Use of a Thermal Analogy to Find Electrical Resistances of the Electrical Breaks in the TPX Passive Stabilization Systems*

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ABSTRACT

The inner and outer passive stabilization systems for the Tokamak Physics Experiment (TPX) are similar in design in that they both utilize copper passive plates that form large toroidal rings. The rings are electrically continuous except at one toroidal location where a high resistance break must exist. Vertical conductors connect the rings together on either side of the electrical break forming a saddle coil. In order to prevent all the current during initial plasma start-up from flowing through the rings instead of the plasma, the resistances of the breaks for the inner and outer stabilizers must be greater than 70 and 300 $\mu\Omega$ respectively. A thermal-electrical analogy has been developed so that 2–D heat transfer finite element codes can be used to find the electrical resistances in the proposed designs of the high resistance breaks. This analogy is based on classical heat transfer theory using an electrical analogy for finding the equivalent conductances of materials that are in series or parallel. In these cases the conductivities of the materials are converted into conduction resistances. The conduction resistances are associated with actual electrical resistances, the heat transfer rate with current, and the temperature difference with potential drop. Therefore the basic heat transfer equation, $q = K\Delta T$, can be used to express the electrical equivalent equation, $V = IR$ as $\Delta T = q(1/K)$. By imposing a temperature drop across the 2–D finite element thermal models of a break and having the code determine the total heat flow through the model, the resistance of the break, $R = 1/K$, can then be calculated.

INNER PASSIVE STABILIZER

The Inner Passive Plates (IPP) are mounted on copper rings, Fig. 1. The three ring design has one ring at the upper rim, one ring at the lower rim and one ring at the mid plane. Each IPP covers a toroidal angle of 22.5°for ease of remote handling. They extend the full length between the upper and lower support rings, which also facilitates remote handling. The support rings of the IPP have a toroidal angle of 90° for each section. This large angle is not a problem since they are category 2 components and need not be actively cooled.

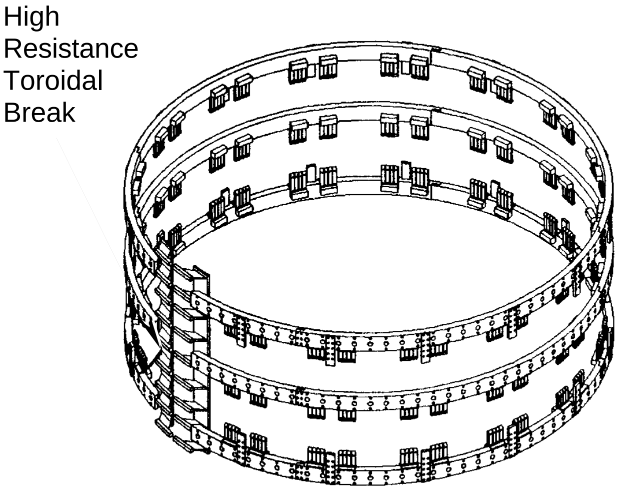

Fig. 1. Inner passive toroidal break.

The mounting rings and the passive plates form a uniform structure that expands during periods of elevated temperature copper alloy components of the passive plates/support ring structure and the titanium center post is absorbed by the titanium brackets that attach the ring/plate structure to the vacuum vessel center post [1].

An electrical as well as mechanical connection takes place at the "High Resistance Break" between the passive plates at 157.5°, Fig. 1. Here the passive plates are bolted solidly to a vertical string of titanium alloy brackets. The purpose of these brackets is to fasten the plates to the center post to resist the disruption forces, to provide a calibrated high resistance path for the current that flows during a disruption, and to provide vertical flexibility during bake-out without over stressing the vacuum vessel wall and the Inner Passive Plates. The bolted joint can be disconnected remotely and the fasteners are captive.

