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**Westinghouse Electric Corporation
Fusion Power Systems Department**

MASTER

**THERMAL ANALYSIS OF THE TFTR
VACUUM VESSEL WALL PROTECTIVE PLATE**

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THERMAL ANALYSIS OF THE TFTR VACUUM VESSEL WALL PROTECTIVE PLATE

Prepared by:
Alan Y. Lee

Approved by:

T. C. Varljen
Engineering Manager
TFTR Project

Approved by:

C. K. Kim, Manager
Systems Engineering and Analysis
TFTR Project

Westinghouse Electric Corporation
Fusion Power Systems Department
Post Office Box 10864
Pittsburgh, Pennsylvania 15236

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ABSTRACT

The TFTR vacuum vessel is to be protected with tungsten plates from the effects of neutral beam impingement. A thermal analysis is performed to determine the maximum allowable beam intensity (power per unit area) under normal and faulted operating conditions. In order to permit a faulted pulse, or unattenuated injection, to occur after a normal pulse series, the maximum neutral beam energy flux should be below 10 kW/cm^2 depending on the beam design configuration, to prevent the melting of the plates. The analyses were performed using an injection time of 0.5 second and a cycle time of 300 seconds.

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1.0 INTRODUCTION

The TFTR is designed to have a number of neutral beam systems to inject high energy neutral deuterium (or hydrogen) atoms into a plasma to raise and then maintain the temperature of the plasma during test operation. Under normal conditions the bulk of the energy will be absorbed by the plasma, while the remainder would impinge onto the vacuum vessel wall. Under a faulted condition the unattenuated energy reaching the vessel wall would cause failure. Protective plates are therefore used locally to protect the vessel wall. The plates form a continuous band extending 126° around the major circumference and 15° above and below the equatorial plane. The energy flux of the beams is in the range of 10 to 20 kW/cm². The net heat flux reaching the protective plate surface depends, however, on the design parameters of the TFTR. The functional requirement of the plate is to keep the surface layer from melting under all operating conditions. Hence the thermal design criterion for the plate is that the maximum surface temperature be below the melting temperature of the material, which is tungsten. The melting temperature is taken to be 3370° C. The plates are not cooled by external means, such as forced convection by gas or liquid. The only cooling is by thermal radiation from the plate surfaces. Since the details of the neutral beam design are not firm at this time, multiple pulse transient analysis was performed parametrically using different values of input heat flux reaching the plate surface to determine the surface temperature response of the plate. The results are presented in graphical form, so that the maximum beam energy flux allowable, before surface melting occurs, can be selected for a particular beam design.

2.0 METHOD AND MODEL OF ANALYSIS

The protective plate is composed of 1 cm (3/8") cubes of tungsten, diffusion bonded to a 0.33 cm (1/8") thick molybdenum backing plate. The gaps between the cubes are approximately 0.1 cm wide. Since the angle of impingement of the beam is approximately 45° , the beam particles cannot directly strike the molybdenum plate. A schematic diagram of the vacuum vessel and the plates is shown in Figure 1. The plates are mechanically attached to molybdenum struts about 60 cm long which are in turn, attached to the vessel structure. It is intended that the heat conduction path across the protective plate and through the joints and the struts provide sufficient thermal impedance to protect the stainless steel vessel wall.

As shown in Figure 1 a beam will spread over an area covering about two plates.

Some of the tungsten cubes located at the axis of the beam would receive the peak flux from the beam. The cube receiving the maximum value of attenuated energy from the beam was analyzed as the worst case.

The calculation was performed using a one dimensional TAP-A⁽¹⁾ heat conduction model. The modes of heat transfer were heat input to the tungsten surface and heat losses by thermal radiation from the front and the back surfaces to the surrounding wall. The plate was divided into 16 equal layers across its thickness as shown in Figure 2. Various values of input heat fluxes were specified for the calculations. The analysis parameters are as follows:

Heat flux input to tungsten surface	=	0.1 to 7.5 kW/cm ²
Heat deposition duration	=	0.5 second
Initial material temperature	=	20°C
Surrounding sink temperature	=	20°C
Surface emissivity	=	0.3
Pulse cycle time	=	300 seconds

The thermal properties of the tungsten and molybdenum used in the calculations are shown in Appendices A & B.

3.0 RESULTS OF ANALYSIS

The plate surface temperature response during the first pulse for a heat flux from 0.1 to 7.5 kW/cm^2 is shown in Figure 3. The pulse cycle consists of 0.5 second of energy deposition time, followed by 299.5 seconds of cooldown time. The initial material temperature is 20°C . The figure shows that for a heat flux as high as 7.5 kW/cm^2 , the surface temperature reached about 3437°C which is slightly above the tungsten melting temperature of 3370°C . By interpolation of the curves, it appears that for a single pulse operation, a net heat flux of approximately 7.2 kW/cm^2 with an energy deposition time of 0.5 seconds is the maximum value the plate can tolerate. The figure also shows that the surface temperatures dropped off rapidly during the cooldown period but did not return to its initial value at the end of the 300 second cycle time.

