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*Theoretical Predictions and Experimental
Assessments of the Performance
of Alumina RF Windows*

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*Theoretical Predictions and Experimental
Assessments of the Performance
of Alumina RF Windows*

Karen Ann Cummings

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by

Karen Ann Cummings

ABSTRACT

Radio frequency (RF) windows are the most likely place for catastrophic failure to occur in input power couplers for particle accelerators. Reliable RF windows are essential for the success of the Accelerator Production of Tritium (APT) program because there are over 1000 windows on the accelerator, and it takes more than one day to recover from a window failure. The goals of this research are to analytically predict the lifetime of the windows, to develop a conditioning procedure, and to evaluate the performance of the RF windows.

The analytical goal is to predict the lifetime of the windows. The probability of failure is predicted by the combination of a finite element model of the window, Weibull probabilistic analysis, and fracture mechanics. The window assembly is modeled in a finite element electromagnetic code in order to calculate the electric fields in the window. The geometry (i.e. mesh) and electric fields are input into a translator program to generate the mesh and boundary conditions for a finite element thermal/structural code. The temperatures and stresses are determined in the thermal/structural code. The geometry and thermal/structural results are input into another translator program to generate an input file for the reliability code. Material, geometry and service data are also input into the reliability code. To obtain accurate Weibull and fatigue data for the analytical model, four point bend tests were done. The analytical model is validated by comparing the measurements to the calculations. The lifetime of the windows is then determined using the reliability code. The analytical model shows the window has a good

thermal mechanical design and that fast fracture is unlikely to occur below a power level of 9 MW.

The experimental goal is to develop a conditioning procedure and evaluate the performance of RF windows. In order to achieve this goal, a high-power RF test stand has been built which has the capabilities to monitor the critical RF and vacuum parameters while also providing the necessary diagnostic equipment, data acquisition systems, and RF interlocks. The conditioning procedure is developed by testing different methods of conditioning. The performance of the window is evaluated using the diagnostic equipment on the test stand.

During the experimental evaluation, much was learned about processing of the windows to improve the RF performance. Methods of processing included grit blasting and using various coatings. The metal surfaces near the ceramic were coated with Teflon based coatings to suppress multipacting. The effects of these coatings were not consistent; therefore, no coatings are recommended on the metal. Grit blasting the ceramic and surrounding metal surfaces proved to be critical to the success of the windows. Grit blasting was also found to be a remedy for windows which were arcing and heating excessively.

Various methods of conditioning were used, including continuous wave (CW), amplitude modulation, and pulsed conditioning. The most successful method is amplitude modulation. Advantages of amplitude modulation include being able to maintain a lower pressure during conditioning as well as conditioning over a wide range of power levels. Using amplitude modulation the conditioning time is significantly reduced. Thus, amplitude modulation is the recommended method of conditioning.

A total of 16 windows were tested and evaluated. The electrical parameters were measured at low powers with a network analyzer. Of the 16 tested, one failed at 527 kW and a second one was heating and arcing excessively at that power level. After the window broke, grit blasting was implemented. Windows which were arcing and heating

excessively were grit blasted again and then were conditioned to 1 MW without excess heating and arcing. Then, the remaining 14 windows were tested to 1 MW.

Materials characterization was done to determine the topographical and chemical effects of grit blasting on the alumina surface. It is believed that grit blasting increases the peak-to-valley distance but at the same time flattens out local or small deviations found within the valleys and peaks. Surface analysis of the ceramic has shown that grit blasting removes a significant amount of carbon, a cleaning affect. It also removes the discolorations on the ceramic surface. Grit blasting changes the surface topography of the metal and ceramic.

CHAPTER 1

INTRODUCTION

1.1 Background

Ceramic windows are used in radio-frequency (RF) linear particle accelerators as part of the device to couple RF power into accelerators. The purpose of RF windows is to provide a vacuum barrier while being transparent to the RF power. The ceramic RF window and surrounding structure which transitions from the RF transmission line to the accelerating structure coupling loop or iris is the input power coupler. RF windows are the most likely part of an input power coupler to suffer catastrophic failure.

This research supports the Accelerator for Production of Tritium (APT) Project. APT is a proposed accelerator which will be used to make tritium, a radioactive isotope of hydrogen required for national defense. Tritium can be produced by nuclear reactors; however, nuclear reactors are shut down in the United States (US). The present supply of tritium is being depleted by radioactive decay, and starting in the year 2005, new supplies of tritium will be needed. The US government has funded two prototype projects to make tritium for the national defense needs: APT and a nuclear reactor project. The advantage of the accelerator approach is a greatly decreased output of long half-life radioactive waste. In October of 1998, the government will evaluate both technologies and decide which one will be used to make tritium. The prototype project for APT is the Low Energy Demonstration Accelerator (LEDA) which is the low energy portion of the APT accelerator. This RF window research deals with the 350 MHz RF windows used in LEDA, and the results and procedures will be applied toward APT.

This work is critical to the APT, which is a continuous wave(CW) accelerator in which the majority of the machine is superconducting. As mentioned above, windows are historically the place most likely for failure to occur in the accelerator. On the APT machine there are over 1000 high power RF windows, and it is absolutely critical for the success of

the APT project to have reliable windows. Consider the case where the mean time between window failure is 20,000 hours. With a total of 1000 windows on the machine every 20 hours on average a window will need to be replaced. Assuming that it takes 48 hours of downtime to replace a failed window and recondition it implies that window failures alone will keep the machine from running. If the mean time between failure is 100,000 hours, then with a total of 1000 windows on the average every 100 hours a window will need to be replaced. However, note the mean time between failure predicts, as the name implies, the mean lifetime of the windows. This may not predict a specific failure, as there will be a variation in the time to failure among the windows. Nevertheless, it is important to be able to predict the lifetime and mean time between failure of the windows and to understand how to condition windows, and to be able to predict window failures before they occur.

To illustrate the role of RF windows in accelerators, a simplified overview of the proposed APT accelerator is shown below in Figure 1A. Initially, the ion beam is produced in the injector. Then the particles go through the radio frequency quadrupole (RFQ) where they are simultaneously bunched and accelerated to an energy of 6.7 MeV. The particles enter a coupled-cavity drift tube linac (CCDTL) where they are accelerated to an energy of 100 MeV. Following the CCDTL, the particles are accelerated by a coupled cavity linac (CCL) to 217 MeV and then by a superconducting linac (SCRF) to an energy of 1.3 GeV. Upon exiting the superconducting linac the particles are directed into the target area where they collide with a target and produce neutrons. The neutrons are then used to produce tritium.

RF power is coupled into the RFQ, CCDTL, CCL, and superconducting cavities to accelerate the particles. All four of these accelerator components use different structures to accelerate the particles and are suitable for accelerating different particle energies. Thus, the

Figure 1A. Components of a Linear Accelerator (not to scale)

accelerating structure is chosen for which the efficiency of energy transfer is greatest for a particular particle energy.

To demonstrate how the RF power is used to accelerate the particles, a simple pillbox cavity with a single accelerating gap is discussed. Electric fields are created within this cavity as shown in Figure 1B. The length of the arrows represents the magnitude of the electric field, and the largest electric field is in the center of the cavity. The electric fields oscillate at the frequency of the structure. The force (in Newtons) on the particle is represented by Equation 1.1.

$$F = q E$$

Eq. 1.1

where q is the charge of the particle, 1.60×10^{-19} Coulombs and E is the electric field in the cavity⁴. When the sinusoidally varying electric field is positive, there is a forward force accelerating the particles along the beam line. When the electric field is negative, the particles are traveling in a shielded “drift” space between the cavities so the particles are never exposed to a reverse force. Thus, the particles are accelerated by the oscillating electric fields and absorb energy from the cavities. RF power is coupled into the different accelerating structures to accelerate the particles.

The RF power is generated by klystrons. Electromagnetic waves are transmitted to the accelerator through waveguides; see Figure 1C. One klystron provides the RF power to a small section of the accelerating structure; therefore, many klystrons are required to provide the RF power to the entire accelerator. The cavities are grouped in supermodules²³. Each supermodule, or section, is driven by a small number (3 to 7) of klystrons. The supermodule has one more klystron than required to meet the power requirements of the

Figure 1B. The Electric Field in a Pillbox Cavity

cavity and beam. This allows one klystron to fail and the remaining klystrons to compensate for the failure.

While coaxial line is used at lower frequencies, rectangular waveguides are able

to transmit more power than coaxial lines and are the standard approach at frequencies greater than 300 MHz for high average power RF accelerators. Aluminum is the common waveguide material in the frequency range typically used for linear proton accelerators.

RF windows are used in waveguides to separate the atmospheric pressure in the waveguide from the vacuum in the accelerator and to separate the vacuum of the klystron from the atmosphere of the waveguide. The vacuums in the klystron and the accelerator are a in the range of 10^{-6} Torr to 10^{-9} Torr while the waveguide pressure is typically that of the ambient environment. In addition, the ceramic windows must pass large amounts of RF power with minimal losses.

A large amount of RF power needs to be coupled into the accelerating structure in order to accelerate the proton beam. Up to 30 MW peak power (5 kW average power) at a frequency of 2856 MHz has been coupled into cavities in the KEK accelerator². The amount of average power coupled through an RF window ranges from about 250 kW to below 5 kW. While there are some isolated cases where more than 250 kW has been coupled through windows, all large accelerators with many windows couple less than 200 kW, as shown in Figure 1D³.

To examine the power requirements on the APT window, the voltage standing wave ratio (VSWR) must be considered. The VSWR quantifies the reflected power. If in a transmission line all the components and the termination have the same impedance, the line is said to be matched throughout its length. This means that perfect transmission of energy occurs without reflection; however, if the impedance of any RF component in the transmission line is not exactly the same as the characteristic impedance of the line, a mismatch will exist and reflection of power will occur at the mismatch. Impedance changes are caused by changes in the coupling, damage to RF components,

Figure 1C. How RF Power is Transmitted from the Klystrons into the Accelerator.

changes in the behavior of the beam, or fluctuations in the beam current. Therefore, reflected power cannot be avoided. Since the supermodule allows for klystrons connected to the accelerating structure to be “turned off,” the windows experience another source of VSWR which results from this variable external load. CW and superconducting machines represent high levels of beam loading, which means that a majority of the load is due to the beam, rather than the result of copper losses or other lossy parts of the accelerator structure. When there is a beam current fluctuation, the load is changed, and power is reflected back through the RF windows. This reflected power can constructively interfere with the incoming power to create high peak voltages at the window. The window must be able to withstand not only the incoming power but also reflected power. To characterize this reflected power, the VSWR is defined as

$$VSWR = \frac{v_{\max}}{v_{\min}} = \frac{1 + \Gamma}{1 - \Gamma} \quad \text{Eq. 1.2}$$

Figure 1D. Average Power Levels for Windows/Couplers³

where $v_{\max}$ is the maximum voltage $v_{\min}$ is the minimum voltage. The reflection coefficient, Γ , is defined as

$$\Gamma = |S_{11}| = \frac{Voltage_{Reverse}}{Voltage_{Forward}} = \sqrt{\frac{Power_{Reverse}}{Power_{Forward}}}. \quad \text{Eq. 1.3}$$

The maximum voltage at any one point along the standing wave can be calculated by Eq. 1.4,

$$v_{\max} = Voltage_{Forward} + Voltage_{Reverse}. \quad \text{Eq. 1.4}$$

The ohmic power density shows that the power is proportional to the square of the electric field, as shown in Equation 1.5⁴ as

$$P = \sigma E^2 \quad \text{Eq. 1.5}$$

where P is the ohmic power (watts), σ is the conductivity (siemens/meter) and E is the electric field (volts/meter). Since P is proportional to E^2 , and E is proportional to V , then P is proportional to V^2 . Thus, the maximum power at the peak of the standing wave is proportional to the square of the voltage.

$$P_{\max} \propto (Voltage_{Forward} + Voltage_{Reverse})^2. \quad \text{Eq. 1.6}$$

To determine the maximum effective power on the window from the average power and the VSWR, rearranging Eq. 1.2 and solving for Γ results in

$$VSWR = \frac{1 + \Gamma}{1 - \Gamma} \quad \text{Eq. 1.7}$$

$$VSWR(1 - \Gamma) = 1 + \Gamma \quad \text{Eq. 1.8}$$

$$VSWR - VSWR\Gamma = 1 + \Gamma \quad \text{Eq. 1.9}$$

$$VSWR - 1 = \Gamma + (VSWR)\Gamma \quad \text{Eq. 1.10}$$

$$VSWR - 1 = \Gamma(1 + VSWR) \quad \text{Eq. 1.11}$$

$$\Gamma = \frac{VSWR - 1}{VSWR + 1} \quad \text{Eq. 1.12}$$

For example, if the VSWR is 1.2 and the highest average power is 175 kW, then to calculate the highest effective power on the window first calculate the reflection coefficient. The reflection coefficient, Γ , is calculated using Eq. 1.12 as follows:

$$\Gamma = \frac{1.2 - 1}{1.2 + 1} = 0.091 \quad \text{Eq. 1.13}$$

Assume $Voltage_{Forward} = 1$ and substitute this in Eq. 1.3. This yields $Voltage_{Reverse} = \Gamma$.

Next, the maximum power is calculated by substituting the $Voltage_{Forward}$ and the $Voltage_{Reverse}$ into Eq. 1.6.

$$P_{\max} = (Voltage_{Forward} + Voltage_{Reverse})^2$$

$$P_{\max} = (1 + 0.091)^2$$

$$P_{\max} = 1.19$$

Thus, the highest effective power is calculated as follows:

$$\text{highest effective power} = (P_{\max}) (\text{average power}) \quad \text{Eq. 1.14}$$

$$\text{highest effective power} = 1.19 (175 \text{ kW}) = 208 \text{ kW}$$

Also note that if the $VSWR = 1$, then $P_{\max} = 1$ and if $VSWR = \infty$, then $P_{\max} = 4$, increasing the power four times. In this case where the $VSWR = 1$, none of the power is being reflected, thus $\Gamma = 0$, $P_{\max} = 1$, and the highest effective power equals the average power.

In the case where $VSWR = \infty$, all of the power is being reflected, thus $\Gamma = 1$, the voltage is doubled, and $P_{\max} = 4$.

Table 1A summarizes the power requirements under normal operating conditions with no window or RF system failures. Note that the power from each klystron is split either 4 or 6 times before reaching the windows. This splitting is done to keep the average power through each window to a range of 200 kW to 250 kW. This corresponds to power levels used on other large accelerators, as shown in Figure 1C. Without this splitting, the average power through one window would be 800 kW to 1000 kW. This is not acceptable on APT because it is too large a step in technology compared with the window power capacity of other CW accelerators. If the window is at the peak of the standing wave, the maximum power through a window is the power capacity of the klystron divided by the number of windows per klystron. As shown in the above example the VSWR has to be considered to determine the maximum effective power at the location of the RF windows. If the VSWR changes, then the numbers shown in Table 1A and Table 1B will also change. The VSWR is dependent on the coupling, which has not yet been determined. The columns list the RF power requirements at the RFQ, CCDTL, CCL and superconducting parts of the machine, the four different accelerating structures along the linac.

On the APT accelerator, redundancy is designed in to accommodate for RF system failures by two separate methods²³. The first method is the supermodule architecture on the RFQ, CCDTL, CCL cavities. There are seven klystrons delivering RF power to the supermodule and only six klystrons are required. If one klystron fails, the remaining RF systems can provide the necessary RF power by increasing the output from the remaining klystrons. Thus klystrons in multiple supermodules can fail at once. However, if more than 1 klystron fails per supermodule, then the accelerator will have to be shut down and the defective RF system(s) repaired. The second method is to create redundancy on the superconducting linac.

	RFQ	CCDTL & CCL	Superconducting Linac
Frequency	350 MHz	700 MHz	700 MHz
Number of Klystrons	3	47	186
Power split per klystron	4	4	4 or 6
Number of Windows	12	188	804
Highest Average Power	175 kW	154 kW	231 kW
VSWR	1.2	1.25	∞
Maximum Effective Power at Voltage Max	208 kW	190 kW	274 kW*

* Fields decrease because there is no beam.

Table 1A. APT RF power requirements during normal operation with no window or RF system failures

The RF windows on the superconducting linac are designed with two alumina ceramic windows in each input power coupler. Thus if one ceramic breaks, the cavity which it feeds is detuned, RF is no longer passed through the coupler by shutting a waveguide switch, the region between the two ceramics is evacuated, and the second ceramic is the vacuum barrier. In the superconducting section, the klystrons can compensate for a failure of up to 5% of the klystrons.

In the event of a klystron failure the external coupling of the cavity will change. The change in the external coupling will change the VSWR which, in turn, will change the average power and the maximum effective power at the window. The magnitude of the change in the VSWR is determined by the coupling. Table 1B summarizes an example of the power requirements for the windows with the case of one RF system failure. Thus, note that an RF system failure changes the amount of power at the windows.

To summarize the APT RF window requirement: 208 kW to 323 kW will be coupled through each window into the RFQ at a frequency of 350 MHz, 190 kW to 274 kW per window will be coupled into the CCDTL at a frequency of 700 MHz. In the

superconducting part of the linac, 274 kW will be coupled through each window. These power levels are approximations, because they are dependent on the coupling-which at this time has not yet been determined. A range of power requirements is stated because of the redundancy in the RF power system to account for window and klystron failures.

	RFQ	CCDTL	Superconducting Linac
Frequency	350 MHz	700 MHz	700 MHz
# of Klystrons	2	47	237
Power split per klystron	4	4	4 or 6
Number of Windows	8	188	804 (With failed window)
Highest Average Power	263 kW	231 kW	231 kW
VSWR	1.25	1.2	∞
Maximum Effective Power at Voltage Max	323 kW	274 kW	274 kW*

* Cavity is detuned, waveguide switch shut, and does not affect power on other cavities.

Table 1B. APT RF power requirement during normal operation with one RF system failure

1.2 Goal

The goal of this research is to develop analytical and experimental methods to evaluate the performance of RF windows. Analytically, the goal is to predict the lifetime of windows, and thus the mean time between failure of the windows. Experimentally, the goals are to develop a window conditioning procedure and to evaluate the performance of the RF windows for APT. Long term objectives are to gain a better understanding of the failure mechanism of RF windows, to gain a better understanding of the conditioning mechanism, to obtain information to improve window designs, and to increase the durability of RF windows under high power in order to reduce the number of windows needed on the machine.

1.3 Description of Approach

Distinct goals, both experimental and analytical, have been set in this research to gain an understanding of the failure mechanisms of RF windows and improve the durability of RF windows. Each goal is stated below and the approach to accomplishing the goal is described.

The analytical goal is to predict the lifetime of the windows and the mean time between failure. The probability of failure is predicted by the combination of a finite element model of the window, Weibull probabilistic analysis and fracture mechanics. The window assembly is modeled in a finite element electromagnetic code in order to obtain the electric fields in the window. The geometry(i.e. mesh) and electric fields are input into a translator program to generate the mesh and boundary conditions for a finite element thermal / structural code. The temperatures and stresses are determined in the thermal / structural code. The geometry and thermal structural results are input into another translator program to generate an input deck for the reliability code. Material, geometry and service data are also input into the reliability code. Material testing of RF windows is done in order to obtain accurate material data. The analytical model is validated by comparing the experimental thermal results to the analytical results. Then, the lifetime of the windows and the mean time between failure is determined using the reliability code.

The experimental goal is to develop a conditioning procedure and evaluate the performance of RF windows. In order to achieve this goal a test stand has been built which has the capabilities to monitor the critical RF and vacuum parameters while also having the necessary diagnostic equipment and data acquisition systems. The conditioning procedure is developed by experimentally evaluating the successes and failures of different methods of conditioning. The performance of the window is evaluated using the diagnostic equipment on the test stand.

CHAPTER 2

LITERATURE REVIEW AND THEORETICAL BACKGROUND

2.1 Failure Mechanisms of RF Windows

The exact failure mechanism is not fully understood, but multipacting, dielectric stresses, thermal induced stresses, material imperfections, and ohmic losses are implicated. Of all these phenomena, multipacting seems to play the most important role, and many of these phenomena may be the result of multipacting. On a failed or failing window a luminescence glow has been observed which is thought to be due to multipacting and material imperfections⁶. Multipacting causes thermal heating which leads to surface melting, fracture and/or puncture of the RF window. Dielectric stresses may also contribute to the failure of the windows. Copper deposition, which is a result of multipacting, has also been observed on failed windows. Thus, multipacting seems to be at the root of the problems which lead to the failure of RF windows.

Multipacting is a surface phenomenon which is driven by the electric fields in the RF environment, and occurs at particular electric field levels which are dependent on geometry and RF frequency. The classic case of multipacting occurs between two parallel plates in a RF field. When the mean free path is less than the distance between the two plates, free electrons are accelerated within the gap as shown in Figure 2A³⁴. When these free electrons strike the surface, they initiate the release of secondary electrons and lead to an discharge of electrons between the two surfaces. A material property, the secondary electron emission (SEE) coefficient determines the number of electrons liberated from the window surface per incoming electron when the RF window or surrounding structure is bombarded by electrons. When the energy of the primary electron is within a certain range (ωf_1 to ωf_2) the SEE is greater than unity (see

Figure 2A. Multipactor Electron Avalanche Process within Parallel Plates³⁴

Figure 2B. Secondary Electron emission Coefficient to Electron Energy³⁴

Figure 2C. a. An RF Window² b. Electron Trajectories in an RF Window³⁵

Figure 2B) then electron multipacting is possible. Another condition is that the transit time between the plates must be an odd number of half cycles of the RF period³⁴. Other sources of primary electrons are soft-x-rays, field emission or gas ions⁵. If these freed electrons return to the window surface with the appropriate energy, electron multipacting will occur. Figure 2Ca illustrates the region between the copper and the alumina ceramic on a RF window. Multipacting at the location in Figure 2Ca is shown in Figure 2Cb. This figure illustrates the simulated trajectory of electrons, with the primary electron hitting the surface at position P³⁵.

Spectral analysis of the optical emission shows that certain bands of luminescence glow are due to multipacting³. Another study suggests that "the optical emission is not from ionized or excited gas molecules adjacent to the disk surface, but is luminescence of the alumina due to electron bombardment"⁶. A luminescence has been observed when multipacting is believed to be occurring. This luminescence is assumed to be a direct result of multipacting.

Material imperfections may also contribute to the failure mechanism of windows. There is this evidence: another band of the luminescence glow corresponds to F centers and material impurities. An F center is caused by an oxygen vacancy in alumina. Due to

the -2 valence of oxygen, this atom donates two electrons to the crystal lattice to maintain the neutrality within the lattice structure. However, when there is an oxygen vacancy, electrons will be attracted to the vacancy to complete the lattice structure. Because the energy levels in the electron orbitals are quantized, each level has a different energy. The energy emitted from the first two shells is in the visible spectrum. The electrons attracted to the F center cause a luminescence glow. This phenomenon is known as an F center. Spectral analysis of the luminescence glow shows that a band of this glow corresponds to F centers and another band corresponds to impurities such as chromium¹. The F centers cause an increase in the loss tangent. Increasing losses result in more heating, and thus the window material becomes more susceptible to surface melting and increased multipacting. This increase in the loss tangent at F centers has been observed in several studies^{6,7}. It was concluded that bands of the luminescence glow observed are due to oxygen defects and material impurities; luminescence may be part of the window failure mechanism.

Multipacting causes additional heating and thermal mechanical stresses which lead to window failures. One study estimated that an alumina window was locally heated to above 1900 °C during operation⁶. This localized heating causes expansion of the material and resultant mechanical stresses. If the heating is very intense and localized it can damage the surface material and surface melting can occur². The high mechanical stresses can lead to puncture and/or fracture in the RF window. High stresses lead to high strains, and in alumina which results in cracking. If the heating is localized to a small area, and high thermal mechanical stresses, a star-shaped crack in the ceramic will occur²⁴. If a radial crack is seen in a disk window, this is a result of a large tensile hoop stress around the outer perimeter²⁴. Therefore localized heating, a known result of multipacting, causes high stresses and can lead to failure of the RF window.

Figure 2D. A Waveguide Section Illustrating the Charges on Klystron Window

The contribution to the failure mechanism of a force due to a charge build up on the window ceramic surface has been studied at the Stanford Linear Accelerator (SLAC)⁹. Fields are created on the klystron window because electrons gain a net drift velocity away from the klystron. This creates a negative charge on the vacuum side of the window and a positive charge on the air side. These localized areas of charge create a positive charge on the vacuum surface of the window and a negative charge on the air surface of the window. These charges create a field across the ceramic that leads to a dielectric failure of the window. As a result of these fields, multipacting is enhanced on the vacuum side of the windows. Electrons are freed and attracted back to the positive surface with an increased kinetic energy. Because additional electrons are also freed easier, the increased kinetic energy initiates multipacting.

Copper deposition on the ceramic surface has also been observed as a result of multipacting. This copper deposition occurs as a result of evaporation or sputtering. On the Advanced Light Source(APS) at Argonne National Laboratory(ANL), the windows fail because an uneven copper layer is deposited on the alumina from surrounding surfaces during conditioning. Large thermally induced mechanical stresses develop because of the uneven copper coating. Thus, the windows become more lossy over time and eventually fail by large stresses, a pin hole leak through the window or because they reflect too much power¹⁷. Copper sputtering was also observed during the initial testing

of the APT windows. One of the prototypes failed because copper was deposited on the ceramic surface of the window causing the window to become very lossy and absorb RF power¹⁸. This sputtering is thought to be due to arcing and multipacting resulting from the failure of a mechanical joint. In both cases, the copper sputtering of the ceramic surfaces was the consequence of multipacting which lead to the failure of the RF windows.

Although the failure mechanism of RF windows is assumed to be due to dielectric fields, ohmic losses, material imperfections, and/or temperature gradients, multipacting from the bombardment of electrons seems to be an important contributor to the failure mechanism. The multipacting can cause a luminescence glow, the formation of F centers, copper deposition, heating, and even fracture of the ceramic. Multipacting can also create large electric fields across the window that leads to dielectric stresses. The results of multipacting and the dielectric stresses may lead to surface melting, puncture, and/or fracture of the RF window.

2.2 Coatings

Many different materials have been used as anti-multipacting coatings on the surface of the RF window. These films suppress multipacting by decreasing the secondary electron emission (SEE) coefficient of the alumina surface. Studies have shown that thin coatings of TiN suppress multipacting^{1,2,6,10}. Another study has shown “Cr₂O₃ coated windows are at least as good as the best TiN coated windows”¹¹. It was also found that layers of TiN oxidize to form 0.6 nm thick layers of TiO₂ when heated to 550 °C. The TiO₂ layer showed a significant drop in the SEE¹¹. A study at Daresbury Laboratory found “copperblack was superior to five different tested materials including TiN”¹². Besides TiN, Cr₂O₃, and copper black, other materials used for coatings include titanium, Si₃N₄, and gold black¹². Copper black is thought to suppress multipacting by

roughening the surface; this reduces the freeing of electrons by increasing the chances of the emitted electron hitting the surface rather than being freed. At the former Los Alamos Meson Physics Facility (LAMPF), RF windows have been coated with titanium, resulting in a titanium oxide or a titanium nitride coating¹⁶. Talcott used titanium as a coating to decrease the SEE coefficient on dielectric materials¹⁴. Therefore, candidate materials for anti-multipacting coatings include TiN, TiO₂, Cr₂O₃, Ti, Si₃N₄, copper black, and gold black.

The thickness of the coatings is very critical. If the coating is not thick enough, it will not decrease the SEE sufficiently to suppress multipacting. If the coating is too thick it will act as a conductor and will create significant RF losses. The amount of RF losses in a coating is dependent on both the thickness and the RF frequency. The skin depth (depth of penetration) of the electric field is a function of frequency. The skin depth of a material is the depth at which the magnitude of the electric field is reduced by $1/e$ or 37 percent³³. The skin depth is defined as

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \quad \text{Eq. 2.1}$$

where f is the frequency, μ is the permeability, and σ is the conductivity³³. Hence, as frequency increases, the skin depth decreases, increasing the ohmic losses in the coating. One study found the optimal thickness for TiN and Chrome Oxide coatings to be 2.5 nm and found that a thickness greater than 4 nm will cause excessive heating⁹. Some studies concluded that the optimum film thickness was 0.5 to 1.5 nm^{7,10}, while in other studies a coating thickness of 5 nm has been satisfactory^{1,2,6}. At LANL, the coating thickness is measured by the amount of resistance per unit area. Tests at LANL show that 1 M Ohm/square titanium sputtering of windows will significantly reduce multipacting¹⁵. 1 M Ohm/square corresponds to a thickness of about 2 nm¹⁶.

Thus, a variety of coatings with a low SEE have been used on RF windows to suppress multipacting. The commonly used materials include TiN, TiO₂, Cr₂O₃, Ti, Si₃N₄, copper black, and gold black. The thickness of the coatings is critical. Significant RF losses will occur if the coating is too thick. If the coating is too thin, it will not adequately suppress multipacting.

2.3 Fracture Mechanics to predict the reliability of RF windows

Regardless of the detailed physical phenomena involved, heating of RF windows causes temperature gradients, which lead to mechanical stresses in the ceramic, which in turn, can lead to failure of the window by fracture. As discussed previously, heating can be caused by multipacting, dielectric heating due to dielectric loss in the ceramic, ohmic losses in copper depositions on the RF window due to multipacting, and thermal stresses. Once the mechanical stress reaches a critical level, the windows will fracture. This section will outline fracture theory that is used to predict the reliability of the alumina ceramic and examine factors that affect the reliability of alumina.

2.3a Fracture Reliability Theory

This section is a summary of the theory behind the Ceramic Analysis and Reliability Evaluation of Structures(CARES) Life Prediction program which predicts the reliability of a ceramic component [See the CARES manual for more details¹⁹]. Fracture mechanics combined with Weibull probability is used to predict the reliability of RF windows¹⁹. The Weibull probability method is used to characterize the variation in strength of a brittle component. The CARES program uses linear elastic fracture mechanics, relates the strength of the ceramics to the size, shape orientation, and growth of critical flaws, uses statistics to get the flaw size distribution as a material property, and considers the material microstructure¹⁹.

In the CARES program, the user can select the method that will be used to model the subcritical crack growth, the multiaxial stress criteria, and the crack geometry. Subcritical crack growth can be modeled in the CARES program by the power law, Paris Law, or Walker Equation¹⁹. Using the power law, the crack velocity is a function of the stress intensity factor. The Paris Law models crack growth during cyclic loading. The crack growth per cycle is a function of the stress intensity factor. The Walker Equation correlates the crack growth per load cycle to the crack tip stress intensity factor and the maximum stress intensity factor. The CARES program uses the two-parameter Weibull function to model the variation in strength²⁰. The user can select the method for modeling multiaxial stresses from either the principal of independent action (PIA), Weibull's normal stress fracture criteria, maximum tensile stress criteria, or Shetty's semi-empirical criteria. The user can also select the method for modeling the crack geometry from a Griffith crack, a penny shaped crack, a Griffith notch, or a semicircular crack. The effective stress is calculated using a different equation corresponding to the four choices of crack geometry. Thus the choices available in the CARES program enable the user to build a realistic model of the ceramic component¹⁹.

Either a volume flaw analysis or a surface flaw analysis can be performed in CARES. A surface flaw reliability analysis has been performed on the RF window; this analysis will be discussed in Chapter 3, The Analytical Procedure, and Chapter 9, The Analytical Results. In order to understand the surface flaw analysis theory, the background for a volume flaw analysis will be discussed first, then the background for the surface flaw analysis will be presented.

To understand a volume flaw analysis, the two parameter crack density function is examined. The two parameter crack density function is defined as

$$N_v(\sigma) = \left[\frac{\sigma}{\sigma_{ov}} \right]^{m_v} \quad \text{Eq. 2.2}$$

where σ is the applied stress, σ_{ov} is the scale parameter, and m_v is the shape parameter. The scale parameter is defined as the stress where 63.2 percent of the specimens with unit volumes fracture. A dimensional analysis on Equation 2.2 explains why the scale parameter has units of $(\text{stress})(\text{volume})^{1/m_v}$ and shows that the crack density function represents the number of flaws per volume. The dimensional analysis is shown in Equation 2.3.

$$N_v(\sigma) = \left[\frac{\text{stress}}{(\text{stress})(\text{volume})^{1/m_v}} \right]^{m_v} = \frac{1}{\text{volume}}. \quad \text{Eq. 2.3}$$

The shape parameter is also known as the Weibull modulus. Equation 2.2 is known as the “two parameter crack density” because of its dependence on two parameters: the scale parameter and the shape parameter. As the Weibull modulus increases, the probability of failure decreases. This relationship is because dispersion is decreased with an increasing Weibull modulus, meaning there are less flaws. As the Weibull modulus approaches infinity, as in a ductile material, the strength of the material approaches the ultimate strength, the strength at which a ductile material will fracture. Both the Weibull modulus and the scale parameter are temperature and processing dependent¹⁹.

The risk of rupture, B_v , represents the number of critical flaws and is

$$B_v = \int_v N_v(\sigma) dV. \quad \text{Eq. 2.4}$$

The probability of failure, P_{fv} , is

$$P_{fv} = 1 - \exp \left[- \int_v N_v(\sigma) dV \right] = 1 - \exp(-B_v). \quad \text{Eq. 2.5}$$

The ceramic will fail if it has a flaw in which the critical stress is exceeded. The probability of the crack being oriented in the proper direction to cause the material to fail also must be considered. This probability is known as, P_{2v} , and is

$$P_{2v} = \frac{\Omega(\Sigma, \sigma_{cr})}{4\pi}, \quad \text{Eq. 2.6}$$

where $\Omega(\Sigma, \sigma_{cr})$ is known as the solid angle. This is the area of the sphere containing all the projected equivalent stresses greater than the critical stress. The surface area of a unit sphere is 4π and is the solid angle containing all possible flaw orientations. Equation 2.6 represents the probability of the crack being oriented in the proper direction to cause a failure. Thus, in a volume flaw analysis, the component failure probability is the combined probability of having a critical flaw weaker than the critical stress and the critical flaw being oriented in a direction which will cause failure. This combined probability is represented as

$$P_{fv} = 1 - \exp \left\{ - \int_v \left[\int_0^{\sigma_{e_{max}}} \frac{\Omega(\Sigma, \sigma_{cr})}{4\pi} \frac{dN_v(\sigma_{cr})}{d\sigma_{cr}} d\sigma_{cr} \right] dV \right\}, \quad \text{Eq. 2.7}$$

where $\sigma_{e_{max}}$ is the maximum effective stress a randomly oriented flaw could experience and $N_v(\sigma_{cr})$ is the crack density function. The Batdorf crack density is

$$N_v(\sigma_{cr}) = k_{BV} \sigma_{cr}^{m_v}, \quad \text{Eq. 2.8}$$

where k_{BV} is the Batdorf crack density coefficient, σ_{cr} is the critical stress, and m_v is the Weibull modulus. The CARES program numerically evaluates equation 2.7 in order to determine the probability of failure in a volume flaw analysis¹⁹.

The surface flaw analysis theory is similar to the volume flaw analysis theory. In the surface analysis, surfaces are used instead of volumes, and the stress is projected on a unit radius circle rather than a sphere. The Batdorf crack density function is defined analogous to Equation 2.8 for the volume analysis.

$$N_s(\sigma_{cr}) = k_{BS} \sigma_{cr}^{m_s} \quad \text{Eq. 2.9}$$

where k_{BS} is the uniaxial Weibull surface crack density coefficient, σ_{cr} is the critical stress, and m_s is the surface Weibull modulus. In the surface analysis, the scale parameter has units of (stress)(area)^{1/ m_s} as opposed to the volume scale parameter with units of (stress)(volume)^{1/ m_v} . The probability of failure is predicted using Equation 2.10, which is analogous to Equation 2.5 .

$$P_{fs} = 1 - \exp \left[- \int_s N_s(\sigma) dS \right] \quad \text{Eq. 2.10}$$

To predict the overall component surface reliability, Equation 2.10 is combined with the probability of the crack being oriented in the correct direction. This results in the following, which is analogous to Equation 2.7.

$$P_{fs} = 1 - \exp \left\{ - \int_A \left[\int_0^{\sigma_{e_{\max}}} \frac{\omega(\Sigma, \sigma_{cr})}{2\pi} \frac{dN_s(\sigma_{cr})}{d\sigma_{cr}} d\sigma_{cr} \right] dA \right\} \quad \text{Eq. 2.11}$$

where $\sigma_{e_{\max}}$ is the maximum effective stress a randomly oriented flaw could experience and $N_s(\sigma_{cr})$ is the crack density function. To account for all the possible flaw orientations, $\omega(\Sigma, \sigma_{cr})$ is the total arc length of a unit radius circle in principal stress space whose projection contains all the projected equivalent stresses greater than the critical stress. The total arc length of the circle is 2π . The CARES code numerically evaluates Equation 2.11 to determine the probability of failure for a surface flaw analysis¹⁹.

2.3b Variables Affecting the Reliability of Alumina

Many variables can affect the reliability of alumina, including grain size, processing, and surface roughness. This section examines the effects of these variables on the material properties and therefore, the reliability of alumina.

One study examined the effect of grain size on the reliability of alumina ceramic²¹. The fracture strength of the material is known to decrease with increasing grain size by the following relationship²¹:

$$\sigma \propto G^{-1/2} \quad \text{Eq. 2.12}$$

where σ is the strength and G is the grain size. No dependence of the Weibull modulus on the grain size was found. It was found that the bending strength increased with decreasing grain size and the fracture toughness was independent of grain size²⁶. Thus a small grain size is favorable, because the strength increases with a decreasing grain size.

The effect on the reliability of ceramics of processing and machining has also been investigated²². It was found that the Weibull modulus was not affected by cold-isostatic pressing or hot-isostatic pressing. Hot isostatic pressing eliminates large pores; however, the effect of this on the Weibull modulus is unknown²². It was also found that as the machining grit size increased, the ceramic strength decreased. Grinding and polishing can increase the strength significantly. It was found that grinding the ceramic in the green state with a fine grit can lead to a high strength ceramic. Salem, *et. al.*, found that in silicon carbide, failures occurred at cracks caused by machining damage²⁸. They also found that annealing would eliminate failures due to machining damage. Fett, *et. al.*, found that a high purity sintered alumina was superior to a hot isostatically pressed alumina for long term applications²⁷. This material was sintered at 1550°C then hot isostatically pressed (HIP) at 1450°C and a pressure of 1000 bar in Argon. Thus, processing does not seem to directly affect the Weibull modulus. Annealing does affect the Weibull modulus by eliminating failures resulting from machining damage. Processing affects the reliability by affecting the strength of the material. For example, by eliminating large voids and making material with the theoretical density, a higher strength is obtained. This higher strength will yield a more reliable component. From this it can be concluded that machining affects the Weibull parameter and the strength.

Another study found that the environment strongly affects the fracture toughness of 96 wt. alumina²⁵. The fracture toughness decreased as the moisture content increased; fracture strength increases in liquid nitrogen and silicon oil environments. Thus, in the case of the RF window, the only environmental variable which can be controlled and which affects the fracture toughness is the moisture content. Therefore, a dry environment is highly desirable to increase the reliability of the RF windows.

There are two variables which affect the reliability of alumina: strength and the Weibull parameter. The reliability of alumina is affected by processing, machining, and the environment. An effect of processing on reliability is that a stronger material is

obtained when the density of the material approaches the theoretical density. In machining, a small grit size leads to a finer surface finish and a stronger material. However, machining can decrease the reliability by causing surface damage. Finally, a dry environment can increase the fracture strength. Hence, to optimize the reliability of RF windows, a theoretically dense material should be selected, machined with a fine grit size, annealed to eliminate machining damage, and should be used in a dry environment.

CHAPTER 3

ANALYTICAL PROCEDURE

3.1 Outline

The objective is to build an analytical model to predict the lifetime of the window based on the thermally induced mechanical stresses and stresses due to the pressure differential between the air side and the vacuum side. First, the electric fields inside the window are calculated. Then, the power absorbed in the window is calculated from the electric fields. The power absorbed in the window is used to calculate the temperatures in the window. Thermal stresses are calculated from the temperatures. The probability of survival is calculated from the temperatures, stresses, and material properties of the ceramic. Thus, using the analytical model, the temperature, stresses, and lifetime of an RF window as a function of the incident power in the waveguide are predicted.

The analytical model predicts the window lifetime based on the dielectric heating of the ceramic. Nevertheless, as discussed in Chapter 2, the cause of the window failure seems to be non-uniform surface heating due to multipacting or secondary effect of multipacting, such as copper deposition on the ceramic. Thus, the calculated results may not correspond to the experimental measurements. However, this model does provide a method with which ensure that the window has a sound electrical, mechanical and thermal design. The analytical model also provides a basis for comparing different window designs; a tool that will be invaluable in the future. Presently, the lifetime of the windows can only be measured experimentally. Once a failure mechanism is understood, it can be incorporated into an analytical model.

Computer codes are used as tools to achieve the analytical model objective. A finite element computer code, High Frequency Structure Simulator (HFSS), is used to calculate the electric fields inside the window. A FORTRAN program has been written to translate the data from HFSS to ABAQUS, a thermal /structural finite element code.

In the FORTRAN program, the thermal and structural boundary conditions are applied to the ABAQUS input file. ABAQUS is then used to calculate for the distribution of temperatures and stresses in the window. The output of ABAQUS is run through the translator program ABACARES to generate the input deck for CARES (Ceramics Analysis and Reliability Evaluation of Structures). CARES is then used to evaluate the probability of survival of the ceramic. Thus, five codes are used in the analytical model: HFSS, a FORTRAN program, ABAQUS, ABACARES, and CARES.