The resistance break was designed using Princeton Plasma Physics Laboratory (PPPL) supplied magnetic loads and electrical currents. A double row of titanium brackets is used to connect the IPP to the vacuum vessel. The bracket web has a parallelogram shape in order to spread the brackets apart as far as possible to increase the electrical resistance from IPP to IPP across the gap. The thicknesses of these webs vary depending on poloidal placement. The support bracket locations are shown in Fig. 2. The thicker web brackets are located

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*Work supported by the U.S. Department of Energy under Contract No. DE-AC03-89ER51114.

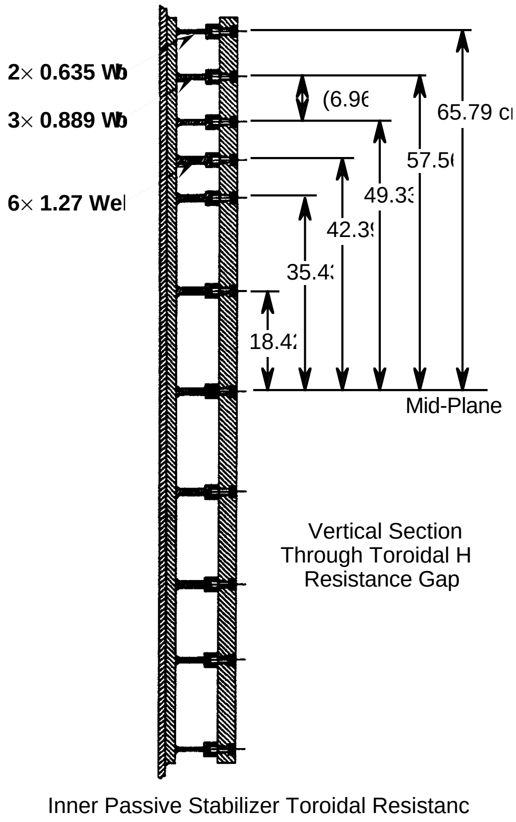

Fig. 2. Support bracket locations.

closer to the machine mid plane and the thinner web brackets closer to the upper and lower edge to avoid over stressing during bake-out. The brackets provide a hard connection between the vacuum vessel center post and the support structure of the IPP. Results of stress analyses for magnetic loads just prior to a vertical disruption and restrained thermal expansion during bakeout at 350°C are provided in [1].

Each bracket is welded to a vertical weld pad, that extends from the upper to the lower support ring. This enables the manufacturer to complete the weldment, match drill the IPP and the bracket assembly, and weld the bracket assembly to the vacuum vessel center post without the risk of weld distortion. Each bracket has three tapped attach holes to which the IPP will be bolted, using remote handling bolts. A design effort is under way to investigate the use of 1/4 turn fasteners at this location to eliminate the need for costly remote repairs in case a thread is stripped. Other methods of fastening are also under consideration.

OUTER PASSIVE STABILIZER

The outer passive plate (OPP) structure consists of two toroidal copper rings, a lower ring and an upper ring. The two rings are toroidally electrically continuous except at one toroidal location where a high resistance electrical break must also exist.

Vertical conductors connect the top and bottom rings together on either side of the electrical break. Fig. 3 shows an isometric view of the electrical break area. There are four identical structures which connect from the copper passive plates to the vacuum vessel wall. The final cross sectional areas of the support beams in the break structures are to be determined by the results from the electrical/thermal analogy analysis and subsequent stress analyses.

ANALYSIS

Knowing the resistances of the toroidal breaks is necessary in order to prevent all the current during initial plasma start-up from flowing through the rings of the inner and outer stabilizers instead of the plasma and also to provide a calibrated high resistance path for the current that flows