With consecutive multiple pulses and normal input heat flux, the peak surface temperature at the end of each 0.5-second pulse and the temperature at the end of the pulse cycle time continue to increase after each pulse, until an equilibrium condition is reached at which the energy deposited during the first 0.5 second can be dissipated by thermal radiation to the surroundings during the remaining 299.5 seconds of cooldown. Figure 4 shows the plots of the peak surface temperatures at the end of the pulse cycle in a multiple pulse operation at several heat flux values. It is seen from the figure that the peak surface temperature levels off after a few pulses, especially at higher heat fluxes. This indicates that the plates will tolerate a large number of consecutive pulses under normal conditions. Figure 6 shows the plot of the peak surface temperature and the surface temperature at the end of the cycle as a function of heat flux at normal equilibrium conditions, as shown in Figure 4 and 5. Under normal conditions, it is seen from the figure that the surface input flux, or the attenuated energy from the neutral beam, can be as high

as 6.0 kW/cm^2 or the peak intensity of the beam be as high as, for example, $6.0/(0.04 \times 0.707) = 212 \text{ kW/cm}^2$, with a 96% plasma attenuation (4% of the beam energy reaching the plate) and 45° angle of impingement ($\cos 45^\circ = 0.707$). However, when the equilibrium condition is reached after a normal pulse series the allowable peak intensity (power per unit area) of the beam under faulted or unattenuated conditions must be much less than the 212 kW/cm^2 given above. The allowable peak intensity is determined by the following procedure, so that the resulting plate surface temperature is at or below the melting temperature of tungsten:

$$\text{Max Intensity} = I(T_e + \Delta T)$$

where T_e is the surface temperature at the end of a pulse after normal multiple pulses with intensity I , obtained from the lower curve of Figure 6; and ΔT is the surface temperature rise due to a faulted injection with intensity I , obtained from Figure 3 (temperature at 0.5 second minus the initial temperature).

Based on the reasoning presented above, a parametric study was carried out to estimate the allowable peak intensity for the neutral beam for operations under both normal and abnormal conditions. Figure 7 shows the result of the study in which the maximum peak intensity is plotted for different percentages of plasma attenuation and angles of impingement. As seen from the figure, the maximum intensity is between 6.5 and 10 kW/cm^2 depending on the design configuration. The peak intensity of the beams can, therefore, be selected or designed based on a faulted condition injection constraint after a few normal multiple pulses, so that the plate can function at all operating conditions from thermal design considerations in protecting the vacuum vessel.

An illustration of the temperature distributions across the plate thickness is given in Figure 8. The input surface heat flux for the illustration is 6.0 kW/cm^2 . The temperature distributions may be used for thermal stress evaluation.

It should be noted that the calculated surface temperature depends on the surface emissivity used for the calculations. The value of 0.3 used, is within the range published in references 2, 3 and 4 and is considered adequate.

REFERENCES

- (1) "TAP-A A Program For Computing Transient or Steady State Temperature Distributions", WANL TME-1872, B. L. Pierce, and H. J. Stumpf, December, 1969
- (2) "Heat Transmission", 3rd Ed., W. H. McAdams, 1954
- (3) "Materials Properties Data Book", Report 2275, REON NERVA Program, Aerojet Nuclear System Co., 1970
- (4) "Handbook of Chemistry and Physics", 41st Ed. 1960

APPENDIX A
THERMAL PROPERTIES OF TUNGSTEN

Temperature		Thermal Conductivity		Specific Heat
<u>°F</u>	<u>°C</u>	<u>Btu/Hr-ft-°F</u>	<u>Watts/m-°C</u>	<u>Btu/lb-°F</u> or <u>Cal/gm-°C</u>
0	-18	96.8	167.5	.032
210	99	92.0	159.3	.033
800	427	73.4	127.1	.033
930	499	69.9	121.1	.034
1500	816	61.3	106.2	.036
1700	927	60.1	103.9	.036
2600	1427	56.2	97.2	.038
4500	2482	54.0	93.5	.038
9000	4982	54.0	93.5	.038

$$\text{Density} = 1204.4 \text{ lbs/ft}^3 = 19294.7 \text{ kg/m}^3$$

APPENDIX B

THERMAL PROPERTIES OF MOLYBDENUM

Temperature		Thermal Conductivity		Specific Heat
<u>°F</u>	<u>°C</u>	<u>Btu/Hr-ft-°F</u>	<u>Watts/m-°C</u>	<u>Btu/lb-°F</u> or <u>Cal/gm-°C</u>
0	-18	76.9	133.1	.061
210	99	73.9	127.9	.062
800	427	65.7	113.7	.067
930	499	64.8	112.2	.068
1500	816	62.2	107.7	.073
1700	927	61.3	106.2	.074
2600	1427	60.5	104.7	.081
9000	4922	60.5	104.7	.081

$$\text{Density} = 635.9 \text{ lb/ft}^3 = 10187.2 \text{ kg /m}^3$$

Figure 1. TFTR Vacuum Vessel and Protective Plates

Figure 2. Heat Transfer Analysis Model of Protective Plate

Figure 3. Protective Plate Surface Temperature Responses During First Pulse Cycle

Figure 4. Protective Plate Peak Surface Temperatures During Normal Multiple Cycle Operation

ENERGY DEPOSITION TIME = 0.5 SECONDS

SURFACE EMISSIVITY = 0.3

INITIAL TEMP = 20°C

PULSE CYCLE TIME = 300 SECONDS

Figure 5. Protective Plate Surface Temperatures at End of Cycle During Normal Multiple Cycle Operation

ENERGY DEPOSITION TIME = 0.5 SECONDS

SURFACE EMISSIVITY = 0.3

INITIAL TEMP = 20°C

PULSE CYCLE TIME = 300 SECONDS

Figure 6. Plate Surface Temperatures at Normal Equilibrium Condition
As Function of Heat Flux

Figure 7. Maximum Neutral Beam Flux Allowable For Current Design of Protective Plate

Figure 8. Temperature Distributions Across Plate Thickness
With Input Heat Flux 6.0 kW/cm²