3.2 Electromagnetic Model

The software HFSS is used to solve Maxwell's equations to determine the magnitude and phase of the electric and magnetic field in the window. This software finds the solution in the frequency domain in three dimensions using traveling wave boundaries. A propagating mode at the ports is assumed, as opposed to calculating the fields in a standing wave structure. HFSS uses tetrahedral elements and refines the mesh as it solves the problem. The mesh refinement is beneficial because in areas where the gradient of the fields is high, a finer mesh will be generated which results in a more accurate solution.

3.3 Translator from Electromagnetic code to Thermal /Structural code

The objective of the translator is to generate thermal and structural ABAQUS input files using the output from HFSS. The translator is composed of five parts:

- 1) The geometry is translated from HFSS to ABAQUS
- 2) Heat fluxes are calculated from the electric fields and applied at the appropriate locations.
- 3) The boundary conditions for the thermal model are applied to the model.
- 4) The boundary conditions for the structural model are applied to the model.
- 5) The thermal and structural input files are written.

The ABAQUS to HFSS translator consists of a series of FORTRAN codes. The FORTRAN codes and the role of the codes in the translation are described below. The following sequence is used for the translation:

1. Find the phase where the magnitude of the electric field is the maximum. This is done using the post processor in HFSS. The magnitude of the electric field is plotted on the surface of the window while incrementing the phases. From the magnitude of the electric fields, the phases for the maximum and minimum fields are found.

2. The post processor in HFSS are used to write the electric field data to an ASCII file. The output from HFSS is a file containing the coordinates of the tetrahedral mesh and the electric field vector at ten points on each tetrahedron. The name of the output file is *.arg.

3. Add the word “end” to the end of the data file. This can be done in a word processor or in the UNIX shell. Because of the large size of the *.arg file, it is faster to create a file containing only the word “end” and then use the command in a UNIX shell:

```
cat *.arg end >> *.arg1
```

In this command, *.arg is the original data file from HFSS, “end” is the file containing only the word “end”, and *.arg1 is the new data file with the word “end” at the bottom. The word “end” is added so the FORTRAN program will know when all the data from the file has been read into the program.

4. Run SORT.f . This program sorts the data file generated by HFSS and generates a data file (window.dat) which contains the coordinate information and the electric field vectors of all tetrahedra in the window. The program can either sort by location (geometry) or by the number of the tetrahedra. Sorting by the number of the tetrahedra

seems to be the preferred method because the tetrahedra in the *.arg file are in the order of the objects as viewed in the show > object > mesh in the fields part of HFSS. The order of the objects in HFSS is alphabetical. Therefore, if the window is given a name with a low number or with a letter at the beginning of the alphabet, it will be near the beginning of the data file *.arg. The input and output for SORT.f is summarized in Table 3A.

input for SORT.f:	*.arg (data file generated by HFSS)
output for SORT.f:	window.dat (data file containing the tetrahedra in the window)

Table 3A. Input and Output for SORT.f

5. Run READE.f This program generates both the thermal and structural input files for ABAQUS. This code translates the HFSS data into input files for ABAQUS by using the following procedure:

- a. READE.f translates the tetrahedra from HFSS notation into ABAQUS notation. The translation, illustrated in Figure 3A, for the data of the nodes is made. The node number schemes of HFSS and ABAQUS are also illustrated in Figure 3A.

Figure 3A. Tetrahedral Node Numbering Scheme in HFSS and ABAQUS

HFSS node numbering:

1 - vertex 1

2 - vertex 2

3 - vertex 3

4 - vertex 4

5 - between 1 and 2

6 - between 1 and 3

7 - between 1 and 4

8 - between 2 and 3

9 - between 2 and 4

10 - between 3 and 4

ABAQUS node numbering:

1 - vertex 1

2 - vertex 2

3 - vertex 3

4 - vertex 4

5 - between 1 and 2

6 - between 2 and 3

7 - between 1 and 3

8 - between 1 and 4

9 - between 4 and 2

10 - between 4 and 3

b. The real and imaginary parts of x, y, and z are each averaged. Then the magnitude of the electric field is calculated using Eq. 3.1.

$$|E| = \sqrt{\bar{x}_{real}^2 + \bar{x}_{imag}^2 + \bar{y}_{real}^2 + \bar{y}_{imag}^2 + \bar{z}_{real}^2 + \bar{z}_{imag}^2} \quad \text{Eq. 3.1}$$

where:

$\bar{x}_{real}$ = the average of the real components of x of the electric field

$\bar{x}_{imag}$ = the average of the imaginary components of x of the electric field

$\bar{y}_{real}$ = the average of the real components of y of the electric field

$\bar{y}_{imag}$ = the average of the imaginary components of y of the electric field

$\bar{z}_{real}$ = the average of the real components of z of the electric field

$\bar{z}_{imag}$ = the average of the imaginary components of z of the electric field

c. Then READE.F is used to calculate the heat flux absorbed in each tetrahedral by using the following equation:

$$P = \frac{1}{2}(\sigma + \omega\epsilon'')E^2 \quad (W/m^3) \quad \text{Eq. 3.2}$$

where σ is the DC conductivity (1.0E-12 S/m, for AL300 alumina), ω is the Radial Frequency ($2\pi f$, 2.2×10^9 1/sec, for 350 MHz), ϵ'' is the imaginary part of the permittivity (6.286E-15 F/m, for AL300 alumina), and E is the magnitude of the electric field in V/m as calculated HFSS.

- d. READE.f is used to generate a list of nodes (the x, y and z coordinates) used in each tetrahedron and assigns each node a number.
- e. READE.f is used to sort and rennumbers the nodes to ensure that no specific node used in two different tetrahedra has the same node number in both tetrahedra.
- f. READE.f is used to generate a list of elements (tetrahedra) and the corresponding nodes for each element. The thermal boundary conditions are entered in READE.f
- g. The structural boundary conditions are entered in READE.f
- h. READE.f then generates the input file for a thermal and structural model for ABAQUS.

The input and output files for READE.f are summarized in Table 3B.

input for READE.f:	window.dat (output file from SORT.f)
output for READE.f:	thermo.inp (input file for ABAQUS for a thermal model)
output for READE.f:	struc.inp (input file for ABAQUS for a structural model)

Table 3B. Input and Output for READE.f

3.4 Thermal Model

ABAQUS is a finite element code used to calculate the temperatures in the window using the boundary conditions and the amount of power absorbed in the window. ABAQUS models the power absorbed in the window as an internal heat generation source term in the tetrahedra.

In the thermal model, it is necessary to model the cooling mechanism for the window. All three methods of heat transfer, conduction, convection and radiation, are applied to the model. Convection cooling by forced air is present on the air side of the window (the window has forced air cooling over the surface of the ceramic). Conduction is applied on the inside and outside surfaces of the window, where the ceramic is brazed to the copper inner and outer conductors. Radiation occurs on both the air and the vacuum surface. Therefore, the methods of heat transfer included in the model of the window are conduction, convection, and radiation.

To perform the thermal run, the following commands must be included in the ABAQUS input file in order to write the information needed for the structural run:

```
*EL PRINT, POSITION=INTEGRATION POINTS
*NODE PRINT, GLOBAL=YES
NT, RFL, RFLE
*NODE FILE, GLOBAL=YES
NT
```

The files needed to run the ABAQUS thermal model are summarized in Table 3C.

ABAQUS input:	thermo.inp	(output file from reade.f)
ABAQUS output:	thermo.fil	(input file for ABAQUS structural run)

Table 3C. Input and Output Files for ABAQUS Thermal Run

3.5 Structural Model

ABAQUS is also used to calculate stresses and displacement in the window due to the thermal gradients. This program uses the results of the thermal analysis to

calculate the stresses and displacements. The braze joint between the ceramic and the metal is modeled as a simply supported beam. This joint can be modeled as a simply supported beam because of the flexibility of the thin copper membrane. A uniform force on the air side of the window is included to represent the pressure differential between the air and vacuum sides of the window.

The ABAQUS user must specify some specific output for the ABACARES program. The following commands are included in the ABAQUS input file:

```
*EL FILE, ELSET=VOL1, POSITION=INTEGRATION POINTS
S
SINV
TEMP
*EL PRINT, POSITION=INTEGRATION POINTS
S
SINV
TEMP
*NODE PRINT, GLOBAL=YES
U
*NODE FILE, GLOBAL=YES
U
```

These commands will write the stresses, stress invariants, and temperatures to the *.fil file to be used in the ABACARES translation. In addition, the following command should be included in the input file in order to read the temperatures calculated in the thermal run.

```
*TEMPERATURE, FILE=eev2, ESTEP=1, BSTEP=1, EINC=1, BINC=1
```

ABAQUS input:	struc. inp	(output file from reade.f)
ABAQUS input:	thermo.fil	(output file from ABAQUS thermal run)
ABAQUS output:	struct.fil	(input file for ABACARES)

Table 3D. Input and Output Files for an ABAQUS Structural Run

3.6 Translator from the Thermal /Structural code to Reliability Model

ABACARES is the program used to translate the ABAQUS output to the input for the survival probability code, CARES. ABACARES consists of a FORTRAN program, abacares.f²⁹. This is compiled using ABAQUS subroutines and using the following UNIX command on a machine which has both ABAQUS and a f77 compiler:

```
ABAQUS make job=abacares
```

This command will generate the executable file abacares.x. The input file required from ABAQUS is the *.fil file. To run ABACARES, the *.fil file must be in the same directory and type: abacares.x. The output of the translation will be the CARES neutral file, ABACARES.NEU. The input and output files for ABACARES are summarized in Table 3E.

ABACARES input:	struc.fil (output file from ABAQUS structural run)
ABACARES output:	ABACARES.NEU (input file for CARES)

Table 3E. Input and Output Files for ABACARES

3.7 Reliability Model

CARES uses the results of the thermal and structural runs recorded in the neutral file, ABACARES.NEU and the material data information from the file *.inl. In the *.inl files, the user can select which fracture criteria to use to predict the probability of survival and the material properties. Table 3F summarizes the input and output files for CARES.

CARES input:	ABACARES.NEU (output file from ABACARES)
CARES input	stuct.inl (user input file for CARES)
CARES output:	struc.oul (output file for CARES)

Table 3F. Input and Output Files for CARES

3.8 Summary

The analytical model is an electromagnetic thermal structural model which predicts the survival probability of the ceramic. The electric field vectors are calculated from HFSS, and the temperatures and stresses are calculated in ABAQUS. The survival probability is determined in CARES. The input decks used for the model can be found in Appendix B through Appendix E.

CHAPTER 4

EXPERIMENTAL TEST APPARATUS

4.1 Goals of the Test Stand / Design Objectives

The experimental test apparatus is a complete system that includes the test equipment, diagnostic equipment, and data acquisition system necessary to achieve the experimental goals. The experimental goals are to develop a window conditioning procedure and to evaluate the performance of the windows during operation. In addition to these goals there exists a goal critical to the APT project: To condition and perform high power acceptance tests on the 15 RFQ windows to be used in the LEDA accelerator. Thus, the experimental test apparatus must be capable of conditioning, evaluating RF windows at a high power level.

To develop a conditioning procedure and to evaluate the performance of the windows, the test stand must simulate an input power coupler environment and have the appropriate diagnostics to observe and evaluate window performance. To simulate a RF window in an input power coupler environment, the test stand must have a vacuum on one side of the window and air on the other side so the window is acting as a vacuum barrier. Additionally the test stand must be capable of passing a large amounts of RF power. Diagnostic equipment essential for monitoring the experimental data is needed to evaluate the performance of the windows. A data acquisition system that records these variables as a function of time is also essential. Therefore, the experimental test apparatus is designed to include the required diagnostic equipment and data acquisition system.

4.2 Test Parameters

The tests will be performed at a frequency of 350 MHz (the frequency of the radio frequency, quadrupole (RFQ) on LEDA and the RFQ on the APT accelerator). The power is generated by a klystron and transmitted to the test stand through standard WR2300 and half-height WR2300 waveguide. The klystron is capable of producing 1.2 MW of continuous wave (CW) RF power.

4.3 Test Stand Description

The layout of the test stand, test stand components, cooling systems, and the diagnostic equipment on the test stand are described. The high power RF power is generated in a klystron and transmitted through the test section waveguide components and into a high power water/glycol load, where it is absorbed. In the test stand there are four windows, consisting of two pairs with the windows positioned back to back (See Figure 4A). All the waveguide components are filled with air, except the two regions between the windows, which are under a vacuum. The test stand schematic, Figure 4A, illustrates the components of the test stand. Each component is described below in the order encountered on the schematic, following the flow of RF power:

Klystron- Up to 1.2 MW of RF power is generated in the klystron and transmitted to the test stand through full height and 1/2 height WR2300 waveguide. The klystron is not shown in the test stand schematic.

Circulator- The purpose of the circulator is to prevent reflected power from going back into the klystron; it is included as a safety precaution to protect the klystron. The circulator is not shown in the test stand schematic.

Reducer -The reducer is a transition from full height WR2300 waveguide to half height WR2300. The windows are half height to match the waveguide on the RFQ. Reducers are needed on either side of each pair of windows to transition from half height to full height.

Forty-Five Degree E Bend - Forty-five degree E bends are on the air side of the window in order to fit four windows in one cross section on the RFQ. So, in the test stand, forty-five degree bends are attached to each pair of windows. The window assembly includes a 45 degree bend. By attaching a second 45 degree bend to the window, the waveguide is positioned horizontal on the test stand. This is only done for convenience of setting up the test stand and does not affect the RF power.

RF Test Windows - The RF test windows are set up in pairs, back to back, with a vacuum section between the windows. This test stand has the capability of simultaneously testing four windows (two pairs of windows).

Vacuum Waveguide - The section of vacuum waveguide between the two windows has two functions. The first function is to increase the electrical separation between the windows. The second is to add an additional vacuum pump port and two 1 1/2 inch diameter ports to the system.

Ninety Degree H Bend - Two ninety degree bends are used on the test stand to make a one hundred and eighty degree turn. The turn is needed so the test stand will fit in the allotted space.

Dual Directional Coupler - The purpose of the dual directional coupler is to measure the forward and reflected power in the waveguide at a given location. There are three directional couplers in the system, one before the windows, one between the first pair and second pair, and one after the second pair. In case a mismatch section is used, a fourth dual directional coupler will be added after the second pair of windows. In the event that a mismatch section is used, the mismatch will be placed between these two directional couplers. A mismatch section creates a standing wave. If the windows are placed at the peak of the standing wave, the voltage at the window is increased simulating a higher effective power at the windows.

Glycol Load - The glycol load is used to absorb the RF power without reflecting it. A mixture of 70% water and 30% glycol circulates through the load at a rate of 200 gpm.

Figure 4A. Test Stand Layout

4.4 Cooling Systems

The test stand contains three separate cooling systems: a glycol system, an air system, and a water system. The glycol system is used to dissipate the power in the RF load. The water cooling system cools the T-Bars in the windows, and the air cooling system cools the ceramic windows. The three systems are described below.

4.4a Glycol Cooling System

The glycol cooling system must dissipate the power in the RF load. This glycol load must be able to dissipate up to 1.2 MW RF power. This is done by circulating a 70% water and 30% propylene glycol mixture through the load and then through a heat exchanger. The flow rate for the glycol cooling loop is nominally 200 gpm. The power dissipated in the glycol load can be calculated by Eq. 4.1

$$P = \dot{m} c_p \Delta T \quad \text{Eq. 4.1}$$

where P is the power dissipated (kW), $\dot{m}$ is the mass flow rate (kg/sec), c_p is the specific heat (kJ/kg K), and ΔT is the temperature rise (the return temperature minus the supply temperature) in Kelvin.

4.4b Water Cooling System

The water cooling system cools the T-bar on the vacuum side of the RF windows. In the water cooling circuit (illustrated in Figure 4B) the windows are cooled in series. The water circulates through the Contentional cooling cart where water flow rate is interlocked to RF power. If the flow rate falls below 4 gpm, RF power is shut off. The temperature before the first window, between the windows, and after the last window are measured by resistive thermal devices (RTDs). The flow rate is also recorded in order to calculate part of the power dissipated in each window using Eq. 4.1. For example, the power dissipated in window #2 is the product of the flow rate, the delta T, and the

Figure 4B. Water Cooling System for the RF Windows

Figure 4C. Air Cooling System for the RF Windows

the specific heat. The delta T is the outlet temperature (RTD #3) minus the inlet temperature (RTD#2). The flow rate is monitored on the Contential Cooling Cart.

4.4c Air Cooling System

The air cooling system cools the inner conductor and air side of the RF windows. The system is illustrated in Figure 4C. A Spencer VB-075 10 horse-power blower is used to circulate the air for the cooling system. After leaving the blower the air is mixed in a plenum on the Contential cooling cart and then exits the plenum through four hoses, one to each window. The air inlet and outlet temperatures are measured by RTDs. The flow rate is measured manually using a hand held Veloci-calc Flow meter; the value is entered in the data acquisition program. The air exits the windows through a series of small holes and is vented to the atmosphere. The temperatures and flow rate are used to calculate the power dissipated in the air flow in each window. The air circulation is also interlocked to the RF power using a flow switch. If there is insufficient air flow, RF power will be shut down.

4.5 Diagnostic Equipment

Diagnostic equipment essential to monitoring the performance of the RF windows. The equipment includes ion gauges to monitor vacuum pressure and arc detectors to monitor arcs. Directional couplers are used to monitor the forward and reflected power and thermal devices to record the temperatures of the cooling air, water, and the coaxial surface temperatures. Also an RGA is used to monitor the gas species in the vacuum chamber.

RF power is measured by three dual directional couplers connected to power meters. The first directional coupler is located before the test sections, the second one is between the first and second set of windows and the third is after both sets of windows. The position of the directional couplers is illustrated in Figure 4A. To prevent damage

to the power meters attenuators are attached to the directional couplers. The attenuation through the attenuators and cables to the power meters is measured using a network analyzer. This attenuation is then entered as an offset in the power meter so the instrument will accurately display the signal seen in the waveguide.

The pressure in the vacuum systems is measured by ion gauges mounted at three locations in each pair of RF windows. The detailed description and layout of the vacuum system is discussed in Chapter 5. The pressure for each pair of windows is displayed on three ion gauge controllers. The pressure at each controller is interlocked to the RF power. If the pressure in the system reaches a specified level, RF power is shut off until the pressure is once again below the specified level. The level at which the pressure is interlocked can be easily adjusted during the experiments and is usually in the range 1×10^{-6} Torr to 1×10^{-5} Torr.

On each RF window there are two optical arc detectors, one on the vacuum side and one on the air side of the ceramic. Thus there is a total of 8 arc detectors on the windows. The numbering of the arc detectors follows the flow of RF power and is displayed in Figure 4F. The arc detectors are interlocked with the RF power. If an arc is detected RF power will be shut off for 1.6 seconds. The detectors are light sensitive and thus use fiber optic cables.

RTDs are used to record the surface temperature of the outer conductor of the coaxial line near the ceramic, as illustrated in Figure 4D. These measurements are an indicators of the temperature of the ceramic temperature because only a thin metal layer separates the ceramic from the RTD. See Figure 10J for a more detailed description of this interface. The numbering scheme for the coaxial surface RTDs is illustrated in Figure 4E.

A Residual Gas Analyzer (RGA) is connected to the vacuum system on window #1 and window #2 to observe the gas species in the vacuum during RF processing. The

Figure 4D. Location of Coaxial Surface Temperatures (not to scale)

Figure 4E. Number of the Coaxial Surface RTDs.

Figure 4F. Layout of Arc Detectors

Figure 4G. RF Window Pair on the Test Stand

Figure 4H. Control Racks for the Test Stand

RGA is manufactured by Leybold Inficon, Inc. and is a Transpector model with a C100M sensor. The RGA is connected to an IBM PC where a LabView program is used for data acquisition (gas species are recorded as a function of time). The LabView program also records the RF power, pressure, and coaxial surface temperatures at the same time intervals.

4.6 Data Acquisition System

The data acquisition system used to transfer and record data from the RF window test stand and the klystron. The system layout is illustrated in Figure 4I. Data are collected at various computers; Data Highway is used to transfer the data to different locations. The coaxial RTD, vacuum and arc detector data is read by a LabView program on the Macintosh, archived, and also sent out on the Data Highway system. The RGA data is transferred to a PC where it is recorded by a LabView program and archived. Other information such as vacuum data and power meter data is also transferred to the PC via Data Highway and archived with the RGA data. The glycol flow rate, inlet temperature, outlet temperature, air inlet temperature, outlet temperature, water inlet temperature, water outlet temperature and water flow rate are all transferred to the Contential Cooling Cart. Data from the Contential Cooling Cart is then transferred via Data Highway to the klystron transmitter. Some of this data is then transferred to other locations where it is archived. Information transferred to the klystron transmitter includes the cathode current and voltage, klystron RF output power, and cooling data of various components in the klystron. Some of the klystron transmitter information is sent out on the Data Highway system to be archived and displayed. A Sun Workstation is also used to archive and display all the data. In the future, this workstation will be used to control the klystron and the RF window testing remotely.

Figure 4I. Data Acquisition System Description

4.7 IR Imaging system

The temperature of the windows can be measured with an infrared imaging camera, a non-contact method to characterize the temperature of the surfaces. The windows are viewed through a sapphire window with the IR camera. The sapphire window is on the same port as the arc detectors. Therefore either the arc detector or the IR camera can be used; however, both cannot be used at the same time. The IR system is a PRISM DS infrared imaging camera manufactured by Flir Systems. This system has 320 vertical pixels and 244 horizontal pixels. The IR cameras were connected to a VCR to record video images. Images could also be stored on a PC card, which could be downloaded for further data analysis.

4.7a Background

The emissivity is a measure of how well a body can radiate energy compared to a black body. Since the alumina ceramic is nearly thermally opaque, this can be shown by Kirchoff's law:³⁰

$$\varepsilon_{\lambda} = \alpha_{\lambda} \text{ at any wavelength, } \lambda \quad \text{Eq. 4.2}$$

where ε_{λ} is the emittance and α_{λ} is the absorptance at wavelength λ .

Since the alumina is very nearly opaque, the transmission is negligible, and the following relationship can be applied:³⁰

$$\varepsilon_{\lambda} + \rho_{\lambda} = 1 \quad \text{Eq. 4.3}$$

where ε_{λ} = emittance and ρ_{λ} = the reflectance at wavelength λ . For example, an emissivity of .8 means that absorptivity also equals 0.8 and 80% of the incident energy will be absorbed by the object and 20% will be reflected. The energy absorbed causes the object to heat up and radiate more energy. The amount of energy radiated depends on

the object's temperature, emissivity and the geometric relationship to other thermal exchange surfaces. This geometric relationship can be accounted for by using a view factor. In this application the view factor was assumed to be 1.0. Hence, an IR Imaging system calculates the objects temperature based on the amount of energy the object emits.

4.7b Emissivity Tests

The emissivity of alumina samples were measured with an infrared reflectometer to verify the feasibility of using the IR imaging camera. To obtain accurate temperature measurements, a high emissivity and a high temperature are desirable. The average emissivity of alumina samples is 0.68 , which means that IR imaging is practical. In anticipating future work, the samples that were tested include alumina, boron nitride, rexolite, beryllia, and copper. The samples were tested (a) with no coating and (b) with the following coatings: titanium oxide, chrome oxide, titanium nitride, and silicon nitride⁴¹.

CHAPTER 5

VACUUM SYSTEM DESIGN

5.1 System Description

Experimental results were used to determine the vacuum system requirements for the 350 MHz RF windows on the RFQ. Two prototype windows from EEV of Chelmsford, England were tested at Argonne National Laboratory Oct. 1996 through Jan 1996. The RF windows were tested in a back-to-back configuration with a vacuum section between the two windows, as illustrated in Figure 5B and Figure 4F. During the high power acceptance tests the EEV prototype windows were conditioned up to 1 MW and ran at that power level for 4 hours. To determine the RF window vacuum system requirements, the vacuum pumping speed and out gassing rates were measured during RF operation.

5.1a Layout of Roughing Vacuum system

The components used in the vacuum system are illustrated in Figure 5A and are described in this section. The ion gauges are used to measure the vacuum pressure in the high vacuum region, 1×10^{-3} to 1×10^{-9} Torr. Thermocouple gauges are used to measure the vacuum pressure from atmospheric pressure to 1×10^{-3} Torr. The nitrogen vent valve is used to backfill the system with nitrogen and to ensure that the pressure does not go above atmospheric pressure when filling the system with nitrogen. The roughing valve connects the roughing system with the mechanical pump. Gate valves are used to isolate the vacuum chamber system from the cryopumps. The cryo pumps are used to pump the system down into the high vacuum range, 10^{-2} Torr to 10^{-10} Torr. The foreline valves are used to isolate the cryo pumps from the roughing (mechanical) pump. The leak checking valve is used to isolate the system to leak check.

Figure 5A. Schematic of the Roughing Vacuum System

the roughing system. The mechanical pump is used to pump the system down to the cross-over pressure of about 50×10^{-3} Torr, where the cryo pumps can start pumping.

5.1b Layout of High Vacuum System

The high vacuum system on the RF window test stand is illustrated in Figure 5B. The vacuum section includes the vacuum side of an RF window, a section of vacuum waveguide, and the vacuum side of a second RF window. The vacuum section also includes the length of tube between the RF windows and the pumps. This section is pumped using three CTI-cryogenics Cryo-Torr 8 (CT-8) pumps. The vacuum pressure is monitored by three Granville-Phillips STABIL-ion gauges.

Figure 5B. High Vacuum System Layout

5.2 Vacuum Calculations

For vacuum components, the conductances and pumping speeds are calculated using either nitrogen or hydrogen. All stated pressures in this section are for nitrogen. Therefore, conductances and outgassing rates are nitrogen-based.

5.2a Load Calculations

The vacuum load is due to the outgassing of the copper-plated stainless steel surfaces, on both the RF window and the spacer piece, and the alumina ceramic. In order to calculate the load, first the total copper surface area is calculated.

$$A_{\text{Copper}} = 2 * A_{\text{RF Window Cu}} + A_{\text{Spacer Cu}} \quad \text{Eq. 5.1}$$

where $A_{\text{RF Window Cu}}$ is the total copper surface area on the RF from EEV Drawing # MA3512LPART1 and $A_{\text{Spacer Cu}}$ is the total copper surface area on the vacuum spacer piece from LANL Drawing # 143Y606006 D1. Substituting the values into Eq. 5.1 yields the total copper surface area.

$$\begin{aligned} A_{\text{Copper}} &= 2 * 818,931 \text{ mm}^2 + 801289 \text{ mm}^2 \\ &= 2,439,151 \text{ mm}^2 = 24,392 \text{ cm}^2 \end{aligned}$$

The total alumina surface area is shown calculated in Eq. 5.2.

$$\begin{aligned} A_{\text{RF Window Al}_2\text{O}_3} &= 2 * 33071 \text{ mm}^2 \\ &= 66142 \text{ mm}^2 = 661 \text{ cm}^2 \end{aligned} \quad \text{Eq. 5.2}$$

where $A_{\text{RF Window Al}_2\text{O}_3}$ is the total alumina vacuum surface area on the RF window, from EEV Drawing # MA3512LPART1. The effect of the alumina outgassing is neglected in these calculations, because the alumina surface area is only 2% of the total surface area. Thus, the total load is calculated by multiplying the copper surface area by the copper outgassing rate as shown in Eq. 5.3:

$$L_{\text{Total}} = O_{\text{Cu}} * A_{\text{Cu}} \quad \text{Eq. 5.3}$$

where O_{Cu} (the outgassing rate of copper after 10 hours) is $2 \times 10^{-9} \text{ Torr L / sec cm}^2$.³¹

Substituting the values into Eq. 5.3 yields the total load.

$$L_{\text{Total}} = (2 \times 10^{-9} \text{ Torr L / sec cm}^2)(24,392 \text{ cm}^2)$$

$$L_{\text{Total}} = 4.8 \times 10^{-5} \text{ Torr L / sec}$$

5.2b Conductance Calculations / Effective Pumping Speed

The conductance is calculated in order to determine the effective pumping speed. Conductance of the individual components shown in Figure 5B are calculated first, then the total conductance is calculated. For a circular tube the following formula is used:³²

$$C_{\text{tube}} = 12.1 \frac{D^3}{L + 1.33D} \quad \text{Eq. 5.4}$$

where D is the diameter (in cm) and L is the length (in cm). The conductance in an aperture is calculated using the following formula:³²

$$C_{\text{Aperture}} = 11.6 \frac{\pi D^2}{4} \quad \text{Eq. 5.5}$$

where D is the diameter (in cm). The conductance of a grill with holes is calculated by determining the conductance in each hole and then multiplying this value by the total number of holes. Once the individual conductance is known, the total conductance may be calculated. The conductance for pump 2 is calculated as follows.

$$\frac{1}{C_{2\text{Total}}} = \frac{1}{C_{\text{RF Grill 2}}} + \frac{1}{C_{8''}} \quad \text{Eq. 5.6}$$

where $C_{2\text{Total}}$ is the conductance for pump port 2, $C_{\text{RF Grill 2}}$ is the conductance for the RF Grill in port 2, and $C_{8''}$ is the conductance for the 8" diameter tube in port 2. Substituting the values into Eq. 5.6 yields the total conductance:

$$\frac{1}{C_{2\text{Total}}} = \frac{1}{1222.705 \text{ liter / sec}} + \frac{1}{2149.1 \text{ liter / sec}}$$

$$C_{2\text{Total}} = 779.3 \text{ liter / sec}$$

Next, the conductance for pump 1 and 3 are calculated as follows:

$$\frac{1}{C_{1\text{Total}}} = \frac{1}{C_{\text{RF Grill 1}}} + \frac{1}{C_{4''}} + \frac{1}{C_{4'' \text{ to } 8''}} + \frac{1}{C_{8''}} \quad \text{Eq. 5.7}$$

where $C_{1\text{Total}}$ is the conductance for pump port 1 (or 3), $C_{\text{RF Grill 1}}$ is the conductance for the RF Grill in port 1 (or 3), $C_{4''}$ is the conductance for the 4" diameter pump port, $C_{4'' \text{ to } 8''}$ is the conductance for the 4" to 8" aperture, and $C_{8''}$ is the conductance for the 8" diameter tube in port 1 (or 3). Substituting the known values into Eq. 5.7 yields:

$$\frac{1}{C_{1\text{Total}}} = \frac{1}{355.09 \text{ liter / sec}} + \frac{1}{282.43 \text{ liter / sec}} + \frac{1}{911 \text{ liter / sec}} + \frac{1}{1849.2 \text{ liter / sec}}$$

$$C_{1\text{Total}} = 125.1 \text{ liter / sec}$$

Thus, the total conductance is calculated by Eq. 5.8.

$$C_{\text{Total}} = 2 * C_{1\text{Total}} + C_{2\text{Total}} \quad \text{Eq. 5.8}$$

$$C_{\text{Total}} = 2(125.1 \text{ liter / sec}) + 779.32 \text{ liter / sec}$$

$$C_{\text{Total}} = 1029.5 \text{ liter / sec}$$

The effective pumping speed is calculated next. The effective pumping speed is calculated from Eq. 5.9:

$$P_{\text{eff}} = \frac{C_{\text{Total}} P_{\text{Total}}}{C_{\text{Total}} + P_{\text{Total}}} \quad \text{Eq. 5.9}$$

where C_{Total} is the total conductance for the system, P_{Total} is the rated pumping speed for the three CT-8 Cryo pumps = 3 x 1500 liter / sec = 4500 liter / sec, and P_{eff} is the effective pumping speed. Substituting the values into Eq. 5.9 yields the effective pumping speed.

$$P_{eff} = \frac{(1029.5 \text{ liter / sec})(4500 \text{ liter / sec})}{1029.5 \text{ liter / sec} + 4500 \text{ liter / sec}}$$

$$P_{eff} = 837.8 \text{ liter / sec}$$

5.2c Required Pumping Speed

The required pumping speed is the total load divided by the target pressure and is calculated from Eq. 5.10.

$$P_{Req} = \frac{L_{Total}}{P_{ult}} \quad \text{Eq. 5.10}$$

Substituting the calculated values into Eq. 5.10 yields the required pumping speed.

$$P_{Req} = \frac{4.8 \times 10^{-5} \text{ Torr liter / sec}}{1.0 \times 10^{-7} \text{ Torr}}$$

$$P_{Req} = 480 \text{ liter / sec}$$

Thus, since $P_{eff} \geq P_{req}$, the system has sufficient pumping capacity to maintain the target vacuum pressure.

5.3 Experimental Results of ANL Tests

The experimental results from the high power RF tests done at Argonne National Laboratory are described in detail in LANL memo L-5:97-028 dated 3/20/97⁴².

5.3a Outgassing Rate Without RF Power

The outgassing rate during the experiments without RF power can be calculated by Eq. 5.11.

$$L_{exp} = \frac{(P_{Measured}) * (P_{eff})}{A_{Total}} \quad \text{Eq. 5.11}$$

where L_{exp} is the experimental load without RF power, $P_{Measured}$ is

the measured pressure, from page 2 of LANL memo L-5:97-028⁴², P_{eff} is the effective pumping speed, and A_{Total} is the total surface area. Substituting these values into Eq. 5.11 yields the load with no RF power.

$$\begin{aligned} L_{exp} &= \frac{(1.92 \times 10^{-8} \text{ Torr})(837.82 \text{ liter / sec})}{24392 \text{ cm}^2} \\ &= 6.60 \times 10^{-10} \text{ Torr liter / sec cm}^2 \end{aligned}$$

5.3b Outgassing Rate with RF Power

Next, the outgassing rate with RF power can be calculated as follows from Eq.

5.11:

$$\begin{aligned} L_{exp \text{ RF}} &= \frac{(P_{Measured}) * (P_{eff})}{A_{Total}} \\ &= \frac{(1.17 \times 10^{-7} \text{ Torr})(837.82 \text{ liter / sec})}{24392 \text{ cm}^2} \\ &= 4.02 \times 10^{-9} \text{ Torr liter / sec cm}^2 \end{aligned}$$

where $L_{exp \text{ RF}}$ is the experimental load with RF power (*torr l / sec cm*²), $P_{Measured}$ is the measured pressure in Torr after passing 1 MW RF power for 4 hours, from ANL test data, P_{eff} is the effective pumping speed (l/sec), and A_{Total} is the total surface area (*cm*²).

5.3c Summary of Degraded Vacuum Tests done at Argonne National Laboratory

Tests were performed to determine the effect of a degraded vacuum pressure on the performance of the RF windows. Pump #1 and pump # 2 were isolated from the system so that the total pumping capacity was from pump #3. The vacuum pressure stabilized at 8.31×10^{-7} Torr, see Appendix B. Thus, the vacuum pressure increased from 1.17×10^{-7} Torr to 8.31×10^{-7} Torr during RF operation due to the increase of outgassing.

The higher vacuum pressure had no effect on the performance of the windows under full power (1 MW). The performance was evaluated by recording the number of

arcs and the temperature of the alumina ceramic windows and the temperature of the outside of the coax near the alumina. At both vacuum pressure levels the amount of arcing and ceramic temperatures were comparable. However, these windows were well conditioned and had been operated at full power before the vacuum tests were performed. For the initial conditioning, where the highest gas loads occur, a low vacuum pressure is ideal. A lower pressure will decrease the severity as well as the number of arcs during conditioning. A larger effective pumping speed will also decrease the time required to condition the windows.

Even though the results of the degraded vacuum tests demonstrated a comparable performance of the windows during the RF operation, it is still important to have a large effective pumping speed, especially during conditioning. A useful experiment would be to compare the initial conditioning of windows with (a) a higher vacuum pressure and (b) a lower vacuum pressure.

5.4 Experimental Results of LANL Tests

At LANL, vacuum tests were performed by Valdiviez to measure the outgassing rate at different power levels⁵². The effective pumping speed is required to determine the outgassing rates. Once the effective pumping speed is known the outgassing rates is calculated.

The effective pumping speed was determined by injecting a known flow rate of hydrogen gas into the vacuum system and measuring the resulting pressures. The effective pumping speed is then calculated from Equation 5.11.

$$P_{eff} = \frac{(L_{injected})}{P_{Measured}}$$

Eq. 5.12

where P_{eff} is the effective pumping speed, L_{injected} is the flow rate of hydrogen injected into the system, P_{Measured} is the measured pressure. The measured effective pumping speeds are listed in Table 5A.

Pump Number	Measured Effective Pumping Speed (liters/second)
1	125
2	506
3	125
Total	756

Table 5A. Measured Effective Pumping Speeds

Once the effective pumping speed is known, the outgassing rate can be determined. The steady state pressure is measured. The outgassing rates are calculated by substituting the steady state pressure into Equation 5.11. The steady state pressures and the resulting outgassing rates are listed in Table 5B. The outgassing rate is plotted as

RF Power, kW	Average Pressure, Torr	Outgassing Rate, $\frac{\text{Torr l}}{\text{sec cm}^2}$
50	6.0 E-9	1.86E-10
100	7.0 E-9	2.17E-10
300	7.2 E-8	2.23E-09
500	1.5 E-7	4.65E-09
700	1.7 E-7	5.27E-09
800	1.8 E-7	5.58E-09
1000	1.8 E-7	5.58E-09

Table 5B. Results of Outgassing Rate Tests

a function of power in Figure 5C. This plot shows that the outgassing rate is not linear with power. As the power level increases, the outgassing rate approaches an asymptotic value.

Figure 5C. Outgassing Rate vs. Power

Figure 5D. Power vs. Time during the Outgassing Tests

5.5 Summary of Vacuum Calculations

The calculations show that the required pumping speed is 480 liter/sec based on the outgassing rate for copper of 2.0×10^{-9} Torr L/sec cm² found in the literature. From the experimental results at ANL, the actual outgassing rate was calculated to be 6.60×10^{-10} Torr L/sec cm² without RF power and 4.02×10^{-9} Torr L/sec cm² with RF power. These outgassing rates require a pumping speed of 160 liter/sec and 980 liter/sec respectively based on the conductances and surface area of the RF windows on the test stand to obtain an ultimate pressure of 1×10^{-7} Torr. At LANL, the outgassing rate was measured as a function of RF power. The outgassing rate with no RF power was 6.6×10^{-10} Torr L/sec cm² and 5.6×10^{-9} with 1 MW of RF power. The outgassing rates are summarized in Table 5C. The outgassing rate of 5.6×10^{-9} Torr L/sec cm² is the

Source	Power Level	Outgassing Rate (Torr liter /sec cm ²)
Straussen ³¹	No RF power	2.0×10^{-9}
Tests at ANL	No RF Power	6.6×10^{-10}
Tests at ANL	1 MW	4.0×10^{-9}
Tests at LANL	1 MW	5.6×10^{-9}

Table 5C. Summary of Outgassing Rates

recommended outgassing rate to use for future vacuum system designs. This is the highest outgassing rate measured and thus would be the most conservative case. It is important to obtain the largest effective pumping speed that is reasonable in order to facilitate the conditioning process of the windows on the RFQ.

CHAPTER 6

MATERIALS TESTING AND CHARACTERIZATION PROCEDURES

Material testing was performed on the alumina ceramic to determine mechanical properties for the analytical model. Microscopy was performed to characterize the surface of the alumina.

First an overview of the materials work is presented. Next the material history and sample layout are discussed, and finally the specific materials testing and characterization sections are presented. The materials testing consists of four point bend tests to determine the material properties. The materials characterization consists of fractography, surface characterization, and scanning electron microscopy.

6.1 Overall Materials Testing Procedure

The sequence of steps for the strength, fractography and microscopy is illustrated in Figure 6A. The first step in the materials work was to obtain the alumina material. EEV purchased the AL300 alumina ceramic material for the RF windows from WESGO in Germany. WESGO had three spare alumina pieces left from the batch they made for EEV, therefore, these three alumina ceramic disks were purchased from WESGO to do the material testing. The samples of material used for the material testing are a very good representation of the alumina ceramic used in the EEV windows, and they are even from the same batch. Radiography was done to check the alumina disks for any gross defects; none were found. The samples were then machined. Some were grit blasted as shown in Table 6A. A special test fixture was made to hold the samples during grit blasting. It consists of a slotted aluminum plate to place the samples in, see Figure 6B, and a slotted cover plate, see Figure 6C, to ensure that the edges of the samples are not damaged during grit blasting, as this damage could unfavorably affect the measured strength. Then the samples were divided into two groups. One group was sent to NASA

Figure 6A. Overall Materials Procedure

Figure 6B. Grit Blasting Test Fixture

Figure 6C. Cover Plate for the Grit Blasting Test Fixture

Sample Type	Disk 1 (pattern A)	Disk 2 (pattern A)	Disk 3 (pattern b)	Total
Disk	0	0	-----	0
Radial, Size A	-----	-----	0	0
Tangential, Size A	-----	-----	0	0
Radial, Size B	0	3 (+15 spares)	0 (+5 spares)	23
Tangential, Size B	30	0 (+5 spares)	24 (B1-12, B13-24)	59

Table 6A. Summary of the Number of Grit Blasted Samples

Lewis, another to LANL. Four point bend tests and fractography were done at NASA. Surface analysis and SEM were performed at LANL. After this sequence of testing, analyses were done using mechanical testing and microscopy, and then the information was compiled.

6.2 Sample Layout and History

The processing and manufacturing procedures for alumina ceramic are very important to the final material properties. The alumina was isostatically pressed at 700 bar with a sintering temperature of 1700 Deg. C. The disks were centric ground with a surface finish of Ra 1.2 -1.6 (40 μm to 63 μm surface finish). Next, a thin ring of molybdenum was metalized at 1500 °C to the outer diameter of the disks. This geometry is discussed in chapter 9 in detail.