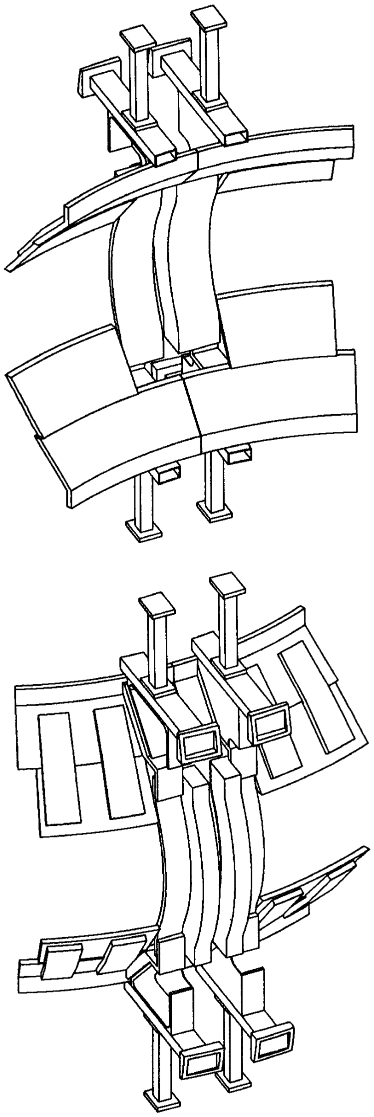

Fig. 3. Isometric views of toroidal break area.

during a disruption. The resistances of the toroidal breaks for the inner and outer stabilizers must be greater than 70 and 300 μΩ respectively.

The thicknesses of the electrical paths for IPP and the vacuum vessel wall are assumed to be the same. The greater the thickness of the electrical path through the IPP and vacuum vessel wall, the smaller the electrical resistance of the path. Thus this maximum path thickness is used in the analysis in order to provide a lower boundary on the resistance of the path. If the poloidal electrical paths through the IPP do not overlap between adjacent support brackets, then the thickness of the electrical path would be determined by the shortest poloidal distance between support bracket weldments. The shortest distance between brackets is 6.95 cm., Fig. 2. There-fore the greatest thickness of the electrical path on one side of the bracket is half that thickness. The total path includes both sides of the bracket resulting in a thickness 6.95 cm.

The electrical/thermal analogies are shown in Table I. The resistance is analyzed for each type of support bracket and then added in parallel to get the total resistance. The temperature drop across the model is set at 1000°C. The resulting heat flux contours in the model of a 1.27 cm thick bracket web are shown in Fig. 4. For this particular case the heat flux through the mid span of the inner passive plate is $1.37\text{x}10^5$ W/cm^2, which is a heat flow of 1.238 MW. Therefore from Table 1 the resistance of the bracket is:

$$R = 1/K = \Delta T/Q = 1000°\text{C}/1.238\ \text{MW} = 808\ \mu\Omega$$

The resistances for the 0.89 cm and 0.635 cm thick brackets are 885 μΩ and 988 μΩ respectively. The total resistance of the toroidal gap is:

$$R = 1/[(2/988) + (4/885) + (7/808)] = 66\ \mu\Omega$$

Table I
Thermal-Electrical Analogy

Electrical		
I	= Current	= Amp
V	= Voltage	= Volts
r	= Resistivity	= Ω – m
L	= Length	= m
A	= Area	= m^2
R	= Resistance	= Ω ⇒R =Σ rL/A
Thermal		
Q	= Heat Transfer Rate	= W
T	= Temperature	= °C
K	= Overall Conduction Coeff	= W/°C ⇒1/K =Σ (1/k)L/A
k	= Thermal Conductivity	= W/(m–°C)
Equations		
V	= IR	(1)
DT	= Q/K	(2)
Analogs		
	Thermal	Electrical
	T [°C]	V [Volts]
	Q [W]	I [Amps]
	1/K [°C/W]	R [Ω]
	1/k [m–°C/W]	r [Ω – m]

