SINGLE PASS COLLIDER MEMO

CN- 250

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REPLACES CN#

TITLE: ENGINEERING BASIS FOR SELECTION OF POSITRON SOURCE MATERIAL

ABSTRACT

This note describes the Engineering Basis for the selection of the Positron Source material. It assumes the approximate physics parameters have already been chosen (i.e. a high Z material of 6 radiation lengths thickness). As part of this study a basic heat transfer analysis of the target was performed and is discussed. It is concluded that Ta-10W is the most likely material to meet required physics parameters and not fail structurally.

INTRODUCTION

In the past, some of the positron target materials undergoing beam tests have suffered structural failures (see CN-128). It was obvious from these tests that incident beam power, the number of particles per pulse, and beam radius played an important role in determining whether or not structural failure would occur. What was not obvious was how the failure mechanism worked and how material selection could be used to advantage in preventing failure. This note describes a method for the selection of the positron source material assuming that the failure mechanism is structural failure due to beam induced thermal stresses exceeding target material mechanical strength. Another potential failure mechanism, shock focusing, is discussed in attachment one. Since shock focusing is precluded by our design geometry, though not that of the currently used stationary targets, it is not discussed here. A third failure mechanism, fatigue failure is only lightly touched upon.

STRESS ANALYSIS

If a thin circular disc at uniform temperature has the temperature changed ΔT throughout a small central circular portion then the peak stress will be

$$\sigma_{max} = 1/2 \Delta T \alpha E$$

where

α = coefficient of linear expansion

E = Young's modulus

This stress occurs inside the heated part as a compressive radial and tangential stress. At the outside edge of the heated portion there are compressive radial stresses and tensile tangential and shear stresses of the same magnitude.

The above case differs from the positron target, in that the beam has a more or less Gaussian distribution rather than a square distribution. This would mean that the above case would be very conservative if the peak ΔT caused by the beam were used. This note will use the average ΔT assuming

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that all of the heat is deposited in the one sigma diameter of the beam. I believe that this is still somewhat conservative but not by much (i.e. 10-20%). In any case the stress is going to depend on $\Delta T \sigma E$ and so this can be used as a figure of merit to determine relative stresses in different materials.

The temperature rise due to one beam pulse is

$$\Delta T_{\text{beam}} = q/MC_p$$

where

q = heat deposited

M = mass over which heat is deposited

C_p = specific heat

The mass of material is equal to the volume, v , multiplied by the density, ρ , of the material.

$$M = \rho v$$

The volume of the material is

$$v = \pi r^2 l$$

where r is the effective radius of energy deposition and l is the length of interest. If we chose the last radiation length as l then

$$l = X_0/\rho$$

where X_0 is the radiation length in grams per cm^2 . It follows that

$$v = \pi r^2 X_0/\rho$$

and

$$M = \pi r^2 X_0$$

and

$$\Delta T = \frac{q}{\pi r^2 C_p X_0}$$

and

$$\sigma = 1/2 \frac{q \alpha E}{\pi r^2 C_p X_0}$$

Since the last radiation length was chosen as the length of interest then q will be constant for any material. Further if it is assumed that the effective radius of energy deposition will not change with material, the stress for any material is proportional to

$$\frac{\alpha E}{C_p X_0}$$

and this can be used as a figure of merit. Stress and target material pulse temperature rise can be calculated by assuming values for q and r . In this note the beam radius was assumed to be 1.3 mm. The amount of heat deposited into the last radiation length is 3.59 kw or 4.77 gm-cal per pulse (from CN 21). From basic material properties and the above equations the data in Table 1 can be generated.

Even if the stresses shown in Table I are in error as far as their absolute values, they must be approximately correct in relation to one another. That is, W-26Re has a stress twice as high as Ta-10W.

These stresses must now be compared to some allowable stress, either the ultimate tensile strength or the 0.2% yield stress. In order to find these allowable stresses the peak temperature of the target must be known.

PULSE AND STEADY STATE HEAT TRANSFER ANALYSIS

The current reference target design is shown in Figure I. It is a rotating wheel design with water cooling on the inside. The water is forced through a series of passages whose boundaries form heat transfer fins. Hydraulic calculations indicated that for the 9.55 kw expected to be deposited in the target the water temperature (6.55 gpm) should rise 5°C. Calculations of the thermal resistance to convective heat transfer, involving estimates of flow turbulence, surface area, and fin efficiency, yielded a value of 9.26 cal/sec °C for the convective film conductance (i.e. hA).