Two patterns were used for the sample layout, as illustrated in Figure 6D and 6E. The fabrication drawings were done by J. Salem at NASA.³⁸ Of the three disks, two were machined according to pattern A and one according to pattern B. The two size beams are in accordance with the ASTM C1161 type "A" and "B" standard. Two different beam sizes were used to provide accurate measurement of the Weibull parameters since they are size dependent. Both radial and tangential beams are used. The tangential beams may show residual stresses in the disk.

Figure 6D. Specimen Removal Pattern A³⁸

Figure 6E. Pattern B for samples from alumina disk³⁸

If high residual stresses are in the disk, the strength of the tangential samples will vary as a function of radius. The circular disks are to determine any multiaxial effects of stresses by applying stresses in more than one direction during testing. The number of samples, type of samples, and organization for testing the samples are shown in Table 6B.

Sample Type	Disk 1 (pattern A)	Disk 2 (pattern A)	Disk 3 (pattern B)	Total
Disk	12	12	-----	24
Radial, Size A	-----	-----	40	40
Tangential, Size A	-----	-----	28	28
Radial, Size B	66	66	48	180
Tangential, Size B	44	44	48	96

Table 6B. Summary of Samples from WESGO Alumina Ceramic

There are two categories of sample histories to be tested, as illustrated in Table 6C. The SH1 samples have not been grit blasted; the SH2 samples have been grit blasted. None of the samples tested have had RF exposure. By comparing SH1 to SH2 the effect of grit blasting can be observed. The SH2 samples were grit blasted with 220 alumina grit at a pressure of 80 psi.

Sample History	Description
SH1	as received - not grit blasted
SH2	grit blasted

Table 6C. Summary of Sample History

6.3 Mechanical Testing

The mechanical testing is divided into four parts:

- Effects of radial position
- Surface finish

- Fatigue
- Disk to disk variation

The objectives of the mechanical testing are outlined in Table 6D.

There is no special sample preparation procedure after the samples undergo the procedures described in Section 6.2. Care was taken not to contaminate or scratch the surfaces of the samples. The ceramic RF window surfaces are put in tension during the bend tests. Thus the bend test puts the RF window surface in tension.

Section	Objective:
Radial Position	• determine the effects of radial position • determine if there are any significant residual stresses
Surface Finish	• determine if grit blasting affects the mechanical properties
Fatigue	• determine the fatigue properties
Disk to Disk Variation	• determine the variations between disks in the mechanical properties

Table 6D. Objectives of the Mechanical Testing

6.3a Effects of Radial Position

One objective of this section is to determine whether there are any differences in the mechanical properties due to the radial position of the samples. Differences found will be an indication of residual stresses in the disks. All samples were tested at the stressing rate of R1 because fast fracture data is being acquired. All the samples are also tangential samples since these tests are designed to determine the affect of radial position. Thus a change in the slope of strength vs. radial position shows the effect of radial position. The sample location designation is the following format: Dx:n1-n12. In this format, Dx represents the disk where the samples were taken from. Because there are

three disks, they are designated D1, D2, and D3. The n1-n12 represents the surface of the disk and location of the beams on the surface, as illustrated in Figure 6E.

6.3b Effects of Surface Finish

The objective of this section is to determine the effect of surface finish on the mechanical properties. The two surface finishes being compared are “as received”, SH1, and grit blasted, SH2. This has been incorporated into the radial position test matrix. Thus half of the samples being tested for the radial position will be grit blasted and half will be “as received”, as shown in Table 6E. Differences in strength between the grit blasted and the “as received” samples will show the effect of surface finish.

Test #	To determine effect of:	Test Rate	Sample Type	Sample History	Sample Location	Number of Samples
1	Radial Position	R1	Tangential, Size B	SH1	D3: A1-A24	24
2	Grit Blasting & Radial Position	R1	Tangential, Size B	SH2	D3: B1-B24	24
3	Orientation	R1	Radial, Size B	SH1	D3: Radial	24

Table 6E. Surface Finish Testing Matrix

Figure 6F. Location of Samples on Disk 3

6.3c. Fatigue Effects

The fatigue data are determined for both the grit blasted and the as received samples. The strength at four different stressing rates is used to determine the fatigue data. The stressing rates are illustrated in Table 6F. Tests number 4 through 7 are used to determine the fatigue data as illustrated in the fatigue test matrix, Table 6G.

Test Rate	Loading Rate (N/Sec))	Stressing Rate (MPa / Sec)
R1	36	30
R2	3.6	3.0
R3	0.36	0.30
R4	0.036	0.03

Table 6F. Summary of Stressing Rates

Test #	To determine effect of:	Test Rate	Sample Type	Sample History	Sample Location	Number of Samples
4	Fatigue	R1	Radial, Size B	SH1	D1: radial	24
5	Fatigue	R2	Radial, Size B	SH1	D1: radial	10
6	Fatigue	R3	Radial, Size B	SH1	D1: radial	10
7	Fatigue	R4	Radial, Size B	SH1	D1: radial	10
8	Fatigue	R1	Tangential, Size B	SH2	D1: tangential	10
9	Fatigue	R2	Tangential, Size B	SH2	D1: tangential	10
10	Fatigue	R3	Tangential, Size B	SH2	D1: tangential	10
11	Fatigue	R4	Tangential, Size B	SH2	D1: tangential	10

Table 6G. Fatigue Testing Matrix

6.3d Disk to Disk Effects

To determine if there are any variations in strength between samples taken from different disks, a comparison is made and shown in Table 6H. Thus samples from test #12 will be compared to samples from test #1 and #3.

Test #	To determine effect of:	Test Rate	Sample Type	Sample History	Sample Location	Number of Samples
12	Disk to Disk Variation	R1	Tangential, Size B	SH1	D2: tangential	15

Table 6H. Disk to Disk Variation Testing Matrix

6.3e Mechanical Properties for Analytical Model

The CARES parameter estimation code (CARES Pest) will be used to determine the mechanical properties for the analytical model from the 4 point bend data. Table 6I lists the files needed for the CARES Pest code. The data listed in Table 6H includes the data that are needed to determine the fast fracture and fatigue data for both the grit blasted and the as received samples.

CARES Pest input:	C5Pest.inp (input file with 4 point bend data)
CARES Pest input	stuct.tmp (output file of CARES Pest, can be used as an input file for CARES Life)
CARES Pest output:	struc.oup (output file for CARES Pest)

Table 6I. Input and Output Files for CARES Pest

6.4 Fractography

Fractography will be performed on every broken sample after the mechanical tests. Therefore, the test matrix for fractography is the same as the test matrix for the mechanical testing. The objective of the fractography is to examine the origin of fracture. One can determine whether material imperfections or impurities are near the fracture origin. In addition, the alumina can be inspected for the glassy phase.

6.5 Surface Characterization

The objective of the surface analysis is to compare the elemental composition in the surface layers of the grit blasted samples to those of the as received samples. The test matrix, shown in Table 6J, consists of two grit blasted samples and two as received samples. All the samples for the surface characterization were samples that have not undergone the four point bend tests or fractography.

Test Objective	Sample Type	Sample History	Location of Tests	Disk sample is from	Number of Samples
1) grit blasted	Tangential, Size B	SH2	LANL	Disk 2	1
2) not grit blasted	Tangential, Size B	SH1	LANL	Disk 2	1

Table 6J. Surface Characterization Test Matrix

The surface analysis is done using x-ray photoelectron spectroscopy (XPS). The sample is irradiated with soft x-rays and the kinetic energy of the electrons emitted from the surface is measured. The binding energy can then be determined by subtracting the measured kinetic energy from the incident x-ray energy. The XPS data is plotted as a function of binding energy. On this plot, the patterns of the energies of photoelectrons emitted for a specific atom can be recognized and thus the atom may be identified. The surface composition may be calculated by integrating the elemental peak areas, correcting for the analyzer sensitivity, and including considerations for the measurement depth. The machine in which the data is acquired by is a multi-technique 5600ci surface apparatus manufactured by Physical Electronics, Eden Prairie, MN.

6.6 Scanning Electron Microscopy (SEM)

The objective of the SEM is to examine the surface topography. The test matrix for SEM is shown in Table 6K. Effects of grit blasting will be studied with SEM. A conductive coating on the samples is needed to dissipate the charge. This coating is very thin, about 50 Angstroms, thus it does not affect the results of the SEM. However,

Test Objective	Sample Type	Sample History	Location of Tests	Disk Sample is from	Number of Samples
1) grit blasted	Tangential, Size B	SH2	LANL	Disk 2	2
2) not grit blasted	Tangential, Size B	SH1	LANL	Disk 2	2

Table 6K. SEM and AFM Test Matrix

it does prevent charge from accumulating in the samples. Of the four samples in the Table, two (one grit blasted and one not grit blasted) were coated with carbon, and the remaining two (one grit blasted and one not grit blasted) were coated with gold and shadowed. Shadowed means the samples was held at an angle while coating it to bring out the topographical features.

6.7 Atomic Force Microscopy

The objective of the atomic force microscopy (AFM) is to determine the difference in surface topography between the grit blasted samples and the as received samples. The test matrix for the AFM is the same as the SEM test matrix.

CHAPTER 7

EXPERIMENTAL PROCEDURE

This chapter summarizes the experimental procedure for the low and high power RF testing. The first step in the experimental procedure is to perform the low power electrical measurements. This is done to ensure the windows meet the electrical specifications. The LANL high power conditioning and testing is done to verify the windows achieve the required power capacity of 1 MW continuous wave into a matched load.

7.1 Low Power Electrical Measurements

The low power electrical measurements were performed at the EEV factory in Chelmsford, England. The windows are required to demonstrate the following electrical performance characteristics: an operating frequency of 350 MHz, a 6 MHz bandwidth, and an insertion and return loss of less than 1% over the bandwidth. A HP 8753D network analyzer with a MCI WR2300 half height sliding load as a calibration standard were used to verify these electrical requirements.

Scattering (S) parameters are measured. The S parameters are best explained by considering a coaxial line. There are two conductors in a coaxial line, one at a higher

Figure 7A. Incident and Reflected Waves for a Two Port Device³⁶

potential and the other at ground. Now examine a two port device with two conductors. One conductor is at ground potential and the other is at a higher potential, as illustrated in Figure 7A. The S parameters are the forward and reverse gain of this two port network³⁶. If a_2 is set equal to zero, S_{11} is the ratio of the reflected input signal to the incident input signal, as shown in Equation 7.1.

$$S_{11} = \left. \frac{b_1}{a_1} \right| a_2 = 0 \quad \text{Eq. 7.1}$$

where a_1 is the incident input signal into the two port device and b_1 is the reflected input signal. Setting a_2 to zero is the mathematical equivalent of terminating the device under test into a matched load. In the RF window low power electrical measurements S_{11} is a measurement of the input reflection coefficient and is used to calculate the return loss. S_{22} is the ratio of the reflected output signal to the incident output signal and is defined as

$$S_{22} = \left. \frac{b_2}{a_2} \right| a_1 = 0, \quad \text{Eq. 7.2}$$

where a_2 is the incident output signal into the two port device and b_2 is the reflected output signal. In this instance, setting a_1 equal to zero can be considered as terminating the device under test into a matched source. S_{21} is a composite measurement of insertion and return loss and can be used with S_{11} to calculate the insertion loss. S_{21} is the ratio of the reflected output signal, b_2 , to the incident input signal, a_1 , and is defined as

$$S_{21} = \left. \frac{b_2}{a_1} \right| a_2 = 0. \quad \text{Eq. 7.3}$$

Likewise, S_{12} the ratio of the reflected output signal, b_2 , to the incident input signal, a_1 , and is defined as

$$S_{12} = \left. \frac{b_1}{a_2} \right| a_1 = 0. \quad \text{Eq. 7.4}$$

The S parameters are also defined as:

- S_{11} is the input reflection
- S_{12} is the reverse transmission coefficient
- S_{21} is the forward transmission coefficient
- S_{22} is the output reflection coefficient³⁶

The electrical specifications can be determined by measuring the S parameters with a calibrated network analyzer. The specifications are outlined in Table 7A.

Parameter	Frequency	Requirement
S21 and S12	347 MHz	> 0.043 dB
S21 and S12	350 MHz	> 0.043 dB
S21 and S12	353 MHz	> 0.043 dB
S11 and S22	347 MHz	< -20.0 dB
S11 and S22	350 MHz	< -20.0 dB
S11 and S22	353 MHz	< -20.0 dB

Table 7A. Low Power Electrical Specifications and Requirements

In order to remove contaminants from handling and to outgass the vacuum surfaces, the windows underwent a high temperature bakeout at the EEV factory after the electrical calibrations. This was done before they were shipped to Los Alamos. The windows were pumped down to a pressure of approximately 1×10^{-7} Torr before, during, and after the bakeout. The windows were under vacuum until they cooled to room temperature. The windows were vented to nitrogen gas to atmospheric pressure. The

factory bakeout was for 50 hours at 300 °C. The bakeout is done to remove water vapor and other materials from the metal and ceramic surfaces in the vacuum side of the waveguide.

7.2 High Power RF Conditioning

This section presents the conditioning goal and conditioning methods available in the literature as well as the conditioning tools and diagnostic equipment available. The goals of the conditioning are to increase the amount of the RF power through the window while maintaining a good vacuum and limiting arcs. During conditioning it is important to ensuring nonlinear heating, a sign of multipacting, does not occur. This goal is achieved by slowly increasing the RF power while waiting for the vacuum pressure to decrease and minimize the arc rate.

There are two conditioning methods described in the literature. Pisharody, *et. al.*, have developed a processing method for windows called “tickle processing”³⁷. In this method, 100 microseconds pulses, are superimposed on wider pulses, at 1% to 50% duty cycle, as shown in Figure 7B. The success of this method is attributed to the shorter RF pulses, which limit the vacuum bursts and thus improve the efficiency of the conditioning³⁷. Using this processing method, a power level of 300 kW CW was obtained in 20 hours at Thomas Jefferson Laboratory³⁷. A second method of conditioning involves recording the window temperature as a function of RF input. The window temperature should increase linearly with RF input. A nonlinear increase is an indication of multipacting, as shown in Figure 7C. This multipacting and nonlinear heating may lead to the failure of the window^{5,8}.

Figure 7B. Tickle Processing at 400 kW³⁷

Figure 7C. Window Temperature vs. RF Input Power^{5,8}

There are several available tools and diagnostic equipment that can be used in conditioning. The diagnostic equipment includes ion gauges, arc detectors, directional couplers, thermal devices and a Residual Gas Analyzer (RGA). These diagnostic devices are discussed in detail in Chapter 4, Section 4.5.

This section discusses the basis and tools for conditioning. Combining the conditioning goals with the diagnostic equipment and tools and previous conditioning experiences from the literature, the conditioning procedure will be developed from the experimental results and will be discussed in Chapter 8.

7.3 High Power RF Testing

The purpose of the high power RF tests is to verify that the windows meet the performance specifications listed in the statement of work. The three performance specifications are summarized in Table 7B. To ensure steady state temperatures and pressures are achieved, the high power RF tests are performed for 4 hours.

Specification	Requirement	Required Tests
Typical Operation	475 kW with a VSWR of 1.25:1	1 MW for 4 hours
Worst Case VSWR	300 kW with a VSWR of 2.5:1	1 MW for 4 hours
Maximum Power	700 kW with a VSWR of 1.5:1	1 MW for 4 hours

Table 7B. High Power RF Specifications and Requirements

The required maximum power capacity for all three specified requirements is 1 MW. The equivalent voltages for the specified power levels and VSWRs may be calculated. For example, in the maximum power case the power level is 700 kW and the VSWR is 1.5:1. So the objective is to determine at what power level the voltage is equal to the voltage of the specified power and VSWR, assuming the window is at the peak of the standing wave. First, the value of VSWR is substituted into Eq 1.12 to yield the value of the reflection coefficient.

$$\Gamma = \frac{VSWR - 1}{VSWR + 1}$$

$$\Gamma = \frac{1.5 - 1}{1.5 + 1}$$

$$\Gamma = .2$$

These calculations assume that the VSWR of the load is 1.0, see Chapter 1. Assume $Voltage_{Forward} = 1$ and substitute in Eq. 1.3.

$$\Gamma = \frac{V_{Reverse}}{V_{Forward}}$$

$$0.2 = \frac{V_{Reverse}}{1}$$

$$V_{Reverse} = 0.2$$

Next, the maximum power is calculated by substituting the $Voltage_{Forward}$ and the $Voltage_{Reverse}$ into Equation 1.5.

$$P_{max} = (Voltage_{Forward} + Voltage_{Reverse})^2$$

$$P_{max} = (1 + 0.2)^2$$

$$P_{max} = 1.44$$

Now the maximum power is calculated by substituting P_{max} into Equation 1.14.

$$\text{effective power} = (P_{max}) (\text{average power})$$

$$\text{effective power} = 1.44 (700 \text{ kW}) = 1008 \text{ kW}$$

The details for the other two cases are not shown, but the equivalent power levels are summarized in Table 7C. Thus, if the windows can pass 1 MW of RF power,

these calculations demonstrate that the windows satisfy all three specifications. Hence, the high power RF acceptance tests for the windows consist of running the windows at 1 MW for 4 hours.

Specification	Power	VSWR	Γ	$P_{\max}$	Effective Power
Typical Operation	475 kW	1.25:1	0.11	1.23	584 kW
Worst Case VSWR	300 kW	2.5:1	0.43	2.04	612 kW
Maximum Power	700 kW	1.5:1	0.20	1.44	1008 kW

Table 7C. Equivalent Voltages for High Power RF Requirements

7.4 Vacuum Tests

Vacuum tests were performed to determine both the effects of conditioning on the outgassing rate and the outgassing rates of the windows at different power levels. The outgassing information is very relevant to the design and operational aspect of vacuum system for the windows on the RFQ. The outgassing rates will also help in evaluating conditioning. A well conditioned window will have a low outgassing rate. The vacuum tests were performed after the windows were conditioned to 1 MW and after the high power acceptance tests were complete.

The outgassing rate was measured at the following power levels: 0 kW, 50 kW, 100 kW, 300 kW, 500 kW, 700 kW, 800 kW, and 1000 kW. The procedure to experimentally determine the outgassing rate is:

- 1) Determine the effective pumping capacity of the vacuum system . The effective pumping speed was calculated in Chapter 5(the vacuum system design chapter) to be 837.82 liters/sec. This calculation is based on the manufacturer's rating for the pumping capacity, and the total calculated conductance. There is a method for experimentally measuring the effective pumping capacity. It is called a "rate of rise" test. A rate of rise test consists of isolating the vacuum pumps from the vacuum system. By shutting the gate valves between the pumps and the vacuum system, the vacuum system is isolated.

The pressure will increase with time and eventually achieve a steady state pressure.

During the rate of rise test, the pressure is measured at two times. The outgassing rate can be calculated by the following equation:

$$L = \frac{V (P_2 - P_1)}{(T)(A)} \quad \text{Eq. 7.5}$$

where V is the total volume of the vacuum system, P_2 is the final pressure and P_1 is the beginning pressure, T is the time between the two pressure readings, and A is the surface area of the vacuum system. This experimental method for calculating the load will be used in the vacuum tests.

2) Measure the steady state pressure. This is done while the pumps are operating and in the situation in which the outgassing rate is determined.

3) Calculate the outgassing rate. The outgassing rate is then calculated by equation 5.11 as shown below:

$$L_{\text{exp}} = \frac{(P_{\text{Measured}}) * (P_{\text{eff}})}{A_{\text{Total}}}$$

Note, that equation 7.5 cannot be used to calculate the outgassing rate during RF operation because it requires the vacuum pumps to be isolated from the system. The experimental method for calculating the load is: First, the load is experimentally collocated by isolating the pumps and doing a rate of rise test. From the results, the effective pumping capacity is calculated. Next, the steady state pressure can be measured and the load at that pressure can be calculated without disturbing the vacuum system. This method can be used under RF power.

CHAPTER 8

EXPERIMENTAL RESULTS

8.1 Low Power Electrical Results

The purpose of the low power electrical tests is to verify that the windows meet the specifications listed in Table 8A. The first part of the electrical results demonstrates that a full two port calibration was done and the calculated calibration coefficients are satisfactory. The next step illustrates that the electrical requirements specified are met. The third step rechecks the calibrations after the electrical tests are complete to verify the calibrations are still good.

The network analyzer was calibrated with a full 2 port waveguide calibration to ensure that the losses and the phase delay through the cables and the type N to waveguide transitions do not affect the measurements. Once the 2 port calibration is completed, port 1 is connected to port 2 and the transmission and reflection are measured. This measurement is done to verify the quality of the calibration. Table 8A contains the attributes of an acceptable calibration, the physical meaning of the measured parameter, and the measured result. If the calibrations are done properly, the S11 and S22 curve will be very low, which means that very little power is being reflected. The S21 and S12 curves should ideally be very close to zero which means that nearly all the power is being transmitted. Figure 8A illustrates the transmission (S21 curve) after the calibration. This curve should ideally be 0 dB (no loss). Figure 8B illustrates the reflection (S22 curve) after the calibration. The S12 and S11 are not shown because they are very similar to the S21 and S22, respectively. Thus Figures 8A and 8B and Table 8A show that the calibrations are indeed sufficient and show that the cables and transitions do not affect the electrical measurements.

The results of the electrical tests, shown in Figures 8C through 8E and Table 8B,

Curve:	Desired Result:	Meaning of Result:	Actual Results: (at 350 MHz)
S11 and S22	very low values (< -50 dB)	Small amount of reflected power	S11 = -65.4 dB S22 = -63.4 dB
S21 and S12	very high values (close to 0.0 dB)	High amount of transmitted power	S21 = -0.0021 dB S12 = -0.0031 dB

Table 8A. Summary of the 2 port Calibrations

demonstrate the windows meet all the electrical specifications. The shape of the S12 and S21 curves in Figures 8C and 8D, respectively, show very low loss as desired at the center frequency. These curves also have positive values on the left side, decreasing toward the right side. Because these are the transmission curves, they would normally peak around the center frequency. The S12 and S21 curves have this particular shape because of a phase difference. In the S12 and S21 calibrations, the waveguide transitions were put back to back in order to calibrate a through. After the calibrations, when the windows were tested. During the tests an extra physical length was added to the system; the physical length of the window. This additional length causes a phase shift. The signal due to this phase difference is added on the low side of the center frequency and it

Requirement	Results		Req. Meet
Minimum of the S11 and S22 curves should be close to 350 MHz	S11 Curve: Min = 350.75 MHz	S22 Curve: Min = 349.75 MHz	Yes
S12 and S21 Curve: < -0.043 dB between 347 MHz and 353 MHz	S12 Curve: 347 MHz = -0.0209 dB 350 MHz = -0.0251 dB 353 MHz = -0.0245 dB	S21 Curve: 347 MHz = -0.0147 dB 350 MHz = -0.0325 dB 353 MHz = -0.0303 dB	Yes
S11 and S22 Curves should be below -20 dB between 347 MHz and 353 MHz	S11 Curve: 347 MHz = -26.783 dB 350 MHz = -30.959 dB 353 MHz = -29.183 dB	S22 Curve: 347 MHz = -29.758 dB 350 MHz = -53.057 dB 353 MHz = -30.207 dB	Yes

Table 8B. Low Power Electrical Requirements and Results

subtracted on the high side, as illustrated in Figures 8C and 8D. However, this phase difference does not create a problem, because in the region of concern(347 - 353 MHz) the phase difference is relatively small and does not affect the measurements significantly. The calibrations were rechecked after the electrical results were measured, and were still within the specified requirements.

Figure 8A. S21 Curve after the Calibrations

Figure 8B. S22 Curve after the Calibrations

Figure 8C. S21 Curve of a RF window

Figure 8D. S12 Curve of a RF window

Figure 8E. S₁₁ Curve of a RF window Figure 8F. S₂₂ Curve of a RF window

8.2 Conditioning Data

The windows are divided into "batches". A batch consists of the windows that were tested at one time on the test stand as illustrated in Table 8C. The results of each batch are presented and then the results of all the batches are compared.

Test Batch Number	Windows in Batch	EEV Vacuum Serial Number	Dates Tested
1	P1 -prototype P2 - Prototype	01 02	Dec 09-11, 1996
2	W1 W2	n/a n/a	Dec 10-12, 1997
3	RFQ1 RFQ 2 RFQ 3 RFQ 4	11 13 07 12	Jan 28- Feb 6, 1998
4	RFQ 5 RFQ 6 RFQ 7 RFQ 8	15 19 14 18	Feb 13-18, 1998
5	RFQ 9 RFQ 10 RFQ 11 RFQ 12	04 05 10 09	Feb26 -Mar5,1998

Table 8C. Summary of the Windows included in each Test Batch.

8.2a Batch 1 Data

Batch 1 consists of the first two windows tested, prototypes P1 and P2. They were tested at Argonne National Laboratory (ANL) in December 1996. The processing history and test results for the prototype windows are summarized in Table 8D. The ceramics on both windows were coated with copper black. During the bakeout, the coatings discolored and were redistributed over the surrounding metal surfaces. The coatings were removed by grit blasting the windows with an alumina grit at 90 psi. Both of these windows were conditioned up to 1 MW in about 26 hours with no excess heating or arcing. The windows were conditioned CW. They were run at 1 MW for 4 hours. Figure 8G shows the RF

power vs. time for the prototypes. After the prototypes were tested, 15 windows were ordered for the RFQ.

Window Number	Batch Number	Processing History	RF Testing Results	Pass / Fail
P1	1	• Ceramic coated with copper black • Copper black removed by grit blasting	• Conditioned to 1 MW in 26 hours • Operated at 1 MW for 4 Hr.	Pass
P2	1	• Ceramic coated with copper black • Copper black removed by grit blasting	• Conditioned to 1 MW in 26 hours • Operated at 1 MW for 4 Hr.	Pass

Table 8D Processing History and Test Results of Batch 1

Figure 8G. Results of the prototypes tested at ANL (Batch 1)

8.2b Batch 2 Data

Batch 2 consists of the first two windows (W1 and W2) received at LANL for the RFQ. The processing history and RF testing results for these windows are summarized in Table 8E. These windows were not grit blasted. After 11 hours these windows reached a power level of 527 kW. However, there was also significant arcing and heating. At 527 kW, after about 14 hours of conditioning, window W2 broke. W1 and W2 did not behave like the prototypes. These windows did not “remember” previous conditioning, had a much higher arc rate, developed very high temperatures, and the pressure was very low (good vacuum) during the later part of conditioning.

Window Number	Batch Number	Processing History	RF Testing Results	Pass / Fail
W1	2	Not grit blasted	- Conditioned to 527 kW in 11 hr. - Excess heating and arcing occurred	Fail
W2	2	Not grit blasted	- Conditioned up to 527 kW in 11 hr. - Excess heating and arcing occurred - Ceramic broke	Fail

Table 8E. Processing History and Test Results of Batch 2

The windows were not affected by previous conditioning. For example, the windows were conditioned to 300 kW, and then the power was lowered to 100 kW. When the power level was increased to 300 kW again, there was no indication they had been previously conditioned to 300 kW. These windows did not seem to remember any previous conditioning.

Excess heating was also a problem in windows W1 and W2. The temperature profile vs. test time is shown in Figure 8H. The top graph in the figure was from data taken using the Labview program on the window test stand. The acquisition rate was 1 data

point about every half second. The second graph is plotted from data acquired from the Labview program at the RGA and has a data acquisition rate of approximately 1 data point every second. Notice the difference in maximum temperatures between the two graphs due to the different sampling rate. The testing for batch 2 occurred over three days.

Unfortunately, on the second day the data files were corrupted. Therefore, on all the graphs, the gap in the middle of the graph represents missing data from the second day. The data before the empty space is the first day and the data after the empty space is the third day. Notice that early in the tests, after about 1.5 hours, the temperatures of the two windows became distinctly different. This point is marked on the graph. This behavior is indicative of multipacting and has been determined to be a predictor of an impending window failure. The temperature of window W2 is clearly nonlinear with the RF power and is much greater than the temperature of window W1.

The arc rate was much higher and the pressure was lower than for the prototypes. When an arc is detected, the interlock turns off the RF power for 1.6 seconds. These two windows were arcing so much that the RF power was always off due to the interlock. Pulse conditioning was attempted. Another anomaly is that the vacuum pressure was very low. Typically when conditioning, the standard procedure is to increase the RF power and then wait for the vacuum pressure to decrease, then increase the RF power again. However in this case, the vacuum pressure was very low and it stayed very low. This behavior is illustrated in Figures 8I, RF Power vs. Time, and Figure 8J, Pressure vs. Time. On the first day, the power was steadily increased with time. The vacuum pressure was the factor limiting the rate of increasing the RF power. This is typical behavior for conditioning. However, on the third day, the windows were behaving completely different. The vacuum pressure is very low and the power level could not be increased because of the high arc rate. The pulsed conditioning on the third day can be seen on Figure 8I. The power meters read average power, thus when pulsed conditioning was done the average power level is decreased. The window W2 broke after a little over 14 hours test time. On two graphs,

one can see a significant increase in temperature for both windows when the window broke and one can also see the vacuum pressure increase suddenly to atmospheric pressure. The arc rate (not pressure) was limiting the RF power.

There is a possibility that some of the arcs detected were not high energy arcs but instead a low energy glow discharge. The high energy arcs are capable of causing damage to the window. A low energy glow discharge is more of a processing nuisance than a potential source of damage. Unfortunately there is no method of distinguishing which phenomena is occurring. If the arcs are real, significant damage to the window may occur. To avoid damaging the window all arc detector indications were treated as high energy arcs.

Figure 8H. Window Temperature vs. Time for Batch 2

Figure 8I. RF Power vs. Time for Batch 2

Figure 8J. Pressure vs. Time for Batch 2

8.2c Batch 3 Data

Batch 3 consists of windows RFQ1, RFQ2, RFQ3 and RFQ4. The processing history and RF testing results are summarized in Table 8F. Before any testing was done, all the windows were grit blasted with 220 alumina grit at 80 psi. Next, the windows were run for 11 hours. Window RFQ1 was heating excessively as illustrated in Figure 8K, so

Window Number	Batch Number	Processing History	RF Testing Results	Pass / Fail
RFQ1	3	Grit blasted @ LANL	- Conditioned to 363 kW in 11 hr. - Excessive heating	Pass
		- Grit blasted @ LANL again - metal near the ceramic coated with WD40	- Conditioned to 1 MW in an additional 6 hr. - Ran at 1 MW for 1 hr	
RFQ2	3	Grit blasted @ LANL	- Conditioned to 500 kW in 33 hr. - Excessive heating	Pass
		- metal near the ceramic coated with DGF123 - Grit blasted @ LANL again	- Conditioned to 1 MW in an additional 6 hr. - Ran at 1 MW for 1 hr	
RFQ3	3	grit blasted @ LANL	- Conditioned to 1 Mw in 17 hr. - Ran at 1 MW for 1 hr	Pass
RFQ4	3	grit blasted @ LANL	- Conditioned to 1 Mw in 17 hr. - Ran at 1 MW for 1 hr	Pass

Table 8F. Processing History and Test Results of Batch 3

conditioning was switched to the pulsed conditioning. An advantage of pulsed processing is that the average power is lower and the windows can be conditioned to higher peak power levels without significant heating. The thermal load is dependent on the average power and the conditioning is dependent on the peak power. Pulsed conditioning allows for a lower thermally driven outgassing rate while still achieving conditioning. The pulsed

Figure 8K. Coaxial Surface Temperature vs. Test Time for Batch 3 (RFQ1, RFQ2, RFQ3, RFQ4)

Figure 8L. RF Power vs. Test Time for Batch 3 (RFQ1, RFQ2, RFQ3, RFQ4)

conditioning data can be seen on Figure 8L, RF Power vs. Test Time, at around 14 hours of testing where the average power level is much lower. Pulsed conditioning did not work, as the temperatures on window RFQ1 were still excessively high, as illustrated in Figure 8K, and RFQ1 was considerably hotter than the other 3 windows. After about 11 hours a maximum power level of 363 kW was reached, conditioning was stopped and window RFQ1 was replaced with prototype window P1. The remaining windows (RFQ2, RFQ3, and RFQ4) and the prototype (P1) were then tested for an additional 22 hours and reached a maximum power level of 500 kW. Window RFQ2 was heating excessively (see Figure 8M). To suppress heating, pulsed conditioning was implemented. In order not to risk breaking window RFQ2, this window and the prototype window were removed from the test stand by replacing them with a waveguide bypass. After eliminating windows RFQ1, RFQ2 and the prototype, windows RFQ3 and RFQ4 were successfully tested to 1 MW.

Some experiments were performed on RFQ1 and RFQ2. Multipacting was thought to be occurring on the metal surfaces near the ceramic. A coating with a low secondary electron emission(SEE) was desired that could be easily applied. Carbon has a very low SEE so DGF123 and WD40 were considered. DGF123 is a colloidal solution of graphite suspended in freon. After it is applied, the freon evaporates and a coating of carbon remains. This carbon coating is conductive. WD40 is an oil which is hydrocarbons and can easily be applied. The WD40 is not conductive. Hence, the metal surfaces near the ceramic were coated with DGF123 or WD40 to suppress multipacting.

The metal surfaces near the ceramic on window RFQ2 were coated with DGF123. In the process of coating the metal, DGF123 was accidentally applied to parts of the ceramic. Window RFQ2 was grit blasted to remove the DGF123 from the ceramic. Window RFQ1 was also grit blasted. While grit blasting RFQ2, the goal was to clean the ceramic; however, in the process of grit blasting the ceramic, most of the DGF123 was removed. After grit blasting window RFQ1, WD40 was applied to the metal surfaces near the ceramic. The WD40 was diluted with ethanol. Then windows RFQ1 and RFQ2 were

put back on the test stand and all four windows were retested. The windows conditioned up to 1 MW in under 7 hours and no excessive heating or arcing was observed. Figures 8O and 8P show the temperatures and power levels of these tests. In the power graph, all the sudden decreases in RF power caused by interlock trips unrelated to the windows. The results show that windows RFQ1 and RFQ2 conditioned very quickly up to 1 MW. It was not clear if the coating or grit blasting had caused the success of the windows. Because windows RFQ3 and RFQ4 had previously been conditioned to 1 MW, they would be expected to condition up quickly the second time.

Figure 8M. Temperature vs. Test Time for Batch 3 (P1, RFQ2, RFQ3, RFQ4)

Figure 8N. RF Power vs. Test Time for Batch 3 (P1, RFQ2, RFQ3, RFQ4)

Coaxial Surface Temperature vs. Test Time

Figure 8O. Temperature vs. Test Time -Batch 3 (RFQ1, RFQ2, RFQ3, RFQ4)

RF Power vs. Test Time

Figure 8P. RF Power vs. Test Time -Batch 3 (RFQ1, RFQ2, RFQ3, RFQ4)

8.2d Batch 4 Data

The next batch of windows tested consisted of windows RFQ5, RFQ6, RFQ7, and RFQ8. The processing history and RF testing results are summarized in Table 8G. These windows were bead blasted but were not coated. All four conditioned up to 1 MW in about 15 hours and then were operated at 1 MW for about 3 hours. No excessive heating or arcing was seen. Figure 8Q illustrates the temperatures and Figure 8R shows the RF power level.

Window Number	Batch Number	Processing History	RF Testing Results	Pass / Fail
RFQ5	4	grit blasted @ LANL	- Conditioned to 1 MW in 13 hr. - Ran at 1 MW for 3 hr.	Pass
RFQ6	4	grit blasted @LANL	- Conditioned to 1 MW in 13 hr. - Ran at 1 MW for 3 hr.	Pass
RFQ7	4	grit blasted @LANL	- Conditioned to 1 MW in 13 hr. - Ran at 1 MW for 3 hr.	Pass
RFQ8	4	grit blasted @LANL	- Conditioned to 1 MW in 13 hr. - Ran at 1 MW for 3 hr.	Pass

Table 8G. Processing History and RF Testing Results of Batch 4

Coaxial Surface Temperature vs. Test Time

Figure 8Q. Temperature vs. Test Time for Batch 4

RF Power vs. Test Time

Figure 8R. RF Power vs. Test Time for Batch 4

8.2e Batch 5 Data

The windows in batch 5 include RFQ9, RFQ10, RFQ11 and RFQ12. The processing history and RF testing results are summarized in Table 8H. The metal surfaces near the ceramic were coated with WD40. When the windows were tested, excess heating and arcing was seen in windows RFQ9 and RFQ10. All four windows were conditioned to 600 kW in 12 hours. Due to excess heating in RFQ9 and RFQ10, the testing was stopped and RFQ9 and RFQ10 were grit blasted again. All four windows were conditioned to 1 MW in an additional 8 hours, and all passed the acceptance tests. It was concluded that the coatings were not as effective as grit blasting.

Window Number	Batch Number	Processing History	RF Testing Results	Pass / Fail
RFQ9	5	- grit blasted @ EEV - coated with WD40	- Conditioned to 600 kW in 12 hrs - Excess heating and arcing	Pass
		grit blasted again @ LANL	- Conditioned to 1 MW in an additional 8 hours - ran at 1 MW for 2 hours	
RFQ10	5	- grit blasted @ EEV - coated with WD40	- Conditioned to 600 kW in 12 hrs - Excess arcing	Pass
		grit blasted again @ LANL	- Conditioned to 1 MW in an additional 8 hours - ran at 1 MW for 2 hours	
RFQ11	5	- grit blasted @ EEV - coated with WD40	- Conditioned to 600 kW in 22 hrs - Well behaved	Pass
RFQ12	5	- grit blasted @ EEV - coated with WD40	- Conditioned to 600 kW in 22 hrs - Well behaved	Pass

Table 8H. Processing History and RF Testing Results of Batch 5

During the initial conditioning, these windows behaved as expected until approximately 475 kW was reached and window RFQ10 started arcing. The power was reduced to 358 kW to stop the arcing. The decrease in power can be seen on the plot of RF power vs. Test Time, Figure 8T, shortly after 5 hours of testing. At the time of the arcing, the vacuum pressure fluctuated rapidly (see Figure 8U). 475 kW was the highest power level attained. After that, whenever the power was increased to approximately 420 kW either, window RFQ9 or RFQ10 would start arcing continuously. The temperatures and vacuum of all four windows behaved as expected. In fact, the vacuum pressure was very good on windows RFQ9 and RFQ10 as seen on Figure 8U. This low vacuum pressure was surprising, as usually the main obstacle in conditioning is the vacuum pressure. Any attempts to go above 420 kW proved unsuccessful.

Because the temperature and pressure was so low, the arc detectors on windows RFQ9 and RFQ10 were removed. The arc detectors were removed because it was thought that glow discharge might be occurring rather than arcing. Amplitude modulation was tried as a conditioning method to pass through this arcing band. Amplitude modulation (AM) means varying the amplitude of the signal. Consider the case of AM of 10% at a frequency of 400 Hz at a power level of 100 kW. This means the amplitude of the signal is 100 kW and the signal would be modulated by plus or minus 10% at a frequency of 400 Hz. Thus the amplitude of the signal would vary from 110 kW to 90 kW. Bands of multipacting exist that can only be conditioned by RF processing at specific power levels. With amplitude modulation, these bands of multipacting can be easily conditioned because of the large range power levels conditioned. Amplitude modulation is illustrated in Figure 8X. The idea of AM conditioning is that the windows would be run repetitively at the power level causing the arcing hoping to clean up the problem. Amplitude modulation can also be observed in the frequency domain. In a plot of power vs. frequency, two sidebands occur. The distance they are from the primary frequency is the modulation frequency. This was observed and documented in Figure 8N.

Figure 8S. Temperature vs. Time for Batch 5

Figure 8T. RF Power vs. Time for Batch 5

Figure 8U. Vacuum Pressure vs. Time for Batch 5

The results of this AM conditioning were not successful. After the AM modulation was turned off, the maximum power level attained was 600 kW. To achieve this power level, the arc detectors were once again removed from windows RFQ9 and RFQ10. The pressure and the temperatures for these two windows keep increasing steadily. Once the temperature of RFQ10 reached 85 degrees C, the conditioning was stopped.

Examination of the windows before grit blasting revealed there were many black spots on the ceramic which were assumed to be due to the WD40. On one window there was a large discoloration due to arcing on the metal surface underneath the T-Bar on the end wall. Windows RFQ9 and RFQ10 were grit blasted again, which removed all the discolorations, and the carbon coating was determined to be ineffective and stopped on all further windows.

Figure 8V. Illustration of Amplitude Modulation

Figure 8W. Power vs. Frequency Plot Showing Sidebands

The testing was resumed. Windows RFQ9 and RFQ10 were very gassy, as seen in Figure 8X and 8Y. It took 4 hours to get to 50 kW due to the high pressures. At that point, amplitude modulation was tried again. The procedure was to gradually increase the percent modulation to about 20%. The rate at which the percentage is increased is dependent on the pressure. Once a amplitude modulation of 20% was reached, the percentage was lowered to 8% and the power was increased. It was usually increased 20 kW to 50 kW depending on the pressure. Then the process was repeated. The results of amplitude modulation were amazing. The windows conditioned up to 1 MW in 4 additional hours, the same amount of time it had taken to reach 50 kW. In addition, both the vacuum pressure and temperatures were very low as seen in Figures 8Y and 8Z. After amplitude modulation the temperatures of all four windows are very close to each other. The discrete power levels at which the modulation was varied can be seen in Figure 8X between 5 and 8 hours. Also the lower pressure can be seen by comparing the first four hours to the second four hours of testing. The temperatures were also very low during the conditioning using amplitude

modulation, as seen in Figure 8Z. Amplitude modulation is the recommended method of conditioning because of its successes. In section 12.1e, amplitude modulation is discussed in detail, and the reasons why it works so well are also discussed.