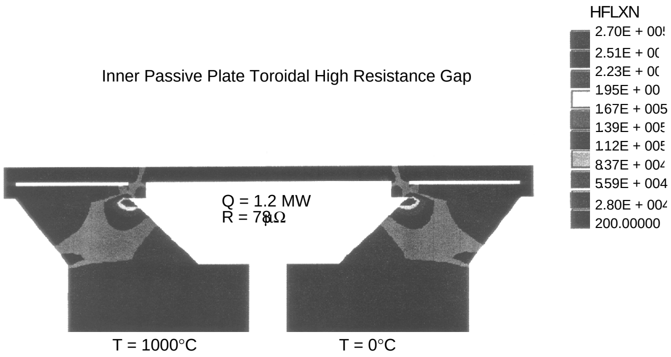

Fig. 4. Heat flux contours for a 1.27 cm thick bracket web K = ΔT, R = 1/K

For the outer passive stabilizer the four support structures are in series-parallel. Since the resistance across the electrical break (through the T_i support structure) must be ≥300 μΩ, the resistance of each of the four structures including the resistance through the vacuum vessel itself must be 300 μΩ Fig. 5. Equivalent material thicknesses were used to model the hollow beams as flat plates with equivalent cross-sectional areas. The thickness of the flat plates were varied until an overall resistance of 300 μΩ was obtained. The temperature drop across the mode was set at 1000°C. The total heat flow through the model is the sum of the heat flows through each leg, Fig. 6. Hence the resistance of the break is:

$$R = 1/K = \Delta T/(Q1+Q2) = 1000°\text{C}/3.41\ \text{MW} = 293\ \mu\Omega$$

Stress analysis of the outer passive stabilizer using these thicknesses has yet to be performed.

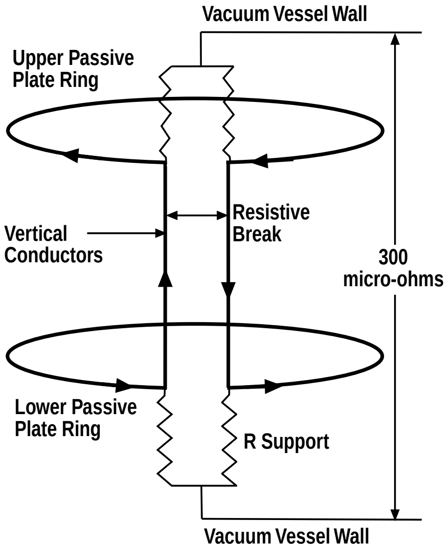

Fig. 5. Outer passive plate electrical circuit arrangement. There are four structural support legs each having a resistance (R support) from the copper rings to the vacuum vessel. The structural supports must be sized so that R support = 300 micro-Ohms.

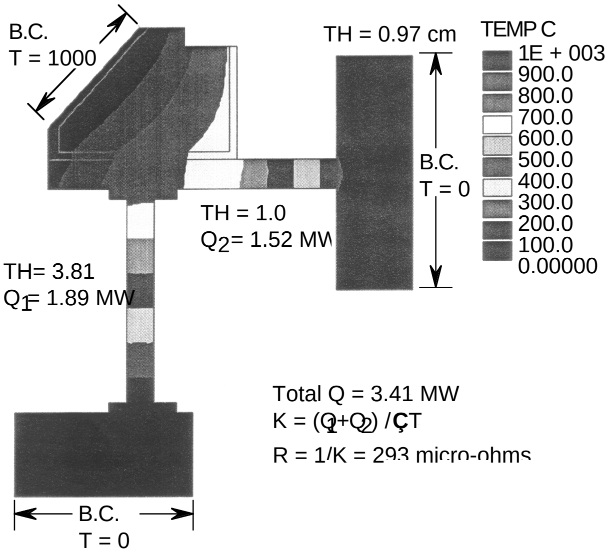

Fig. 6. Temperature plot shown with boundary conditions and heat transfer rate through each of the two legs.

CONCLUSION

A 2–D thermal model can be used for calculating the electrical resistances of complicated assemblies. For the inner passive stabilizer the high resistance toroidal gap was first designed to withstand mechanical and thermal loads. The final design was then found to have an electrical resistance of 66 μΩ. For the outer passive stabilizer the resistance gap was first designed to have a resistance of 293 μΩ and the stress analyses to follow. In both cases the thermal analogy allows the design engineer to perform electrical analyses with a common thermal analysis code.

REFERENCES

[1] E. Chin and E. Reis, "Stress analysis of the 22.5 degree section design for the TPX passive stabilizer," TPX:0057:EC:95, unpublished.