aluminum chambers can start after two weeks.

Acknowledgment

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