Figure 8X. RF Power vs. Test Time after grit blasting RFQ9 and RFQ10

Figure 8Y. Pressure vs. Test Time after Grit blasting RFQ9 and RFQ10.

Figure 8Z. Coaxial Surface Temperature vs. Test Time after Grit blasting RFQ9 and RFQ10.

8.2f Comparison of all Batch Data

The time to condition the windows to 1 MW is shown in Figure 8AA, and the maximum temperatures at 1 MW are shown in Figure 8AB. See Table 8J for a comparison of the conditioning for the various windows. The average conditioning time is approximately 19 hours and the average temperature at 1 MW is approximately 75 degrees C (as seen in Table 8K). These two averages do not include W1 and W2 because these windows failed. From this data it is difficult to determine which factors enable a window to run at a lower steady state temperature and condition in minimal time. Factors that are believed to affect these two variables include the processing technique and grit blasting.

The effect of grit blasting is believed to be very important in order to help the windows condition at a rapid rate. This can be seen by comparing the grit blasted windows (all the windows except W1 and W2) to the non grit blasted windows (W1 and W2). The non grit blasted windows experience excess heating and arcing and the maximum power reached was only half a megawatt. All the grit blasted windows achieved the expected power level of 1 MW and conditioned in a timely manner. Windows that were originally grit blasted at EEV occasionally had to be grit blasted again at LANL. The difference in the grit blasting is assumed to be due to differences in nozzle size and geometry. At LANL a small nozzle with a 90° bend was used allowing easy access to the corners and back sides. EEV has now adapted the same nozzle as at LANL.

A low pressure was found to be essential during processing. At higher pressures, arcs and heating are more likely to occur. Starting in batch four, the vacuum interlocks were set at 1×10^{-5} Torr for power levels less than 100 kW, 5×10^{-6} Torr for power levels between 100 kW and 500 kW, and 2×10^{-6} Torr for power levels above 500 kW.

During conditioning it is very important to monitor the rate of temperature increase. As more windows were conditioned, nonlinear temperature increases became easier to detect, as the typical values are more obvious. If a large temperature increase was detected, the power level was immediately reduced until the temperatures became more typical. If

Figure 8AA. Comparison of Window Conditioning Times to 1 MW

Figure 8AB. Comparison of Window Temperature at 1 MW

Win- dow #	Initial Test Results				Corrective	Test Results		Max	Pass
	Processing Summary	Max Power	Test Time	Problem Descr.	Corr. Proc. Summary	Max Power	Test Time	Tem	/Fail
P1	Copper black / grit blasted	1 MW	26 hr	-----	-----	-----	----- --	94	Pass
P2	Copper black / grit blasted	1 MW	26 hr	-----	-----	-----	----- --	85	Pass
W1	Nothing	527 kW	11 hr	heating / arcing	-----	-----	----- --	95	Fail
W2	Nothing	527 kW	11 hr	heating / arcing	-----	-----	----- --	145	Fail
RFQ 1	Grit blasted	363 kW	11 hr	heating	Grit blasted / WD40	1 MW	6 hr	65	Pass
RFQ 2	Grit blasted	500 kW	33 hr	heating	DGF123 / grit blasted	1 MW	6 hr	75.0	Pass
RFQ 3	Grit blasted	1 MW	17 hr	-----	-----	-----	----- --	64.0	Pass
RFQ 4	Grit blasted	1 MW	17 hr	-----	-----	-----	----- --	64.0	Pass
RFQ 5	Grit blasted	1 MW	13 hr	-----	-----	-----	----- --	74.3	Pass
RFQ 6	Grit blasted	1 MW	13 hr	-----	-----	-----	----- --	86.0	Pass
RFQ 7	Grit blasted	1 MW	13 hr	-----	-----	-----	----- --	81.6	Pass
RFQ 8	Grit blasted	1 MW	13 hr	-----	-----	-----	----- --	84.0	Pass
RFQ 9	Grit blasted /WD40	600 kW	12 hr	heating / arcing	Grit blasted	1 MW	8 hr	73.9	Pass
RFQ 10	Grit blasted /WD40	600 kW	12 hr	heating / arcing	Grit blasted	1 MW	8 hr	67.2	Pass
RFQ 11	Grit blasted /WD40	600 kW	12 hr	none	-----	1 MW	8 hr	63.6	Pass
RFQ 12	Grit blasted /WD40	600 kW	12 hr	none	-----	1 MW	8 hr	67.0	Pass

Table 8I. Comparison of Conditioning Data for the Windows

	Average
Test Time to 1 MW	18.5 hours
Temperature at 1 MW	74.5 Deg. C (not including W1 and W2)

Table 8J. Average Test Time and Temperatures at 1 MW

the nonlinear temperature increase persisted the windows had to be grit blasted. The temperature increase is an indication of the occurrence of a non linear heating mechanism. The non linear heating mechanisms are thought to be ion bombardment and multipacting. Thus, during conditioning it is important to avoid nonlinear heating.

Amplitude modulation is the preferred method of conditioning. The advantages of amplitude modulation are that a wider range of power levels are thoroughly conditioned. As the power level is increased, the windows are not at high power level for a long time, thus the vacuum pumps have time to pump away the discharge and the pressure can be kept lower during conditioning. Without amplitude modulation, the power is increased in discrete steps. If the outgassing load from the increase in power is too much for the vacuum pumps, the pressure increases. A wide range of power levels can be conditioned with amplitude modulation because of the rapid variation in power. For example to thoroughly condition the windows from 0 to 1 MW one can run at 500 kW with a 100% amplitude modulation. Hence amplitude modulation conditions a wide range of power levels, not just discrete steps, while keeping the pressure low.

Based on the results using DGF123 and WD40, these coatings are not recommended. The test results do not show repeated successes with these coatings. The windows RFQ9 and RFQ10 had been coated with WD40 and demonstrated excessive arcing during conditioning. In addition discoloration were found on the windows that had been coated with DGF123 and WD40. This discolorations are believed to be from the

coatings which were removed during conditioning. However, based on unfavorable results of WD40 on RFQ9 and RFQ10, these coatings were not used again.

8.3 High Power Test Data

8.3a Steady State Data at 1 MW

This section outlines the steady state results at 1 MW. The coaxial surface temperatures are shown in Figure 8AC. Windows RFQ6 through RFQ8 stabilized at approximately to 81 to 83 degrees C. Window RFQ5 stabilized at about 75 degrees C. It is not known why window RFQ5 is so much cooler than the other windows. It could be that some nonlinear surface heating is occurring in all the windows except RFQ5 which is just dielectric heating. Or it could be that something went wrong with the cables on RFQ5. However, this is unlikely since there are four RTD's on the same window which all correspond to about the same temperatures. The steady state power level during the time these temperatures were measured is shown in Figure 8AD. Note that for the duration of the steady state measurements, the power level is very constant. Also note that there is a significant drop in the steady state temperatures about 2 hours into the steady state tests (starting at about 16 hours and 40 minutes). This is thought to be because the garage door to the outside was opened and then shut briefly. Since the outside temperature is significantly cooler than the inside temperature this explains the drop in temperature.

Another interesting plot is to examine the temperatures in each window in more detail. Refer to Figure 4E for the number to the RTDs on each window. Figures 8AE through 8AJ show the four RTDs on windows RFQ5 through RFQ8, respectively. Table 8L summarizes the maximum, temperatures, minimum temperatures, and delta T seen on each window. Note that this delta T is probably not the largest delta T on the window. It is just the delta T seen around the outer edge. The largest delta T will probably occur from the inner conductor to the outer conductor; however, no temperature data was taken at the inner conductor.

Window	Max Temp (at 17 hrs. 43 min)	Min Temp (at 17 hrs. 43 min)	Delta T (at 17 hrs. 43 min)
RFQ5	74.3	63.3	11
RFQ6	86.0	72.0	14
RFQ7	81.6	52.7	28.9
RFQ8	84.0	71.2	12.8
Average	81.5	64.8	16.7

Table 8L. Comparison of Coaxial Surface Temperatures.

Figure 8AC. Steady State Temperatures at 1 MW (from Batch 4)

Figure 8AD. RF Power during High Power Acceptance Tests (Batch 4)

Temperature for RFQ5 vs. Test Time

Figure 8AE. Surface coaxial temperatures on window RFQ5

Temperature for RFQ6 vs. Test Time

Figure 8AF. Surface coaxial temperatures on window RFQ6

Temperature for RFQ7 vs. Test Time

Figure 8AG. Surface Coaxial Temperatures on Window RFQ7

Temperature for RFQ8 vs. Test Time

Figure 8AH. Surface Coaxial Temperatures on Window RFQ8

8.3b Residual Gas Analyzer Data

A Residual Gas Analyzer (RGA) is used to obtain information regarding the species of gasses in the vacuum chamber and to determine the effect RP power has on the gas species. Information about the gas species is used to learn about conditioning. This information will be studied before and during RF conditioning to determine what gas species is emitted during conditioning.

A typical example of the RGA data is illustrated in Figures 8AI and 8AJ. In the figures, the RGA data is plotted as Intensity vs. Test Time. The intensity is recorded on the RGA as a current (Amps). The relative intensity of the various constituents is of importance rather than the absolute value. The primary constituent found in the vacuum was water. The second most prominent species was AMU 28 (either nitrogen or carbon monoxide) and the third was hydrogen. The water was the most prevalent species by almost an order of magnitude.

With RF power on, the intensity of AMU 28 and hydrogen increased while the intensity of the water vapor stayed fairly constant, as seen in Figure AI. It is not understood why the water level stayed so constant. The water vapor was expected to decrease with time, but this did not occur. Possible reasons could include the RGA sensor has water in it or there is a constant source of water somewhere in the vacuum chamber. The RGA sensor was baked out with no effect on the results. During conditioning, spikes of hydrogen and AMU 28 occurred, as seen in Figure AL. The hydrogen level and the AMU 28 level seemed to always track each other. Thus hydrogen and nitrogen and/or carbon monoxide are emitted during conditioning.

Figure 8AI. Example of RGA Data with RF Power, on the Left Side, compared to with out RF Power, on the Right Side

RGA Data during Conditioning

Figure 8AJ. Example of RGA Data during Conditioning

8.3c IR camera Data

The infrared camera was used on the prototypes to obtain a typical temperature distribution across the ceramic. This temperature distribution was correlated to the measured coaxial surface temperatures. This correlation was used to analyze subsequent windows. On the RFQ adding an IR port in addition to the arc detector port would provide additional protection.

Figure 8AK lists the temperatures of the ceramic measured by the IR camera while the window was running at a power level of 1 MW. Note that the IR viewport is at an angle to the ceramic window, thus circles appear as ellipses in the photo. In the picture, the alumina ceramic lies between the two distinct convex radii. In the picture the boundary at the outer radius between the ceramic and the metal is a metal lip, not the true ceramic to metal interface. This metal lip is illustrated in Figure 8AM. In the photo a series of dots appear in radial lines. These dots are temperature sensitive paint that EEV put on the ceramic as a diagnostic tool. In Figure 8AK a line (L1) has been superimposed on the ceramic IR picture; the temperatures over this line are plotted in Figure 8AL. The figure appears to show what looks like a hot spot at the bottom of the window. This local temperature increase is believed to be due to reflections from the long narrow metal IR viewport. The IR camera shows that the maximum temperature of the ceramic is approximately 75 degrees C. Table 8L. lists the coaxial temperatures at the time of the photo. This temperatures are correlated to the analytical model in Chapter 9. The IR camera data show that the temperature gradient is small over the window, thus this gradient is not likely to cause stresses large enough to cause a problem.

IR Temp.	Coaxial 1A	Coaxial 1B	Coaxial 1C	Coaxial 1D	Power
75 Deg C	80.2 Deg C	79.42 Deg C	85.43 Deg C	83.39 Deg C	1 MW

Table 8L. Temperatures of the Window P2 at 1 MW

Figure 8AK. IR camera data from window P2 at 1 MW power

Figure 8AL. Temperatures over the line, L1.

Figure 8AM. Illustration to Show the Field of View

CHAPTER 9

ANALYTICAL RESULTS

The goal of the analytical model is to predict the lifetime of the window. The information required to predict the window lifetime includes the electric fields in the waveguide and window, the temperature and stress profiles in the window and the material properties of alumina. HFSS is used to obtain the electromagnetic solution, then the ABAQUS input files are generated by a FORTRAN translator program. ABAQUS is used to calculate the thermal and structural results in the window. Next, the CARES neutral file is made using ABACARES. CARES is then used to predict the reliability of the window. Results of the electromagnetic model from HFSS and the thermal/structural results from ABAQUS and CARES are presented. All the input files are included in APPENDIX B through APPENDIX D.

9.1 Electrical Results

9.1a Electrical Boundary Conditions

The electrical boundary conditions and the HFSS model of the window assembly are shown Figure 9A. Power enters the structure at port 1 and exits at port 2. A symmetry plane is used to reduce the computing time and the memory necessary to solve the problem. This symmetry plane is defined as a perfect magnetic boundary, implying that the magnetic field is normal to the surface of the symmetry plane and that the electric field is tangential to the symmetry plane. The HFSS solution is normalized to an input power of 1 watt.

9.1b Electrical Results

An important part of the electromagnetic solution is to determine the modes that are propagating in the structure. The mode in the waveguide, excluding the coax and

window region, is the rectangular TE_{10} mode of propagation. The TE_{10} mode of propagation is the fundamental mode for a rectangular WR2300 waveguide transmitting at this frequency. The circular TEM mode exists throughout the coaxial structure and the window. In addition to the fundamental TEM mode, a higher order coaxial mode exists. The higher order mode is an eminent mode and there is not enough distance to attenuate the mode before the ceramic window. Hence, the mode at window is a combination of the TEM mode and a higher order mode. The magnitude of the electric field throughout the window assembly is shown in Figure 9B, with a close-up of the region near the window shown in Figure 9C. The areas of high electric field intensity vary with phase and position along the axis of the waveguide. The phase shown in Figure 9B and Figure 9C is 50 degrees. This phase the phase where the electric field is maximum in the alumina ceramic. Figure 9D shows the magnitude of the electric field on the air surface of the window, and Figure 9E shows the direction of the electric field on the ceramic window. The asymmetry of the electric field is due to the higher order mode.

The S Parameters characterize how much power is transmitted and reflected through the structure. Table 9A shows the S parameters at 350 MHz and Figure 9G illustrates the S parameters as a function of frequency. From the S parameters, a power

S11	S12	S22	S21
0.1105	0.9938	0.1107	0.9938

Table 9A. S Parameters from HFSS at 350 MHz

balance can be calculated to determine the amount of power absorbed by squaring the S parameters. Table 9B shows the results of the power balance. The results of this

Reflected (From HFSS) = S_{11}^2	Transmitted (From HFSS) = S_{21}^2	Absorbed (From HFSS) = $1 - (S_{11}^2 + S_{12}^2)$	Absorbed (From FORTRAN program)
1.22%	98.7%	0.0161% (161 W)	(55 W)

Table 9B. Power Balance

calculation imply that with 1 MW incident power in the waveguide, 151 Watts is absorbed. The last column in Table 9B lists the absorbed power calculated with a FORTRAN program, power.f, by summing the power absorbed in each element. See Appendix F for a copy of the program and the calculated output.

9.1c Effects of Mesh Density

One of the most difficult parts of the electrical simulation was obtaining an adequate mesh for the thermal, structural and reliability models from HFSS. This program performs an adaptive analysis when solving a problem. Hence, it refines the mesh in areas where the electric field gradient is large. The mesh refinement conserves the amount of hard disk space and CPU needed to solve problems, because the mesh is adjusted appropriately as needed, coarse in less critical areas and fine in more critical areas. However, for this problem it is essential that a good mesh is obtained in the ceramic window. The mesh must be fine enough to not impede the accuracy of the thermal, structural and reliability models. There is a delicate balance between the mesh density in the ceramic window and the ability of the computer to solve the problem without running out of disk space or CPU. To help overcome this, seed points can be used in HFSS to limit the size of each element in the mesh. Seed point must be applied carefully to not exceed the capacity of the computer. The final mesh used was the finest mesh in which the problem could be solved without the computer running out of computer memory. Figure 9F shows the final mesh after using a seed value of .7, which created 224 seed points in the window. This resulted in 4799 tetrahedral elements in the

window mesh and 19,150 elements in the whole structure. The final mesh used is adequate for the thermal, structural and reliability models; however, this mesh is also the limit of what the computer can solve. After four adaptive passes in HFSS, the absolute change in the S parameters was very small (less than .0082). This change leads to a 0.08% error, so the solution is sufficiently accurate. The computer could not solve a 5th adaptive pass or do a frequency sweep because of lack of memory. Thus, a model with a less dense mesh was used to obtain the frequency sweep results. This should not significantly affect the accuracy of the results because the less dense mesh was not used in any of the other models. Another struggle pertaining to the mesh was related to the number of segments used in HFSS to create the circles to draw the ceramic window. The HFSS default is 12 segments. However, if 12 segments were used, in the straight sections unrealistic stress concentrations formed. This problem is very similar to the mesh density problem in that the problem is a delicate balance between the accuracy and the computer's capability. The most segments that the computer was able to solve was 48. Therefore, 48 segments were used in the final model. The stress concentrations at the straight sections can be detected if the data is carefully studied. However, they are not large enough (< 2 MPa) to impact the reliability results. Therefore, the mesh density and the number of segments used to create the circular geometry in the window proved to be critical parameters in the electrical model, and care had to be taken to maximize both parameters to the limits of the computer's capacity in order to obtain reliable results in the thermal, structural and reliability models.

Figure 9A. Electromagnetic Model with the Boundary Conditions

Figure 9B. Magnitude of the Electric Field (volts/meter) in the Window Assembly with an Incident Power of 1 W

Figure 9C. Magnitude of the Electric Field (volts/meter) Near the Ceramic Window with an Incident Power of 1 W

Figure 9D. Magnitude of the Electric Field (volts/meter) on the Ceramic Window with an Incident Power of 1 W

Figure 9E. Direction of the Electric Field on the Ceramic Window

Figure 9F. Mesh on the Ceramic Window

Figure 9G. S_{11} as a Function of Frequency

Figure 9H. S_{21} as a Function of Frequency

9.2 Thermal and Structural Results

The objectives of the thermal and structural models are to predict the temperatures and stresses in the window caused by the dielectric heating from the electric fields. Thus, the heating and cooling mechanisms must be accurately represented to accurately predict the temperatures of the window in the thermal model, and the structural model must accurately represent the structural joints and attachments to accurately predict the stresses in the window.

The results of the thermal and structural model calculations are presented in a series of sections. First, the results of the thermal and structural modeling of the base case are presented. The base case represents a window passing 1 MW of power, thus the boundary conditions represents a window at a steady state condition of 1 MW of incident power. Next, the effects of variations in both the thermal and structural boundary conditions are presented. Then a detailed analysis of the base case is presented. The final part in the section summarizes the thermal and structural results.

9.2a Base Case Boundary Conditions

The thermal and structural boundary conditions for the base case are presented. The thermal boundary conditions include the method by which heat is entering the window, the heat generation, and the method by which the heat is leaving the window. The structural boundary conditions represent the loads resulting from the differential pressure acting on the window and the window supports.

The internal heat generation in the window is the power dissipated in each element. The power dissipated is calculated in the FORTRAN program `readef.f`. The amount of power dissipated is dependent on the magnitude of the electric field, the material dielectric losses and the operational frequency. The FORTRAN program (see Appendix A) described in Chapter 3 uses Equation 3.2 to calculate the power dissipated. The ABAQUS input file for the thermal model is listed in Appendix B.

The thermal boundary conditions(illustrated in Figure 9I) include the description of the mechanisms used to cool the window. The cooling mechanisms include conduction, convection and radiation. Radiation is included on both the air and the vacuum surfaces of a window. The radiation loss is based on the emissivity of the surfaces and the temperature differential between the surface and the environment. The emissivity of the alumina surface was measured as 0.92 by Moore⁴¹. The temperature difference is the difference between the ceramic temperature(calculated from ABAQUS) and the background temperature(set at 80°C from results of experimental testing). The heat lost to convection is greatly affected by the convection coefficient. The convection coefficient was determined to be 0.018 w/ m² °C by Rietter⁴³. He verified this value by comparing a transient model of the 350 MHz window to experimental data taken at Argonne National Laboratory⁴³. The conduction through the inner and outer walls was modeled as a contact resistance rather than a perfect conduction path. This contact resistance is modeled by determining an effective heat transfer coefficient resulting from an energy balance. The details of the ceramic to metal interface geometry are shown in Figure 9J. The energy balance assumes that the amount of energy leaving the ceramic through the surface between the molybdenum and the ceramic is equal to the amount of energy going through the three contact layers. Thus,

$$E_w = E_{cr} \quad \text{Eq. 9.1}$$

where E_w is the energy leaving the ceramic, and E_{cr} is the energy going through the contact layers. The energy leaving the ceramic is the product of the boundary area, the effective heat transfer coefficient, and the temperature difference as shown in Equation 9.2.

$$E_w = (\text{area of the outer boundary})(\text{film coef})(\text{deltaT}) \quad \text{Eq. 9.2}$$

CONDUCTION - outer surface
- inner surface

RADIATION - vacuum side surface
- air side surface

CONVECTION - air side surface

Figure 9I. Thermal Boundary Conditions

DETAIL A

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Figure 9J. Geometry of the Ceramic to Metal Interface

Substituting the equation for the area, the film coefficient, and the delta T into Equation 9.2 yields Equation 9.3.

$$E_w = (t_w 2\pi r_o)(h)(T_B - T_C) \quad \text{Eq. 9.3}$$

where t_w is the window thickness in meters, T_B is the ceramic temperature at the outer edge in degrees C, T_C is the temperature of the outer conductor in degrees C, r_o is the outer radius of the ceramic in meters, and h is the effective film coefficient, $\left[\frac{W}{m^2 \cdot ^\circ C} \right]$.

The energy going through the layers is modeled as a series of contact resistances as shown in Equation 9.4.

$$E_{cr} = \frac{(T_B - T_C)}{R_M + R_N + R_C} \quad \text{Eq. 9.4}$$

where R_M is the thermal resistance through the molybdenum layer, R_N is the thermal resistance through the nickel layer, and R_C is the thermal resistance through the silver copper eutectic layer. Substituting in the appropriate thermal resistances Equation 9.4 yields Equation 9.5:

$$E_{cr} = \frac{(T_B - T_C)2\pi t_w}{\frac{\ln(r_1/r_0)}{k_M} + \frac{\ln(r_2/r_1)}{k_N} + \frac{\ln(r_3/r_2)}{k_c}} \quad \text{Eq. 9.5}$$

where r_0, r_1, r_2, r_3 are the radiuses as shown in Figure 9J, and k_M, k_N, k_c , are the thermal conductivities of the molybdenum, nickel and silver copper layers. Next, the energy leaving the ceramic is set equal to the energy through the contact layers, as shown below:

$$(t_w 2\pi r_o)(h)(T_B - T_C) = \frac{(T_B - T_C)2\pi t_w}{\frac{\ln(r_1/r_o)}{k_M} + \frac{\ln(r_2/r_1)}{k_N} + \frac{\ln(r_3/r_2)}{k_c}} \quad \text{Eq. 9.6}$$

Equation 9.6 is solved for h. Rearranging the equation yields Equation 9.7:

$$h = \frac{1}{r_o \left(\frac{\ln(r_1/r_o)}{k_M} + \frac{\ln(r_2/r_1)}{k_N} + \frac{\ln(r_3/r_2)}{k_c} \right)} \quad \text{Eq. 9.7}$$

Substituting in the appropriate values for the radius and conductivities yields

$h = 23,404 \text{ W/m}^2 \cdot ^\circ\text{C}$. This value is used as a film coefficient to model the contact resistance between the ceramic and the metal.

Radiation was included in the model on both the air and vacuum surfaces. The critical parameter when modeling radiation is the emissivity. This emissivity was used in the model. However, since the alumina ceramic window is surrounded by copper surfaces it is enclosed in a metal box. This metal box can change the effective emissivity of the structure, especially at higher temperatures. The effective emissivity of a rexolite window in a metal waveguide was shown to be a little different than the measured emissivity⁴¹. In this case, the temperatures are not much above room temperature, so the measured emissivity of 0.92 was used in the model.

Two possible methods of modeling the physical support of the windows are “simply supported” and “fixed”, as illustrated in Figure 9K. In the “simply supported” model the window is free to move in the radial direction and is fixed in the axial direction. In the “fixed” model it is fixed in both the radial and the axial directions. The window was modeled as a “simply supported” beam, because it is brazed to a thin copper member. Details of this interface at both the inner and outer radial surfaces, are shown in

Figure 9K. Window Support Configurations

Figure 9J. This braze fixed the motion of the window in the axial direction.

Nevertheless, because this copper membrane is so thin, it is able to deflect in the radial direction. Hence, the membrane allows for freedom of movement in the radial direction. Because the window is fixed in the axial direction and free to move in the radial direction it is modeled as a “simply supported” condition. In order to implement this “simply supported” condition in the structural model, the window was fixed in the axial direction. As shown in Figure 9L, this is done by constraining a set of nodes in the axial (y) direction. At first, the nodes on the inner and outer radii at $y = 0$ were constrained in the y direction. However, high shear stresses were seen if all the nodes are not exactly on the same xz plane. Thus, to ensure that all the nodes constrained in the y direction are on the same xz plane, the nodes on the positive xz surface of the window were constrained in the y direction, as shown in Figure 9L. One consequence of the “simply supported” boundary condition is that the beam is free to move in the radial direction. In the model, one node had to be constrained in the x and z directions to prevent the whole window from moving in the xz plane. Deflections are acceptable in the xz plane; but, movement

of the whole window should be prevented. Another structural boundary condition must be included is the symmetry

Figure 9L. Structural Model Constraints

plane of $z=0$. Therefore, all the nodes on the symmetry plane are constrained in the z direction. In order to model the pressure differential between the air and vacuum sides of the window, atmospheric pressure (101352 Pa) is applied to the air side surface in the negative y direction.

In summary, the base case thermal and structural boundary conditions include the heating, cooling, the physical support of the window, and the pressure differential across the window. The internal heat generation in the window is due to the dielectric heating from the electric fields. The cooling mechanism includes radiation on both vacuum and air surfaces, thermal conduction through the inner and outer radius surfaces, and convection on the air surface. The window support is modeled as a simply supported beam which is constrained in the radial direction to prevent motion of the window in the

radial direction. The pressure differential was modeled by applying atmospheric pressure to the air side face of the window.

9.2b Base Case Thermal and Structural Results

Results of the thermal and structural calculations include the temperature profile and the stresses on the window. Important results are the maximum temperature gradient, the temperature profile, and the maximum stresses. The temperature and stresses affect the reliability, and therefore the lifetime, of the window.

The input parameters used in the base case are summarized in Table 9C. The material properties used in all analytical models are summarized in Table 9I.:

RF Inputs	Incident Power	1 MW
	VSWR	1.0
Convection Inputs	Air Temperature	321.2 K (48.2°C)
	Air Convection Coefficient	0.018 $\text{W}/\text{m}^2 \text{ } ^\circ\text{C}$
Conduction Inputs	Ceramic to Metal Contact Temperature	353 K (80°C)
	Ceramic to Metal Contact Resistance	.023404 $\text{W}/\text{m}^2 \text{ } ^\circ\text{C}$
Radiation Inputs	Emissivity	0.92
	Background Radiation Temp	298 K (25°C)

Table 9C. Base Case Parameters

The thermal profile of the base case, shown in Figures 9M and 9N, is similar to the profile of the magnitude of the electric field shown in Figure 9D. As one would expect, the highest temperatures in the window correspond to the areas of high electric field magnitudes. The inner and outer edges of the window are the coolest because these are the areas in which thermal conduction is included as a contact resistance. For the base case, the contact temperature at the ceramic to metal boundary is set to 353 K

(80°C); a number obtained from the experimental results. The inlet air temperature is set to 321.2 K (48.2°C), also obtained from the experimental results at 1 MW. In the model, the only difference between the air and the vacuum side is that the air side has convection across the surface. Hence, the vacuum surfaces temperatures are slightly higher than the air surfaces temperatures. The temperature difference between the air and the vacuum side of the window is not large enough to create significant thermal gradients through the thickness of the window. This is fortunate because thermal gradients through the thickness of the window are highly undesirable because they create additional stresses.

The maximum principal stresses in the window are shown in Figures 9O. These stresses are due to the temperature gradients across the window surface resulting from the dielectric heating as well as the pressure differential between the vacuum and air sides of the window. Though alumina can withstand very high compressive stresses, areas of high tension are of concern in such a brittle material as alumina. In the stress plots, the ABAQUS sign convention is negative for the compressive stresses and positive for tensile stresses. By examining the maximum principal stresses (SP3 stresses), one can see that there are hoop stresses in the window, with the highest areas of tension along the circumference. One can also see that the stresses near the center of the window are either very small or slightly negative (compressive). The thermal and structural results are summarized in Table 9D. These stresses are relatively low compared to the flexural strength of this alumina(296 MPa).

Temperature Difference (Deg)	Maximum Temperature (K)	Minimum Temperature (K)	Maximum Stress (MPa)
17	368	351	16.8

Table 9D. Thermal and Structural Results for the Base Case

Figure 9M. Thermal Profile on the Air Surface of the Window

Figure 9N. Thermal Profile on the Vacuum Surface of the Window

Figure 90. Maximum Principal Stresses in the Window

The stress pattern seen in the window is explained by a few examples. A flat plate that is constrained on all the edges can be used to explain the compression on the inner part of the disk. As the plate is heated the material will expand. As the plate tries to expand and cannot, compressive stresses in the material will be created. This situation occurs on the inner part of the disk, where the temperatures are highest and expansion is greatest. The outer part of the disk does not have a large temperature gradient or areas of high temperature. There is almost no temperature gradient around the circumference. In order to explain the high hoop stresses at the circumference, consider a wedge shaped piece, as shown in Figure 9P. The inner part of the wedge is trying to expand in the circumferential direction and cannot because of the material constraints. Therefore compressive stresses are seen on the inner part of the disk as described in our flat plate example. As these circumferential stresses are transferred to the outer part of the wedge, they will try to pull the wedge apart, as illustrated in Figure 9P. This creates tensile

Wedge of the Window

Figure 9P. Circumferential Stresses in the Window

stresses or hoop stresses in the circumferential direction. In the radial direction, the window is not rigidly constrained because it is brazed to a thin, flexible copper member. Because the window is free to expand in the radial direction, high stresses do not occur in that direction. This stress state commonly occurs in targets that have a similar heat loading and geometry⁴⁴.

9.2c Effects of Boundary Condition Variations

Variations of the input parameters used in the thermal and structural models can sometimes significantly affect the results of the calculation. Hence, it is important to characterize these variations. The variations studied in the thermal model include (a) the value of the film coefficient used to simulate the contact resistance between the ceramic and the metal and (b) the temperature at which the metal surfaces at the ceramic to metal interface were set (contact temperature). This section examines the effect of variations of these parameters on the base case.

The film coefficient used to model the contact resistance was calculated to be $0.023404 \text{ W/m}^2 \cdot ^\circ\text{C}$; this value is used in the base case. Table 9E shows the effects of the variation of this contact resistance. When the contact conduction is very low (a small film coefficient), large temperature differences result which cause severe stresses. However, it is important to realize that the temperature profile changed significantly from the base case to the low contact conduction temperature case. The regions of highest temperature moved closer to the edge of the alumina. This lower contact conduction case demonstrates that the contact conduction between the ceramic and the metal was not small, because the experimental temperature profile did not match the profile seen with the poor contact conduction. When the contact conduction became very large, it approaches an asymptote and does not affect the temperature profile or

Contact Conduction $W/m^2 \cdot ^\circ C$	Temperature Difference (Deg)	Maximum Temperature (K)	Minimum Temperature (K)	Maximum Stress (MPa)
0.000023404	43	393	350	27.0
(Base Case) 0.023404	17	368	351	16.8
23404.00	16	367	351	16.0

Table 9E. Effects of the Variation of the Contact Resistance

temperature difference very much. Because the contact conduction does not affect the temperature difference, the stresses are unaffected as well.

The next parameter that was varied was the temperature of the metal on the ceramic-to-metal interface. Table 9F shows the effect of the variations. As the contact temperature decreases, the temperature difference increases, so the stresses (which are proportional to the temperature gradient) also increase.

Contact Temperature (K)	Temperature Difference (Deg)	Maximum Temperature (K)	Minimum Temperature (K)	Maximum Stress (MPa)
340	19	359	340	23.6
(Base Case) 353	17	368	351	16.8
366	15	376	361	12.6

Table 9F. Effects of the Variation of the Contact Temperature

The contact temperature used in the base case model is 80 °C (353 K) , as measured at the outside surface of the copper outer conductor in the region of the window. These results demonstrate that at lower contact temperatures, the minimum temperature decreases with the contact temperature unless the contact conduction is very small as discussed previously. As the contact temperature increases the temperature difference decreases, lowering the stresses.

9.2d Detailed Analysis of the Base Case

This section analyzes the base case in more detail. Computer runs were performed to represent various operating conditions. By comparing the results of these runs, one can gain a better understanding of the results of the base case. In addition, the temperatures, temperature gradients and stresses were correlated to the incident power in the waveguide.

The results of the runs performed are summarized in Table 9G. The base case data is also shown in the table for an easy comparison to the base case. A description of the runs follows, as well as a discussion of the results and the implications of the results.

Case Number	Case description	Temperature Difference (Deg)	Maximum Temperature (K)	Minimum Temperature (K)	Maximum Stress (MPa)
Base Case	air, vacuum, and RF	17	368	351	16.8
BC1	air, vacuum, no RF	1	299	298	5.74
BC2	vacuum, no air, no RF	0	298	298	3.94
BC3	air, no RF, no vacuum	1	299	298	1.78

Table 9G. Effects of the Variation of the Operating Condition

The first run(BC1) represents the case without RF, but with vacuum and air cooling. The input file was modified by deleting the RF heating. The air temperature was set to 301.6 K (28.6°C) and the coaxial surface temperature was set to 298 K (25°C), values measured during experimental testing. The temperature difference of 1 degree is significantly less than the difference of 17 degrees in the base case, as seen in Figure 9R. This figure represents the temperature distribution of the BC3 case, because in both the BC1 and BC3 cases, all the heating is due to the air flow. This makes sense because some of heating in the base case comes from the dielectric heating. The temperature

difference seen in the BC3 and BC1 cases represents the heating due to the air flow. Due to the flow restrictions, the blower fans are working quite hard to force the air through the air cooling path. This causes the air to be heated as it is compressed and forced through the cooling path. The high air temperature causes the temperature rise in this case. By examining the BC1 stresses and comparing them to the base case, one can see that they are lower than the base case. The stresses are illustrated in Figure 9T. In the BC1 case, the stresses are caused by the temperature difference due to the air flow and the differential pressure between the air and vacuum sides of the window. The high stresses along the inside radius exist because nodes were constrained in the Y direction. The high tensile stress in the center is due to the vacuum and air pressure differential. The high stresses near the outer radius are due to the temperature difference from the air cooling.

The second case, BC2, represents the case without RF or air cooling, but with vacuum. In this case there is no heating because heating is entirely due to the air flow and the RF. All the stresses are caused by the pressure differential between the air and the vacuum side of the window, as illustrated in Figure 9U. Note that the window is in tension in the center and compression near the edges. This is the expected stress distribution resulting from the differential pressure. The high stresses along the edge on the inner surface are because the nodes along this edge were constrained in the Y direction. The contribution of the pressure differential can be easily seen in this case.

The third case, BC3, is without RF or vacuum, but with air cooling. In this case, the stresses are due to air heating only. This case (air heating stresses) and BC2 (pressure differential stresses only) add up to BC1 (air heating and pressure differential stresses). This case also shows the same temperature difference as BC1, where all the heating is due to air flow. The temperature profile is shown in Figure 9R and the stress distribution is shown in Figure 9S. The stresses are from the temperature gradient, thus there are hoop stresses at the edges.

The analytical results are highly dependent on the values of the contact temperature and the airflow temperatures. The temperatures used in the analytical model were obtained from the experimental results to ensure that the temperatures used in the analytical model are correct. Figure 9V illustrates the measured coaxial surface temperature vs. RF power. The contact temperature in the analytical model is the measured coaxial surface temperature. Figure 9W illustrates the measured air inlet and outlet temperatures vs. RF power. The air temperature in the analytical model was set to the measured air outlet temperature.

Effects of air cooling (blowing hot air over the surface of the window) at lower power levels are examined in more detail. The air inlet and outlet temperatures are plotted as a function of RF power in Figure 9W. The maximum stress is plotted as a function of RF power (with air cooling), as shown in Figure 9Q. As power is increased, the stresses increase linearly. Note that below a power level of approximately 400 kW the inlet temperature is hotter than the outlet temperature. This variation in temperature implies that until 400 kW is reached, heat is transferred from the air into the window. Above 400 kW, when the air outlet temperature is greater than the air inlet temperature, heat is being transferred from the window into the air. Hence, above 400 kW the air is cooling the window. This point is also illustrated by comparing Figure 9Q, the stress with no air cooling, to Figure 9X, the stress with air cooling, as shown in Figure 9Y. At low power levels the stress in the window is lower without air cooling than with air cooling. This is because at lower power levels, heat is flowing from the air into the window. Also note, how the maximum stress vs. RF power with air cooling has two distinct slopes, as shown in Figure 9X. The change in slope is due to the air cooling and the flow of heat into the window at lower power levels.

The temperatures, temperature differences and maximum stresses were correlated to the incident power in the waveguide. Table 9H lists the temperature inputs and the

maximum temperature and stress results as the RF power was varied. Figure 9V

illustrates the stress in the window as a function of incident power. The stress at 1 MW is

Figure 9Q. Maximum Stress vs. RF Power with no Air Cooling

very low compared to the strength of the material. Figure 9X shows that at 1 MW , the maximum stress is 16.8 MPa. The flexural strength of AL300 alumina is 296 MPa.

Therefore, the stress of 16.8 MPa is relatively low as it is only a 6 % of its strength.

Figure 9R. Temperature Gradient due to Only Air Heating (BC3 Case)

Figure 9S. Stresses due to only Air Heating (BC3 Case)

Figure 9T. Stresses due to Air Heating and Pressure Differential with no RF (BC1 Case)

Figure 9U. Stresses from the Vacuum to Atmospheric Pressure Differential (BC2 Case)

Figure 9V. Coaxial Surface Temperature vs. Incident Power

Figure 9W. Air Inlet and Outlet Temperature vs. RF Power

Incident Power (kW)	Inputs		Outputs			
	Contact Temp. (K)	Air Temp. (K)	Min. Temp. (K)	Max. Temp. (K)	Delta Temp. (K)	Max. Stress (MPa)
0	298	301.6	298	299	1	5.74
100	303	303.1	303	306	3	5.93
200	308	304.5	308	312	4	6.07
300	313	306.1	313	318	5	6.92
400	318	307.8	318	325	7	8.48
600	329	311.8	328	339	11	11.4
800	340	316.5	339	352	13	14.6
1000	353	321.2	351	368	17	16.8

Table 9H. Effects of Variations of the Incident Power on Temperature and Stress

Stress vs. Incident RF Power

Figure 9X. Maximum Stress as a Function of Incident Power

Figure 9Y. Maximum Stress with and without air Cooling vs. RF Power

The curve of stress in the window as a function of RF power has two distinct slopes, as shown in Figure 9Y. The lower slope occurs at lower power levels where the air inlet temperature is above the window temperature. In this region, the stresses with the air cooling are lower than the stresses without the air cooling. The larger stresses with the air cooling are because heat is transferred from the air into the window. At higher power levels, heat is being transferred from the window into the air, and the window temperature increases linearly with the RF power.

9.2e Thermal and Structural Conclusions

In summary, the heat source was modeled as an internal heat generation problem. The cooling mechanisms in the window include conduction at the ceramic to metal boundaries, convection on the air surface, and radiation on both the air and the vacuum surfaces. Structurally, the window is modeled as simply supported to allow for expansion in the radial direction. When studying the boundary conditions, it was found that a low contact resistance at the ceramic to metal joint produced a different thermal profile than what was observed experimentally, while a very large contact resistance did not affect the results. A low contact temperature leads to large stresses. Larger contact temperatures at the ceramic-to-metal interface decreased the temperature gradients so that the stresses also decreased. The results of the analysis show that the temperature profile follows the magnitude of the electric field. The resultant stresses are due to the temperature gradient from the dielectric heating, the temperature gradient from the hot air that is blown over the surface of the window, and the pressure difference between the air and vacuum sides. The resultant stresses are hoop stresses with areas of tension near the outside radius and areas of compression near the inside. At lower power levels, the air inlet temperature is greater than the air outlet temperature, which means that heat is transferred into the window at lower power levels. At higher power levels(above 100 kW), the air cooling decreases the stresses in the window by having a cooling affect. The temperatures and stresses increase with increasing RF power. At 1 MW, the stresses in the window are relatively low compared to the flexural strength of AL300 alumina.

9.3 Material Properties

The material properties used in the model are critical to the results. Some of the material properties were measured from four-point bend tests, as discussed in Chapter 6 and Chapter 11.

