Measurement of Cooling Characteristics of the ISIS Tantalum Target.

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Introduction

An ISIS spallation neutron target, shown schematically in Figure 1, comprises 23 heavy metal discs of different thicknesses, separated by narrow water cooling channels. Two types of target disc are used on ISIS, depleted uranium clad in zircaloy-2 and pure tantalum. The target discs have stainless steel frames shrunk on to them, and the assembly of frames is electron beam welded to form a solid structure, to which heavy-water cooling manifolds are fitted. Coolant is fed via three loops that are pressurised to supply approximately the same high velocity flow rate for each of the inter-plate coolant channels. Plate temperature is monitored by a thermocouple at the bottom of a radial hole, that extends to the centre of each plate. For the tantalum target only every other plate is fitted with a thermocouple.

This report describes measurements of target plate cooling before and after irradiation of targets. The deterioration in cooling of uranium targets has been shown to correlate with the onset of target failure. Cooling measurements on the tantalum target indicate a steady decrease in cooling efficiency with proton irradiation. The reasons for such a deterioration can only be speculative, until the cooling measurements can be correlated with a post-mortem examination of an irradiated target. However, the measurements indicate that some care must be exercised when considering the use of tantalum for the much higher power targets of the proposed European Pulsed Spallation Neutron Source.

ISIS Target Cooling

The ISIS target is force cooled using heavy-water as the coolant. A hot body under conditions of forced cooling should obey Newton's Law of Cooling, which states that the rate of heat loss is proportional to the temperature difference between the hot body and the coolant stream.

If -dH corresponds to the heat loss

then $$-\frac{dH}{dt} = \kappa(\theta - \theta_o) \qquad (1),$$

where θ is the temperature at any instant,
θ_o is the coolant temperature (assumed constant)
and κ is a constant for a given body under given conditions.

A small loss of heat $-\delta H$ in a time δt correspond to a temperature change $-\delta\theta$

and $$-\delta H = -ms\delta\theta \ ,$$

where, m = mass of body, and s = specific heat of body.

The average rate of heat loss over the interval is

$$-\frac{\delta H}{\delta t} = -ms\frac{\delta\theta}{\delta t} \ ,$$

which in the limit δt very small becomes

$$-\frac{dH}{dt} = -ms\frac{d\theta}{dt} \qquad (2).$$

Substituting from equation (1) into equation (2) for $\frac{dH}{dt}$,

then
$$-\frac{d\theta}{dt} = -\frac{\kappa}{ms}(\theta - \theta_o)$$

Integrating with initial conditions, $\theta = \theta_{max}$ at $t = 0$, gives:

$$\ln\left\{\frac{\theta - \theta_o}{\theta_{max} - \theta_o}\right\} = -\frac{\kappa}{ms}\cdot t$$

or
$$\theta = \theta_o + (\theta_{max} - \theta_o)e^{-t/t_c} \quad ,$$

where $t_c = \frac{ms}{\kappa}$ = characteristic cooling time (CCT).

The plates in the spallation target all have the same face area, but there are four sizes of plate thickness. The mass of a plate is therefore proportional to the plate thickness. Assuming that cooling at the plate edges is small *c.f.* cooling from the disc faces then the characteristic cooling time may be normalised to plate thickness. The thickness normalised characteristic cooling time (TNCCT) should then be a constant for all target plates.

For a given material the TNCCT is directly proportional to its specific heat and inversely proportional to its thermal conductance. If it is assumed that the thermal conductance is directly proportional to the thermal conductivity in target plates of different materials but with the same geometric design, then it is possible to make the following comparison for the TNCCT's of tantalum and uranium targets before irradiation:

$$\mathrm{Ta}_{\mathrm{TNCCT}} = \frac{\mathrm{Ta}_{\text{specific heat}}}{\mathrm{U}_{\text{specific heat}}} \cdot \frac{\mathrm{U}_{\text{thermal conductivity}}}{\mathrm{Ta}_{\text{thermal conductivity}}} \cdot \mathrm{U}_{\mathrm{TNCCT}}$$

It must be borne in mind when making such a comparison that the uranium is clad in a very thin coat of zircaloy-2 and the effective thermal conductance will be affected by the quality of the adhesion at the interface between the two metals. In addition there are three small zircaloy ribs 1.0 mm wide by 1.5 mm high on one side of the zircaloy clad plates that are not included in the mass normalisation.