If it is assumed that the portion of the target material between the beam line and the water is a hollow cylinder with the energy of the beam passing from the O.D. to the I.D. then

$$\dot{q} = \frac{2\pi K L \Delta T}{\ln(r_o/r_i)}$$

where

- $\dot{q}$ = rate of heat transfer
- K = thermal conductivity
- L = length of cylinder
- ΔT = temperature drop across the cylinder
- r_o = outer radius of cylinder
- r_i = inner radius of cylinder

then

$$\Delta T = \frac{\dot{q} \ln(r_o/r_i)}{2\pi KL}$$

but since $\dot{q}$, r_o , and r_i will be constant irrespective of the target material, then ΔT varies as

$$\frac{1}{KL}$$

this can be used as a figure of merit for the steady state heat transfer. This figure of merit and the actual ΔT_{ss} across the target material are shown in Table II. The steady state temperature rise ΔT_{ss} was calculated using the last radiation length as the area of interest. As stated above the energy deposited in this region was calculated to be 859 cal/sec (CN-21). The beam line is at a diameter of 5.5 inches. To the value of ΔT_{ss} must be added the film drop which we have assumed as a constant of

$$\begin{aligned} \Delta T_{fil} &= \frac{859 \text{ cal/sec}}{9.26 \text{ cal/sec}^\circ\text{C}} \\ &= 93^\circ\text{C} \end{aligned}$$

This must be added to the water inlet temperature, assumed to be 30°C , to reach a calculated steady state peak temperature T_{peak} . This T_{peak} is very conservative in that it does not allow for axial heat transfer in the target. In practice considerable heat will flow from the hot end toward the cool end, not only making use of the path between the beam line and the water but also the path between the beam line and the target material O.D. Figures 2A and 3A represent the solution of 24 node finite difference calculations of the W-26Re and Ta-10W targets respectively. Figures 2B and 3B detail the thermal model used. Note that all numbers are in English units and need to have the 30°C water inlet temperature added. If this is done we would have a ΔT_{peak} that is more realistic than that previously calculated. In fact it is about 100°C lower than the previous conservative calculations. Further the ΔT 's calculated seem to scale well with ρ/KX_o as they are supposed to do (i.e. $\Delta T(\text{W-26Re}) = 263.5^\circ\text{F}$ figure 2A, $\Delta T(\text{Ta-10W}) = 300.6^\circ\text{F}$ figure 3A a ratio of 0.877; the ratio of ρ/KX_o for the two cases is 0.869). If we use ρ/KX_o to calculate an approximate ΔT for the other

materials and add the 30°C water inlet temperature we arrive at a more realistic estimate of the peak temperature. This has been done and the results are shown in Table II. If we then add the ΔT_{pulse} from Table I we will have a peak pulse temperature T_{pp} , as shown in Table II, at which to evaluate the allowable stress.

If the calculated stress from Table I is compared to even a room temperature tensile strength, T_a , P_t , and A_u will be eliminated. The other material's calculated stress, σ , must be compared to its tensile strength σ_t at the calculated temperature T_{pp} . This is done in Table II. Further a figure of merit, MS, may be determined by taking the value σ_t/σ . This has been done in Table II. Because physics requirements call for a high Z material Cu is eliminated. Thus Ta-10W and W-26Re look the most promising. In as much as Ta-10W is also more readily available, less expensive, and apparently easier to work with, it is the obvious material of choice.

The above calculations have only dealt with single pulse stresses and potential failure. It is possible, in fact even probable that fatigue failure cracking or fracture is the failure mechanism. Fatigue failure of a ductile member is caused by repeated loading (even when below the yield stress), not accompanied by noticeable yielding. The failure is a gradual or progressive fracture. The minimum number of cycles necessary to cause fatigue failure is $\sim 10^6$. The target diameter is 5.5 inches with a 1.3mm beam spot. Spot overlap should occur every 168 pulses, or about once a second. Thus, 10^6 cycles would be reached in about 12 days of full time operation. Therefore it is obvious that the target is susceptible to fatigue failure.

Unfortunately the determination of the endurance limit of a material can only be found by testing. Also the endurance limit changes with the range of the stress (i.e. complete reversal, a maximum to zero, a maximum to a minimum), any scratches or material defects, and a variety of other parameters. No fatigue data appears to be available for Ta-10W or W-26Re and therefore no judgement can be made. However for informational purposes a fatigue curve for pure Ta is shown in figure 4.