Category	Property	Value	Source
Electrical	Dielectric Constant	9.53	Ref. 45
	Electrical Conductivity (σ)	10^{-12} S/m	Ref. 45
	Loss Tan	0.00035	Ref. 45
Mechanical	Flexural Strength (σ)	296 MPa	Ref. 45
	Youngs Modulus (E)	3.03×10^{11} Pa	Ref. 43
	Specific Heat (C_p)	778 J/kg-K	Ref. 43
	Density (ρ)	3670 kg/m ³	Ref. 45
	Thermal Conductivity (k)	26.8 W /m K	Ref. 45
	Thermal Expansion Coefficient (α)	6.9×10^{-6} /°C	Ref. 45
	Stefan-Boltzman Constant (σ)	5.669×10^{-14} W / (mm ² K ⁴)	Ref. 46
	Poissons Ratio (ν)	0.21	Ref. 45
Reliability	Weibull Modulus (m)	14.26	Experimentally Measured*
	Scale Parameter (σ)	356.6 MPa / mm ^{1/m}	Experimentally Measured*
	Fatigue Exponent (n)	20.36	Experimentally Measured*
	Fatigue Constant (B)	3137.6 MPa ² Sec	Experimentally Measured*

*See Sections 6.3f and 11.1f

Table 9I. Material Properties used in the Analytical Model

9.4 Reliability Results

The results of the reliability analysis are divided into three parts. The first part is the fast fracture results. The second part is the fatigue results, and the third part is to determine how variations of the fracture criteria affect the results.

9.4a Fast Fracture Results

The results on the fast fracture reliability code are illustrated in Figures 9Z through 9AC. The probability of failure vs. maximum stress in the window is shown in Figure 9Z and Figure 9AA. Note that the probability of failure starts to occur at a stress of approximately 140 MPa. The window is very likely to rupture at a stress above 210 MPa. This stress is lower than the flexural strength of alumina because the CARES Life code accounts for the variation in strength, the failure criteria, flaw geometry, the size effect and the effect of multiaxial stresses. The variation in strength is represented as the Weibull parameter¹⁹. As the parameter decreases the variation in strength increases. The failure criterion is modeled by the Shetty Criteria. The flaw geometry used in the model is the Griffith crack. The size effect and the effect of multiaxial stresses are calculated by using the CARES code from the ABAQUS finite element information. Hence, the stress at which failure has a chance of occurring is expected to be lower than the materials flexural strength.

The probability of failure was correlated to the RF power by correlating the RF power to the maximum stress. The RF power vs. stress is shown in Figure 9AD. The low power data in the region where the stresses were affected by the high inlet temperatures were not included because the objective is to extrapolate the data to higher power levels to determine the stress and RF power level where failure will occur. A linear curve fit was applied to obtain the relationship between the RF power and the stress (See Figure 9AD). This relationship was used to generate Figures 9AB and 9AC, the probability of failure vs. incident RF power. These figures show that failure in the

Probability of Failure vs. Maximum Stress

Figure 9Z. Probability of Failure vs. Maximum Stress

Probability of Failure vs. Maximum Stress

Figure 9AA. Probability of Failure vs. Maximum Stress (zoomed in)

Probability of Failure vs. RF Power

Figure 9AB. Probability of Failure vs. RF Power

Probability of Failure vs. RF Power

Figure 9AC. Probability of Failure vs. RF Power (zoomed in)

Figure 9AD. RF Power vs. Maximum Stress Curve Fit

ceramic may occur at approximately 9 MW and the ceramic failure is likely to occur by 15 MW.

The implications of this result need to be carefully understood. This results only means that stresses due to dielectric heating in the alumina ceramic are not likely to cause failure of the window until powers well over 1 MW. This results does not mean that the window assembly is capable of passing 9 MW of power. Other mechanical joints and components in the window were not designed to pass 9 MW, and a careful analysis would need to be performed to determine the maximum power capacity of the window assembly. This results does imply that the window has a good thermal mechanical design and will not fail at power levels less than 1 MW due to thermally induced mechanical stress from dielectric heating in the ceramic. On the RFQ, the typical operating conditions are 250 kW and the worst case operating condition is less than 300 kW (from Table 1A).

9.4B Fatigue Results

The first step in obtaining the fatigue results is to approximate the time per cycle. A full stress cycle is defined as the stresses going from the maximum value to zero and then returning to the maximum stress. A partial stress cycle is defined as the stresses vary from the maximum value to some lower stress value and then returning back to the maximum stress. In a particle accelerator, many factors will cause a stress cycle. The majority of the stresses are caused by the thermal gradients. Changes in the thermal gradients are caused by fluctuations in the window temperature. The window temperature is affected by the RF power. In an accelerator, there are many factors which will lead to changes in the RF power. Some factors cause a complete shutdown of the RF power while others cause only a decrease in the RF power. The factors that cause a complete RF power shutdown and thus a full stress cycle in the windows include system shutdown and RF shutdowns, as listed in Table 9J. Factors that cause a partial stress cycle include loss of beam, as listed in Table 9K. Other shutdowns, such as loss of RF power due to vacuum and arc interlocks are not included because they do not cause a variation in the temperatures or stresses. Two fatigue models have been developed to reflect the different factors which cause a stress cycle, as summarized in Table 9L. Fatigue Model A represents the effects of fatigue from complete stress cycles. Fatigue model B represents the effects of fatigue from partial stress cycles. The total probability of failure due to the fatigue effects is

$$PF = (PF_A^2 + PF_B^2)^{1/2} \quad \text{Eq. 9.8}$$

where PF is the total probability of failure, PF_A is the probability of failure considering fatigue with a complete stress cycles, and PF_B is the probability of failure considering

Factor	Description	Frequency of Occurrence
System Shutdown	Shutdown due to causes other than RF problems or loss of beam (i.e., water system shutdown)	$= \frac{1 \text{ Shutdown}}{1 \text{ Week}} = \frac{1 \text{ Window Thermal Cycle}}{1 \text{ Week}}$ $= \frac{0.00595 \text{ Window Thermal Cycles}}{1 \text{ Hour}}$
Crow Bar / RF Shutdown	Klystron is shut down so RF power is shut down instantaneous	$= \frac{1 \text{ Shutdown}}{3 \text{ Days}} = \frac{1 \text{ Window Thermal Cycle}}{3 \text{ Days}}$ $= \frac{0.0139 \text{ Window Thermal Cycles}}{1 \text{ Hour}}$
Total		$= \frac{0.01985 \text{ Window Thermal Cycles}}{1 \text{ Hour}}$ $= \frac{5.5 \text{ E} - 6 \text{ Window Thermal Cycles}}{1 \text{ Sec}}$ $= \frac{1.811 \text{ E} 5 \text{ Seconds (50.3 hours)}}{1 \text{ Window Thermal Cycle}}$

Table 9J. Time per Full Stress Cycle in the RF Windows for Fatigue Model A

Factor	Description	Frequency of Occurrence
Loss of Beam	The loss of beam leads to a full reflection. Thus, depending on the position of the window with respect to the standing wave, the power level at the window will be 0 to 4 times the operational power.	$= \frac{1 \text{ Shutdown}}{30 \text{ Minutes}} = \frac{1 \text{ Window Thermal Cycle}}{1800 \text{ Seconds}}$ $= \frac{5.556 \text{ E} - 4 \text{ Window Thermal Cycles}}{1 \text{ Second}}$
Total		$= \frac{5.556 \text{ E} - 4 \text{ Window Thermal Cycles}}{1 \text{ Second}}$ $= \frac{1800 \text{ Seconds (30 Minutes)}}{1 \text{ Window Thermal Cycle}}$

Table 9K. Time per Partial Stress Cycle in the RF Windows for Fatigue Model B

	Fatigue Model A	Fatigue Model B
$RCYC = \frac{\text{Min Stress}}{\text{Max Stress}}$	0.0	0.857
Time per Cycle	1.811×10^5 Seconds	1800 Seconds

Table 9L. Fatigue Model Parameters

fatigue with a partial stress cycle. The parameters used in the fatigue models are summarized in Table 9L. The stress RCYC parameter represents the ratio of the minimum stress over the maximum stress. When RCYC is zero, the stress is cycling from 0 to the maximum stress. For Fatigue model B, the RCYC is set to .857, because this represents a maximum stress of 7 MPa and a minimum stress of 6 MPa. This represents a variation in power from 300 kW to 200 kW, from Figure 9X.

In the CARES code, fatigue can be modeled by the Paris Law, the Walker Law, or the Power Law¹⁹. The Power Law was chosen because the fatigue data is dA/dt (change in area as a function of time). To use the Paris or the Walker Law, the fatigue data required is dA/dN (change in area as a function of cycles).

The Probability of Failure vs. Time at different power levels for Fatigue Model A is illustrated in Figure 9AE. The results for Fatigue Model B are illustrated in Figure 9AF. In Fatigue Model A the probability of failure at 1 MW increases from 2×10^{-16} after 1 second to 1×10^{-10} after 100 years. In Fatigue Model B the probability of failure at 1 MW increases from 1×10^{-16} after 1 second to 1×10^{-10} after 100 years. In both models the probability of failure is not shown for 200 kW because the probability of failure is very close to zero. Figure 9AG shows the combined probability of failure from model A and model B. The probability of failure is dominated by Fatigue Model B. This is expected

Figure 9AE. Results of Model A: Probability of Failure vs. Time at Different Power Levels

Figure 9AF. Results of Model B: Probability of Failure vs. Time at Different Power Levels

Figure 9AG. Combined Results of Model A and B: Total Probability of Failure vs. Time at Different Power Levels

Figure 9AH. Stress vs. Time showing the Probability of Failure

Figure 9AI. Power vs. Time showing the Probability of Failure

because the period per cycle, for Fatigue Model B is much greater than the period per cycle for Fatigue Model A. Stress vs. Time is shown in Figure 9AH and Power vs. Time is shown in Figure 9AI. In both of these figures, the curves represent various probabilities of failure. The safe operating region below the curves represents a probability of failure of zero. The region above the curves represents a probability of failure of one and is the unsafe operating region.

9.4c Variation of Fracture Criteria

It is important to determine how the variations in fracture criteria affects the results. The three options for the fracture criteria in the CARES program for a surface analysis are the normal stress criteria (principal stresses), the co-planar strain energy release criteria, and the Batdorf-shear sensitive criteria¹⁹. The Batdorf-shear sensitive criteria was used in the model because it considers shear stresses as well as principal stresses. The values of the other criteria are compared to the Batdorf-shear sensitive criteria in Figure 9AJ. The variation in the results is relatively small as the total variation is only 2%, from 0.5533 to 0.5407.

Figure 9AJ. Probability of Failure vs. Fracture Criteria

9.4d Variation of Flaw Geometry

As the exact flaw geometry is not known, it is important to determine how the variations in flaw geometry affect the results. The Griffith crack was used in the model because this was thought to be the most likely geometry of an existing flaw. The effects of flaw geometries are shown in Figure 9AK. The effect of using different flaw geometries is only 0.2%.

Figure 9AK. Probability of Failure vs. Crack Geometry

9.5 Summary of Analytical Results

The analytical model shows that the window has a good thermal mechanical design. The maximum temperature at 1 MW is 95 °C with a delta T of 17 °C. The maximum stress at 1 MW is 16.8 MPa which is very low compared to the flexural strength of about 300 MPa for alumina. At lower power levels, the air inlet temperature is higher than the air outlet temperature, thus heat is being transferred into the window. Hence, at lower power levels the maximum stress is not linear with power. At higher RF power levels, once the air inlet temperature is lower than the air outlet temperature, the maximum stress exhibits a linear increase with power. Once the variation in the material strength, probability of a flaw, and size effect are considered, the CARES program predicts that fast fracture due to dielectric heating will not occur below power levels of 1 MW. To determine the lifetime of the window, a linear relationship was found between the maximum stress and the power. After considering the possible shutdowns that may occur in an accelerator and the effects the shutdowns have on the window stresses, the fatigue model was divided into two models. One model represents shutdowns that cause a complete stress cycle and the other model represents shutdowns that cause a partial stress cycle. The total probability of failure is then the combined probability of failure. Over time, the probability of failure increases due to subcritical crack growth. At an operating power of 200-300 kW, it is very unlikely that the window will break due to dielectric heating. Changes in the flaw geometry used in the model and the fracture criteria have relatively small effects on the overall results of the probability of failure. The window design is capable of handling the calculated thermally induced mechanical stresses due the dielectric heating.

CHAPTER 10

COMPARISON OF EXPERIMENTAL AND ANALYTICAL RESULTS

The electrical, thermal, and structural analytical results are compared to the respective experimental results. The reliability results cannot be compared because the test time and sample size did not allow for the collection of meaningful reliability data. Results of the experimental electrical calibrations will be compared to the calculations using the electromagnetic finite element code HFSS. The thermal results from the finite element code are compared to temperatures experimentally measured. The measured and calculated structural results are compared. This comparison is done by using the analytical model to predict the experimental stresses from the measured temperatures.

10.1 Comparison of S parameters

The comparison of electrical results is done by comparing the experimental S parameters to the analytical S parameters. The experimental values are taken from a representative window. The values of the S parameters at 350 MHz are listed in Table 10A. The measured S11 and S21 curves, Figure 8E and 8C, are compared to the calculated S11 and S21 curves, Figures 9G and 9H. The experimental and analytical S11 and S21 curves are plotted in Figure 10A and Figure 10B, respectively. The experimental values for S11 and S22 are less than the analytical values. For S11, the values of -19 dB to -30 dB may seem quite different, but in fact they only indicate a 0.5% absolute difference in reflected power(see Table 10A). For S21, the difference in measured and calculated values are a 0.9% absolute difference in transmitted power(see Table 10A). In addition, experimental values below -20 dB are very small, thus are affected very much by the calibration and measurement errors. The shapes of the curves in Figures 10A and 10B are similar, which is important because it indicates both results show that the

Comparision of S11 Parameter

Figure 10A. Comparison of the Experimental and Analytical S11 Curves

Comparision of S21Paramter

Figure 10B. Comparison of the Experimental and Analytical S21 Curves

	Calculated	Measured
S11	-19.132 dB (0.1105)	- 30.959 dB
S21	-0.0540 dB (0.9938)	-0.0325 dB
S12	-0.0540 dB (0.9938)	-.00251 dB
S22	-19.117 dB (0.1107)	-53.057 dB
Power Reflected = $(S_{11})^2$	1.22 %	0.7 %
Power Transmitted = $(S_{21})^2$	98.7 %	99.63 %
Power Absorbed = $1 - (S_{11}^2 + S_{12}^2)$	0.0161 %	-----

Table 10A. Comparison of S Parameters at 350 MHz

window is matched at 350 MHz. Differences between the measured and calculated values may also be due to the tuning post. Fine adjustments to the match of the window are accomplished by using tuning posts. These posts were individually sized to each window to account for small differences due to fabrication. The average size tuning post is analytically modeled. Therefore, the experimental and analytical values are very close.

The calculated and measured amount of power absorbed are compared in Table 10A. The analytical model shows that 0.0161 % of the power will be absorbed. This means that if the incident power in the waveguide is 1 MW, 161 Watts will be absorbed. The measured values of $S_{11}^2 + S_{12}^2$ are greater than one, so experimentally the amount of power absorbed is zero. This is probably due to error in the calibration caused by the phase difference, as explained in Section 8.1.

10.2 Comparison of Thermal Results

Differences in the measured and calculated thermal results are determined by comparing the temperature distribution and the absolute values of temperatures. The analytical model shows that the temperature profile is asymmetric because of the

asymmetric electromagnetic fields. The experimental results also show this asymmetry in the temperature distribution. The coaxial temperatures were measured every 90 degrees around the windows, and these temperature measurements showed a gradient around the circumference. This gradient is thought to be due to the asymmetric temperature distribution. The absolute values of the temperatures are compared in Table 10B. The coaxial surface temperatures are the average temperatures obtained from Table 8K (steady state temperatures at 1 MW). The IR camera temperatures are shown in Figure 8AF (the IR photo). The calculated temperatures are shown in Figure 9M and 9N (the thermal plots). The temperature difference from the IR camera is much less than the temperature difference from the coaxial surface RTDs and the analytical model. The temperature difference is less with the IR camera because the field of view is limited with the IR camera (see Figure 8AM), and hence, the IR camera is not detecting the full range of temperature from the inner conductor to the outer conductor. A comparison of the temperature difference between the experimental and analytical results is more important than the absolute temperatures because the stresses are proportional to the temperature difference. Note that the temperature difference between the experimental and analytical results is the same. Thus, the stresses in the windows that were tested should be very close to the stresses calculated from the analytical model.

	Experimental Coaxial Surface	IR Camera	Analytical
Maximum Temperature	82 Deg C	78 Deg C	95 Deg C
Minimum Temperature	65 Deg C	73 Deg C	78 Deg C
Temperature Difference	17 Deg C	5 Deg C	17 Deg C

Table 10B. Comparison of the Analytical and Experimental Temperatures.

10.3 Comparison of Structural Results

The stresses were not experimentally measured. However, the allowable analytical stresses were compared to the experimental stresses at the time window W2 broke. This comparison was done by recording the maximum temperature the window reached before the ceramic broke. Then the analytical model was used to predict the maximum stresses in the window for that maximum measured temperature. This maximum stresses were compared to the strength of the material.

The maximum temperature recorded before the window broke was 155 °C (428 K). The Temperature vs. Power curve was extrapolated in order to determine the equivalent maximum power level, as shown in Figure 10C. According to the extrapolation, the maximum equivalent power is 1.8 MW. The stresses were extrapolated from the Stress vs. Power curve shown in Figure 10D. The maximum extrapolated stress is 21 MPa. This stress is far below the flexural strength of 300 MPa for alumina.

This comparison shows a significant amount of nonlinear temperature increases at the time the window failed. The nonlinear temperature increase is probably due to multipacting, and is over a local area. This comparison assumed that the heating was due to only dielectric heating. This assumption is not valid if localized heating was occurring due to multipacting. Multipacting can cause incredibly intense heat at one region of the ceramic. One study reported local temperatures over 1900°C due to multipacting². The outer coaxial temperatures do not indicate this local heating and are not a good basis for comparison with the occurrence of multipacting. Hence, the temperature profile with multipacting can not be compared to the calculated results.

Another possibility to compensate for the differences is that the maximum temperature was much greater than the maximum temperature recorded. As discussed previously, increasing the time between data points by a half second decreases the maximum temperature that was recorded from 155 °C to 85 °C. Regardless of the exact

Figure 10C. Extrapolated Temperature vs. Power

Figure 10D. Extrapolated Stress vs. Power

maximum temperature or stress reached before failure, this comparison indicates that a large amount of nonlinear heating occurred at the time of the window failure.

10.4 Summary of the Comparisons

The difference between the measured and calculated values of the S parameters at 350 MHz is a 1% absolute difference. The shape of the measured S parameter curves vs. frequency differ because of the extra phase added after the calibration, as explained in Section 8.1. Nevertheless, the results are very similar. The thermal results were verified by comparing the coaxial surface temperatures and the temperatures measured from the IR camera to the calculated temperatures. The temperature difference calculated is the same as the measured temperature difference; however, the analytical model indicates higher absolute temperatures than the experimental data has shown. Because the temperature difference is the same the stresses should be similar. It is impossible to compare the stresses, because the stresses were not measured. The stresses calculated using the maximum temperature recorded at a window failure were much lower than the materials strength. Therefore, at the time of failure, a significant amount of multipacting occurred, which increased the stresses and changed the temperature profile. With the occurrence of multipacting, comparison of the stresses between the experimental results and calculated results can not be made. The analytical model provides a good representation of stresses and temperatures in window due to dielectric heating (without the presence of multipacting).

CHAPTER 11

MATERIALS TESTING AND CHARACTERIZATION RESULTS

11.1 Mechanical Testing Results

This section summarizes the mechanical testing done on three alumina disks. The procedure for these tests was outlined in Chapter 6. The number identifying the performed tests correspond to the test numbers described in Chapter 6. The effects of radial position, surface finish, orientation, and fatigue are described. The mechanical properties used in the analytical model are also discussed.

11.1a Effects of Radial Position

The objective of this section is to determine if the strength varies with radial position. A trend of increasing or decreasing strength with radial position

Figure 11A. The strength of the as received samples, SH1, vs. radial position

Figure 11B. The Strength of the As Received Samples, SH1, vs. Radial Position

is an indication of the presence of residual stresses in the alumina disks. The strength of the grit blasted samples (SH2) and the as-received samples, SH1, are plotted vs. radial position in Figures 11A and 11B, respectively. No trend with radial position can be seen in these plots. Therefore, the test results do not indicate the presence of residual stresses.

11.1b Effects of Surface Finish

The grit blasted and as-received samples were compared to determine whether there are any effects of surface finish on the strength of the sample. Table 11A summarizes the strength for the grit blasted and as-received samples. The as-received

Test	Rate	Location of Samples	Number of Samples	Surface Finish	Strength (MPa)	Standard Dev.
1	R1	D3:A1-24	21	SH1 (as received)	251.00	23.8
2	R1	D3:B1-24	22	SH2 (grit blasted)	245.67	9.0

Table 11A. Effects of Grit Blasting on Strength

samples are slightly stronger than the grit blasted samples. This could be because grit blasting damages the surface which, in turn, weakens the material.

11.1c Fatigue Results

The fatigue parameters are obtained by performing tests at different loading (stressing) rates. Table 11B and Figure 11C summarize the fatigue data. As the

Test	Rate	Location of Samples	Number of Samples	Surface Finish	Strength (MPa)	Standard Dev.
4	R1	D1:Radial	20	SH1 (as received)	244.42	10.9
5	R2	D1:Radial	5	SH1 (as received)	205.97	8.9
6	R3	D1:Radial	5	SH1 (as received)	184.80	11.7
7	R4	D1:Radial	10	SH1 (as received)	174.79	8.2
8	R1	D1:Tangential	22	SH2 (grit blasted)	228.76	27.2
9	R2	-----TEST	WAS NOT	PERFORMED ---	-----	
10	R3	D1:Tangential		SH2 (grit blasted)	177.18	10.7
11	R4	D1:Tangential		SH2 (grit blasted)	169.3	11.5

Table 11B. Effect of Loading Rate on Strength to Determine Fatigue Data

Figure 11C. Strength vs. Stressing Rate for Grit Blasted and As-received Samples

stressing rate decreases, the strength decreases. This decrease in strength is due to the lower stressing rate. As the samples are stressed at a slower rate, the subcritical cracks have more time to grow. Thus the material is weakened by the subcritical crack growth. As with the fast fracture fatigue results, the as-received samples are slightly stronger than the grit blasted samples.

11.1d Disk to Disk Variations

There seems to be a noticeable strength variation from disk to disk. The strengths between the disks varied by 14 MPa. The difference in strength between the grit blasted and the as-received was usually less than this but varied from 16 MPa to 5 MPa. The results of the differences between disks are illustrated in Table 11C and Figure 11D.

Test	Rate	Location of Samples	Number of Samples	Surface Finish	Strength (MPa)	Standard Dev.
3	R1	D1:Tangential	21	SH1 (as received)	236.94	16.0
12	R1	D2:Tangential	15	SH1 (as received)	238.66	16.6
1	R1	D3:Tangential	21	SH1 (as received)	251.00	23.8

Table 11C. Effect of Disk to Disk Variation

Figure 11D. Disk to Disk Variation in Strength

11.1e Mechanical Properties for Analytical Model

The Weibull and fatigue data for the analytical model were obtained from the 4-point bend test data. The 4-point bend data for the grit blasted samples was used in the analytical model because all the windows are grit blasted. The material properties required by the CARES Life code were calculated using the CARES Parameter Estimation code¹⁹. The dynamic fatigue data from the 4-point bend tests and the geometry of the 4 point bend specimens were input into the CARES Parameter Estimation Code. The input file for the CARES Parameter Estimation is listed in

Appendix E. Shetty's Semi-Empirical Criterion was used as the fracture criterion and the maximum likelihood method was used to calculate the Weibull parameters. Data for the grit blasted samples is compared to the as-received samples and other results found in

Material Property	As-received Samples	Grit Blasted Samples	From Powers ⁴⁸	From Nemeth ¹⁹	From Fett ⁴⁹
Weibull Modulus (m)	18.26	14.26	16.92	23.76	10.1
Scale Parameter (σ), MPa / mm ^{1/m}	350.28	356.6	361.8	425.29	404.25
Fatigue Exponent (n)	19.71	20.36	40.1	40.84	33.0
Fatigue Constant (B), MPa ² Sec	3601.49	3137.6	1.01 x 10 ⁻⁶	.0562	-----

Table 11D. Material Properties for the Analytical Model Compared to the Literature

the literature(See Table 11D). Note that the grit blasted data is very similar to the as-received samples. The Weibull modulus is slightly lower for the grit blasted compared to the as-received, which indicates slightly more variation in the data from the grit blasted samples. The scale parameters for the two sets of samples are comparable: They differ by less than 2%. The fatigue properties, n and B are also very comparable. The material data obtained from this work are also compared to data found in the literature. The main difference is found in the fatigue exponent, n. The fatigue exponent determined here is much lower than the reported data. A lower fatigue exponent indicates that the material strength is more likely to decay with time if the alumina is subject to fatigue. This decay in strength results in poorer RF window performance. It is difficult to make a comparison of the fatigue constant, B. This constant is obtained from a log-log plot, so very small variations will show up as very large variations on a linear plot. Variations of 1×10^{-6} to 10,000 are not unusual for B.

11.2 Fractography Results

A crack was found through a number of the beams on disk 3. This crack was studied under the optical microscope and then with SEM. Figure 11E shows the crack as seen with the optical microscope. Figure 11F shows a crack on another sample, also with the optical microscope. At the machine shop where the beams were machined from the alumina disks, the samples were labeled by drawing a number in pencil on the original window surface of the ceramic disks. The sample shown in Figure 11F shows an example of a number used for labeling. By examining the crack near the number, it was deduced that the crack was there before the number was drawn because some of the lead was found in the crack. The crack was also studied with SEM. At higher magnifications, it can be seen that the grains near the crack are different from the surrounding grains. Figures 11G and 11A illustrate a crack and the surrounding grains. This crack is believed to have occurred during the green state and before sintering occurred. The grain growth patterns show evidence of this region being a free surface during sintering. The grains are much larger near the crack boundaries than on the surrounding surfaces. During sintering, the grains near the crack grew into coarse grains to minimize the area of grain boundaries and thus the surface energy. Therefore, the crack was a result of the ceramic processing before sintering.

This crack raises an area of concern regarding the quality control of the ceramic used for the windows. The manufacturer of the ceramic was contacted after the crack was discovered. The manufacturer stated that the ceramic undergoes a dye penetrant check after the sintering and after the final dye penetrant test after all the machining. He assures that 100% of the samples will not have a crack. However, this crack was present and easily detected in one of three disks. This finding is not consistent with the manufacturer's statement. Based on this finding, a quality assurance procedure for the alumina ceramic is recommended.

Fractography was performed on the fast fracture samples. This was done to determine the origin of the fracture. The fracture origin was thought to be a group of coarse grains near the top surface. A photograph of the coarse grains at a higher magnification is shown in Figure 11J. A second example of a coarse grains at the fracture origin is shown in Figure 11K. The fractography shows that the fracture occurred at the grain boundaries(intergrainular fracture). Only one example of fracture within a grain was found, as shown in Figure 11L(transgranular).

Some of the fracture origins were located at the corners of the sample instead of the edge along the tensile surface. This could imply that stress concentration factors due to the corners increased the stress locally which made the sample break at the corners. If some of the data are affected by the stress concentration factors, the strength values calculated from the data will be lower than the actual strength which will make the calculations conservative. The corners on the beams were beveled to help eliminate the effects of the corners.

In summary, the fractography results show that the fractures are probably occurring at weakness in the sample caused by groups of coarse grains. The fractography has also uncovered a crack which is believed to have occurred prior to the sintering of the ceramic. A quality assurance program should be implemented to ensure similar cracks are not present in RF windows.

Figure 11E. Photo of Crack with the Optical Microscope

Figure 11F. Photo of Crack through Number Written on Sample with the Optical Microscope

Figure 11G. SEM Photo of the Crack at 144 X

Figure 11H. SEM Photo of the Crack at 595 X

Figure 11I. The Fracture Surface

Figure 11J. Coarse Grains at the Fracture Origin

Figure 11K. On Another Sample, an Area of Coarse Grains is at the Fracture Origin

Figure 11L. Broken Facets Illustrate Fracture within a Grain

11.3 Surface Characterization Results

The objective of surface characterization is to compare the elemental composition of the surface layers of the grit blasted samples to surface layers on the as-received samples. The surface analysis was done by Tom Taylor at Los Alamos National Laboratory⁵¹. An approximately 1 mm² area on each sample was analyzed. The best results were obtained by using a monochromatized X-ray source on the neutralizing electron gun. The electron gun was needed to stabilize the sample potential because charge will accumulate on the alumina sample surface. The data was taken at a pressure below 10⁻⁸ Torr. An Al_K source which has an x-ray energy of 1483.6 eV was used. Using the x-ray energy and the mean free path of the electrons, it is calculated that the data obtained is from the outer 50-75 Å of the sample surface.

The as-received samples and the grit blasted samples were examined, then sputtered for 10 minutes with argon and examined again. The purpose of the sputtering is to examine layers deeper than 5 Å. The broad band spectrum for the as-received sample is shown in Figure 11M, and the spectrum after sputtering is shown in Figure 11N. For the grit blasted sample the spectrum is shown in Figure 11O; after sputtering the spectrum is

Element	As-Received Surface	As-Received Sputtered	Grit Blasted Surface	Grit Blasted Sputtered
Al	10.4	26.3	27.9	36.4
O	27.2	42.4	52.5	61.0
C	58.6	29	14.7	trace
Si	1.3	1.0	1.6	1.3
Ca	0.4	0.6	0.8	0.8
Mg	0.4	0.2	0.4	<1.0
Na	0.4	0.1	0.3	nd
N	1.3	0.5	0.8	nd
Fe	nd	<1.0	0.1	<1.0
Ti	nd	nd	0.5	0.6
F	nd	nd	0.4	nd

nd = not detected in survey spectrum

Table 11E. Surface Composition in % Atom Fraction

shown in Figure 11P. All the detectable signals for both the as-received and grit blasted, both before and after sputtering, are summarized in Table 11E. In the spectrum for the as-received sample, the major elements detected are Al, O and C. Other elements detected include Mg, Na, N, Ca, and Si. Of the elements detected, Al and O are expected for an alumina sample. Carbon is also expected from handling and exposure to the atmosphere. The sintering additives consist of a proprietary mixture of CaO, MgO, and SiO₂. The only abnormality is that the amount of Si detected is larger than expected. Expected levels of Si would be about 0.4 %, which is the amount detected for the other sintering additives. Comparing the spectrum for the as-received sample to that of the sputtered sample indicates that the amount of carbon has significantly decreased and the Al and O components have increased. The ratio of Al to O is consistent with the alumina stoichiometry. The levels of Si, Ca, N, Mg and Na are all very low as expected. The ratio of Si to Al has significantly decreased as a result of sputtering, indicating that Si is a surface impurity. A trace amount of Ti was detected after sputtering. In the spectrum for the grit blasted sample, (Figure 11O), the same elements are detected as on the as-received samples, plus small amounts of F and Ti. A comparison between the grit blasted and the as-received samples is done in Table 11E. The amount of carbon is significantly reduced on the grit blasted samples. Also, the ratio of Si to Al is considerably lower than on the as-received samples. Sputtering the grit blasted sample reduces the carbon to a trace amount near the noise level. Other elements detected include Fe, Mg, Ti and Ca, and Na. N, and F are below detectable levels.

The surface analysis shows that grit blasting cleans the surface and significantly decreases the amount of carbon on the surface. The Si to Al ratio decreases after grit blasting; however, the absolute concentration is not noticeably changed. The binding energy of Si indicates that it may be in complex with oxygen and carbon. It is not clear whether the Si is in particle or compound form, or whether it is distributed across the surface uniformly or with a variable thickness. SiO₂ is part of the sintering mixture added

to the alumina, however there may have been an external source of silica. The most important conclusion from the surface analysis is that grit blasting significantly reduces the amount of carbon on the surface.

Figure 11M. XPS Survey from an As-Received Sample

Figure 11N. XPS Survey from an As-Received Sample after 5 Minutes of Sputtering

Figure 11O. XPS Survey from a Grit Blasted Sample

Figure 11P. XPS Survey from a Grit Blasted Sample after 5 Minutes of Sputtering

11.4 SEM Results

The objective of the SEM analysis was to compare the grit blasted samples to the as-received samples. The SEM photomicrographs are shown in Figure 11Q through 11X. The order shown is by increasing magnification. Figures 11Q and 11R were taken at the lower magnification($\times 50$) to determine whether features such as machining and grinding directions can be observed. No obvious machining directions can be seen, and there is no apparent difference between the grit blasted and the non grit blasted in these two photomicrographs. Figures 11S and 11T are the same as figures 11Q and 11R but with a magnification of 200 times. In these photos, grains may be seen. The specified average grain size of the material from the vendor is 15 to 25 microns. Grains in this size range can be seen by using the scaled length of 50 micron on the right of the photo. One cannot be certain that what is thought to be a grain is indeed a grain. In order to quantitatively verify the grains with certainty, an etching and polishing procedure would need to be done. But from examining the photos, it does look as if grains can be seen that are much smaller and also much larger than the 15 to 25 microns specified. The specified size is probably the average grain size not the inclusive range. Figures 11U and 11V are at 1000 $\times$ magnification. Machining damage can be seen in Figure 11U. Damage from the grit blasting can be seen on some edges in Figure 11V. The 220 alumina grit size corresponds to a 60 to 75 micron grain size. This is significantly larger than the specified 15 to 20 micron grain size. In addition, by comparing the photos of the grit blasted to the as-received samples, it is speculated that in the photo of the as-received samples there is a high frequency of bumps with a smaller amplitude. The grit blasted sample has a surface with a lower frequency of bumps with a larger amplitude. This difference is illustrated in 11Y. Surface roughness is defined as the amplitude of the bumps, thus grit blasting increases the surface roughness of the alumina. This difference can also be seen by comparing the grit blasted to as-received regions on the same sample, as seen in Figures 11W and 11X.

Figure 11Q. As-Received Sample, x 50

Figure 11R. Grit Blasted Sample, x 50

Figure 11S. As-Received Sample, x 200

Figure 11T. Grit Blasted Sample, x 200

Figure 11U. As-Received Sample, x 1000

Figure 11V. Grit Blasted Sample, x 1000

Figure 11W. Non Grit Blasted / Grit Blasted Transition Zone, x 200
(The top half is grit blasted and the bottom half is not grit blasted)

Figure 11X. Non Grit Blasted / Grit Blasted Transition zone, x 400
(The top half is grit blasted and the bottom half is not grit blasted)

Figure 11Y. The Speculated Differences between the Grit Blasted Surface and the Surface that was not Grit Blasted.

11.5 Atomic Force Microscopy Results

Atomic force microscopy (AFM) was done to compare the surface topography of the grit blasted sample to that of the as-received sample, and to verify the speculated surface topography drawn in Figure 11Y. On both the grit blasted and as received samples, a square region of $60\text{ }\mu\text{m}$ by $60\text{ }\mu\text{m}$ was examined. A line was drawn on both samples and the surface topography was plotted over the line on both samples. Figure 11Z illustrates the section on the grit blasted sample and Figure 11AB shows the section on the as received sample. Figure 11AA and 11AC show the location of the sections on the grit blasted and as received samples, respectively.

Differences between the surface topography can be seen by comparing the two sections; however, these two sections are small. Comparing the grit blasted section to the as received section shows the grit blasted has a smaller frequency of larger bumps, as speculated. However, it appears as if the peak to valley distance of both samples is approximately the same. Decreasing the frequency of bumps on the grit blasted sample eliminates the smaller sharper bumps. This reduction of bumps may decrease the field emission which reduces multipacting because there are fewer free electrons. The region in the center of Figure 11AA is blurred because the surface topography is out of range for the AFM in this region. The size of the area sampled ($60\text{ }\mu\text{m} \times 60\text{ }\mu\text{m}$) may not be large enough to provide an accurate representation of the whole surface to make definitive generalizations regarding the surface topography. In addition, the blurred region, consisting of about 1/8 of the statistical data, is useless on Figure 11AA because the AFM was out of range. A more detailed study is needed to determine the surface roughness and differences between the surface topography of the grit blasted and as-received samples.

Figure 11Z. A Section of the Grit Blasted Sample

Figure 11AA. A Photo of the Grit Blasted Sample that illustrates the Location of the Section. The Photo is $60\text{ }\mu\text{m} \times 60\text{ }\mu\text{m}$.

Figure 11AB. A Section of the As Received Sample

Figure 11AC. A Photo of the As Received Blasted Sample that illustrates the Location of the Section. The Photo is $60\ \mu\text{m} \times 60\ \mu\text{m}$.

CHAPTER 12

DISCUSSIONS AND CONCLUSIONS

12.1 Discussion of Experimental Results

12.1a Comparison to Other Results Found in the Literature

The average time required for the windows to condition to 1 MW is 18.5 hours(See Table 8J). This time is exceptionally good compared to other test results reported in the literature. The test results of this work are compared to others found in the literature in Table 12A. This work tests windows at the highest power level reported in the literature. The conditioning time to 1 MW is fast compared to the average reported conditioning times.

Location	Window Type	Frequency	Max. Power (on test stand)	Test Time to reach Max. Power	Comments
LANL/LEDA	Coaxial	350 MHz	1 MW	18.5 Hours	Average of 18 windows tested
CESR ³⁷	Planar	500 MHz	250 kW	200 Hours	
CESR ³⁷	Planar	500 MHz	400 kW	75 Hours	
SLAC/B Factory ³⁹	Planar	450 MHz	500 kW	30 Min	
SLAC/B Factory ³⁹	Planar	500 MHz	500 kW	4 Days	window broke
ANL/APS ¹⁷	Cylindrical	350 MHz	100 kW	3 to 5 Days	
KEK/Tristan	Coaxial	508 MHz	200 kW	8 Hours	
CERN/LEP-Room Temp ⁴⁷	Coaxial	352 MHz	140 kW	1 Week	
CERN/LEP - Super Cond. ⁴⁷	Coaxial	352 MHz	200 kW	2 to 3 Days	

Table 12A. Comparison of LANL Test Results to Other Work

12.1b Conditioning Hypothesis

Conditioning is believed to be a cleaning process on the microscopic level. At a certain power level with a specific geometry, the electrons liberated from the surface follow a particular trajectory^{35,40}. The electric fields reach a value large enough to cause field emission from contaminated sites or to cause the electrons or ions driven by the electric fields to bombard the material surface. As the power level is increased the electron trajectories change slightly, and the electrons will collide with the surface at a new position. Hence, for a specific power level, the electrons will tend to collide with the surfaces at specific locations. If contaminants exist at these locations, a sudden increase in pressure will occur; arcing may follow. This bombardment of electrons cleans the surface by removing contaminants. After the surface contaminants are dislodged from the electron collisions and pumped away, the vacuum pressure will decrease. Then the power can be increased, and the window is conditioned at that power level.

During conditioning, two separate phenomena, multipacting and ion bombardment, are thought to be occurring. Multipacting has been documented in the literature many times. The signs of multipacting are rapid fluctuations in the vacuum pressure and nonlinear temperature increases with power. Multipacting tends to occur at specific power levels for a given window geometry. Effects of multipacting can be seen by comparing Figure 8I, RF Power vs. Test Time for Batch 2, to Figure 8J, Pressure vs. Test Time for Batch 2. For the first four hours of testing the effects of multipacting can be seen by examining the vacuum pressure. In the first four hours the vacuum pressure is high and has large fluctuations. In the later part of the test (hours 11 through 14), multipacting is not occurring and the vacuum pressure is much lower. Another effect of multipacting is the nonlinear increase in temperature as a function of power, as seen in Figure 8H. The second phenomenon is believed to be due to ion bombardment. As electrons are freed from the surface, they are colliding with molecules in the vacuum

chamber which produces ions. The ions collide with the surfaces on the vacuum chamber, which causes heating and additional electrons to be freed due to the high kinetic energy of the ions at the time of the collision. As more electrons are freed, more ions are made. In addition, there is a second method in which ions may form. When molecules are exposed to small electric fields at less than very good vacuum conditions, the electric fields may pull the molecule apart. These ions are then accelerated by the Lorenz forces into a surface where they cause heating and liberate more gas that further drives the process. The ion bombardment can be observed by a slow steady increase in the vacuum pressure. Following the slow steady pressure increase, nonlinear heating can be observed. An example of this phenomenon can be seen by comparing Figures 8U, coaxial temperatures vs. test time, to Figure 8W. Note that around 10 hours of test time, a nonlinear temperature increase was seen in 1A (window RFQ9). Also the vacuum pressure for these two windows (RFQ9 and RFQ10) steadily increased.

12.1c Effects of Processing Techniques

Many different processing techniques were tried on the windows, as summarized in Table 8J. Grit blasting is critical to the success of the windows. Grit blasting is reduces the nonlinear temperature increases by cleaning the surface and changing the surface topography. Changes in the surface topography dull the potential field enhancement sites which reduces multipacting. A window that was not grit blasted failed, and a second non-grit blasted window showed extensive nonlinear temperature increases. Windows that were grit blasted performed well. WD40 and DGF123 were used because the windows were thought to be multipacting on the metal surface near the ceramic. A coating material was sought that has a low SEE and that could be easily applied to the windows. Titanium is commonly used on metal because of its low secondary electron emission coefficient(SEE), however, a titanium coating would require the development of a complex system for applying the coating. WD40 had no consistent effect on the

window performance. Some windows coated with WD40 operated exceptionally well. Others coated with WD40 could not be conditioned, and had to be grit blasted. Grit blasting is believed to work well because it roughens and cleans the surface and thus suppresses the SEE. DGF123 was not a consistently successful processing technique. In addition DGF123 is a conductor. If it is deposited on the ceramic surface, large ohmic losses in the DGF123 coating will cause excessive heating. Because it is too difficult to apply it to the metal surfaces around the ceramic without contaminating the ceramic, this coating is deemed to be unsatisfactory. The effects of a copper black coating on the performance of the windows cannot be determined from these tests. Only the prototypes were coated with copper black, but then they were grit blasted to remove the coating. The coating was removed at the factory and could not be trusted. Therefore, based on the experimental results, grit blasting is critical to the success of a window and can even revive a "sick" window, while WD40 and DGF123 seem not to affect the performance of the window.