Measurements of Target Cooling

Cooling of the target plates is measured by recording the temperature indicated by each of the thermocouple monitors as a function of time, immediately after switching off the proton irradiation of the target. Typical Plate cooling curves are shown in Figure 2. The measurements are made using a Hewlett Packard HP54510A Digital Sampling Oscilloscope.

Apart from the initial 'knee' of the curve, it is found that for all plates, the cooling curves fit very closely the exponential decay of temperature with time predicted by Newton's Law of Cooling.

Measurements of the thickness normalised characteristic cooling time are plotted in Figure 3 for a uranium target before proton irradiation. At the time these measurements were started, the tantalum target had already received approximately 400 mAh proton irradiation. The measurements on the non irradiated uranium target show that the constancy of the TNCCT's is in close agreement with prediction. The measurements give an average value of $U_{TNCCT} = 0.1967$ s mm^{-1} for uranium before irradiation . The measurement error for the characteristic cooling time is estimated to be very small, ±0.03%, but the tolerance on plate thickness of ±0.35 mm must be added to this. Also, the normalisation assumes that the specific heat is a constant and the thermal conductance κ is constant. The discs are a layered structure of two materials, zircaloy-2 (specific heat 276 J $°C^{-1}$ kg^{-1}) and uranium (116 J $°C^{-1}$ kg^{-1}). The thickness of zircaloy-2 on each plate is non uniform, ranging from 0.25 mm to 0.6 mm and the zircaloy-2 forms a smaller fraction of the thicker plate composition. The thermal conductance has a dependence on how well the zircaloy-2 is bonded to the uranium and no allowance is made for the perturbing effect of the additional mass of the zircaloy-2 ribs. However, the simple thickness normalisation does show a remarkable constancy of value from plate to plate.

Also plotted in Figure 3 are TNCCT's measured for a uranium target after a 295 mAh, 800 MeV proton irradiation. These measurements show relatively large changes to the TNCCT values for Plate #2 and #3. Plate #8 also has a value that is above the average. The remainder of the values are only slightly higher than the average value for uranium before irradiation. This target was replaced shortly after making these measurements when plate temperature and coolant flow rate measurements confirmed critical damage to the target.

In Figure 4 the TNCCT's for a tantalum target are plotted for several levels of proton irradiation. The dotted line plotted on the graph is for the scaled value of the average TNCCT measured for uranium before irradiation. Thus, using the following tabulated values for the specific heat and thermal conductivity:

Metal	Specific Heat J $K^{-1}Kg^{-1}$	Thermal Conductivity W m^{-1} K^{-1}
uranium	116	27.5
tantalum	140	57.5

together with the measured value of U_{TNCCT}, the scaling for tantalum before irradiation becomes:

