SIMULATION OF HIGH-AVERAGE POWER WINDOWS FOR ACCELERATOR PRODUCTION OF TRITIUM*

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Abstract

Development of a robust, high-average-power (210 kW, CW) microwave transmission line system for the Accelerator Production of Tritium (APT) facility is a stringent engineering and operational requirement. One key component in this RF transmission system is the vacuum barrier window. The requirement of high-power handling capability coupled to the desirability of good mean time to failure characteristics can be treated substantially with a set of microwave, thermal-structural, and Weibull analysis codes. In this paper, we examine realistic 3-D engineering models of the ceramic windows. We model the detailed cooling circuit and make use of accurate heat deposition models for the RF. This input and simulation detail is used to analyze the thermal-structural induced stresses in baseline coaxial window configurations. We also use a Weibull-distribution failure prediction code (CARES), using experimentally obtained ceramic material failure data and structural analysis calculations, to infer probability of failure.

1 INTRODUCTION

The Accelerator Production of Tritium (APT) project is a Department of Energy (DOE) sponsored investigation into the feasibility of using linear accelerator technology (as opposed to traditional reactors) to produce tritium. A major technical issue is the design of vacuum barrier ceramic windows inside the RF transmission system. Specifications call for material transparent to microwaves at as much as 700 MHz and 500 kW, CW (actual operation will be at half that power). Compromise of the system results in vacuum breach and costly down time for the accelerator.

The objective of this analysis is to develop a simulation that will model the thermal and structural effects of transmission inefficiencies coupled to an atmospheric load to determine if, and more appropriately, when the ceramics will fail.

Since ceramics have much higher deviations in strength and wear properties than conventional structural materials, the output of the continuum, thermomechanical, Finite Element Analysis (FEA) will be coupled to a Weibull statistics code. Weibull analysis is performed with CARES (Ceramic Analysis and Reliability Evaluation of Structures) [1], a finite element probabalistic software developed by NASA. Probability of Failure (POF) is inferred from calculated Weibull parameters using data from four point bending tests on AL300 (97.6% alumina ceramic).

2 PHYSICAL DESCRIPTION

Two RF waveguide geometries are presented in this paper: (1) a generic, single window, design that has been used in experiments, and (2) one of the competing designs for the power coupler on the APT linac (courtesy of CPI Communications & Power Industries).

Electric fields from microwave transmission produce heat loads from imperfections in the electrical properties of copper and alumina. For the test geometry, there is active cooling from air flowing through the inner conductor and out across the window surface. The walls of the inner conductors, outer conductors, and t-bars are plated with copper (for electrical properties) and are otherwise aluminum and stainless steel. For the CPI geometry, the active cooling circuit is a more aggressive, water cool, in the inner conductor coupled with airflow between the ceramics. The conductors are copper and copper-plated stainless steel. The windows are kept in place by a brazed joint.

3 FINITE ELEMENT MODEL

The single window Finite Element (FE) model is built using 8-node bricks and 4-node shell elements and the CPI model is built as a 2-D axisymmetric simulation with 4-node quads. Using a 2-D axisymmetric simulation for the CPI geometry (as opposed to the 3-D implemented in the single window test case) is assumed from the observation that very little problem insight is gained from the addition

* The work was performed under the auspices of the U.S. Department of Energy by LLNL under contract W-7405-ENG-48.

of 3-D effects. There is geometric axisymmetry of the problem (in the region that we are interested) and our main concern is the stress state of the windows, not the entire system.

The heat deposition as a result of the electric field calculation along the walls of the inner and outer conductor and the ceramic is conservatively approximated to be axisymmetric with the maximum azimuthal values represented. The values of the electric field are calculated using a 3-D direct Maxwell equation solver. The values for power deposition are determined from the calculated electric field averaged over a RF cycle for the perfectly matched case.

Convective cooling is accounted for by computing heat transfer coefficients from correlations for fluid flow [2]. Enclosure radiation is accounted for in the vacuum cavities (in the 2-D axisymmetric case) using gray diffuse view factors. Natural convection and radiation exchange with the surroundings are accounted for on all outside surfaces.

The simulation is performed in two steps: (1) solution of the thermal profile from the given power load (using TOPAZ [3]) and (2) solution of stress contours throughout the window from the sum of thermal stress and mechanical stress from the vacuum pull (using NIKE [4]). These combine to give the thermal stress result.

4 RESULTS

There are three significant results presented here and each allow insight into to the fundamental physics of the problem.

4.1 Single Window Geometry

An experiment was performed at Argonne National Laboratory (ANL) [5] (using an EEV/WESGO AL300 ceramic) and is used for comparison with the test FE model. This experiment provides the temperature at the outer radius of the window and a temperature profile across the vacuum surface courtesy of an infrared camera. These experiments were done in the range of 1000 kW, CW at 350 MHz. The test FE model has been run and benchmarked to these experiments. This model helps us understand the significance of the cooling circuit in the stress distribution of the window. Running 1000 kW at 350MHz, the effects of too aggressive an inner conductor cooling without adequate attention to the air cooling across the window could be disastrous. It is discovered from varying the heat transfer coefficients (effectively changing the flow rates of air and water in the system) the stress is significantly effected. The results are seen in Figure 1.

It can be seen that as the heat transfer coefficient value on the inner conductor is decreased, the maximum principal stress in the window actually decreases. This is an important result - that less cooling results in less stress.

