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FIRST WALL MATERIALS SELECTION IN THE LIGHT ION BEAM TARGET DEVELOPMENT FACILITY

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ABSTRACT

The choice of material for the first wall of the Light Ion Beam Target Development Facility is discussed. Materials considered are Al 6061, Al 5086, 304 stainless steel, HT-9 (ferritic steel), Ti-6Al-4V, Cu-Be C17200, and Cu-Be C17600. The thermal response, mechanical response and induced radioactivity in first walls made of each of these materials are calculated. Minimum thicknesses of these walls are determined and cost estimates are made for the material requirements for each wall. Finally Al 6061 is suggested as the best choice of first wall material.

I. INTRODUCTION

First wall design is a critical part of Inertial Confinement Fusion reactor design and is also important to any experimental device where repetitive fusion target explosions are to be contained. An important first wall design feature is the choice of material. Important issues in the choice of first wall material include chemical compatibility with coolants and cavity gases, tritium retention, induced radioactivity, mechanical response to shocks and thermal response to heat fluxes. In this paper, these issues are faced for the first wall design in the Light Ion Beam Target Development Facility (TDF).[1]

In the TDF, fusion targets yielding approximately 200 MJ of energy would be tested roughly 10^4 times during the lifetime of the facility at the rate of 10 shots/day. The target chamber is a cylinder 3 meters in radius and is filled with 5-50 torr of gas. The target explosion generates a blast wave in the cavity gas that transmits a pulsed heat flux and a shock overpressure to the first wall. These effects have been simulated by the computer code FIRE[2] for various densities of argon with a 0.2% impurity of sodium and of xenon with a 0.5% impurity of cesium. The results of these simulations are shown in Table I where the density is expressed as the pressure the gas would have at room temperature. The maximum overpressure, the arrival time of the mechanical shock at the first wall, the maximum heat flux, its arrival time, and the temperature that an HT-9 wall would attain are all shown in Table I. Since there is some uncertainty about what cavity gas pressure would fill the TDF target chamber, the wall should be designed at this time to withstand the largest possible overpressure and the largest feasible heat flux.

Several materials are proposed for the first wall. These materials are Al 6061, Al 5086, 304 stainless steel, HT-9, Ti-6Al-4V, Cu-Be C17200 and Cu-Be C17600. Important properties of these materials include fabricability, compatibility with cavity gas, T_2 retention, and compatibility with borated water. As long as the cavity gas is dry NH_3 or N_2, the only material of these with any problems is Ti-6Al-4V having a high T_2 retention. If the cavity gas is NH_3, much of the tritium may get bound up in NT_3 and T_2 retention might no longer be a problem. If the cavity gas contains Na or Cs then aluminum is not a good first wall choice.

II. THERMAL AND MECHANICAL PROPERTIES

The critical thermal and mechanical properties of the candidate metal alloys include density, heat capacity, thermal conductivity, melting temperature, thermal expansion coefficient, Poisson's ratio, Young's modulus, and tensile yield strength. Properties at room temperature are well known and there is a fair amount of data for moderately elevated temperatures.[3] Table II contains a quantitative comparison of the seven alloys considered in terms of the thermal and mechanical properties which are the most important to TDF cavity wall design philosophy.

Resistance to thermal damage in the materials can be compared through the thermal diffusivity, $K/\rho C_p$. Aluminum and copper alloys have higher thermal diffusivities than Ti and Fe

TABLE I. Pressure, Heat Flux, and Temperature at First Wall (200 MJ Explosion, Cavity Radius = 3 m)

Gas (Ambient)	Gas Pressure	Code Version	ΔP_{max} (Overpressure) MPa	Time (msec)	Q''_{max} (Heat Flux) kW/cm^2	Time (msec)	ΔT_{max} (°C) in Wall
Argon and 0.2% Sodium	10 Torr	FIRE	0.21	0.31	123	0.184	1244
		X-RAY	0.20	0.33	114	0.183	1203
	20 Torr	FIRE	0.64	0.43	42	0.45	662
		X-RAY	0.61	0.43	42	0.32	675
	50 Torr	FIRE	1.25	0.626	20.5	0.676	294
		X-RAY	1.29	0.613	22.6	0.664	324
	70 Torr	FIRE	1.64	0.67	20.9	0.69	300
Xenon and 0.5% Cesium	5 Torr	X-RAY	0.089	0.136	422	0.136	2901
	10 Torr	FIRE	0.18	0.40	177	0.386	1670
	20 Torr	FIRE	0.69	0.695	92	0.695	809
	50 Torr	FIRE	1.33	1.16	19	1.16	243
	70 Torr	FIRE	1.71	1.32	12.9	1.35	150

based alloys and thus allow much lower temperature gradients and smaller thermal stresses in the wall. However, they have lower melting temperatures and there may be a melting layer at the surfaces facing the incident radiating heat flux. Temperature diffusion calculations indicate that all the candidate metal alloys may undergo some melting.