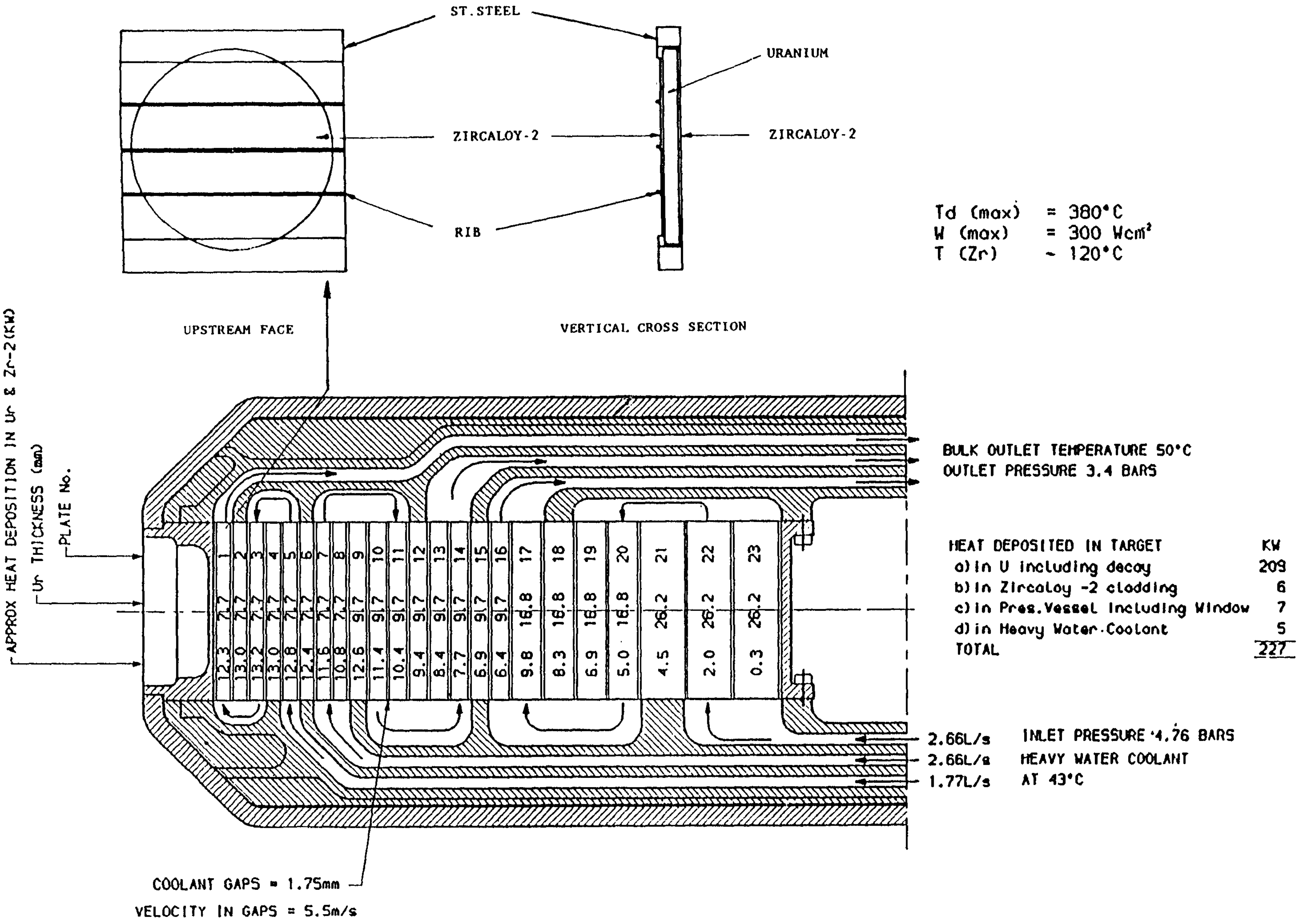
$$Ta_{TNCCT} = 0.5772\,U_{TNCCT} = 0.1135\ \mathrm{s\ mm^{-1}}$$

From the measurements shown in Figure 5 it can be seen that for the lowest proton irradiation of 417 mAh, the values of TNCCT lie very close to the scaled value for Plate #17 and #19 at the downstream end of the target. This may be coincidence, but the downstream plates might be expected to be closer to the value with no irradiation since the downstream end of the target would suffer a lower irradiation by a factor five less than the thinner upstream plates. The thicker downstream plates should also be less prone to mechanical distortions resulting from heat and/or irradiation. Measurements on all plates upstream of Plate #17 show a large increase in the values of TNCCT relative to the scaled value. The measurements also show a steadily increasing deviation with increasing irradiation as shown in Figures 5 and 6. The rate of deterioration in cooling appears to be roughly similar for the plates with a large change in their TNCCT.

For the irradiated uranium target, critical damage occurred when the TNCCT of one of the plates had increased by a factor ~ 4. The measurements on the irradiated tantalum target are already showing a similar factor increase, but from an initial value approximately half that of uranium.

Conclusion

The cooling of the target plates in the ISIS spallation neutron target appears to obey Newton's Law of Cooling. A single parameter, the thickness normalised characteristic cooling time, may be used to characterise the cooling of all target plates. There is some evidence that the parameter scales appropriately with the thermal properties of the materials. Measurements of the parameter for plates in a tantalum target indicate considerable reduction in cooling efficiency after an irradiation of nearly 1 Ah, with 800 MeV protons. It cannot be ascertained without a detailed examination of the irradiated target plates, whether the deterioration is due to mechanical distortion, crystal growth or gas swelling, or due to changes in the thermal properties of the material or a change in thermal conductance from some form of corrosion. Such an examination would seem to be essential if tantalum is to be considered for the higher power targets of the proposed European Spallation Neutron Source.