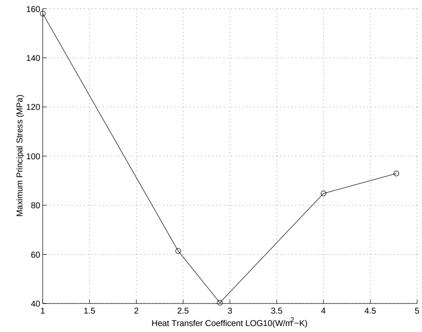

Figure 1: Maximum principal stress at various flow rates inside the inner conductor (window cooling held constant).

Conventional heat transfer rule-of-thumb would suggest the opposite, that less cooling will result in higher thermal stress. Further analysis shows that the magnitude of the face cooling is just as important. Figure 2 shows the variation of stress when the flow rates across the window are varied.

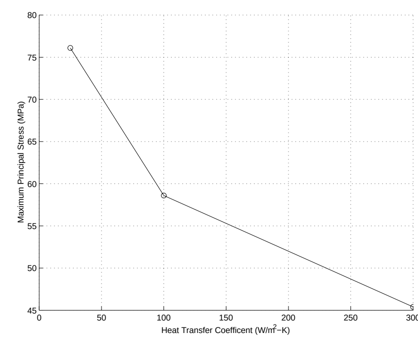

Figure 2: Maximum principal stress at various flow rates across the ceramic windows (inner conductor cooling held constant).

This geometry provided the first look of the effects of RF shields on the resultant heat load on the ceramic. These shields are place in the transmission line before and after the ceramics to prevent significant loading on the brazed joint. In preventing this build-up, the shield creates high electric fields at the same radial location in the ceramic (off the conductor walls). The resultant temperature peak, at a distance out from the inner conductor, results in high thermal loading in that position. This has been a significant influence in the temperature gradient driven thermal stress, because the peak temperature occurs away from the inner conductor wall, rather than directly at the wall, as theory would say. Couple that to the fact that the inner conductor is cooled to low temperatures, creates a strong temperature gradient right at the inner radius.

4.2 Dual Window Geometry

The CPI geometry includes a feature on the inner conductor that mitigates the aforementioned cooling issue (especially when using high flow rate water-cooling). The design features a thin-walled sheet of Oxygen Free

Electronic Copper (OFE-Cu) that the ceramic is directly brazed to. This plate is supported only at the ends, allowing the ceramic to expand, unconstrained, under a thermal load. The resultant stresses decrease by a factor of three over the ridged body assumption. Table 1 shows a comparison of the ridged and flexible support models with inner conductor and window cooling set at 60,000 W/m^2-K and 50 W/m^2-K respectively.

Table 1: Resultant principal stresses.

Maximum Principal Stress (MPa)	Ridged support	Flexible support
(σ_{mean}~250 MPa)	92.9	28.7

The implementation of flexible boundaries, although quite clever, leaves many questions lingering about the integrity of the brazed joint. Stresses in the copper plate are approaching the yield strength of the material and could create some fatigue problems in the long run.

4.3 CARES Predictions

CARES is a probabilistic, public domain software program that was developed at NASA Lewis Research Center. CARES calculates the POF for brittle ceramic materials from Weibull parameters and fatigue parameters for sub-critical crack growth. These parameters are calculated by CARES from test sample data.

Using data for WESGO AL300 ceramic [6], the probability of failure is calculated for extreme stress. Figure 3 shows the POF (as calculated by CARES) is only significant above 189 and below 273 MPa. Since our problem is the 30 MPa range (see Table 1), preliminary results suggest that the probability of failure will be quite low.

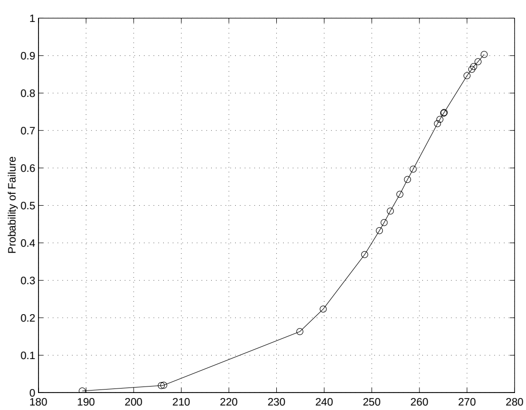

Figure 3: Probability of Failure in AL300 as a function of Stress State.

5 CONCLUSION / WORK IN PROGRESS

The analysis thus far has given much insight into the physics of the problem, significant design features, and their contribution to failure. From the aforementioned analysis we are able to infer trends in stress state when the cooling flow rates are changed. Thus, we are able to recommend optimum values to mitigate premature breakage due to thermally induced stresses. We also discovered that implementation of flexible boundaries for the ceramic vacuum barrier windows proved an excellent means of preventing thermal stress buildup.

Future analysis will be focused on continuing refinement of the current simulations to assure accuracy, as new experimental data becomes available in the coming months. More effort will be put on the interpretation of CARES results for fast-fracture as well as the failure time as a result of sub-critical crack growth (static fatigue). Other emphasis will be placed on the EEV design for the APT power coupler that was not treated here. A major feature of the EEV design is the use of an expanding outer conductor, rather than a shield, to protect the brazed joints. Preliminary results also suggest that the EEV design may not be plagued by the same cooling concerns because of the smooth distribution of power absorption in the ceramic (from the absence of shields) and the more than adequate use of air cooling across the window faces.

More future analysis will examine the structural response to the perfect mismatched case in the transmission (when the RF wave effectively encounters a short and is reflected back down the line) for both the CPI and EEV designs.

6 ACKNOWLEDGEMENTS

Completion of this analysis would not have possible without the contributions of colleagues at LLNL and LANL. The authors acknowledge stimulating discussions with Dr. A. Shapiro and Dr. C. Landram at LLNL, and Dr. B. Rusnak at LANL.

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