12.1d Diagnostic Equipment and Tools

This section discusses the various diagnostic equipment and its uses in conditioning. The diagnostic tools include the pressure, the RGA, the coaxial surface temperatures, the air and water temperatures, the arc detectors, the forward power, and the reflected power.

The pressure is an indicator of arcs, multipacting and absorbed gasses being emitted from the surfaces. When vacuum fluctuates rapidly this is usually evidence of multipacting. When the vacuum pressure increases and remains consistently high, ion bombardment is indicated. In this situation, the only way to lower the vacuum pressure was to decrease the RF power. A steady high pressure that will not decrease is a sign to beware of; this is indicative of ion bombardment which leads to excess heating.

The RGA displays the gas species in the vacuum chamber. Measurements indicate that the primary constituent is water vapor. The amount of water vapor does not fluctuate. This is assumed to be due to water vapor in the RGA sensor, not in the vacuum system. If the high water vapor were a valid reading, it should be affected by the RF power, but it stays constant regardless of the power levels. The second and third species identified by the RGA are hydrogen and AMU 28(either CO or N). Both of these readings are believed to be fairly accurate, because they fluctuate during conditioning and are affected by the RF power. The RGA data shows that sudden pressure increases may be part hydrogen and AMU 28, because increases in these species occurs during conditioning.

The coaxial surface temperatures readings have proved to be invaluable during conditioning. These temperatures are monitored very closely during conditioning. A nonlinear increase with power is indicative of a problem. During conditioning, the coaxial surface temperatures of each window are compared to each other. A sudden deviation, as seen in Figure 8H on window W2, is an indication of a problem. An unexpected increase in the coaxial surface temperature is probably due to a nonlinear heating mechanism - either multipacting or ion bombardment. A variation of the surface temperature readings on this particular window design is expected because of the asymmetric electric field distribution and because the auxiliary fans used at higher power levels. These variations were also observed closely to ensure that the rate of increase was similar to other windows.

The air outlet temperatures proved to be an helpful diagnostic tool at higher power levels. At lower power levels, the delta temperature(outlet temperature minus inlet temperature) could not be used as a diagnostic tool because the air inlet temperatures were high. At power levels below 400 kW, the air inlet temperatures are higher than the air outlet temperatures. In addition the air inlet temperatures changed with hose length. Nevertheless, the air outlet temperature was used as a diagnostic tool, because it is a good

indication of the overall heating in the window. The air outlet temperature was recorded at 20 kW, and this value was used as a baseline. From these values, air outlet temperature differentials were calculated and compared. A large differential was an indication of a problem. Usually the air outlet temperature differential corresponded to the surface temperatures. If an excessively high surface temperature reading was observed, the air outlet temperature would usually also be excessively high.

The arc detectors can also be used as a diagnostic tool; however, when an arc detector tripped, there was no method to determine whether the event was indeed an arc or merely some type of luminescent glow. If the arc detectors were indicating a large number of true arcs(not glows) and the pressure was very low with little fluctuations, the arc was assumed to be occurring on the ceramic, because the ceramic tends to be cleaner than metals in vacuum. If a large number of arcs(not glows) were occurring with large pressure fluctuations, the arcs were assumed to be occurring on the metal near the ceramic. The arc detectors are sensitive to light; therefore, an arc can not be distinguished from a glow discharge. A volumetric glow discharge will create ions which can then cause excessive heating. A large number of arcs detected were an indication of a problem regardless of if they were true arcs or glows discharges. Very few arcs were detected in the windows that were easily conditioned to 1 MW . Many arcs were observed in the windows that broke, or were experiencing excessive heating. In fact, in some cases so many arcs were occurring that the power could not be increased due to the RF interlock tripping. If only one arc detector in the vacuum chamber went off, the arc was assumed to be in the coaxial region. Otherwise the light from the arc would be reflected off the metal walls and detected by the arc detector on the other window. In any case, arcs detected, regardless of where they are, a glow or a true arc are indications of a problem.

The water temperature was not a valuable diagnostic tool. The water cooled the vacuum side T-bar and was not affected by the temperature of the ceramic. The

temperature increase between the water inlet and outlet temperatures was just a few degrees and remained fairly constant.

The infrared camera is a beneficial diagnostic tool. It was used to verify the temperature distribution on the ceramic. It was also used to correlate the temperature of the ceramic to the coaxial surface temperature. The temperatures from the IR camera were similar to the coaxial surface temperatures, as illustrated in Table 8L. One disadvantage to using the IR camera with the current test setup is that the port used for the IR camera is long and narrow in order to attenuate the electromagnetic fields. This is believed to cause reflections off of the metal wall, as seen in Figure 8AF. The IR camera is an excellent non contact method of measuring the temperatures of the window.

12.1e Conditioning Procedures

The various conditioning procedures and the successes and / or failures of the different methods are discussed. The type of conditioning method used depends on the behavior of the windows and the amount of heating and arcing seen in the windows. Different conditioning methods used include CW conditioning, pulsed conditioning, and amplitude modulation.

During conditioning thermal heating (measured by the coaxial surface temperatures or by the air outlet temperature) can indicate the occurrence of multipacting and ion bombardment. If no multipacting or ion bombardment is present, the window temperature increases linearly with the incident RF power in the waveguide. Below power levels of 400 kW the slope of temperature vs. power is lower than the slope above 400 kW due to the high air inlet temperature. This linear increase is because of the heating of the RF window, with no multipacting or ion bombardment, is due to the dielectric losses in the alumina ceramic, a linearly occurrence with RF power. Observations of the window temperature as a function of RF input is a valuable diagnostic tool. When the window temperature deviates from a constant slope or suddenly changes slope, it is an indication of multipacting or ion bombardment. This is

illustrated in Figure 8H. After a window experiences a nonlinear temperature increase and conditioning is continued, it is unrecoverable. The window can only be recovered by grit blasting. Even if the power is turned off and then turned back on, it will still have nonlinear temperature increases. The reason for this is unknown.

When pulsed conditioning was used as a remedy for the nonlinear temperature increase, the windows did not succeed. The advantage of pulsed conditioning is that the window can be exposed to higher peak fields, while still maintaining a lower average power. The lower average power leads to less dielectric heating in the window. A window experiencing nonlinear heating was never conditioned to the full power by using pulsed conditioning. Hence, pulsed conditioning does help decrease the average power and thus the heating in the window; however, it does not eliminate or reverse the nonlinear heating which leads to the failure of the window.

Amplitude modulation was used as a conditioning method to pass a region of high outgassing.. Amplitude modulation was very successful and is the recommended method of conditioning. It is thought to work so well because the peak power is increased in short pulses. This allows the vacuum system time to pump away gasses emitted from the surface during conditioning. A very low pressure can be maintained during conditioning. This low pressure is thought to help prevent excessive heating. Another advantage of amplitude modulation is that the power may be increased in very small steps by increasing the percentage of modulation. Another advantage of amplitude modulation is that a continuous range of power levels are conditioned. Without amplitude modulation the only power levels that are well conditioned are those discrete steps used in increasing the power. These large steps are because the power is increased in decibels, thus these discrete steps increase as the RF power is increased. The power steps become quite large and then the amount of gas emitted is very high each time the power is increased. This causes arcing and excessive heating. The arcing and heating effects are usually

unrecoverable if they are persistent. Amplitude modulation avoids these discrete steps and the problems associated with them.

12.1f Vacuum Experiments

The calculated and the measured pumping speeds agree. The calculated effective pumping speed is 837 l/sec and the measured effective pumping speed is 756 l/sec. This yields a 9.6% error. However, the measured effective pumping speed is expected to decrease over time, as pumped molecules are absorbed in the cryopumps.

The outgassing rate is nonlinear as a function of power, as shown in Figure 8AC. The outgassing rate approaches an asymptotic value as the power level is increased. This is believed to occur for two reasons. First there might be insufficient energy to release more ions at the higher power levels. Second, there may be a lack of molecules. The outgassing rate is believed to be nonlinear with RF power because of the ion bombardment phenomenon that occurs at higher power levels.

12.2 Discussion of Analytical Results

The analytical model generally agrees with the experimental measurements; however, there are small discrepancies. Differences between the measured and calculated S parameter measurements are thought to be due to the phase shift between the calibration and the window measurement, assuming the load is a good match. The asymmetric fields are caused by the existence of a higher order mode between the air side T bar and the vacuum side T bar. In the structural model, the window was modeled as a simply supported beam. In reality, it is a combination of the "simply supported" and "fixed" conditions. There is probably a small resistance as the ceramic expands in the radial direction. Nevertheless, this is not expected to significantly increase the stresses. In the thermal model, convection due to the air flow on the surface of the window was modeled as a uniform flow. In reality this flow is not uniform, as air is blown through a

series of small holes in the inner conductor region directed on the ceramic. Thus, the air convection coefficient may be larger near the center of the disk. Modeling the convection coefficient uniformly leads to worse reliability results. Hence, the model is conservative.

The thermal and structural results from the computer model were compared to the models done at Lawrence Livermore National Laboratory (LLNL) and EEV, as shown in Table 12B. The amount of power absorbed in the alumina for all the models ranges from 55 W to 128 W. Differences in these values will lead to differences in the resultant

	LANL (This work)	LLNL ⁴⁵	EEV ⁵⁰
Power Absorbed	55 W	80.2 W	128 W
Minimum Temperature	351 K	361 K	332 K
Maximum Temperature	368 K	370 K	342 K
Delta T	17	9	10
Maximum Principal Stress	16.8 MPa	30 MPa	10.9 MPa

Table 12B. Comparison of the Thermal and Structural Results to Other Work

temperatures and stresses. A comparison of the absolute maximum and minimum temperatures is not as critical as a comparison as the temperature difference. It is interesting to note that the temperature difference from the LANL model is larger than the other two models. However, the stresses for the LANL model are not the largest. This is due to differences in the boundary conditions applied to the models and the methods in which the structure was constrained. LLNL constrained the window with a fixed boundary condition, which will cause larger stresses than the simply supported condition. Both LANL and EEV used the simply supported boundary condition. The calculated stresses range from 16.8 MPa to 30 MPa. These are small compared to the flexural strength of alumina which is close to 300 MPa. Overall, from studying all three models,

one can conclude that the stresses from the thermal gradients are well within the safe operating range.

12.3 Discussion of Strength and Fracture Results

Results of the mechanical testing show that no detectable residual stresses were found in the disks. Residual stresses may exist; however, if they are uniform over the entire disk, they are not detectable. The possibility of this happening is small because residual stresses usually occur as a result of machining a large hole in the middle of a flange. Sintering the disks minimizes the residual stresses. Therefore, it can be assumed that the windows have no noticeable residual stresses.

The strength of the grit blasted samples was about 5 MPa lower than the non grit blasted samples. This difference is only a 2% decrease in strength and should not unfavorably affect the performance of the window. As discussed previously, this small decrease in strength is probably due to surface damage from the grit blasting.

The Weibull and fatigue data for the analytical model were calculated from the four point bend test data. The Weibull results are close to the anticipated values and the values found in the literature. The fatigue data deviated a little more than the Weibull data from the anticipated values. The fatigue data show that the alumina may be susceptible to the effects of fatigue. However, this does not present a problem, because the analytical model shows that the window has an adequate lifetime even considering the effects of fatigue. One thing to note is that the experimental data are dynamic fatigue data (based on a constant stressing rate), but the model is running cyclic fatigue. This should not affect the conclusions of the analytical model.

12.4 Discussion of Microscopy Results

The experimental results show that grit blasting is critical to improving the performance of the RF windows. The microscopy was performed to determine why the grit blasting has such a favorable effect on the performance of the window. The results of the SEM and the preliminary results of the AFM show that grit blasting changed the surface topography. It is speculated that the grit blasting increased the surface roughness but increased the smoothness on a finer scale by removing local bumps and valleys. The surface analysis showed that the grit blasted samples had a much lower carbon content than samples that were not grit blasted. This indicates that grit blasting has a cleaning effect on the surface of the window. It is not clear why the presence of carbon would degrade the performance of the windows. It is believed that the reason why the grit blasted windows perform so much better is due to changes in surface topography rather than to changes in surface chemistry. Hence, one could speculate that by smoothing out the surface on a local scale, the secondary emission was decreased. This might be because a narrow high peak or bump would tend to act as a "lightening rod" and cause a local intensification to the electric field. Local field intensifications can increase the fields which then in turn increase the secondary electron emission. A more detailed study of the surface topography and a measurement of the secondary electron emission coefficient of both the grit blasted and the as-received samples would test this theory. Another point to consider is that the ceramic and metal surfaces surrounding the ceramic were grit blasted. Therefore, it is not clear whether the success of the grit blasting is due to the effects on the metal, or the ceramic, or both.

12.5 Conclusions

- Hydrogen and AMU 28, CO and/or nitrogen, are emitted during conditioning.
- There are two nonlinear heating mechanisms, multipacting and ion bombardment. Both mechanisms have been experimentally documented. The nonlinear outgassing rate as a function of RF power supports the occurrence of ion bombardment at higher power levels.
- Grit blasting is essential to the successful operation of the windows.
- Grit blasting has cleaning effects and changes the surface topography. High concentrations of carbon were found on the samples that were not grit blasted.
- Once nonlinear temperature increases and repeated arcing occur, these phenomena cannot be conditioned away. The window must be grit blasted to recover it.
- Amplitude modulation is the recommend method for conditioning windows.
- WD40 and DGF123 are not recommended for use on the windows. Experimental results are inconclusive.
- Clusters of coarse grains were found at the fracture origins.
- No detectable residual stress was found in the disks.

12.6 Future Work

Though considerable progress has been made as a result of this research, future investigations will undoubtedly enable designers to produce even more reliable RF windows. The efforts most likely to produce fruitful results fall in these categories:

- a) RF Apparatus and Experiments
- b) Materials Research
- c) Vacuum Investigations
- d) Analytical Work

Recommended work in each category is outline below.

RF Apparatus and Experiments:

- Design and build an automatic conditioning apparatus for RF windows. One feature of the apparatus: When the vacuum has improved RF power will be automatically increased.
- Perform lifetime testing on windows. Test windows for many hours to determine long-term effects.
- Determine from experiments whether the success of the grit blasting is due to grit blasting the metal surfaces or the ceramic surfaces. These experiments might include grit blasting the metal and not the ceramic on one window. On a second window, grit blasting the ceramic and not the metal. Then evaluate the performance of the windows under RF power.

Materials Research:

- Study the effects of conditioning (RF exposure) on the surface of the window. Examine the surface of the window using microscopy to determine the effects of conditioning on the surface of the window. Characterize changes in the surface topography and in the chemistry.
- Etch alumina samples. Then correlate the grain size and number of visible pores to RF performance.
- Test the mechanical properties of alumina after many hours of RF exposure to determine if there has been any degrading of mechanical performance.
- Perform microscopy on the metal surface near the ceramic. Compare the chemistry and topography of the grit blasted to the non grit blasted metal surface. Compare the surfaces, both grit blasted and non-grit blasted, before and after RF exposure.
- Experimentally test different anti-multipacting coatings. Find the optimal thickness for each coating.

- Do a study to find the optimal material for an RF window. Compare the different window materials both analytically and experimentally.
- Do microscopy to determine which flaw geometry in the CARES code would best represent the flaws in the alumina material.
- Develop a method of nondestructive testing that can be used as an acceptance criterion for the ceramic.
- Measure the surface roughness of the grit blasted and non grit blasted sample to determine the effect of grit blasting on the surface roughness.
- Measure the secondary electron emission coefficient of grit blasted samples and non grit blasted samples.

Vacuum Investigations:

- Measure the outgassing rate of copper and alumina as a function of time. This would be particularly useful if done over a long period of time(~ two weeks).

Analytical Work:

- Develop a coupled electromagnetic thermal model. This model would be able to input the thermal temperatures directly into the electromagnetic model. The material properties change as a function of temperature. This change affects the amount of heat absorbed in the window.
- Measure the material properties such as the loss tangent, dielectric constant, thermal conductivity, and specific heat as a function of temperature in alumina. Enter these properties as a function of temperature in the computer model.
- Model the mechanism of multipacting and/or the electron avalanche on a window.
- Include heat loads from multipacting in the thermal, structural and reliability models.

APPENDIX A: FORTRAN PROGRAM Reade.f

```

program reade

c   this program is:
c       - to read in the data from the file of tets in the window
c       - calculate the magnitude of the e field (from the real & img)
c       - generate the input deck for Abaqus
character*1 dum, date*24, fileans, oldfileans
character*8 vert, face*2, pface*2
character*20 filename
character*40 line1
real *8 cond, omega, eps, mage, power
real *8 node(60000,6), kata(60000)
real *8 elnode(60000,11)
real *8 xvalue(20), coord(31), yvalue(20), zvalue(20)
integer element, nnum, ncheck(60000), ele, true(10)
integer n2check(60000), nsymp(60000)
integer nairp(60000), nvacp(60000), n2checka(60000), nchecka(60000)
integer nmem
integer mem(6000,7)

c -----
c   give the option to use the old files, so it doesn't have to resort all the nodes
print *, 'Use the previous element and node data --'
print *, 'Use the old files efield.dat, element.dat, and node.dat?(y/n)'
oldfileans = 'y'
c   read (*,79) oldfileans
print *, 'y'
print *, ' '
if ( oldfileans .eq. 'y') then
goto 62
endif

c -----
c   Enter the amount of power that is to be put into the waveguide
7   print*, ' '
print *, 'Enter the incident power in the waveguide [ watts ]: '
read *, pincident
print *, ' '
write(*,8) pincident
8   format( ' Incident power = ',E10.2, ' Watts.    Is this correct? (y/n)')
read(*,79) dum
if (dum .eq. 'n') goto 7

c -----
c   For a description of the arrays coord and xvalue see subroutine doc
CALL DOC

c -----
c   ask for the directory name and then
c   eliminate extra spaces on the name of the directory
c       CALL FILENAMES(name41,name42,name43,name44,name45,
c       cname46,name52)
c   open data files
c       open(unit=41,file = name41, status='unknown')!lastrun.dat
c       open(unit=42,file = name42, status='unknown')!efield.dat
c       open(unit=43,file = name43, status='unknown')!window.dat
c       open(unit=44,file = name44, status='unknown')!element.dat
c       open(unit=45,file = name45, status='unknown')!node.dat

```



```

open(unit=123,file = 'dia.dat', status='unknown')

open(unit=41,file ='reade.files/lastrun.dat', status='unknown')
open(unit=42,file ='reade.files/efield.dat', status='unknown')
c *****
open(unit=43,file ='eev4/known.dat', status='unknown')
c*****
open(unit=44,file ='reade.files/element.dat', status='unknown')
open(unit=45,file ='reade.files/node.dat', status='unknown')

c data file descriptions:
c 41 lastrun.dat = data file containing the nnum and element
c 42 efield.dat = data file listing the element and the power
c 43 window.dat = data file containing only the elements in the window
c 44 element.dat = data file listing the tetrahedrals by elements
c 45 node.dat = data file listing the x,y,and z coordinates of each
c 46 thermo.inp = input file for the abaqus thermal model
c 47 film.dat = data file of the elements on the win surface
c 48 bound.dat = the nodes on the outer bound between win and coax
c 49 eev3.indat = the input file for the geomety
c 50 boundl.dat = the nodes on the inner bound between win and coax
c 52 struc.inp = input file for the abaqus structural model
c 53 sym.dat = the nodes on sym plane constrained in z direction
c 54 air.dat = the nodes on the air surface of the window
c 55 vac.dat = the nodes on the vac surface of the window
c 56 outfilm.dat = data file of the elements on the outer boundary
c 57 infilm.dat = data file of the elements on the inner boundary
c 58 airfilm.dat = data file of the elements on the air surface
c 59 vacfilm.dat = data file of the elements on the vac surface
c 60 airrad.dat = data file for radiation on the air surface
c 61 vacrad.dat = data file for radiation on the vac surface
c 62 pres.dat = elements on window air surface for pressure diff.
c -----
c find where the tetrahedral data starts
c read in the titles
read(43,12) dum ! first line
read(43,12) dum ! second line
c check to see if there is data ( to see of it is a h or x)
10 read(43,12) dum
c print*, 'dum=',dum
if (dum .eq. 'x') then
goto 10
12 format(A1)
endif
read(43,13) vert
13 format(A8)

c -----
c initialize counters
element = 0 !element = # of elementss
nnum = 0 !nnum = # of nodes
15 element = element + 1
16 coord(1) = element
nmem = 0

c -----
c read in data
CALL READ(coord,xvalue,yvalue,zvalue)

```

```

c -----
c switch from HFSS notation to ABAQUS notation
c to switch from HFSS to ABAQUS I changes the values in the
c coordinates of the midpoints, and changed the order that the coord
c were wrote out in.

c -----
c calculate the coordinates of the midpoints
coord(14) = (coord(2) + coord(5))/2.0
coord(15) = (coord(3) + coord(6))/2.0
coord(16) = (coord(4) + coord(7))/2.0
coord(20) = (coord(2) + coord(8))/2.0
coord(21) = (coord(3) + coord(9))/2.0
coord(22) = (coord(4) + coord(10))/2.0
coord(23) = (coord(2) + coord(11))/2.0
coord(24) = (coord(3) + coord(12))/2.0
coord(25) = (coord(4) + coord(13))/2.0
coord(17) = (coord(5) + coord(8))/2.0
coord(18) = (coord(6) + coord(9))/2.0
coord(19) = (coord(7) + coord(10))/2.0
coord(26) = (coord(5) + coord(11))/2.0
coord(27) = (coord(6) + coord(12))/2.0
coord(28) = (coord(7) + coord(13))/2.0
coord(29) = (coord(8) + coord(11))/2.0
coord(30) = (coord(9) + coord(12))/2.0
coord(31) = (coord(10) + coord(13))/2.0

c -----
c assign the x, y , and z coordinates an node number
k = 1
do 72 j = 1,10
c this is for node j in a tetradedral
nnum = nnum + 1
node(nnum,1) = nnum
k = k + 1
node(nnum,2) = coord(k)
k = k + 1
node(nnum,3) = coord(k)
k = k + 1
node(nnum,4) = coord(k)
72 continue

c -----
c calculate the efield at the center of the tetrahedral
c x part: average the E(x) components of the points on the tetradedral
c 1) add the real parts
xreal = xvalue(1) + xvalue(3) + xvalue(5) + xvalue(7) +
c xvalue(9) + xvalue(11)+ xvalue(13)+ xvalue(15)+
c xvalue(17)+ xvalue(19)
c 2) add the imaginary parts
ximag = xvalue(2) + xvalue(4) + xvalue(6) + xvalue(8) +
c xvalue(10)+ xvalue(12)+ xvalue(14)+ xvalue(16)+
c xvalue(18)+ xvalue(20)
c 3) divide by the total number of points
xreal = xreal/10.0
ximag = ximag/10.0

```

```

c y part:    average the E(y) components of the points on the tetradedral
c            1) add the real parts
c              yreal = yvalue(1) + yvalue(3) + yvalue(5) + yvalue(7) +
c                yvalue(9) + yvalue(11)+ yvalue(13)+ yvalue(15)+
c                yvalue(17)+ yvalue(19)
c            2) add the imagionary parts
c              yimag = yvalue(2) + yvalue(4) + yvalue(6) + yvalue(8) +
c                yvalue(10)+ yvalue(12)+ yvalue(14)+ yvalue(16)+
c                yvalue(18)+ yvalue(20)
c            3) divide by the total number of points
c              yreal = yreal/10.0
c              yimag = yimag/10.0

c z part:    average the E(z) components of the points on the tetradedral
c            1) add the real parts
c              zreal = zvalue(1) + zvalue(3) + zvalue(5) + zvalue(7) +
c                zvalue(9) + zvalue(11)+ zvalue(13)+ zvalue(15)+
c                zvalue(17)+ zvalue(19)
c            2) add the imagionary parts
c              zimag = zvalue(2) + zvalue(4) + zvalue(6) + zvalue(8) +
c                zvalue(10)+ zvalue(12)+ zvalue(14)+ zvalue(16)+
c                zvalue(18)+ zvalue(20)
c            3) divide by the total number of points
c              zreal = zreal/10.0
c              zimag = zimag/10.0

c calculate the magnitude:
c            mage =(xreal**2 +ximag**2 +yreal**2 +yimag**2 +zreal**2
c              +zimag**2)**.5
c HFSS uses the DC power calculation for the power in watts.
c we are using sinusoidal power; therefore, we have to mult.
c the power by the squareroot of 2.

c            mage = mage * ( 2**(.5))
c I am doing this multiplicatoin right before I write out the
c data do thermo.inp

c calculate the power absorbed in watts/cm^3:
c This is the power/dV, assuming the magnetic loss tan = 0
c The equation used simplifies to: P/dv = (cond + omega*Img(epsolon))*E^2
c      cond = 1.0E-12      !s/m , DC conductivity
c      omega = 2.19911485751E9      !for 350 MHz
c      eps   = 2.9532517E-14 !F/m, = loss tan * permittivity
c            where permittivity=relative perm*perm free space
c      power = .5*(cond + omega * eps)* mage**2      !W/m^3
c      power = (cond )* mage**2      !W/m^3
c -----
c      write(123,*) element, mage,power
c      write the data for the tetrahedral to the efield file (efield.dat) :
c      write(42,89) element, power
89      format(1x,I4,',',6x,'BF,',E16.8)
c      print * , element

c -----
c      check to see if there is another tetrahedral
c      read(43,12) dum
c      if (dum.EQ. 'h') then
c      read(43,13) vert

```

```

        goto 15
    endif
    print*, ' The total number of of elements = ', element
c -----
c     write out the nnum and the element to the file lastrun.dat
    write(41,*) nnum
    write(41,*) element
c -----
c to keep track of which nodes are in which tetrahedral write this
c to the node array BEFORE the nodes are reordered and sorted
c first, find which element and node each node is:
    ncow = 0
    do 125 j = 1, nnum
        check = j/10. - int(j/10.)!find out if nnum is at the start of a tet
        if (check .eq. 0.0) then
            nel = int(j/10.0)
            ncow = 0
            node(j,6) = 10                ! node(j,6) = the node # in each element
        else
            ! node(j,5) = the element #
            nel = int((j/10.0) + 1)
            ! nel = element #
            ncow = ncow + 1
            node(j,6) = ncow
        end if
        node(j,5) = nel
125    continue
c -----
c sort nodes by putting them in ascending order
c     print *, ' '
    print *, 'sorting nodes by x,y,z coordinates .....'
    CALL SORT(node,nnum)
c -----
c     write out the node array to check it
    do 105 i = 1, nnum
        write(*,102) int(node(i,1)), node(i,2), node(i,3), node(i,4)
        write(*,88) int(node(i,1)), node(i,2), node(i,3), node(i,4),
c c node(i,5), node(i,6)
105    continue
88    format(1x, I4, ' ', ' ', 4(2x, E16.8, ' ', ' '), 2x, E16.8)
c -----
c generate elnode array for the *ELEMENT file
    print *, ' '
    print *, 'making *ELEMENT file .....'
c check node array
    do 108 i = 1, nnum
        write(*,88) int(node(i,1)), node(i,2), node(i,3), node(i,4)
c c , node(i,5), node(i,6)
        if (int(node(i,1)) .eq. 0) then
            print *, '*****'
        end if
108    continue

c first, copy node array, node, to another array, elnode
    do 106 i = 1, nnum
        do 107 j = 1, 6
            elnode(i,j) = node(i,j)
107    continue
106    continue

```

```

c      do 108 i = 1,nnum
c      write(*,88) int(elnode(i,1)),elnode(i,2),elnode(i,3),elnode(i,4)
c      c , elnode(i,5), elnode(i,6)
c      if (int(elnode(i,1)) .eq. 0) then
c      print *, '*****'
c      end if
c108  continue

c second, sort array, enode, by element number, then by nodes
      CALL ESORT(elnode,nnum,element)
c write out elnode array to check it
      print *, nnum
c      do 108 i = 1,nnum
c      write(123,88) int(elnode(i,1)),elnode(i,2),elnode(i,3),elnode(i,4)
c      c , elnode(i,5), elnode(i,6)
c108  continue
c      close(unit=123)
c -----
c      do 108 i = 1,nnum
c      write(*,88) int(elnode(i,1)),elnode(i,2),elnode(i,3),elnode(i,4)
c      c , elnode(i,5), elnode(i,6)
c108  continue
c      write the data to *ELEMENT file ( element.dat)
c      (which nodes are in which tetrahedrals)
      do 110 j = 1, element
      if (j .eq. 1) then
        i = 1
      else
        i = (j-1)*10 +1
      end if
      write(44,97) j,int(elnode(i,1)),int(elnode(i+1,1))
c      ,int(elnode(i+2,1))
c      ,int(elnode(i+3,1)), int(elnode(i+4,1)),int(elnode(i+5,1))
c      ,int(elnode(i+6,1))
c      ,int(elnode(i+7,1)),int(elnode(i+8,1)),int(elnode(i+9,1))
110  continue
97   format(1x,I6,',',9(I6,','),I6)
c -----
c eliminate duplicate nodes
c initialize kata array
      do 124 i = 1, nnum
      kata(i) = 0 !kata is just an array to mark which nodes are duplicates
124  continue
c -----
c first, throw way duplicate nodes
      print *, ' '
      print *, 'throwing away duplicate nodes .....'
      do 120 i = 2, nnum
      if (node(i,1) .eq. node(i-1,1)) then
        kata(i) = 99E99 !this means it is a duplicate node
      end if
120  continue
      print *, 'writing out *NODE ....'
c second, write out the array to the *NODE (node.dat) file
      iiii = 0
      do 130 i = 1, nnum
      if (kata(i) .ne. 99E99) then
        iiii = i +1

```

```

        write(45,102) int(node(i,1)) ,node(i,2), node(i,3), node(i,4)
c      write(*,*)i,iiii,int(node(i,1)) ,node(i,2), node(i,3), node(i,4)
c      write(*,88) int(node(i,1)) ,node(i,2), node(i,3), node(i,4)
c      c , node(i,5), node(i,6)
        end if
130      continue
c      third, write out node array to check it
c      do 123 i = 1, nnum
c      write(*,102) int(node(i,1)) ,node(i,2), node(i,3), node(i,4)
c123      continue

c      print *, 'nnum =', nnum, 'iiii =', iiii

c -----
102      format(1x, I7, ', ', 2(2x,E16.8, ', '), 2x,E16.8)
90      format(4x,E23.16E2, 2(5x,E23.16E2))
91      format(1x, 'coord ', I2, ' = ', E22.16E2)
92      format(1x, 'xvalue', I2, ' = ', E24.16E2)
93      format(4x,E23.17, 4x,E24.16, 6x,E24.16, 4x,E24.16, 4(5x,E24.16, 3x,E24.16
c      , 5x,E24.16, 5x,E24.16))
94      format(1x, 'yvalue', I2, ' = ', E24.16E2)
96      format(1x, 'zvalue', I2, ' = ', E24.16E2)
98      format(5x, ' 1', 5x, 3E16.8)
99      format(5x, ' 2', 5x, 3E16.8)
100     format(5x, ' 3', 5x, 3E16.8)
101     format(5x, ' 4', 5x, 3E16.8)

c -----
c      put write the word 'end' at the end of the node.dat file and the element
c      .dat file
        write(44,*) '000,      0, 0, 0, 0, 0, 0, 0, 0, 0, 0'
        write(45,*) '000,      0.0,      0.0,      0.0'

c -----
c      close data files
        close(unit=123) !dia.dat
        close(unit=41) !lastrun.dat
        close(unit=42) !efield.dat
        close(unit=43) !evec.arg.short
        close(unit=44) !element.dat
        close(unit=45) !node.dat

c -----
c      find out if the user wants to input the data to define the surfaces
c      and boundaries from a file
62      if ( oldfileans .eq. 'y') then
        nmem =0
607      print*, ' '
        print *, 'Enter the incident power in the waveguide [ watts ]: '
        read *, pincident
c      pincident = 1.0E6
c      print *, ' '
        write(*,8) pincident
c      read(*,79) dum
c      if (dum .eq. 'n') goto 607
        open(unit=41, file='reade.files/lastrun.dat', status='unknown')
        print *, ' '
        print *, 'Enter how many nodes there are'
        read(41,*) nnum

```

```

        print *, nnum
        print *, ' '
        print *, 'Enter how many elements there are'
        read(41,*) element
        print *, element
        close(unit=41)
    endif
    print*, 'Use a file to enter the data to define
c the surface and boundaries? (y/n)'
    fileans = 'y'
    print *, 'y'
    print *, ' '
c    read(*,79) fileans
79    format(A1)
    if (fileans .eq. 'y' ) then
        print *, ' '
        print *, ' Enter the name (use full path) of the file: '
        filename = 'eev3/eev3.indat'
        print *, 'filename = eev3/eev3.indat'
        print *, ' '
c    read (*,80) filename
80    format(A20)
    else
        goto 148
    endif
    print *, ' '
    open(unit=49, file=filename, status='unknown')
    first find out what the surface is:
148    print*, ' '
c    print*, '----- WINDOW GEOMETRY -----'
c    print*, 'Enter what plane describes the surface of the window:'
c    print*, ' 1 =  yz plane (constant x)'
c    print*, ' 2 =  xz plane (constant y)'
c    print*, ' 3 =  xy plane (constant z)'
    if ( fileans .eq. 'y') then
        read(49,81) nplane
c    print *, nplane
81    format(/,I3)
    else
        read(*,150) nplane
    endif
150    format(I4)
    if (nplane .eq. 1) then
        write(*,151)
151    format('Enter the x coordinate of the plane,i.e., x =')
    elseif (nplane .eq. 2) then
c    write(*,152)
152    format('Enter the y coordinate of the plane,i.e., y =')
    elseif (nplane .eq. 3) then
        write(*,153)
153    format('Enter the z coordinate of the plane,i.e., z =')
    else
        write(*,*) 'This is not a valid option'
        goto 148
    endif
    if ( fileans .eq. 'y') then
        read(49,*) plane
c    print *, plane

```

```

        else
        read*, plane
        endif
        planeup = plane + .01
        planelo = plane - .01

c -----
c      MAKE bound.dat: sort and find which elements are on the boundary
c      between the alumina and the metal.
c      Write to file bound.dat
c -----
c      open(unit=123,file = 'dia.dat', status='unknown')
c      open(unit=48,file='reade.files/bound.dat',status='unknown')
c      open(unit=50,file='reade.files/boundl.dat',status='unknown')
c      keep old nplane value, but change the name
c      nplanesuf = nplane
c input where the boundary is.
c      print*, ' '
c      print*, '-----BOUNDARY SURFACE -----'
c      print*, 'Enter how many surfaces define the boundary between the
c      alumina and the waveguide:'
c      if ( fileans .eq. 'y') then
c      read(49,*) nsurfaces
c      print *, nsurfaces
c      else
c      read*,nsurfaces
c      endif
c      nbound = 0      !nbound = a counter for the number of nodes in bound.dat
c      nba= 0
c      nbl=0
c      open(unit=696,file='reade.files/stupid.dat',status='unknown')
c      do 200 j = 1, nsurfaces
c      first find out what the surface is:
248      print*, ' '
c      write(*,249) j
c249      format('Enter what plane describes boundary',I2,' of the window:')
c      print*, ' 1 =   yz plane (constant x)'
c      print*, ' 2 =   xz plane (constant y)'
c      print*, ' 3 =   xy plane (constant z)'
c      print*, ' 4 =   a circle '
c      if ( fileans .eq. 'y') then
c      read(49,*) nplane
c      print *, nplane
c      else
c      read(*,150) nplane
c      endif
c      print *, ' '
c      if (nplane .eq. 1) then
c      write(*,151)
c      elseif (nplane .eq. 2) then
c      write(*,152)
c      elseif (nplane .eq. 3) then
c      write(*,153)
c      elseif (nplane .eq. 4) then
c      print*, 'This is to describe the boundary between the alumina
c      and the metal.'
c      write(*,154)
154      format( 'Radius: ', $)

```



```

        if ( fileans .eq. 'y') then
        read(49,*) brad
c      print *, brad
        else
        read*, brad
        endif
c      print*, '
c -----
        if ( nplanesuf .eq. 1) then !yzplane (constant x)
        write(*,155)
155      format( ' y coordinate of the center point: ', $)
        if ( fileans .eq. 'y') then
        read(49,*) bfirst
        print *, bfirst
        else
        read*, bfirst
        endif
        write(*,156)
156      format( ' z coordinate of the center point: ', $)
        if ( fileans .eq. 'y') then
        read(49,*) bsecond
        print*, bsecond
        else
        read*, bsecond
        endif
        print*, ' '
        print*, 'Enter the thickness of the window.'
        write(*,158)
158      format( '      Enter the x start: ', $)
        if ( fileans .eq. 'y') then
        read(49,*) bstart
        print *, bstart
        else
        read*, bstart
        endif
        write(*,161)
161      format( '      Enter the x end  : ', $)
c -----
        elseif (nplanesuf .eq. 2) then !xz plane (constant y)
c      write(*,157)
157      format( ' x coordinate of the center point: ', $)
        if ( fileans .eq. 'y') then
        read(49,*) bfirst
c      print *, bfirst
        else
        read*, bfirst
        endif
c      write(*,156)
        if ( fileans .eq. 'y') then
        read(49,*) bsecond
c      print *, bsecond
        else
        read*, bsecond
        endif
c      print*, ' '
c      print*, ' Enter the thickness of the window.'
c      write(*,162)
162      format( '      Enter the y start: ', $)

```

```

        if ( fileans .eq. 'y') then
        read(49,*) bstart
c      print *, bstart
        else
        read*, bstart
        endif
c      write(*,163)
163    format( '      Enter the y end : ', $)
        if ( fileans .eq. 'y') then
        read(49,*) bend
c      print *, bend
        else
        read*, bend
        endif
c -----
        elseif (nplanesuf .eq. 3) then !xy plane (constant z)
        write(*,157)
        if ( fileans .eq. 'y') then
        read(49,*) bfirst
        print*, bfirst
        else
        read*, bfirst
        endif
        write(*,155)
        if ( fileans .eq. 'y') then
        read(49,*) bsecond
        print*, bsecond
        else
        read*, bsecond
        endif
        print*, ' '
        print*, ' Enter the thickness of the window.'
        write(*,166)
166    format( '      Enter the z start: ', $)
        if ( fileans .eq. 'y') then
        read(49,*) bstart
        print*, bstart
        else
        read*, bstart
        endif
        write(*,164)
164    format( '      Enter the z end : ', $)
        if ( fileans .eq. 'y') then
        read(49,*) bend
        print *, bend
        else
        read*, bend
        endif
        endif
c -----
c      print*, ' '
c      now we need to sort thru and figure out which nodes are on the boundary
c      between the alumina and the metal.

c      write(*,*) 'brad = ', brad, ' j=', j
c      first, set up some tolerances
        bradup = brad + .01
        bradlo = brad - .01

```

```

c second, open up node file
      open(unit=45,file = 'reade.files/node.dat', status='unknown')
c third, check the the coordinates for the thickness
c      ( they should all be in there if the window is a constant thick)
c      print*, 'nodenum = ', nnum
c      print*, 'bstart = ', bstart
c      print *, ' bend = ', bend
c      print *, 'bfirst = ', bfirst
c      print *, 'bsecond =', bsecond
c      print *, ' nplane =', nplane
c      print*, 'nplanesuf = ', nplanesuf
c      nbound = 0

c      write(*,*) 'nnum =', nnum

      do 147 i = 1, nnum
      read(45,*) nodenum, x,y,z
c      print *, 'node =', nodenum, 'x =', x, 'y =', y
      if (nodenum .eq. 000) then
        close(unit=45)
        goto 282
      endif
      if (nplanesuf .eq. 1) then
c        !compare x coord
      elseif (nplanesuf .eq. 2) then
c        need to see if it falls on the radius
        bradcalc = (( x)**2 +( z )**2)**.5
        if (j. eq. 1) then
          bradlo = 108.367 -.001
          bradup = 108.6 +.01
        elseif (j. eq. 2) then
          bradlo = 25.0 -.01
          bradup = 25.0 +.001
        endif
        write(696,*)i,nodenum, 'j=',j,'bradcalc=',bradcalc
        write(696,*) '          b lo/up=',bradlo,bradup
        if ((bradcalc .ge. bradlo) .and. (bradcalc .le. bradup)) then
          nbound = nbound +1
          write(696,*) '_____ passed radius test, nbound =',nbound
          if (j .eq. 1) then
            nboundo =nboundo +1
            ncheck(nboundo) = nodenum !ncheck=outer brazed nodes
            if ((y .ge. 5.99) .and. (y .le. 6.01)) then
              nba = nba +1
              nchecka(nba) = nodenum
            endif
          elseif (j .eq. 2) then
            nboundi = nboundi +1
            n2check(nboundi) = nodenum !n2check=innner brazed nodes
            if ((y .ge. 5.99) .and. (y .le. 6.01)) then
              nbla = nbla +1
              n2checka(nbla) = nodenum
            endif
          endif
        endif
      elseif (nplanesuf .eq. 3) then
c        !compare z coord
      endif