HEAT DEPOSITED IN TARGET	KW
a) in U including decay	209
b) in Zircaloy -2 cladding	6
c) in Pres.Vessel including Window	7
d) in Heavy Water Coolant	5
TOTAL	227

FIGURE 1 SCHEMATIC DIAGRAM OF ISIS URANIUM TARGET

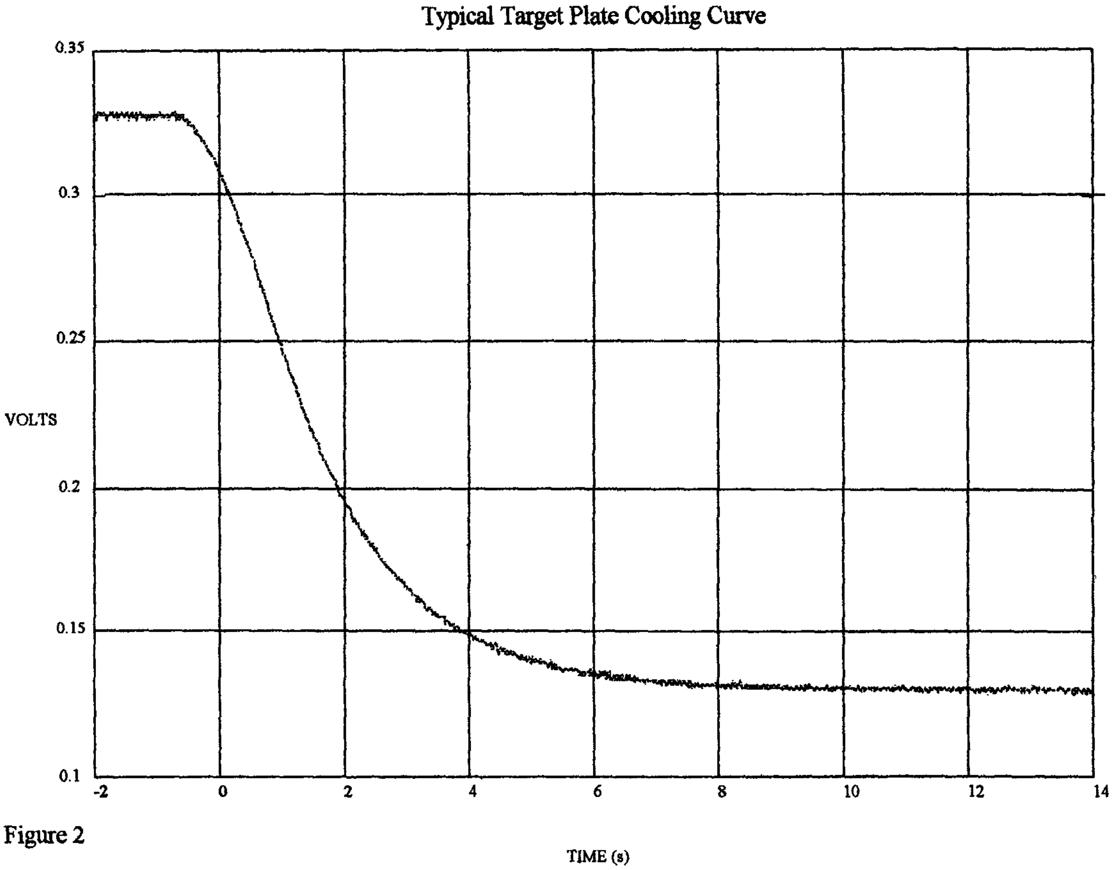


Figure 2

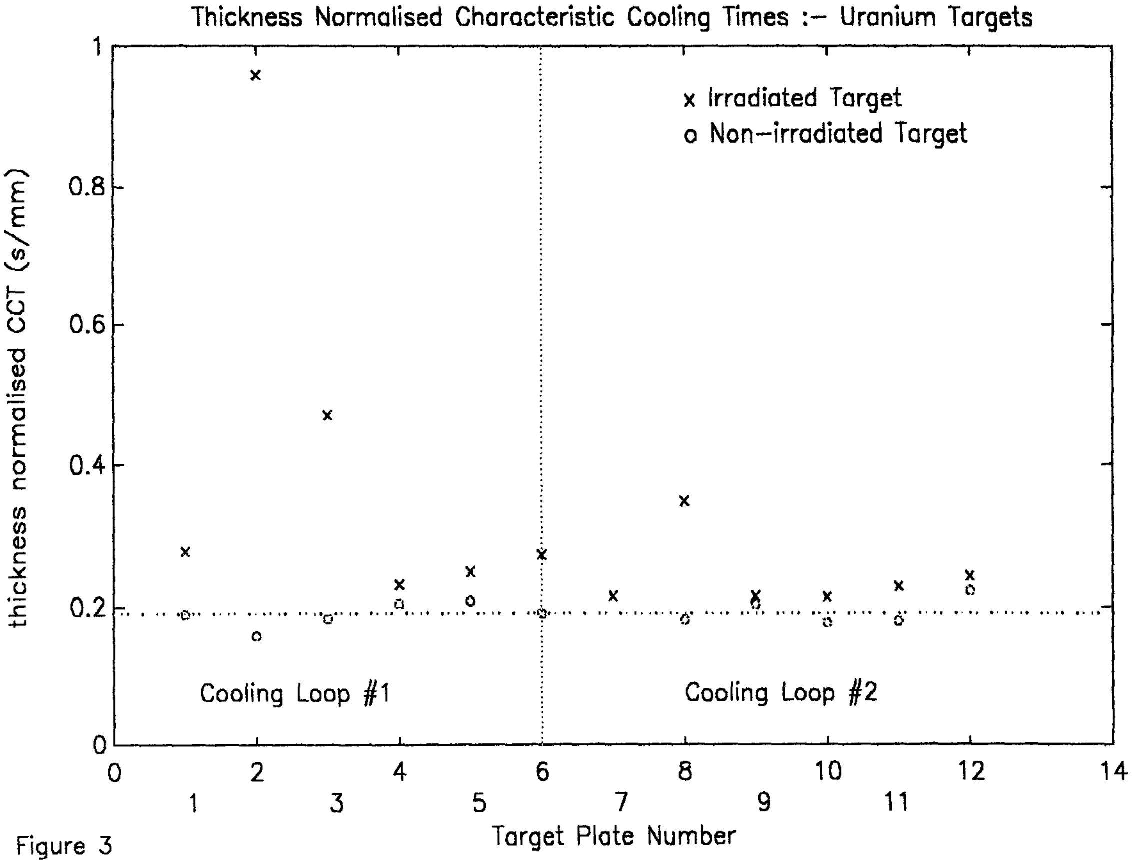


Figure 3

Thickness normalised characteristic cooling times for irradiated tantalum target.