The mechanical properties of the selected metal alloys are also given in Table II. Low thermal expansion coefficients, smaller Young's moduli and high yield (tensile) strengths are desirable. To resolve the paradox of the strongest materials having the worst thermal properties and to qualitatively represent the overall nature of the combined thermal and mechanical properties, the so-called thermal shock parameter is used. This parameter is a measure of the resistance of the metals to thermal stress failure and is defined in the last column of Table II. Large values of this parameter are desired. It can be seen that Al and Cu based metal alloys have larger thermal shock parameters compared to that of the Fe and Ti based alloys.

III. MECHANICAL RESPONSE OF THE FIRST WALL

The stresses due to the flexure of wall panels must not exceed either the tensile yield stress or the stress that would lead to fatigue failure during the first wall lifetime.[4] The first wall should last 10^7 flexures if 10^4 target explosions are expected and 10^3 flexures are allowed for each shot. This may be a conservative number but, as is shown in Section IV, it does not lead to excessively thick panels. Since determination of the damping of the flexures is very difficult and depends on the details of the design, we conservatively chose a large number of flexures per shot. The tensile yield stresses are taken from the values tabulated in Table II.

The mechanical flexural stresses are calculated for the largest overpressure which could be expected in the TDF cavity gas. This overpressure was determined by a FIRE code[2] simulation of the response of a 70 torr cavity gas of xenon with a 0.5% impurity of cesium. The greatest reasonable overpressure is used because of the uncertainty in cavity gas response to the target microexplosion.

TABLE II. Thermal and Mechanical Properties of Selected Metal Alloys (Room Temperature)

Metal Alloys	Density (ρ)	Specific Heat (C_p)	Thermal Conductivity (K)	Melting Point	Thermal Expansion Coef. (α)	Poisson's Ratio (ν)	Young's Modulus (E)	Yield Strength (σ_y)	$\frac{2\sigma_y K(1-\nu)}{\alpha E}$
	g/cm^3	J/g-°K	W/m-°K	°C	10^{-6}/°K		GPa (ksi)	MPa (ksi)	W/m
Al 6061	2.70	0.90	167	652	23.6	0.33	69 (10,000)	276 (40)	37920
Al 5086	2.66	0.90	127	640	23.8	0.33	71 (10,300)	255 (37)	25680
304 SS	8.0	0.50	16.2	1375 ~ 1440	17.2	0.29	193 (28,000)	255 (36.9)	1750
HT-9	7.75	0.59	29	1427 ~ 1482	10.6	0.265	200 (29,000)	442 (64)	8870
Ti-6Al-4V	4.43	0.67	6.8	1660	8.8	0.33	110 (16,000)	1070 (155)	10030
Cu-Be (C17200)	8.25	0.42	118	980	16.7	0.3	128 (18,500)	283 (41)	21890
Cu-Be (C17600)	8.75	0.42	230	1068	16.7	0.3	128 (18,500)	173 (25)	26050

The method of determining the flexural stresses is the same as has been previously reported.[4] This method calculates the dynamic response of the first wall panels by multiplying the static values by a dynamic load factor which is a time-dependent function that includes the effects of material properties and the geometry of the panels. These plots have been made for all of the candidate materials. The panels are assumed to be held fixed on the edges and are solid plates.

The maximum flexural stress has been calculated for several different materials and for plate thicknesses ranging from 1 cm to 7 cm. The dimensions of the panels for all cases are 2 meters by 0.47 meters and they are always solid plates that are held fixed on the edges. In Fig. 1 the maximum flexural stress has been plotted against plate thickness for Al-6061. Also shown in Fig. 1 are the stresses corresponding to fatigue failure after a given number of flexures[3] and the tensile yield stresses.

With these results, the plate thickness required for each material may be determined. The thickness is the maximum of the value corresponding to 10^7 cycles to failure and the value corresponding to the yield stress. Only Cu-Be C17200 and Cu-Be C17600 have their thickness determined by the yield stress. We have ignored the weakening of the wall by welding, which lowers the yield stress. Since the fatigue life is the most important criterion, the conclusions made here should still hold.