```

```

147  continue
c      close(unit=123)
      close(unit=45)
      goto 282
      else
      write(*,*) 'This is not a valid option'
      goto 248
      endif

282  if (j .eq. 1) then    !outer boundary nodes
c      print out the node numbers to bound.dat
      boundtemp = 294.5
      nbvar = 11
      do 210 i = 1,nboundo
      write(48,281) ncheck(i),nbvar,nbvar,boundtemp
281  format(5x,I7,',',',',2(5x,I4,',','),5x,F10.2)
210  continue
      close(unit=48)
      elseif (j .eq. 2) then    !inner boundary nodes
      bound2temp = 294.5
      n2bvar = 11
      do 275 i = 1, nboundi
      write(50,281) n2check(i),n2bvar,n2bvar,bound2temp
275  continue
      close(unit=50)
      endif
200  continue

c      write(*,*) ' nboundo =', nboundo
c      write(*,*) ' nboundi =', nboundi
      close(unit=696)

c -----
c      Sort through ncheck(nb) and n2check(nbl) and make
c      nchecka(nba) and n2checka(nbla) of nodes
c      where y= 6mm
c -----
c      MAKE sym.dat = the nodes on the symmetry plane to be constrained in
c      the z direction
c      symp(nsym) = the array with a list of node numbers
c -----
      open(unit=53,file='reade.files/sym.dat',status='unknown')
c      initialize counters
      sym = 0.0 !defines z coordinate of sym plane
      nsym = 0 ! counter of the number of nodes on sym plane

c      set up tolerances
      symup = sym + .001
      symlo = sym - .001
c      sort for nodes in plane sym = z
      open(unit=45,file = 'reade.files/node.dat', status='unknown')
      do 860 i = 1, nnum
      read(45,*) nodenum,x,y,z
      if (nodenum .eq. 000) goto 878
      if (( z .ge. symlo) .and. (z .le. symup)) then
      nsym = nsym + 1
      write(53,283) nodenum, x,y,z
      nsymp(nsym) = nodenum

```

```

      endif
860      continue
878      write(53,*)'      000,      00,      00,      0.0'
      close(unit=45)
      close(unit=53)
283      format(5x,I7,' ',2(5x,F10.5,' '),5x,F10.2)

c -----
c      MAKE air.dat = the nodes on the air surface
c      airp(nair) = the array with a list of node numbers
c -----
      open(unit=54,file='reade.files/air.dat',status='unknown')
c      initialize counters
      air = 6.0 !defines y coordinate of air surface
      nair = 0 ! counter of the number of nodes on air surface

c      set up tolerances
      airup = air + .001
      airlo = air - .001
c      sort for nodes in air surface
      open(unit=45,file = 'reade.files/node.dat', status='unknown')
      do 880 i = 1, nnum
      read(45,*) nodenum,x,y,z
      if (nodenum .eq. 000) goto 881
      if (( y .ge. airlo) .and. (y .le. airup)) then
      nair = nair + 1
      write(54,283) nodenum, x,y,z
      nairp(nair) = nodenum
      endif
880      continue
881      write(54,*)'      000,      00,      00,      0.0'
      close(unit=45)
      close(unit=54)

c -----
c      MAKE vac.dat = the nodes on the vac surface
c      vacp(nvac) = the array with a list of node numbers
c -----
      open(unit=55,file='reade.files/vac.dat',status='unknown')
c      initialize counters
      vac = -0.006 *1000. !mmmm defines y coordinate of vac surface
      nvac = 0 ! counter of the number of nodes on vac surface

c      set up tolerances
      vacup = vac + .001
      vaclo = vac - .001
c      sort for nodes in vac surface
      open(unit=45,file = 'reade.files/node.dat', status='unknown')
      do 894 i = 1, nnum
      read(45,*) nodenum,x,y,z
      if (nodenum .eq. 000) goto 882
      if (( y .ge. vaclo) .and. (y .le. vacup)) then
      nvac = nvac + 1
      write(55,283) nodenum, x,y,z
      nvacp(nvac) = nodenum
      endif
894      continue

```

```

882  write(55,*) '      000,      00,      00,      0.0'
      close(unit=45)
      close(unit=55)

cc    write(*,*) 'nb=',nb
c     write(*,*) 'nbl=',nbl
c -----
c  NODE DESCRIPTIONS
c -----
c  nodes on the outer alumina/ceramic boundary:
c    array = ncheck, nb=# of nodes, file = bound.dat
c  nodes on the inner alumina/ceramic boundary:
c    array = n2check, nbl=# of nodes, file = bound1.dat
c  nodes on the outer alumina/ceramic boundary where Z=0:
c    array = nchecka, nba=# of nodes
c  nodes on the inner alumina/ceramic boundary where z=0:
c    array = n2checka, nbla=# of nodes
c  nodes on the symmetry boundary (z=0):
c    array = nsymp, nsym=# of nodes, file = sym.dat
c  nodes on the air surface:
c    array = nairp, nair=# of nodes, file = air.dat
c  nodes on the vacuum surface:
c    array = nvacp, nvac=# of nodes, file = vac.dat
c -----
c  FIGURE OUT WHICH FACE AND WRITE OUT OUTFILM.DAT (outer alumina/metal bound)
c -----
      open(unit = 56,file='reade.files/outfilm.dat',status='unknown')
      open(unit=44,file = 'reade.files/element.dat',status = 'unknown')
c  all the nodes on the boundary are in ncheck(i)
c  sort and find which elements are on the surface from the known nodes
      filmtmp = 353.0 ! 80 deg c - temp of metal ceramic bound
      filmh   = .0234040 !mm w/mm^2 - deg c
      nfilm = 0 !counter for the number of elments in outfilm.dat
      do 190 i = 1, element
        true(1) = 0
        true(2) = 0
        true(3) = 0
        true(4) = 0
        read(44,*) ele,n1,n2,n3,n4,n5,n6,n7,n8,n9,n10
        if (i .eq. 00) goto 197
        do 192 j= 1, nnum
          if (true(1) .eq. 1) goto 193
          if (n2 .eq. ncheck(j)) true(1) = 1
193      if (true(2) .eq. 1) goto 194
          if (n3 .eq. ncheck(j)) true(2) = 1
194      if (true(3) .eq. 1) goto 195
          if (n4 .eq. ncheck(j)) true(3) = 1
195      if (true(4) .eq. 1) goto 192
          if (n1 .eq. ncheck(j)) true(4) = 1
192      continue
c    figure out which face is on the surface
      if ((true(1).eq. 1).and.(true(2).eq. 1).and.(true(3) .eq. 1))
c  then
        face = 'F1'
        nmem = nmem + 1
        CALL MFACE(nmem,n2,n3,n4,n6,n10,n9,mem)
c    CALL MFACE(nmem,n2,n3,n4,n5,n6,n7,mem)

```

```

c      CALL MFACE(nmem,n1,n2,n3,n5,n6,n7,mem)
      elseif ((true(1).eq.1).and.(true(4).eq.1).and.(true(2).eq.1))
c then
      face = 'F2'
      nmem = nmem + 1
      CALL MFACE(nmem,n2,n3,n1,n6,n7,n5,mem)
c      CALL MFACE(nmem,n2,n3,n1,n6,n10,n9,mem)
c      CALL MFACE(nmem,n1,n2,n4,n5,n9,n8,mem)
      elseif ((true(2).eq.1).and.(true(4).eq.1).and.(true(3).eq.1))
c then
      face = 'F3'
      nmem = nmem + 1
      CALL MFACE(nmem,n3,n4,n1,n10,n8,n7,mem)
c      CALL MFACE(nmem,n2,n3,n4,n6,n10,n9,mem)
      elseif ((true(3).eq.1).and.(true(4).eq.1).and.(true(1).eq.1))
c then
      face = 'F4'
      nmem = nmem + 1
      CALL MFACE(nmem,n4,n2,n1,n9,n5,n8,mem)
c      CALL MFACE(nmem,n3,n1,n4,n7,n8,n10,mem)
      else
      face = 'no'
      endif
      if (face .ne. 'no') then
      write(56,191) ele,face,filmtemp,filmh
191  format(5x,I4,',',5x,A2,',',5x,F5.1,',',F15.5)
      nfilm = nfilm + 1
      endif
190  continue
197  close(unit = 56) !outfilm.dat
      close(unit = 44) !element.dat
      noutfilm = nfilm
c      write(*,*) 'noutfilm =',noutfilm
c      write(*,*) 'nmem (after outer) =', nmem
c-----
c FIGURE OUT WHICH FACE AND WRITE OUT INFILM.DAT (inner alumina/metal bound)
c-----
      open(unit = 57,file='reade.files/infilm.dat',status='unknown')
      open(unit=44,file = 'reade.files/element.dat',status = 'unknown')
c all the nodes on the boundary are in n2check(i)
c sort and find which elements are on the surface from the known nodes
      filmtemp = 353.0 ! 80 deg c - temp of metal ceramic bound
      filmh = .023404 !mm w/mm^2 - deg c
      nfilm = 0 !counter for the number of elments in infilm.dat
      do 1190 i = 1, nnum
      true(1) = 0
      true(2) = 0
      true(3) = 0
      true(4) = 0
      read(44,*) ele,n1,n2,n3,n4,n5,n6,n7,n8,n9,n10
      if (i .eq. 00) goto 1197
      do 1192 j= 1, nnum
      if (true(1) .eq. 1) goto 1193
      if (n2 .eq. n2check(j)) true(1) = 1
1193  if (true(2) .eq. 1) goto 1194
      if (n3 .eq. n2check(j)) true(2) = 1
1194  if (true(3) .eq. 1) goto 1195
      if (n4 .eq. n2check(j)) true(3) = 1

```

```

1195   if (true(4) .eq. 1) goto 1192
      if (n1 .eq. n2check(j)) true(4) = 1
1192   continue
c     figure out which face is on the surface
      if ((true(1).eq. 1).and.(true(2).eq. 1).and.(true(3) .eq. 1))
c then
         face = 'F1'
         nmem = nmem + 1
         CALL MFACE(nmem,n2,n3,n4,n6,n10,n9,mem)
c       CALL MFACE(nmem,n2,n3,n4,n5,n6,n7,mem)
c       CALL MFACE(nmem,n1,n2,n3,n5,n6,n7,mem)
         elseif ((true(1).eq.1).and.(true(4).eq.1).and.(true(2).eq.1))
c then
            face = 'F2'
            nmem = nmem + 1
            CALL MFACE(nmem,n2,n3,n1,n6,n7,n5,mem)
c          CALL MFACE(nmem,n2,n3,n1,n6,n10,n9,mem)
c          CALL MFACE(nmem,n1,n2,n4,n5,n9,n8,mem)
            elseif ((true(2).eq.1).and.(true(4).eq.1).and.(true(3).eq.1))
c then
               face = 'F3'
               nmem = nmem + 1
               CALL MFACE(nmem,n3,n4,n1,n10,n8,n7,mem)
c             CALL MFACE(nmem,n2,n3,n4,n6,n10,n9,mem)
               elseif ((true(3).eq.1).and.(true(4).eq.1).and.(true(1).eq.1))
c then
                  face = 'F4'
                  nmem = nmem + 1
                  CALL MFACE(nmem,n4,n2,n1,n9,n5,n8,mem)
c                CALL MFACE(nmem,n3,n1,n4,n7,n8,n10,mem)
            else
               face = 'no'
            endif
            if (face .ne. 'no') then
               write(57,191) ele,face,filmtemp,filmh
               nfilm = nfilm + 1
            endif
1190   continue
1197   close(unit = 57)   !infil.dat
      close(unit = 44)   !element.dat
      ninfilm = nfilm
c     write(*,*) 'ninfilm=', ninfilm
c     write(*,*) 'nmem (after inner) =', nmem
c-----
c FIGURE OUT WHICH FACE AND WRITE OUT AIRFILM.DAT (air surface)
c-----
      open(unit=99,file='debug.dat',status='unknown')

      open(unit = 62,file='reade.files/pres.dat',status='unknown')
      open(unit = 58,file='reade.files/airfilm.dat',status='unknown')
      open(unit=44,file = 'reade.files/element.dat',status = 'unknown')
c all the nodes on the boundary are in nairp(i)
c sort and find which elements are on the surface from the known nodes
      pressure = -101352.4 / (1000.**2) !N/mm^2
      filmtemp = 321.2 ! 52 deg c
      filmh     = 180.0000 / (1000.**2) !mm w/mm^2 - deg c
      nfilm = 0      !counter for the number of elments in airfilm.dat
      do 2190 i = 1, element

```



```

      true(1) = 0
      true(2) = 0
      true(3) = 0
      true(4) = 0
      read(44,*) ele,n1,n2,n3,n4,n5,n6,n7,n8,n9,n10
      if (i .eq. 00) goto 2197
      do 2192 j= 1, nnum
      if (true(1) .eq. 1) goto 2193
      if (n2 .eq. nairp(j)) true(1) = 1
2193   if (true(2) .eq. 1) goto 2194
      if (n3 .eq. nairp(j)) true(2) = 1
2194   if (true(3) .eq. 1) goto 2195
      if (n4 .eq. nairp(j)) true(3) = 1
2195   if (true(4) .eq. 1) goto 2192
      if (n1 .eq. nairp(j)) true(4) = 1
2192   continue
c      figure out which face is on the surface
      if ((true(1).eq. 1).and.(true(2).eq. 1).and.(true(3) .eq. 1))
c then
      pface='P1'
      face ='F1'
      nmem = nmem + 1
      CALL MFACE(nmem,n2,n3,n4,n6,n10,n9,mem)
c      CALL MFACE(nmem,n2,n3,n4,n5,n6,n7,mem)
c      CALL MFACE(nmem,n1,n2,n3,n5,n6,n7,mem)
      elseif ((true(1).eq.1).and.(true(4).eq.1).and.(true(2).eq.1))
c then
      pface='P2'
      face = 'F2'
      nmem = nmem + 1
      CALL MFACE(nmem,n2,n3,n1,n6,n7,n5,mem)
c      CALL MFACE(nmem,n2,n3,n1,n6,n10,n9,mem)
c      CALL MFACE(nmem,n1,n2,n4,n5,n9,n8,mem)
      elseif ((true(2).eq.1).and.(true(4).eq.1).and.(true(3).eq.1))
c then
      pface='P3'
      face = 'F3'
      nmem = nmem + 1
      CALL MFACE(nmem,n3,n4,n1,n10,n8,n7,mem)
c      CALL MFACE(nmem,n2,n3,n4,n6,n10,n9,mem)
      elseif ((true(3).eq.1).and.(true(4).eq.1).and.(true(1).eq.1))
c then
      pface='P4'
      face = 'F4'
      nmem = nmem + 1
      CALL MFACE(nmem,n4,n2,n1,n9,n5,n8,mem)
c      CALL MFACE(nmem,n3,n1,n4,n7,n8,n10,mem)
      else
      face = 'no'
      endif

      if (i .eq. 3) then !-----
      write(99,*) ele,n1,n2,n3,n4,n5,n6,n7,n8,n9,n10
      write(99,*) true(1),true(2),true(3),true(4)
      write(99,*) face
      endif !-----

```

```

        if (face .ne. 'no') then
            write(46,303)
            write(58,191) ele,face,filmtemp,filmh
            write(62,2191) ele,pface,pressure
            nfilm = nfilm + 1
        endif
2190     continue
2191     format(5x,I4,',',5x,A2,',',5x,F15.5)
2197     close(unit = 58)    !airfilm.dat
            close(unit = 62)    !pres.dat
            close(unit=99)    !-----
            close(unit = 44)    !element.dat
            nairfilm=nfilm
c       write(*,*) 'nairfilm =',nairfilm
c       write(*,*) 'nmem (after air) =', nmem
c-----
c FIGURE OUT WHICH FACE AND WRITE OUT VACFILM.DAT (vacuum surface)
c-----
            open(unit = 59,file='reade.files/vacfilm.dat',status='unknown')
            open(unit=44,file = 'reade.files/element.dat',status = 'unknown')
c all the nodes on the boundary are in nairp(i)
c sort and find which elements are on the surface from the known nodes
            filmtemp = 325.0    ! 52 deg c
            filmh     = 180.0 / (1000.**2)    !mmmm w/mm^2 - deg c
            nfilm = 0    !counter for the number of elments in infilm.dat
            do 3190 i = 1, element
                true(1) = 0
                true(2) = 0
                true(3) = 0
                true(4) = 0
                read(44,*) ele,n1,n2,n3,n4,n5,n6,n7,n8,n9,n10
                if (i .eq. 00) goto 3197
                do 3192 j= 1, nnum
                    if (true(1) .eq. 1) goto 3193
                    if (n2 .eq. nvacp(j)) true(1) = 1
3193                 if (true(2) .eq. 1) goto 3194
                    if (n3 .eq. nvacp(j)) true(2) = 1
3194                 if (true(3) .eq. 1) goto 3195
                    if (n4 .eq. nvacp(j)) true(3) = 1
3195                 if (true(4) .eq. 1) goto 3192
                    if (n1 .eq. nvacp(j)) true(4) = 1
3192                 continue
c             figure out which face is on the surface
                if ((true(1).eq. 1).and.(true(2).eq. 1).and.(true(3) .eq. 1))
c then
                    face = 'F1'
                    nmem = nmem + 1
                    CALL MFACE(nmem,n2,n3,n4,n6,n10,n9,mem)
c             CALL MFACE(nmem,n2,n3,n4,n5,n6,n7,mem)
c             CALL MFACE(nmem,n1,n2,n3,n5,n6,n7,mem)
                    elseif ((true(1).eq.1).and.(true(4).eq.1).and.(true(2).eq.1))
c then
                        face = 'F2'
                        nmem = nmem + 1
                        CALL MFACE(nmem,n2,n3,n1,n6,n7,n5,mem)
c             CALL MFACE(nmem,n2,n3,n1,n6,n10,n9,mem)
c             CALL MFACE(nmem,n1,n2,n4,n5,n9,n8,mem)
                    elseif ((true(2).eq.1).and.(true(4).eq.1).and.(true(3).eq.1))

```

```

c then
  face = 'F3'
  nmem = nmem + 1
  CALL MFACE(nmem,n3,n4,n1,n10,n8,n7,mem)
c  CALL MFACE(nmem,n2,n3,n4,n6,n10,n9,mem)
  elseif ((true(3).eq.1).and.(true(4).eq.1).and.(true(1).eq.1))
c then
  face = 'F4'
  nmem = nmem + 1
  CALL MFACE(nmem,n4,n2,n1,n9,n5,n8,mem)
c  CALL MFACE(nmem,n3,n1,n4,n7,n8,n10,mem)
  else
  face = 'no'
  endif
  if (face .ne. 'no') then
  write(59,191) ele,face,filmtemp,filmh
  nfilm = nfilm + 1
  endif
3190  continue

3197  close(unit = 59)  !vacfilm.dat
      close(unit = 44)  !element.dat
c  write(*,*) 'nmem (after vac) =', nmem
c-----
c FIGURE OUT WHICH FACE AND WRITE OUT RAD.DAT(air and vac surfaces)
c-----
      open(unit = 77,file='reade.files/rad.dat' ,status='unknown')
      open(unit=44,file='reade.files/element.dat',status='unknown')
c all the nodes on the boundary are in nairp(nair) or nvacp(nvac)
c sort and find which elements are on the surface from the known nodes
      radtemp = 296.0  !deg c
c  rconst  = emmisivity * Stefan-Boltzmann constant
      rconst  = 0.5215756E-07 /(1000.**2) !mmmm with emissivity=.92
c  rconst  = .92 * 5.6693E-12*(100**2)/(1000.**2)!mmmm w/mm^2 - K^4
      nrad = 0  !counter for the number of elments in rad.dat
c -----
c check all the elements on the air surface
      do 390 i = 1, element
      true(1) = 0
      true(2) = 0
      true(3) = 0
      true(4) = 0
      read(44,*) ele,n1,n2,n3,n4,n5,n6,n7,n8,n9,n10
      if (i .eq. 00) goto 397
      do 380 j= 1, nnum
      if (true(1) .eq. 1) goto 293
      if (n2 .eq. nairp(j)) true(1) = 1
293  if (true(2) .eq. 1) goto 294
      if (n3 .eq. nairp(j)) true(2) = 1
294  if (true(3) .eq. 1) goto 295
      if (n4 .eq. nairp(j)) true(3) = 1
295  if (true(4) .eq. 1) goto 380
      if (n1 .eq. nairp(j)) true(4) = 1
380  continue
c  figure out which face is on the surface
      if ((true(1).eq. 1).and.(true(2).eq. 1).and.(true(3) .eq. 1))
c then
      face = 'R1'

```

```

        elseif ((true(1).eq.1).and.(true(4).eq.1).and.(true(2).eq.1))
c then
        face = 'R2'
        elseif ((true(2).eq.1).and.(true(4).eq.1).and.(true(3).eq.1))
c then
        face = 'R3'
        elseif ((true(3).eq.1).and.(true(4).eq.1).and.(true(1).eq.1))
c then
        face = 'R4'
        else
        face = 'no'
        endif
        if (face .ne. 'no') then
        write(77,391) ele,face,radtemp,rconst
391  format(5x,I4,' ',',',5x,A2,' ',',',5x,F5.1,' ',',',E15.5)
        nrad = nrad + 1
        endif
390  continue
397  close(unit=44) !element.dat
c -----
        open(unit=44,file = 'reade.files/element.dat',status = 'unknown')
c check all the elements on the vacuum surface
        do 1390 i = 1, element
        true(1) = 0
        true(2) = 0
        true(3) = 0
        true(4) = 0
        read(44,*) ele,n1,n2,n3,n4,n5,n6,n7,n8,n9,n10
        if (i .eq. 00) goto 1397
        do 1380 j= 1, nnum
        if (true(1) .eq. 1) goto 1293
        if (n2 .eq. nvacp(j)) true(1) = 1
1293  if (true(2) .eq. 1) goto 1294
        if (n3 .eq. nvacp(j)) true(2) = 1
1294  if (true(3) .eq. 1) goto 1295
        if (n4 .eq. nvacp(j)) true(3) = 1
1295  if (true(4) .eq. 1) goto 1380
        if (n1 .eq. nvacp(j)) true(4) = 1
1380  continue
c        figure out which face is on the surface
        if ((true(1).eq. 1).and.(true(2).eq. 1).and.(true(3) .eq. 1))
c then
        face = 'R1'
        elseif ((true(1).eq.1).and.(true(4).eq.1).and.(true(2).eq.1))
c then
        face = 'R2'
        elseif ((true(2).eq.1).and.(true(4).eq.1).and.(true(3).eq.1))
c then
        face = 'R3'
        elseif ((true(3).eq.1).and.(true(4).eq.1).and.(true(1).eq.1))
c then
        face = 'R4'
        else
        face = 'no'
        endif
        if (face .ne. 'no') then
        write(77,391) ele,face,radtemp,rconst
1391  format(5x,I4,' ',',',5x,A2,' ',',',5x,F5.1,' ',',',E15.5)

```

```

        nrad = nrad + 1
    endif
1390    continue
1397    close(unit = 77)    !rad.dat
        close(unit = 44)    !element.dat

c
c -----
c      MAKE INPUT DECK: file is thermo.inp
c -----
c ask if user wants to do a steady state run or a transient run
    print *, ' Do you want to do a steady state run or a transient run?'
    print *, ' (trans = 1, steady state = 2)'
    trans = 2
c      read *, trans
    print *,trans
c -----
c      open the data files

    open(unit=42,file = 'reade.files/efield.dat', status='unknown')
    open(unit=44,file = 'reade.files/element.dat', status='unknown')
    open(unit=45,file = 'reade.files/node.dat', status='unknown')
    open(unit=46,file= 'reade.files/thermo.inp' ,status='unknown')
    open(unit=47,file='reade.files/film.dat' ,status='unknown')
    open(unit=48,file='reade.files/bound.dat' ,status='unknown')
    open(unit=52,file= 'reade.files/struc.inp' ,status='unknown')
    open(unit=56,file= 'reade.files/outfilm.dat',status='unknown')
    open(unit=57,file= 'reade.files/infilm.dat',status='unknown')
    open(unit=58,file= 'reade.files/airfilm.dat',status='unknown')
    open(unit=62,file= 'reade.files/pres.dat',status='unknown')
    open(unit=63,file= 'flux.dat' ,status='unknown')
    open(unit=77,file='reade.files/rad.dat' ,status='unknown')

c ---- write heading -----
    write(46,301)
    write(52,301)
301    format('*HEADING, SPARSE')
    write(*,*) 'Enter the title of the input deck (use all CAPS).'
    if (fileans .eq. 'y' ) then
        read(49,104) line1
        print*, line1
        print*, 'Power: ', pincident,'Watts'
    else
        read(*,104) line1
    endif
    write(46,298) pincident
    write(52,298) pincident
298    format('POWER = ',E10.2,' WATTS')
    close(unit=49)
104    format(A40)
    CALL fdate(date)
    write(46,103) line1
    write(52,103) line1
103    format(1x,A40)
c ---- write nodes -----
    write(46,299) date
    write(52,299) date

```

```

299  format('** ', A24)
      write(46,302)
      write(52,302)
302  format('** NODE DEFINITIONS')
      write(46,303)
      write(52,303)
303  format('**')
      write(46,304)
      write(52,304)
304  format('*NODE, NSET=NALL')
      close(unit=45)
      open(unit=45,file = 'reade.files/node.dat', status='unknown')
      do 121 i = 1, nnum
        read(45,102) inode,n1,n2,n3
        if (inode .eq. 00) goto 122
        write(46,102) inode,n1,n2,n3
        write(52,102) inode,n1,n2,n3
121  continue
c    add node 40000 (center node)
c      inode = 40000
c      n1 = 0.0
c      n2 = 0.0
c      n3 = 0.0
c      write(52,972) inode,n1,n2,n3
c      write(46,303)
c      write(52,303)
972  format(1x,I7,' ',',',2x,E16.8,' ',',',2x,E16.8,' ',',',2x,E16.8)
305  format('** ELEMENT DEFINITIONS')
122  write(46,303)
      write(52,303)
      write(46,306)
      write(52,407)
306  format('*ELEMENT, TYPE=DC3D10, ELSET=VOL1')
407  format('*ELEMENT, TYPE=C3D10, ELSET=VOL1')
      do 131 j = 1,element
        if (j .eq. 1) then
          i = 1
        else
          i = (j-1)*10 +1
        endif
        read(44,97) j,n1,n2,n3,n4,n5,n6,n7,n8,n9,n10
        if (j .eq. 00) goto 132
c    -----These are out of order because otherwise you get
c    a negative volume error in abaqus -----
        write(46,97) j,n2,n3,n4,n1,n6,n10,n9,n5,n7,n8
        write(52,97) j,n2,n3,n4,n1,n6,n10,n9,n5,n7,n8
131  continue
      write(52,222)
222  format('*ELEMENT, TYPE=M3D6, ELSET=SUR2')

      do 224 i =1,nmem
        mem(i,1) = mem(i,1) + 5000
        write(52,223) mem(i,1),mem(i,2),
          cmem(i,3),mem(i,4),mem(i,5),mem(i,6),mem(i,7)
224  continue
223  format(1x,I6,' ',',',5(I6,' '),I6)
c    ---- write material properties -----
132  write(46,303)

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```

        write(52,303)
c      write(52,357)
357    format('*ELSET, ELSET=MAT300')
c      write(52,358)
358    format('VOL1,SUR2')
        write(46,307)
        write(52,307)
307    format('*SOLID SECTION, ELSET=VOL1, MATERIAL=AL1')
        write(46,303)
        write(52,303)
        write(46,308)
        write(52,308)
308    format('*MATERIAL, NAME=AL1')
c      write(46,309)
        write(52,309)
309    format('*ELASTIC')
c      write(46,310)
        write(52,310)
310    format('3.03E5,      .21')      !E [N/mm^2],P.R., T [deg c]
        write(46,311)
        write(52,311)
311    format('*CONDUCTIVITY')
        write(46,412)
        write(52,412)
412    format('** Units are watts/mm-c')
        write(46,312)
        write(52,312)
312    format('.0268 ')      !k [W/mm - deg c], T [deg c]
        write(52,444)
444    format('*EXPANSION, ZERO=294.5')
        write(52,445)
445    format(' 6.9E-6')
        write(46,446)
        write(52,446)
446    format('*DENSITY')
        write(46,447)
        write(52,447)
447    format(' .00000367')      !kg/mm^3
c ---- write steady state initial temperature conditions
        if (trans. eq. 2) then
            write(46,303)
            write(46,700)
            write(46,303)
700    format('*PHYSICAL CONSTANTS, ABSOLUTE ZERO=0.0,STEFAN BOLTZMANN=5.669E-14')
            end if
            write(52,303)
c ---- write transient data -----
        if (trans .eq. 1) then
            write(46,303)
            write(46,413)
413    format('*DENSITY')
            write(46,414)
414    format('** Units are kg/cubic mm')
            write(46,415)
415    format(' .00000367,')
            write(46,303)
            write(46,425)
425    format('*SPECIFIC HEAT')

```

```

        write(46,430)
430    format('** Units are Joules/kg-C')
        write(46,418)
418    format('      778.0,')
        write(46,419)
419    format('*RESTART, WRITE, OVERLAY')
        write(46,303)
        write(46,303)
        write(46,427)
427    format('*STEP, INC=50')
        write(46,303)
        write(46,431)
431    format('*HEAT TRANSFER, DELTMX=50, END=PERIOD')
        write(46,429)
429    format('10.0, 2400.0, 1., 200.0')
        write(46,303)
        goto 500
        end if
c ---- write structural data -----
c    write(52,303)
c    write(52,440)
c440    format('*SPRING, ELSET=FIXER')
c    write(52,441)
c441    format(' ')
c    write(52,442)
c442    format(1x,'10.0')    !spring constant (force/length)
        write(52,303)
        write(52,359)
359    format('*MEMBRANE SECTION,ELSET=SUR2,MATERIAL=THIN2,POISSON=.21')
        write(52,360)
360    format('1.0E-6')
        write(52,361)
361    format('*MATERIAL, NAME=THIN2')
        write(52,309)
        write(52,310)
        write(52,311)
        write(52,412)
        write(52,312)
c    write(52,444)
c    write(52,445)
c    write(52,446)
c    write(52,447)
        write(52,303)
        write(52,444)
        write(52,445)
        write(52,401)
401    format('*INITIAL CONDITIONS, TYPE=TEMPERATURE')
        write(52,402)
402    format('NALL, 294.5')
c ---- write heat transfer data -----
        write(46,303)
        write(52,303)
        write(46,314)
        write(52,314)
314    format('*RESTART, WRITE')
        write(46,303)
        write(52,303)
325    format('*PLOT')

```



```

326  format('*SHRINK, FACTOR=.2')
327  format('*DRAW, ELNUM')
    write(46,303)
    write(52,303)
    write(46,315)
    write(52,315)
315  format('*STEP')
    write(46,303)
    write(52,303)
    write(46,316)
    write(52,416)
416  format('*STATIC')
    write(52,417)
417  format(
c '*TEMPERATURE, FILE=eev3, ESTEP=1, BSTEP=1, EINC=1, BINC=1')
316  format('*HEAT TRANSFER, STEADY STATE')
    write(46,303)
500  write(52,303)
    write(46,324)
324  format('*DFLUX, OP=NEW')
    totpower = 0                                !Sum total power, w / m**3
    do 140 i = 1,element
        read(42,89) element,power                ! P [W/m^3]
        power = power*(1.414214)* pincident/(1000.**3) !mm incident power[w/mm^3]
        totpower = totpower + power
        write(63,89) element,power
        write(46,89) element,power
140  continue
    write(46,303)
c -----THERMAL BOUNDARY CONDITIONS -----
c write *FILM for air surface convection
    write(46,317)
317  format('*FILM, OP=NEW')    !for air surface convection
    do 145 i = 1,nairfilm
        read(58,191) ele,face,filmtemp,filmh ! h [W/mm^2 - deg.c]
        write(46,191) ele,face,filmtemp,filmh
145  continue
c write *FILM for contact resistance on the alumina/ceramic outer boundary
    do 146 i = 1, noutfilm
        read(56,191) ele,face,filmtemp,filmh
        write(46,191) ele,face,filmtemp,filmh
146  continue
c write *FILM for contact resistance on the alumina/ceramic inner boundary
    do 149 i = 1, ninfilm
        read(57,191) ele,face,filmtemp,filmh
        write(46,191) ele,face,filmtemp,filmh
149  continue
c write *RADIATE for air surface radiation and vacuum surface radiation
    write(46,303)
    write(46,217)
217  format('*RADIATE,OP=NEW')
    do 240 i = 1,nrad
        read(77,391) ele,face,radtemp,rconst
        write(46,391) ele,face,radtemp,rconst
240  continue
c -----STRUCTURAL BOUNDARY CONDITIONS -----
c write *BOUNDARY to constrain nodes
    write(52,303)

```

```

        write(52,242)
c nodes on outer ceramic/metal boundary: constrain in y dir
c just on top edge, y=6 mm
c      write(*,*) 'nba (outer) =' ,nba
        do 241 i = 1,nba
            nnode = nchecka(i)
            write(52,243) nnode
241      continue
242      format('*BOUNDARY,OP=NEW')
243      format(1x,I7,' ',',',7x,'2',',',7x,'2',',',7x,'0.00')
c nodes on inner ceramic/metal boundary: constrain in y dir
c just on top edge, y=6 mm
c      write(*,*) 'nbla (inner) =' ,nbla
        do 264 i = 1,nbla
            nnode = n2checka(i)
            write(52,243) nnode
264      continue
c nodes on symmetry plane: constrain in z direction
        do 244 i = 1, nsym
            nnode = nsymp(i)
            write(52,245) nnode
244      continue
245      format(1x,I7,' ',',',7x,'3',',',7x,'3',',',7x,'0.00')
c constrain center node in all directions
c      write(52,247)
c247      format(1x,' 40000',',',',7x,'1',',',7x,'3',',',7x,'0.00')
c put forces on the air surface due to the vacuum/air pressure differential
        write(52,303)
        write(52,232)
        do 230 i = 1,nairfilm
            read(62,2191) ele,pface,pressure
            write(52,2191) ele,pface,pressure
230      continue
232      format('*DLOAD, OP=NEW')
231      format(3x,I7,' ')
        close(unit=62)

c -----
        write(46,303)
        write(52,303)
        write(46,303)
        write(52,303)
        if (trans .eq. 1) then
            goto 501
        end if
        write(52,455)
455      format('*EL FILE, ELSET=SUR2, POSITION=INTEGRATION POINTS')
        write(52,426)
        write(52,432)
432      format('SINV')
        write(52,433)
433      format('TEMP')
        write(46,436)
        write(52,424)
436      format('*EL PRINT,ELSET=VOL1, POSITION=INTEGRATION POINTS')
424      format('*EL PRINT,ELSET=SUR2, POSITION=INTEGRATION POINTS')
c      write(46,457)
c      write(52,457)
457      format('EVOL')

```

```

write(52,426)
426  format('S')
write(52,432)
write(52,433)
write(52,434)
434  format('*EL FILE, ELSET=VOL1, POSITION=INTEGRATION POINTS')
write(52,426)
write(52,432)
write(52,433)
435  format('*EL PRINT,ELSET=VOL1, POSITION=INTEGRATION POINTS')
write(52,426)
write(52,432)
write(52,433)
write(46,319)
write(52,319)
319  format('*NODE PRINT, GLOBAL=YES')
write(46,320)
write(52,420)
320  format('NT, RFL, RFLE')
420  format('U')
write(46,321)
write(52,321)
321  format('*NODE FILE, GLOBAL=YES')
write(46,322)
write(52,420)
322  format('NT')
write(52,303)
501  write(46,323)
write(52,323)
323  format('*END STEP')

```

```

c -----
c calucate the total power dissapted in the window
c   volume = 3.141592 * .12 * (.1086**2 - .0255**2) !m**3
c   totalp = totpower * volume           !watts
c   avepower = totalp / 3470
c   write(*,*) 'The volume of the window = ',volume,'M^3'
c   write(*,*) 'The total power = ', totpower, 'W/M^3'
c   write(*,*) 'The average power in each tet = ', avepower
c   write(*,*) 'The total power in the window = ', totalp, 'W'
c -----
c   close data files
c   close(unit=42)
c   close(unit=43)
c   close(unit=44)
c   close(unit=46)
c   close(unit=47)
c   close(unit=48)
c   close(unit=52)
c   close(unit=56)
c   close(unit=57)
c   close(unit=58)
c   close(unit=63)
c   close(unit=77)

stop
end

```

```

SUBROUTINE MFACE(m0,m1,m2,m3,m4,m5,m6,mem)
integer m0,m1,m2,m3
integer m4,m5,m6,mem(6000,7)
mem(m0,1)=m0
mem(m0,2)=m1
mem(m0,3)=m2
mem(m0,4)=m3
mem(m0,5)=m4
mem(m0,6)=m5
mem(m0,7)=m6
return
end

```

SUBROUTINE DOC

```

c the data in the coord array is the following:
c coord(1) = element number      coord(6) = y2      coord(11)= x4
c coord(2) = x1                  coord(7) = z2      coord(12)= y4
c coord(3) = y1                  coord(8) = x3      coord(13)= z4
c coord(4) = z1                  coord(9) = y3
c coord(5) = x2                  coord(10)= z3

c the following numbers represent the following midpoints:
c 5 = midpoint between vertex 1 and 2
c 6 = midpoint between vertex 1 and 3
c 7 = midpoint between vertex 1 and 4
c 8 = midpoint between vertex 2 and 3
c 9 = midpoint between vertex 2 and 4
c 10= midpoint between vertex 3 and 4
c therefore, the values in the coordinate area corresponding to the
c midpoints are:
c coord(14) = x5      coord(20) = x7      coord(26) = x9
c coord(15) = y5      coord(21) = y7      coord(27) = y9
c coord(16) = z5      coord(22) = z7      coord(28) = z9
c coord(17) = x6      coord(23) = x8      coord(29) = x10
c coord(18) = y6      coord(24) = y8      coord(30) = y10
c coord(19) = z6      coord(25) = z8      coord(31) = z10

c the data in the xvalue, yvalue, and zvalue arrays is the following:
c xvalue(1) = the real part of E(x) at vertex 1
c xvalue(2) = the imag part of E(x) at vertex 1
c xvalue(3) = the real part of E(x) between vertex 1 and 2
c xvalue(4) = the imag part of E(x) between vertex 1 and 2
c xvalue(5) = the real part of E(x) between vertex 1 and 3
c xvalue(6) = the imag part of E(x) between vertex 1 and 3
c xvalue(7) = the real part of E(x) between vertex 1 and 4
c xvalue(8) = the imag part of E(x) between vertex 1 and 4
c xvalue(9) = the real part of E(x) at vertex 2
c xvalue(10)= the imag part of E(x) at vertex 2
c xvalue(11)= the real part of E(x) between vertex 2 and 3
c xvalue(12)= the imag part of E(x) between vertex 2 and 3
c xvalue(13)= the real part of E(x) between vertex 2 and 4
c xvalue(14)= the imag part of E(x) between vertex 2 and 4
c xvalue(15)= the real part of E(x) at vertex 3
c xvalue(16)= the imag part of E(x) at vertex 3
c xvalue(17)= the real part of E(x) between vertex 3 and 4

```

```

c      xvalue(18)= the imag part of E(x) between vertex 3 and 4
c      xvalue(19)= the real part of E(x) at vertex 4
c      xvalue(20)= the imag part of E(x) at vertex 4
c      return
c      end

      SUBROUTINE READ(coord,xvalue,yvalue,zvalue)
      real *8 xvalue(20),coord(31),yvalue(20),zvalue(20)
c      character*10 dum
c -----
c read in the corrdinates of the tets
      read(43,90) coord(2),coord(3),coord(4)
      read(43,90) coord(5),coord(6),coord(7)
      read(43,90) coord(8),coord(9),coord(10)
      read(43,90) coord(11),coord(12),coord(13)

c -----
c convert coordinate units from meters to mm
      do 32 i = 2, 13
        coord(i) = coord(i) * 1000.00
32      continue

c      check the coordinate data by printing it out
c      write(*,90) coord(2),coord(3),coord(4)
c      write(*,90) coord(5),coord(6),coord(7)
c      write(*,90) coord(8),coord(9),coord(10)
c      write(*,90) coord(11),coord(12),coord(13)

c -----
c      read in the xdata
      read(43,93) xvalue(1),xvalue(2),xvalue(3),xvalue(4),xvalue(5)
c      ,xvalue(6),xvalue(7),xvalue(8),xvalue(9),xvalue(10),xvalue(11)
c      ,xvalue(12),xvalue(13),xvalue(14),xvalue(15),xvalue(16),
c      xvalue(17),xvalue(18),xvalue(19),xvalue(20)

c      check the xdata by printing it out
c      do 30 i = 1,20
c        write(*,92) i,xvalue(i)
c30      continue

c -----
c      read in the ydata
      read(43,93) yvalue(1),yvalue(2),yvalue(3),yvalue(4),yvalue(5)
c      ,yvalue(6),yvalue(7),yvalue(8),yvalue(9),yvalue(10),yvalue(11)
c      ,yvalue(12),yvalue(13),yvalue(14),yvalue(15),yvalue(16),
c      yvalue(17),yvalue(18),yvalue(19),yvalue(20)

c      check the ydata by printing it out
c      do 31 i = 1,20
c        write(*,94) i,yvalue(i)
c31      continue

c -----
c      read in the zdata
      read(43,93) zvalue(1),zvalue(2),zvalue(3),zvalue(4),zvalue(5)
c      ,zvalue(6),zvalue(7),zvalue(8),zvalue(9),zvalue(10),zvalue(11)
c      ,zvalue(12),zvalue(13),zvalue(14),zvalue(15),zvalue(16),
c      zvalue(17),zvalue(18),zvalue(19),zvalue(20)