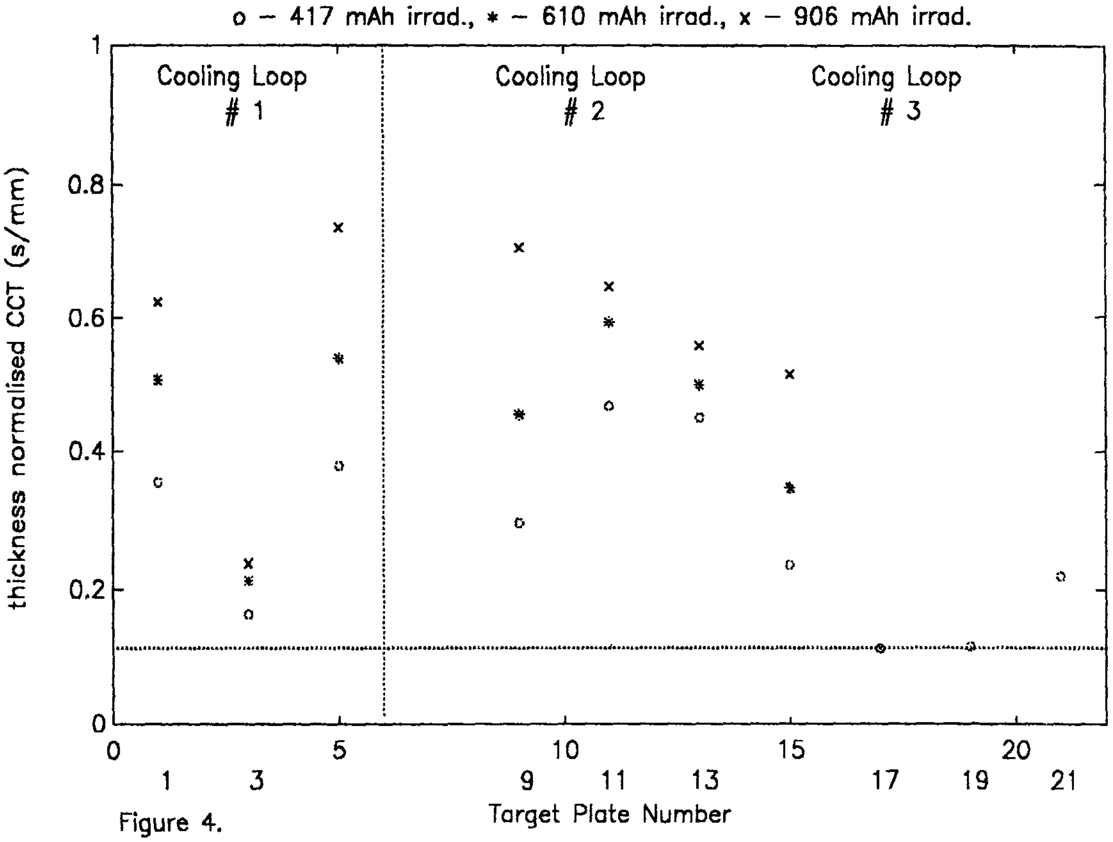


Figure 4.