IV. THERMAL RESPONSE OF THE FIRST WALL

The second important consideration in first wall design is the thermal response of the wall

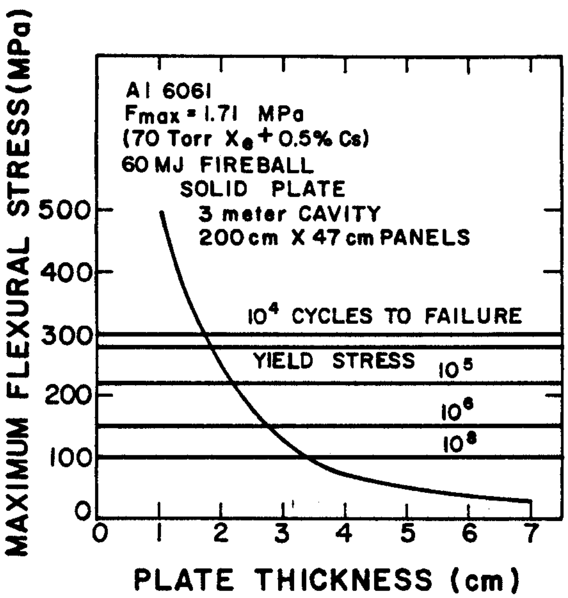

Fig. 1. Maximum Flexural Stresses in a Plate of Al 6061 versus Plate Thickness.

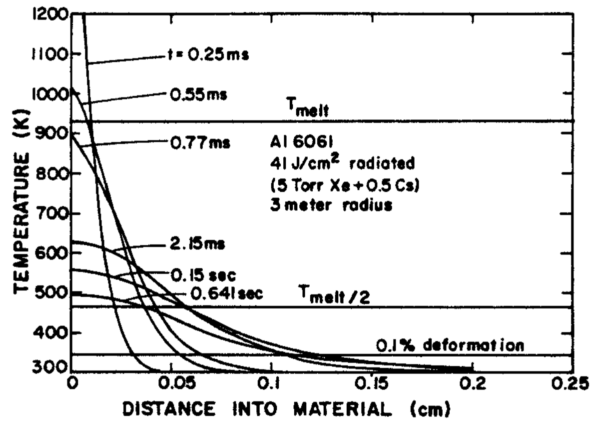

Fig. 2. Temperature Profiles in an Al 6061 Plate versus Distance into Plate.

panels. It is possible that a large fraction of the 60 MJ of non-neutronic target yield may be deposited on the first wall in a fraction of a millisecond. Under such conditions the first wall material may melt or experience large thermal stresses which can cause inelastic deformations or creep. The philosophy used here is to assume the largest possible surface heat flux and analyze the behavior of the innermost layer of the material which undergoes these effects. As long as the effects of heating remain in this layer, i.e., there is no significant growth of cracks, the layer may be treated separately from the remainder of the plate. The load of the shock overpressure is carried by the part of the plate behind the thermally stressed and melted layer and the thickness of the load bearing region is that determined from yield stress and fatigue considerations in Section III.

The heat flux used in the analysis of the thermal response is that which results from a fireball simulation[5] of 60 MJ of non-neutronic target energy propagating through a 5 torr xenon gas with a 0.5% impurity of cesium. In this case roughly 90% of the fireball energy is radiated to the 3 meter radius first wall in less than a millisecond.

The temperature profile in the first wall is calculated by using a simple temperature diffusion computer code with constant heat transfer coefficients. An example of this type of calculation for Al 6061 is shown in Fig. 2. The temperature of the first wall is plotted against the distance into the wall for different times. Also shown are the melting temperature of the material, one half of the melting temperature and the temperature causing a 0.1% deformation in the material. A material hotter than one half of the melting temperature may be assumed to creep and any deformation greater than or equal to 0.1% may be taken as inelastic. From plots like Fig. 2, the duration and width of the layer of melted material may be deduced. The duration of the melt layer in Al 6061 is estimated to be 4.7×10^{-4} seconds.

The thicknesses of the layers dedicated to bearing the effects of the thermal pulse are given for each material in Table III. Also given in Table III are the thicknesses needed to support the mechanical load and the total thickness for each material. The material which requires the thinnest plate is Cu-Be C17200 because it has a high thermal conductivity, a moderate melting temperature, a moderate Young's modulus and good fatigue resistance. The material which requires the thickest plate is Al 6061 because, even though it has a high thermal conductivity, the melting temperature is low so

TABLE III. First Wall Thermal and Mechanical Response and Wall Costs

Material	Melt Layer (cm)	Melt Duration (s)	Deformed Layer (cm)	Fatigue* Width (cm)	Total Plate Thickness (cm)	Wall Material Cost ($)
Al 6061	0.010	4.7×10^{-4}	0.140	3.00	3.140	3.5×10^{4}
Al 5086	0.011	4.7×10^{-4}	0.11	3.00	3.11	3.4×10^{4}
304 SS	0.0055	2.7×10^{-4}	0.035	2.40	2.44	5.6×10^{4}
HT-9	0.0035	7×10^{-4}	0.040	2.0	2.04	6.4×10^{5}
Ti-6Al-4V	0.005	2×10^{-3}	0.030	1.95	1.98	5.5×10^{5}
Cu-Be C17200	0.007	7×10^{-4}	0.075	1.10	1.16	1.8×10^{5}
Cu-Be C17600	0.004	3×10^{-4}	0.086	2.15	2.23	3.7×10^{5}

*10^7 cycles or yield stress

that it has the thickest molten layer. It also has poor fatigue resistance which means that the thickness needed for the mechanical load is large. All materials need thicknesses between 1.16 cm and 3.14 cm, values that are reasonable for construction purposes. In Section V, these plate thicknesses will allow the costs of the materials needed in each case to be determined.