TABLE I
 TARGET MATERIAL PROPERTIES, PULSE
 TEMPERATURE RISE, AND RESULTANT STRESS

Mat'l	Z	ρ GM/CM	C_p CAL/GM°C	X_o GM/CM ²	X_o/ρ CM	T _{pulse} °C	α 10 ⁻⁶ /°C	E* 10 ⁶ PSI	σ KPSI
Ta	73	16.6	0.032	6.82	0.4108	417	6.5	27	36.6
Ta-10W	73/74	16.9	0.035	6.814	0.4032	381	5.6	30	32.0
W	74	19.3	0.034	6.76	0.3503	397	4.44	50	44.1
W-26Re	74/75	19.65	0.032	6.753	0.3437	428	5.02	58	62.3
Pt	78	21.45	0.031	6.54	0.3049	442	8.9	24.2	47.6
Pu	79	19.3	0.0308	6.46	0.3347	450	14.4	11.6	37.6
Cu	29	8.94	0.094	12.86	1.4385	81	16.6	16	10.8

*At room temperature, a conservative assumption

TABLE II
TARGET MATERIAL STEADY STATE TEMPERATURE

Mat'l.	Z	K CAL/S-CM- °C	P/KXo CAL/S-°C	Tss* °C	Tpeak* °C	Tpeak+ °C	Tpp °C	$\bar{\sigma}$ KPSI	$\bar{\sigma}_z$ KPSI	M.S
Ta	73	0.13	18.7	244	367	~260	~677	36.6	<30	< 1
Ta-10W	73/74	0.185	13.39	174	297	197	578	32.0	~71	2.2
W	74	0.476	5.99	78	201	~104	~501	44.1	~60	1.4
W-26Re	74/75	0.250	11.63	151	274	176	604	62.3	~132	2.1
Pt	78	0.1664	19.71	257	380	~272	~714	47.6	<34	<1
Au	79	0.707	4.22	55	178	~83	~533	37.6	<25	<1
Cu	29	0.95	.732	10	133	~39	~120	10.8	~32	3.0

* Conservative Estimate

+ Finite difference calculation (or estimate if preceded by ~) of Tpeak

FIGURE I

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NUMBERS ARE ΔT FROM
WATER INLET TEMPERATURE, $^{\circ}\text{F}$

HEAT BALANCE OVERALL TO -0.18%

WORST NODE TO 19 Btu/hr OR 1.5% OR 0.1°F

AVERAGE NODE TO $\pm 22 \text{ Btu/hr}$ OR $<0.01\%$ OR 0.07°F

TOTAL HEAT GENERATED = 32589 Btu/hr (9 Btu/sec)

AVG Δ TEMPERATURE = 171.8°F

STORED HEAT = 27.4 Btu

MATERIAL : W-26% R:

FIGURE 2A

$$\dot{q} = \frac{1}{r} \Delta T$$

$$1/R_{\text{COND}} = \frac{KA}{Q}$$

$$1/R_{\text{CONV}} = hA$$

MAT'L: W-26 Re

$K_{W26Re} = 60.5 \text{ Btu/hr ft } ^\circ\text{F}$

$hA = 73.79 \text{ Btu/hr } ^\circ\text{F}$ $\left(\frac{5000 \text{ Btu/hr ft } ^\circ\text{F} \cdot 0.0148 \text{ ft}^2}{(2500 \text{ cells})} \right)$

HEAT GENERATION

Node #

$\dot{Q}$ (Btu/hr)

6 6132

5 4877

4 3155

3 1536

2 518

1 116

FIGURE 2B

NUMBERS ARE ΔT FROM
WATER INLET TEMPERATURE °F

HEAT BALANCE OVERALL TO +0.16 %

WORSE NODE TO 70 Btu/hr OR 5.6 % OR 0.5 °F

AVERAGE NODE TO 38 Btu/hr OR 3.5 % OR 0.12 °F

TOTAL HEAT GENERATED = 32589 Btu/hr (9811/sec)

AVG Δ TEMPERATURE = 178.4 °F

STORED HEAT = 31.3 Btu

MATERIAL: Ta - 10% W

FIGURE 3A

$$\dot{q} = \frac{1}{R} \Delta T$$

$$\text{MAT'L : } T_a \text{ 10 W}$$

$$\frac{1}{R_{\text{COND}}} = \frac{KA}{L}$$

$$K_{\text{TALOW}} = 44.8 \text{ Btu/hr ft}^2 \cdot ^\circ\text{F}$$

$$\frac{1}{R_{\text{CONV}}} = hA$$

$$hA = 73.79 \text{ Btu/hr}^2 \cdot ^\circ\text{F}$$

Heat Generation

NODE #	$\dot{Q}$ (Btu/hr)
6	6132
5	4877
4	3155
3	1536
2	518
1	116

FIGURE 3B