Tantalum Target Plate Cooling Coefficients v Proton Irradiation

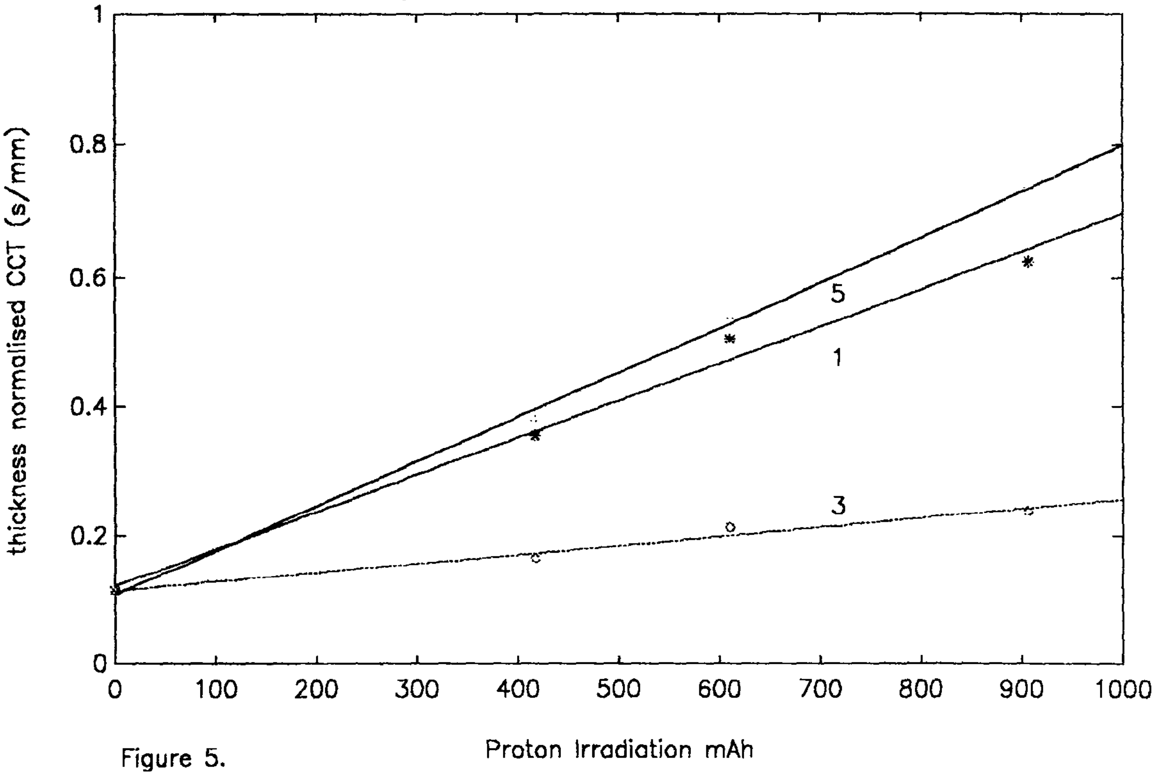


Figure 5.

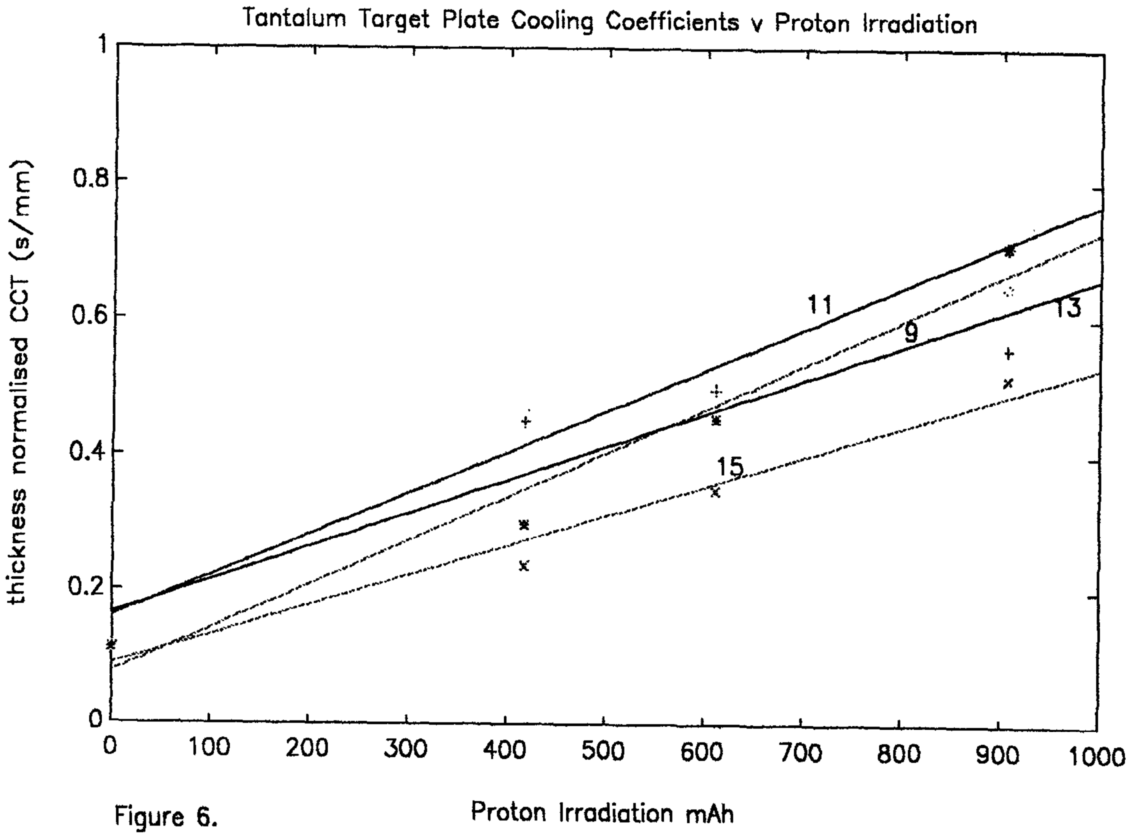

Tantalum Target Plate Cooling Coefficients v Proton Irradiation
thickness normalised CCT (s/mm)
0
0.2
0.4
0.6
0.8
1
0
100
200
300
400
500
600
700
800
900
1000
Proton Irradiation mAh
11
9
13
15

Figure 6.