V. MATERIAL COSTS

The costs of the materials used in constructing a first wall can be obtained from the wall thicknesses determined in Section IV. The costs of construction are much more difficult to obtain and are not considered here. To a first approximation, the construction costs should be independent of choice of material and should be added to the cost of the materials to find the total cost of the cavity. The purpose here is not to provide absolute numbers for the material costs but to provide relative costs that will show how the thicknesses of the materials are balanced by the different unit costs of the materials.

The cost analysis in Table III shows that even though the aluminum walls are the thickest, the material used is the cheapest of all materials considered. Conversely, one of the thinnest walls is made of Ti-6Al-4V but it also has the largest materials cost. In any event, none of these costs appear to be prohibitively large.

VI. RADIOACTIVITY

The radioactivity induced in the first wall and supporting structure by 14 MeV fusion neutrons can cause troublesome maintenance and operating problems for the Target Development Facility. We anticipate that the radioactive inventory will not pose a disposal problem so we have concentrated on the resultant dose from this radioactive structure. We assume that there are ten full yield 200 MJ shots per day. This represents an average fusion power level of 23 kW. We assume that 70% of the energy is in neutrons. Hence, the neutron power is 16 kW. At such low power levels, in comparison to our fusion reactor designs for instance, we would expect that there may be non-saturation effects in the decay chains. For this reason we have computed the dose for one week and for one year of operating time at 16 kW. These calculations have thus far been done for three of our candidate wall materials: Al 6061, HT-9, and 304 stainless steel. The radiation doses experienced at the surface of the first wall and from the operating floor, 8 meters away, are given in Table IV for one year of operation. We show the dose at these two locations as a function of time after shutdown after operating for one year. We see that for Al 6061, we could enter the target chamber at one week after shutdown without experiencing excessive doses. For the ferritic and stainless steels we would see a substantial dose at the first wall even after one week. It is interesting to note that the Al 6061 is much hotter at shutdown than the steels, but it decays much more quickly. If remote handling were acceptable then the steels would allow manipulation from the operating floor while remaining within tolerable radiation levels. This scenario of course assumes that access to the target chamber will be very infrequent.

Similar calculations have been done assuming only one week of operation before shutdown. Again, the Al 6061 is very hot at first and then

TABLE IV. Dose Calculations for LIB-TDF

One Year Operating Time @ 16 kW

Time After Shutdown	Dose At First Wall (mr/hr)	Dose At Operating Floor (mr/hr)
	Al 6061	
0	2.1×10^3	230
1d	2.6×10^2	28
1w	1.65	0.18
	HT-9	
0	489	55
1d	114	13
1w	101	11
	SS 304	
0	481	54
1d	109	12
1w	105	12

quickly decays. The steels reach nearly the same dose levels at shutdown, but their longer-lived radionuclides have not saturated, hence the dose at one week after shutdown is tolerable. However, this dose will build up over time so that in one year it will be nearly the same as in the previous scenario.

From the analysis that has been done thus far, the best choice from a radioactivity standpoint is aluminum. It should be mentioned that high purity aluminum is available if dose levels from impurities pose a serious problem. However, from our current results we conclude that this additional expense is not necessary.

VII. CONCLUSIONS

The choice of first wall material has been investigated for the TDF. Mechanical and thermal properties have been accumulated for the materials considered. Mechanical responses have been predicted for the largest credible shock overpressure and thermal responses have been determined for the largest heat flux on the first wall. Induced radioactivity has been calculated for walls made of some of the materials. Required thicknesses and material costs are finally found for the materials.

It has been found that Al 6061 is a good choice of material for the TDF first wall. Calculations show that one week after shutdown, the radioactivity is low enough for hands-on maintenance. Cost estimates also show that the aluminum alloys are the cheapest of those materials considered. The thicknesses needed for these alloys are reasonable for construction. The major problem with aluminum is its incompatibility with Na and Cs. Recall that these impurities in the cavity gas are present to enhance channel breakdown by laser beams. This leads us to suggest that other cavity gas candidates be investigated for the TDF. With this qualification Al 6061 is suggested for serious consideration as the first wall material.

ACKNOWLEDGMENT

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