```

```

90      format(4x,E23.16E2,2(5x,E23.16E2))
92      format(1x,'xvalue',I2,' = ', E24.16E2)

94      format(1x,'yvalue',I2,' = ', E24.16E2)
95      format(1x,'zvalue',I2,' = ', E24.16E2)
93      format(4x,E23.17,4x,E24.16,6x,E24.16,4x,E24.16,4(5x,E24.16,3x,E24.16
c ,5x,E24.16,5x,E24.16))
      return
      end

      subroutine SORT(node,nnum)
      integer nnum
      real *8 node(60000,6),xcheck,rx,ry,rz
c ** diagnostics
c      open(unit=123,file='dia.dat',status='unknown')
c ---- sort by X coordinates: put in ascending order -----

c      write(123,*) 'node(1,1) = ', node(1,1)
c      write(123,*) 'node(2,1) = ', node(2,1)
c      write(123,*) ' '
      do 874 jj = 2, nnum
      j = jj
873  xcheck = (node(j,2) - node(j-1,2))
      if (xcheck .lt. 0.0) then
          CALL SWITCH(node(j,1),node(j,2),node(j,3),node(j,4),
c      node(j,5),
c      node(j,6),node(j-1,1),node(j-1,2),node(j-1,3),node(j-1,4),
c      node(j-1,5),node(j-1,6))
          if (j .gt. 2) then
              j = j-1
              goto 873
          end if
      end if
c      write(123,*) node(j,1), j,jj
874      continue

c88      format(1x, I4,', ',4(2x,E16.8,', '),2x,E16.8)

c      put in check - after x sort
c      do 885 j = 1, nnum
c      write(123,*)j, ' EEEEEHHHHKKK'
c      write(123,886) node(j,1), node(j,2), node(j,3), node(j,4)
c      if (node(j,1).le. 0.0) then
c      print *, 'AGHHHHHH'
c      end if

885      continue

c print out node array after x sort
c      write(123,*) ' after x sort'
c      do 106 i = 1, nnum
c      write(123,88) int(node(i,1)) ,node(i,2), node(i,3), node(i,4)
c      c , node(i,5), node(i,6)
c106      continue

c ----- if x coordinates are the same, then compare the y coordinates --
      nxsame = 0

```

```

      do 876 j = 2, nnum
      xcheck = (node(j,2) - node(j-1,2))
      if (xcheck .eq. 0.0) then
        nxsame = nxsame + 1
      end if
      if ((xcheck .gt. 0.0) .or. (j .eq. nnum)) then
        if (nxsame .ge. 1) then
          if (j .eq. nnum) then
            jj = j + 1
            nxsame = nxsame - 1
            CALL YSORT(jj,nxsame,node)
          end if
          CALL YSORT(j,nxsame,node)
        end if
        nxsame = 0
      else if (xcheck .lt. 0) then
        print *, 'x coordinate mistake', xcheck, nnum
        print *, node(j,2), node(j-1,2), node(j,1), node(j-1,1)
      end if
876   continue

c print out node array after y and z sort
c   write(123,*) ' after y and z sort'
c   do 106 i = 1, nnum
c   write(123,88) int(node(i,1)) , node(i,2), node(i,3), node(i,4)
c   c , node(i,5), node(i,6)
c106   continue

c rename duplicate nodes
      do 860 j = 2, nnum
      rx = abs(node(j,2) - node(j-1,2))
      ry = abs(node(j,3) - node(j-1,3))
      rz = abs(node(j,4) - node(j-1,4))
      rd = (rx**2 + ry**2 + rz**2)**(.5)
      if (rx .le. .00005 .and. ry .le. .00005
c .and. rz .le. .00005) then      !mmm
        node(j,1) = node(j-1,1)
      elseif (rd .le. .000005) then
        node(j,1) = node(j-1,1)
      end if
c   may need to make tolerances bigger

860   continue
c put in check - after z sort
c   do 885 j = 1, nnum
c   write(*,886) node(j,1), node(j,2), node(j,3), node(j,4)
c885   continue
886   format(2x,f7.2,3(2x,e12.5))
c   put in pause after z sort
c   print *, 'pause after z sort ...'
c   read *, dingy
c   close(unit=123)
c   return
c   end

      subroutine SWITCH(a,b,c,d,e,f,aa,bb,cc,dd,ee,ff)
      real*8 a,b,c,d,e,f
      real*8 aa,bb,cc,dd,ee,ff

```

```

      real*8  one,two,three,four,five,six

c      switch rows - first put a,b,c,d,e,f in buffer
      one = a
      two = b
      three = c
      four = d
      five = e
      six = f
c      second - set a = aa, etc..
      a = aa
      b = bb
      c = cc
      d = dd
      e = ee
      f = ff
c      third - set aa = one
      aa = one
      bb = two
      cc = three
      dd = four
      ee = five
      ff = six
      return
      end

      subroutine YSORT(j,nxsame,node)
      real*8 node(60000,6),ycheck
      integer nxsame,j
      open(unit=124,file='ycheck.dat',status='unknown')
c      this subroutine is to sort the y coordinates of the
c      nodes with the same x coordinate
      beg = j - nxsame ! beg of same x coordinates
      end = j - 1      ! end of same x coordinates
c      sort the y coordinates of the nodes with identical x coordinates
c      write(124,*) ' '
      do 20 ii = beg,end
      i = ii
873  ycheck = (node(i,3) - node(i-1,3))
c      write(124,*) node(i-1,3),node(i,3),ycheck
      if (ycheck .lt. 0.0) then
c      write(124,*) ' CALL switch'
      CALL SWITCH(node(i,1),node(i,2),node(i,3),node(i,4),
c      node(i,5),
c      node(i,6),node(i-1,1),node(i-1,2),node(i-1,3),node(i-1,4),
c      node(i-1,5),node(i-1,6))
c      write(124,*) 'AFTER switch..'
cckk write(124,*) node(i-1,3),node(i,3),ycheck
      if (i .ge. (beg+1)) then
      i = i-1
      goto 873
      end if
      end if
20  continue
c      put in check after y sort and before z sort
      do 21 ii = beg,end
      i = ii
c      write(124,*) node(i-1,3),node(i,3),ycheck

```



```

21      continue
c      write(124,*)' '
c --- just sorted the y coordinates -- now sort the z's -----
      nysame = 0
c go the nodes with identical x coord. to find which ones have
c identical y coordinates
      do 40 i = beg, end
        ycheck = (node(i,3) - node(i-1,3))
        if (ycheck .eq. 0.0) then
          nysame = nysame + 1
        end if
        if ((ycheck .gt. 0.0) .or. (i .eq. end)) then
          if (nysame .ge. 1) then
            if (i .eq. end) then
              ii = i + 1
              nysame = nysame - 1
              CALL ZSORT(ii,nysame,node)
            end if
            CALL ZSORT(i,nysame,node)
          end if
          nysame = 0
        else if (ycheck .lt. 0 ) then
          print *, 'y coordinate mistake',ycheck
        end if
40      continue

c put in check after z sort
      do 22 ii = beg,end
        i = ii
c      write(124,*) node(i,3),node(i,4)
22      continue
c      write(124,*)' '

42      return
      end

      subroutine ZSORT(j,nysame,node)
      real*8 node(60000,6),zcheck
c      integer nzsame
      integer nysame,j
c      this subroutine is to sort the y coordinates of the
c      nodes with the same x coordinate
      beg = j - nysame
      end = j - 1
      do 20 ii = beg,end
        i = ii
873      zcheck = (node(i,4) - node(i-1,4))
        if (zcheck .lt. 0.0) then
          CALL SWITCH(node(i,1),node(i,2),node(i,3),node(i,4),
c          node(i,5),
c          node(i,6),node(i-1,1),node(i-1,2),node(i-1,3),node(i-1,4),
c          node(i-1,5),node(i-1,6))
          if (i .ge. (beg+1)) then
            i = i-1
            goto 873
          end if
        end if
20      continue

```

```

return
end

subroutine ESORT(elnode,nnum,element)
  integer nnum,element
  real*8 elnode(60000,11),elcheck
c ---- sort by elements: put in ascending order -----
c   do 105 i = 1, nnum
c   write(*,88) int(elnode(i,1)) ,elnode(i,2) , elnode(i,3),
c   c elnode(i,4), elnode(i,5), elnode(i,6)
c105  continue

      do 874 jj = 2, nnum
        j = jj
873    elcheck = (elnode(j,5) - elnode(j-1,5))
        if (elcheck .lt. 0.0) then
          CALL SWITCH(elnode(j,1),elnode(j,2),elnode(j,3),
c          elnode(j,4),elnode(j,5),elnode(j,6),elnode(j-1,1)
c          ,elnode(j-1,2),elnode(j-1,3),elnode(j-1,4),
c          elnode(j-1,5),elnode(j-1,6))
          if (j .gt. 2) then
            j = j-1
            goto 873
          end if
        end if
      continue
874
c ----- if elements are the same, then compare the nodes in each element --
      nbeg = 0
      do 877 i = 1, element
        if (i .eq. 1) then
          nbeg = 2
        else
          nbeg = 10*i - 8
        end if
        nend = nbeg + 8
        do 876 jj = nbeg , nend
          j = jj
875    ncheck = (elnode(j,6) - elnode(j-1,6))
          if (ncheck .lt. 0.0) then
            CALL SWITCH(elnode(j,1),elnode(j,2),elnode(j,3),
c            elnode(j,4),elnode(j,5),elnode(j,6),elnode(j-1,1)
c            ,elnode(j-1,2),elnode(j-1,3),elnode(j-1,4),
c            elnode(j-1,5),elnode(j-1,6))
            if (j .ge. nbeg + 1) then
              j = j-1
              goto 875
            end if
          end if
        continue
876
      continue
877
c88  format(1x,2I4,' ',',',4(2x,E16.8,' ','),2x,E16.8)
      return
      end

```

```

SUBROUTINE FILENAMES(name41,name42,name43,
cname44,name45,name46,name52)

```

```

c      character*1 fileans, oldfileans, filman
      character*1 dum, ctest
      character*8 dir,dir7*7,dir6*6
      character*20 dir5*5,dir4*4,dir3*3,dir2*2
      character*20 name41,name42,name43,name44
      character*20 name45,name46,name52

c find out what directory to put the files:
c      print *, ' '
9      print *, 'Enter what directory to put the data files in:'
      read(*,11) dir
11     format(a8)
c      write(*,11) dir
c -----
c test for extra spaces and get rid of them
      ctest = dir(8:)
      name41 = dir//'/lastrun.dat'
      name42 = dir//'/efield.dat'
      name43 = dir//'/window.dat'
      name44 = dir//'/element.dat'
      name45 = dir//'/node.dat'
      name46 = dir//'/thermo.inp'
      name52 = dir//'/struc.inp'
      if (ctest .eq. ' ') then
        dir7 = dir(:7)
        name41 = dir7//'/lastrun.dat'
        name42 = dir7//'/efield.dat'
        name43 = dir7//'/window.dat'
        name44 = dir7//'/element.dat'
        name45 = dir7//'/node.dat'
        name46 = dir7//'/thermo.inp'
        name52 = dir7//'/struc.inp'
        ctest = dir7(7:) !check for blanks
        if (ctest .eq. ' ') then
          dir6 = dir7(:6) !shorten by one
          name41 = dir6//'/lastrun.dat'
          name42 = dir6//'/efield.dat'
          name43 = dir6//'/window.dat'
          name44 = dir6//'/element.dat'
          name45 = dir6//'/node.dat'
          name46 = dir6//'/thermo.inp'
          name52 = dir6//'/struc.inp'
          ctest = dir6(6:)
          if (ctest .eq. ' ') then
            dir5 = dir6(:5)
            name41 = dir5//'/lastrun.dat'
            name42 = dir5//'/efield.dat'
            name43 = dir5//'/window.dat'
            name44 = dir5//'/element.dat'
            name45 = dir5//'/node.dat'
            name46 = dir5//'/thermo.inp'
            name52 = dir5//'/struc.inp'
            ctest = dir5(5:)
            if (ctest .eq. ' ') then
              dir4 = dir5(:4)
              name41 = dir4//'/lastrun.dat'
              name42 = dir4//'/efield.dat'
              name43 = dir4//'/window.dat'

```

```

name44 = dir4//'/element.dat'
name45 = dir4//'/node.dat'
name46 = dir4//'/thermo.inp'
name52 = dir4//'/struc.inp'
ctest = dir4(4:)
if (ctest .eq. ' ') then
dir3 = dir4(:3)
name41 = dir3//'/lastrun.dat'
name42 = dir3//'/efield.dat'
name43 = dir3//'/window.dat'
name44 = dir3//'/element.dat'
name45 = dir3//'/node.dat'
name46 = dir3//'/thermo.inp'
name52 = dir3//'/struc.inp'
ctest = dir3(3:)
if (ctest .eq. ' ') then
dir2 = dir3(:2)
name41 = dir2//'/lastrun.dat'
name42 = dir2//'/efield.dat'
name43 = dir2//'/window.dat'
name44 = dir2//'/element.dat'
name45 = dir2//'/node.dat'
name46 = dir2//'/thermo.inp'
name52 = dir2//'/struc.inp'
end if
end if
end if
end if
end if
end if
c   print *, 'ctest = ',ctest
c   print *, 'path41 = ',name41
c   print *, 'path42 = ',name42
c   print *, 'path43 = ',name43
c   print *, 'path44 = ',name44
c   print *, 'path45 = ',name45
c   print *, ' '
write(*,*) 'The directory is ',dir,' Is this correct? (y/n)'
read(*,79) dum
if (dum .eq. 'n') goto 9
79  format(A1)
return
end

```

APPENDIX B: ABAQUS INPUT FILE Thermo.inp

```

*HEADING, SPARSE
POWER = 0.10E+07 WATTS
10.86 cm radius , half model, al300 , 4799
** Wed Dec 17 07:07:44 1997
** NODE DEFINITIONS
**
*NODE, NSET=NALL
25853, -0.10860000E+03, -0.60000000E+01, 0.00000000E+00
25860, -0.10860000E+03, -0.30000000E+01, 0.00000000E+00

..... some lines omitted .....

25533, -0.10860000E+03, 0.00000000E+00, 0.00000000E+00
25514, 0.10860000E+03, 0.00000000E+00, 0.00000000E+00
25960, 0.10860000E+03, 0.30000000E+01, 0.00000000E+00
25924, 0.10860000E+03, 0.60000000E+01, 0.00000000E+00
**
*ELEMENT, TYPE=DC3D10, ELSET=VOL1
1, 2, 3, 4, 1, 6, 10, 9, 5, 7, 8
2, 12, 13, 14, 11, 16, 20, 19, 15, 17, 18

..... some lines omitted .....

3327, 26922, 233, 27513, 31041, 26926, 27520, 27516, 33148, 33267, 33268
3328, 683, 27504, 31033, 26932, 33259, 33280, 31036, 26936, 27509, 33136
3329, 26922, 683, 233, 31041, 26929, 690, 26926, 33148, 31048, 33267
**
*SOLID SECTION, ELSET=VOL1, MATERIAL=AL1
**
*MATERIAL, NAME=AL1
*CONDUCTIVITY
** Units are watts/mm-c
.0268
*DENSITY
.00000367
**
*PHYSICAL CONSTANTS, ABSOLUTE ZERO=0.0, STEFAN BOLTZMANN=5.669E-14
**
**
*RESTART, WRITE
**
**
*STEP
**
*HEAT TRANSFER, STEADY STATE
**
*DFLUX, OP=NEW
1, BF, 0.26105131E-03
2, BF, 0.16311756E-02

..... some lines omitted .....

```

```

3328,      BF,  0.17594827E-03
3329,      BF,  0.18583402E-03
**
*FILM, OP=NEW
      84,      F1,      320.0,      0.00018
     134,      F4,      320.0,      0.00018

..... some lines omitted .....

     3306,      F2,      298.0,      0.02340
     3307,      F2,      298.0,      0.02340
**
*RADIATE, OP=NEW
      84,      R1,      296.0,      0.52158E-13
     134,      R4,      296.0,      0.52158E-13

..... some lines omitted .....

     3323,      R3,      296.0,      0.52158E-13
     3327,      R4,      296.0,      0.52158E-13
**
**
*EL PRINT, ELSET=VOL1, POSITION=INTEGRATION POINTS
*NODE PRINT, GLOBAL=YES
NT, RFL, RFLE
*NODE FILE, GLOBAL=YES
NT
*END STEP

```

APPENDIX C: ABAQUS INPUT FILE Struc.inp

```

*HEADING, SPARSE
POWER = 0.10E+07 WATTS
10.86 cm radius , half model, al300 ,4799
** Wed Dec 17 07:07:44 1997
** NODE DEFINITIONS
**
*NODE, NSET=NALL
25853, -0.10860000E+03, -0.60000000E+01, 0.00000000E+00
25514, 0.10860000E+03, 0.00000000E+00, 0.00000000E+00

..... some lines omitted .....

25960, 0.10860000E+03, 0.30000000E+01, 0.00000000E+00
25924, 0.10860000E+03, 0.60000000E+01, 0.00000000E+00
**
*ELEMENT, TYPE=C3D10, ELSET=VOL1
1, 2, 3, 4, 1, 6, 10, 9, 5, 7, 8
2, 12, 13, 14, 11, 16, 20, 19, 15, 17, 18
3, 22, 23, 24, 21, 26, 30, 29, 25, 27, 28

..... some lines omitted .....

3328, 683, 27504, 31033, 26932, 33259, 33280, 31036, 26936, 27509, 33136
3329, 26922, 683, 233, 31041, 26929, 690, 26926, 33148, 31048, 33267
*ELEMENT, TYPE=M3D6, ELSET=SUR2
5001, 304, 603, 604, 606, 610, 609
5002, 324, 604, 603, 616, 610, 619

..... some lines omitted .....

7289, 27513, 26922, 31041, 27516, 33148, 33268
**
*SOLID SECTION, ELSET=VOL1, MATERIAL=AL1
**
*MATERIAL, NAME=AL1
*ELASTIC
3.03E5, .21
*CONDUCTIVITY
** Units are watts/mm-c
.0268
*EXPANSION, ZERO=294.5
6.9E-6
*DENSITY
.00000367
**
**
*MEMBRANE SECTION, ELSET=SUR2, MATERIAL=THIN2, POISSON=.21
1.0E-6
*MATERIAL, NAME=THIN2
*ELASTIC
3.03E5, .21
*CONDUCTIVITY
** Units are watts/mm-c
.0268

```

```

**
*EXPANSION, ZERO=294.5
  6.9E-6
*INITIAL CONDITIONS, TYPE=TEMPERATURE
NALL, 294.5
**
*RESTART, WRITE
**
**
*STEP
**
*STATIC
*TEMPERATURE, FILE=basec, ESTEP=1, BSTEP=1, EINC=1, BINC=1
**
**
*BOUNDARY, OP=NEW
  18023, 2, 2, 0.00
  25870, 2, 2, 0.00

  ..... some lines omitted .....

  25960, 3, 3, 0.00
  25924, 3, 3, 0.00
**
*DLOAD, OP=NEW
   84, P1, -0.10135
  134, P4, -0.10135

  ..... some lines omitted .....

   135, P2, -0.10135
   139, P2, -0.10135
  3328, P3, -0.10135
**
**
*EL FILE, ELSET=SUR2, POSITION=INTEGRATION POINTS
S
SINV
TEMP
*EL PRINT, ELSET=SUR2, POSITION=INTEGRATION POINTS
S
SINV
TEMP
*EL FILE, ELSET=VOL1, POSITION=INTEGRATION POINTS
S
SINV
TEMP
S
SINV
TEMP
*NODE PRINT, GLOBAL=YES
U
*NODE FILE, GLOBAL=YES
U
**
*END STEP

```


Appendix D: CARES Life Input File Struc.inl

--- CARES/LIFE TEMPLATE INPUT FILE ---

```
*****
*
*      RELIABILITY PREDICTION FOR BRITTLE MATERIAL STRUCTURES      *
*      --- FAST-FRACTURE AND TIME-DEPENDENT MODELING ---          *
*                                                                 *
*****
```

MASTER CONTROL INPUT

TITLE : PROBLEM TITLE (ECHOED IN CARES OUTPUT)

-----
350 MHz RF Window - Base Case

NE : CONTROL INDEX FOR FINITE ELEMENT POSTPROCESSING

-- (DEFAULT: NE = 0)

3 0 : EXPERIMENTAL DATA ANALYSIS ONLY

-- 3 : COMPONENT RELIABILITY ANALYSIS WITH NEUTRAL FILE
DATA BASE

IPRINC : CONTROL INDEX FOR ELEMENT STRESS OUTPUT

-- (DEFAULT: IPRINC=1)

2 1 : USE PRINCIPAL STRESSES

-- 2 : USE ELEMENT OR MATERIAL COORDINATE SYSTEM STRESSES.
THIS OPTION IS RECOMMENDED FOR MATERIALS MODELED
WITH THE BATDORF THEORY. WHEN TWO NEUTRAL FILES
ARE READ (IPROOF = 1) THEN IPRINC SHOULD BE SET
TO THIS VALUE

NMATS : NUMBER OF MATERIALS FOR SURFACE FLAW ANALYSIS

-- (NMATS+NMATV < 101)

01 (DEFAULT: NMATS = 0)

--

NMATV : NUMBER OF MATERIALS FOR VOLUME FLAW ANALYSIS

-- (NMATS+NMATV < 101)

00 (DEFAULT: NMATV = 0)

--

IPRINT : CONTROL INDEX FOR STRESS OUTPUT

-- (DEFAULT: IPRINT = 0)

1 0 : DO NOT PRINT ELEMENT STRESSES AND/OR FRACTURE DATA

-- 1 : PRINT ELEMENT STRESSES AND/OR FRACTURE DATA

NGP : NUMBER OF GAUSSIAN QUADRATURE POINTS (15 OR 30 OR 50)

-- (DEFAULT: NGP = 15)

30

--

NS : NUMBER OF SEGMENTS IN SYMMETRY PROBLEM

--- (DEFAULT: NS = 1)

002

```

*---*

IPROOF      : CONTROL INDEX FOR RELIABILITY ANALYSIS WITH NEUTRAL FILES
*--*        (DEFAULT: IPROOF = 0)
0           0 : READ ONLY ONE NEUTRAL FILE;
*--*        EITHER STATIC OR CYCLIC LOADING RELIABILITY ANALYSIS
              (NO PROOF TESTING IS CONSIDERED)
1           1 : READ TWO NEUTRAL FILES;
              INCLUDE THE EFFECTS OF PROOF TESTING OR CYCLIC LOADING
              IN THE RELIABILITY ANALYSIS

```

```

IPOST       : CONTROL INDEX FOR PATRAN DATA FILE
*--*        (DEFAULT: IPOST = 0)
1           0 : DO NOT WRITE ELEMENT RISK OF RUPTURE INTENSITIES
*--*        1 : WRITE ELEMENT RISK OF RUPTURE INTENSITIES

```

```

INTERP      : CONTROL INDEX FOR TEMPERATURE INTERPOLATED PARAMETERS
*--*        (DEFAULT: INTERP = 0)
0           0 : DO NOT WRITE INTERPOLATED MATERIAL PARAMETERS
*--*        1 : WRITE INTERPOLATED MATERIAL PARAMETERS

```

```

FACTOR      : LOAD FACTOR FOR WHICH TO MULTIPLY ELEMENT STRESSES
-----
00001.000
-----

```

```

TIME        : SERVICE LIFE FOR RELIABILITY ANALYSIS OF THE FIRST NEUTRAL
-----      FILE IN UNITS OF SECONDS OR CYCLES (DEFAULT: TIME = 0.0)
001.0

```

```

----- WARNING--> | In CARES/LIFE for cyclic loading when using the
-----           | POWER LAW the component reliability is expressed as a
                   | function of time in service (in seconds) and not as a
                   | function of the number of loading cycles in service.
                   | PARIS and WALKER LAW based component reliability
                   | analysis is always a function of the number of loading
                   | cycles.

```

```

*****
$ENDX      : END OF MASTER CONTROL INPUT
*****

```

MATERIAL CONTROL INPUT

```

TITLE      : MATERIAL TITLE (ECHOED IN CARES OUTPUT)
-----

```

ALUMINA DATA FOR SURFACE FLAW ANALYSIS

```

MATID      : MATERIAL IDENTIFICATION NO. FROM THE FINITE ELEMENT
*-----*   MATERIAL PROPERTY CARD (IF POSTPROCESSING IS NOT
0000002    BEING PERFORMED THIS ENTRY SHOULD BE SOME UNIQUE NO.)
*-----*   (NO DEFAULT)

```

```

ID1      : CONTROL INDEX FOR EXPERIMENTAL DATA
  *-*    (NO DEFAULT)
    3     1 : UNIFORM UNIAXIAL TENSILE SPECIMEN TEST DATA
  *-*    2 : FOUR-POINT BEND TEST DATA
        3 : DIRECT INPUT OF THE REQUIRED PARAMETERS
        4 : CENSORED DATA FOR SUSPENDED ITEM ANALYSIS OF
          UNIFORM UNIAXIAL TENSILE SPECIMEN TEST DATA
        5 : CENSORED DATA FOR SUSPENDED ITEM ANALYSIS OF
          FOUR-POINT BEND TEST DATA

ID4      : CONTROL INDEX FOR VOLUME OR SURFACE FLAW ANALYSIS
  *-*    (NO DEFAULT)
    2     1 : VOLUME
  *-*    2 : SURFACE

ID2      : CONTROL INDEX FOR FRACTURE CRITERION
  *-*    (NO DEFAULT)
    5     1 : NORMAL STRESS FRACTURE CRITERION
  *-*        (SHEAR-INSENSITIVE CRACK)
        2 : MAXIMUM TENSILE STRESS CRITERION (VOLUME FLAW ONLY)
        3 : COPLANAR STRAIN ENERGY RELEASE RATE CRITERION
          (G SUB T)
        4 : WEIBULL PIA MODEL
        5 : SHETTY'S SEMI-EMPIRICAL CRITERION

ID3      : CONTROL INDEX FOR CRACK GEOMETRY
  *-*    (NO DEFAULT)
    1     1 : GRIFFITH CRACK (VOLUME FLAW OR SURFACE FLAW)
  *-*    2 : PENNY-SHAPED CRACK (VOLUME FLAW ONLY)
        3 : GRIFFITH NOTCH (SURFACE FLAW ONLY)
          (ID2 = 3 OR 5 IS REQUIRED)
        4 : SEMICIRCULAR CRACK (SURFACE FLAW ONLY)
          (ID2 = 5 IS REQUIRED)

IKBAT    : CONTROL INDEX FOR METHOD OF CALCULATING BATDORF CRACK
  *-*    DENSITY COEFFICIENT (K SUB B) FROM TEST DATA
    1     (DEFAULT: IKBAT = 1)
  *-*    0 : SHEAR-INSENSITIVE METHOD (MODE I FRACTURE ASSUMED)
        1 : SHEAR-SENSITIVE METHOD (FRACTURE ASSUMED TO OCCUR
          ACCORDING TO THE FRACTURE CRITERION AND CRACK SHAPE
          SELECTED BY THE ID2 AND ID3 INDICES)

PR       : POISSON'S RATIO
----- (DEFAULT: PR = 0.25)
00000.2100
-----

C        : CONSTANT FOR SEMI-EMPIRICAL MIXED-MODE FRACTURE CRITERIA
----- (KI/KIC)+(KII/(C*KIC))**2 = 1 REF. D.K.SHETTY
00000.8000 OBSERVED VALUES RANGE FROM 0.8 TO 2. (REF. D.K. SHETTY)
----- NOTE: AS C APPROACHES INFINITY, PREDICTED FAILURE
          PROBABILITIES APPROACH NORMAL STRESS CRITERION VALUES
          (DEFAULT C = 1.0)

CYCLIC   : CYCLIC FATIGUE BASED COMPONENT RELIABILITY EVALUATION
-----

```

```

| 0 |      : Crack growth law and wave form (IWAVE)
-----
0.857      : R-ratio of minimum/maximum cycle stress (RCYC)
-----
8.1E3      : Period (in seconds) of a cycle (PERIOD)
-----
2.0000     : Exponent of power law wave form (QCYC)
-----

```

```

-----
IWAVE = 0 : PARIS LAW OR WALKER LAW
        = 1 : POWER LAW; STATIC LOAD
        = 2 : POWER LAW; SQUARE WAVE
        = 3 : POWER LAW; SAWTOOTH WAVE
        = 4 : POWER LAW; 1/2 SINE WAVE
        = 5 : POWER LAW; SINE WAVE
-----

```

```

*****
$ENDM      : END OF TEMPERATURE INDEPENDENT MATERIAL CONTROL INPUT
*****

```

TEMPERATURE-DEPENDENT MATERIAL CONTROL INPUT DATA
FOR THE ABOVE MATERIAL

!!
PLEASE NOTE THE FOLLOWING:

1. TEMPERATURE-DEPENDENT DATA SETS MUST BE ARRANGED IN ASCENDING ORDER
ACCORDING TO TEMPERATURE (ONE DATA TABLE PER TEMPERATURE).
2. FRACTURE STRESSES FOR A GIVEN TEMPERATURE CAN BE INPUT IN
ARBITRARY ORDER.
3. REGARDLESS OF THE FRACTURE ORIGIN LOCATION, THE FRACTURE STRESS
INPUT VALUE IS THE EXTREME FIBER STRESS WITHIN THE INNER LOAD SPAN
OF THE MOR BAR.

!!

```

TEMP
-----
00273.0000
-----

```

```

PARAM
*-----M-----*-----SP-----*
1.6920000000E+01  3.6180000000+02
*-----*-----*

```

```

TPARAM
*-----N-----*-----B-----*
0.4010000000E+02  1.0100000000-06
*-----*-----*

```

END OF DATA FOR THE ABOVE TEMPERATURE

```

*****
$ENDT      : END OF DATA FOR THE ABOVE MATERIAL
*****

```

Appendix E:
CARES Parameter Estimation Input file Grit.inp

```
*****
*
*
*      --- INPUT TEMPLET FOR CARES/LIFE ---
*
*
*      CERAMICS ANALYSIS AND RELIABILITY EVALUATION
*
*      OF STRUCTURES LIFE PREDICTION PROGRAM
*
*
*
*****
```

MASTER CONTROL INPUT

TITLE : PROBLEM TITLE (LINE OF CHARACTERS ECHOED IN CARES OUTPUT)

-----
fast fracture / dynamic fatigue analysis (data from J. Salem - 3/26/98)

NE : CONTROL INDEX FOR FINITE ELEMENT POSTPROCESSING
-- (DEFAULT: NE = 0)
0 0 : EXPERIMENTAL DATA ANALYSIS ONLY
-- 3 : COMPONENT RELIABILITY ANALYSIS WITH NEUTRAL FILE
DATA BASE

NMATS : NUMBER OF MATERIALS FOR SURFACE FLAW ANALYSIS
-- (NMATS+NMATV < 101)
1 (DEFAULT: NMATS = 0)
--

NMATV : NUMBER OF MATERIALS FOR VOLUME FLAW ANALYSIS
-- (NMATS+NMATV < 101)
0 (DEFAULT: NMATV = 0)
--

NGP : NUMBER OF GAUSSIAN QUADRATURE POINTS (15, 30, OR 50)
-- (DEFAULT: NGP = 15)
15
--

```
*****
$ENDX      : END OF MASTER CONTROL INPUT
*****
```

MATERIAL CONTROL INPUT

TITLE : MATERIAL TITLE (ECHOED IN CARES OUTPUT)

-----
alumina surface analysis -4 pt bend data

MATID : MATERIAL IDENTIFICATION NO. FROM THE FINITE ELEMENT
----- MATERIAL PROPERTY CARD (IF POSTPROCESSING IS NOT
2 BEING PERFORMED THIS ENTRY SHOULD BE SOME UNIQUE NO.)
----- (NO DEFAULT)

ID1 : CONTROL INDEX FOR EXPERIMENTAL DATA
- (NO DEFAULT)
2 1 : UNIFORM UNIAXIAL TENSILE SPECIMEN TEST DATA
- 2 : FOUR-POINT BEND TEST DATA
3 : DIRECT INPUT OF THE REQUIRED PARAMETERS
4 : CENSORED DATA FOR SUSPENDED ITEM ANALYSIS OF
UNIAXIAL TENSILE SPECIMEN TEST DATA
5 : CENSORED DATA FOR SUSPENDED ITEM ANALYSIS OF
FOUR-POINT BEND TEST DATA
6 : CENSORED DATA FOR SUSPENDED ITEM ANALYSIS OF
UNIAXIAL LOADED FINITE ELEMENT MODEL OF SPECIMEN
(SUCH AS THREE-POINT AND FOUR-POINT BEND BAR,
TENSILE SPECIMEN, C-RING, O-RING, ETC...)
7 : CENSORED DATA FOR SUSPENDED ITEM ANALYSIS OF
MULTIAXIALLY LOADED FINITE ELEMENT MODEL OF SPECIMEN
(SUCH AS RING-ON-RING, BALL-ON-RING, TRANSVERSE
PRESSURE LOADED DISK, ETC...)

ID4 : CONTROL INDEX FOR VOLUME OR SURFACE FLAW ANALYSIS
- (NO DEFAULT)
2 1 : VOLUME
- 2 : SURFACE

ID2 : CONTROL INDEX FOR FRACTURE CRITERION
- (NO DEFAULT) (NOTE IPRINC = 0 IF ID2 > 5 IS REQUIRED)
5 1 : NORMAL STRESS FRACTURE CRITERION
- (SHEAR-INSENSITIVE CRACK)
2 : MAXIMUM TENSILE STRESS CRITERION (VOLUME FLAW ONLY)
3 : COPLANAR STRAIN ENERGY RELEASE RATE CRITERION
(G SUB T)
4 : WEIBULL PIA MODEL
5 : SHETTY'S SEMI-EMPIRICAL CRITERION (NONCOPLANAR SERR)
6 : SEMI-EMPIRICAL RELATION $(K_I/K_{IC})^{**2} + (K_{II}/(C*K_{IC}))^{**2} = 1$

7 : COMPRESSION CRITERION (FUNCTION OF SHEAR ONLY)

*** (NOTE IPRINC = 0 IF ID2 > 5 IS REQUIRED) ***

MLORLE : CONTROL INDEX FOR METHOD OF CALCULATING WEIBULL
 -- PARAMETERS FROM THE EXPERIMENTAL FRACTURE DATA
 0 (DEFAULT: MLORLE = 0)
 -- 0 : MAXIMUM LIKELIHOOD
 1 : LEAST-SQUARES LINEAR REGRESSION WITH
 RANK INCREMENT ADJUSTMENT
 2 : LEAST-SQUARES LINEAR REGRESSION WITHOUT
 RANK INCREMENT ADJUSTMENT (THIS OPTION IS NOT
 RECOMMENDED)

OUTLIE : SIGNIFICANCE LEVEL FOR WHICH OUTLIERS ARE TO
 ----- BE DETECTED. INPUT IS IN PERCENT AND MUST BE BETWEEN
 1.0000 THE RANGE OF 0.1 PERCENT TO 10.0 PERCENT
 ----- (DEFAULT OUTLIE = 10.0)

PFCONV : FAILURE PROBABILITY TO CALCULATE THE WEIBULL SCALE
 ----- PARAMETER FOR THE FINITE ELEMENT MODEL
 0.63212056 ----> (ASSUMES MATERIAL PARAMETERS ARE CONSTANT VERSUS
 ----- TEMPERATURE; ONLY ONE TEMPERATURE DATA SET IS INPUT)
 (DEFAULT PFCONV = 0.0 ,THUS QUANTITY NOT CALCULATED)
 NOTE: 0.0 < PFCONV < 1.0

DH : HEIGHT OF THE FOUR-POINT BEND BAR
 ----- (NO DEFAULT)
 0003.00800

DL1 : OUTER LOAD SPAN OF THE FOUR-POINT BEND BAR
 ----- (NO DEFAULT)
 0040.00400

DL2 : INNER LOAD SPAN OF THE FOUR-POINT BEND BAR
 ----- (NO DEFAULT)
 0019.94400

DW : WIDTH OF THE FOUR-POINT BEND BAR
 ----- (NO DEFAULT)
 0004.00500

*****
 \$ENDM : END OF TEMPERATURE-INDEPENDENT MATERIAL CONTROL INPUT
 *****

TEMPERATURE-DEPENDENT MATERIAL CONTROL INPUT DATA
FOR THE ABOVE MATERIAL

!!
PLEASE NOTE THE FOLLOWING:

1. TEMPERATURE-DEPENDENT DATA SETS MUST BE ARRANGED IN ASCENDING ORDER
ACCORDING TO TEMPERATURE (ONE DATA TABLE PER TEMPERATURE).
2. FRACTURE STRESSES FOR A GIVEN TEMPERATURE CAN BE INPUT IN
ARBITRARY ORDER.
3. REGARDLESS OF THE FRACTURE ORIGIN LOCATION, THE FRACTURE STRESS
INPUT VALUE IS THE EXTREME FIBER STRESS WITHIN THE INNER LOAD SPAN
OF THE MOR BAR.

!!

-----> DATA TABLE; EXPLANATION OF INPUT

TEST : TYPE OF DATA TO BE INPUT.

: BLANK CHARACTERS DEFAULT TO THE SETTING OF THE
IMMEDIATELY PRECEDING VALUE (THIS APPLIES TO
TEST AND FIELD1 ONLY FOR THE FAST, STAT, CYCL, AND
DYNA KEYWORDS)

CYCL : CYCLIC FATIGUE SPECIMEN DATA

FIELD1 : MAGNITUDE OF FATIGUE STRESS
(MAXIMUM CYCLE STRESS)

FIELD2 : LEAVE BLANK OR LIFETIME TO FAILURE
(UNITS OF SECONDS FOR POWER LAW)
(UNITS OF CYCLES FOR PARIS AND WALKER

LAWS)

FIELD3 : LEAVE BLANK OR LIFETIME TO FAILURE
(UNITS OF SECONDS FOR POWER LAW)
(UNITS OF CYCLES FOR PARIS AND WALKER

LAWS)

CYCLIC : CYCLIC FATIGUE DATA (IWAVE)

(INPUT IN ALPHA-NUMERIC "FLAW" FIELD)

- 0 : PARIS LAW OR WALKER LAW
- 1 : DIRECT INPUT OF G-FACTOR
- 2 : POWER LAW; SQUARE WAVE
- 3 : POWER LAW; SAWTOOTH WAVE
- 4 : POWER LAW; 1/2 SINE WAVE
- 5 : POWER LAW; SINE WAVE

FIELD1 : R-RATIO OF MIN/MAX CYCLE STRESS OR
DIRECT INPUT OF G-FACTOR

FIELD2 : PERIOD OF THE CYCLE (SECONDS)

FIELD3 : WALKER R-RATIO SENSITIVITY EXPONENT
OR EXPONENT OF POWER LAW WAVE FORM (QCYC)

WHEN QCYC IS SET TO ZERO BY THE USER AND THE WALKER OR
PARIS LAW IS SELECTED, CARES/LIFE AUTOMATICALLY
DEFAULTS QCYC TO THE VALUE OF THE FATIGUE EXPONENT N,
WHICH DEFINES THE PARIS LAW.

WHEN THE WAVE FORM EXPONENT (QCYC) IS USED WITH THE POWER LAW (IWAVE > 1), THEN THE G-FACTOR IS DETERMINED FOR THE SELECTED WAVE FORM RAISED TO THE QCYC EXPONENT. FOR EXAMPLE; IF A ROTATING COMPONENT HAS A SINUSIODAL VARIATION IN ANGULAR SPEED, THE STRESS IS DIRECTLY PROPORTIONAL TO THE SQUARE OF THE ANGULAR SPEED AND QCYC IS SET TO A VALUE OF 2.0

DATA

DYNA : DYNAMIC FATIGUE (CONSTANT STRESS RATE) SPECIMEN

FIELD1 : MAGNITUDE OF STRESS RATE (STRESS/SECOND)
 FIELD2 : LEAVE BLANK OR ULTIMATE FAILURE STRESS OF SPECIMEN
 FIELD3 : LEAVE BLANK OR ULTIMATE FAILURE STRESS OF SPECIMEN

FAST : FAST FRACTURE

FIELD1 : LEAVE BLANK OR SPECIMEN FRACTURE STRESS
 FIELD2 : LEAVE BLANK OR SPECIMEN FRACTURE STRESS
 FIELD3 : LEAVE BLANK OR SPECIMEN FRACTURE STRESS

PARAM : DIRECT INPUT OF FAST-FRACTURE WEIBULL PARAMETERS

FIELD1 : WEIBULL MODULUS OR SHAPE PARAMETER
 FIELD2 : WEIBULL SCALE PARAMETER
 FIELD3 : WEIBULL CHARACTERISTIC STRENGTH

RSTRES : RESIDUAL STRESSES IN THE MATERIAL COORDINATE SYSTEM

FIELD1 : X STRESS COMPONENT (3-D AND 2-D)
 FIELD2 : Y STRESS COMPONENT (3-D AND 2-D)
 FIELD3 : Z STRESS COMPONENT (3-D ONLY)

+STRES : RESIDUAL STRESSES IN THE MATERIAL COORDINATE SYSTEM

FIELD1 : XY STRESS COMPONENT (3-D AND 2-D)
 FIELD2 : YZ STRESS COMPONENT (3-D ONLY)
 FIELD3 : ZX STRESS COMPONENT (3-D ONLY)

RANGE : SEARCH RANGE TO FIND THE FATIGUE EXPONENT N WHEN THE MEDIAN DEVIATION TECHNIQUE IS SPECIFIED
 (SOL = 2)
 (THE DEFAULT RANGE IS 2.1 TO 150.0)

FIELD1 : BOUNDARY OF SEARCH RANGE
 FIELD2 : BOUNDARY OF SEARCH RANGE
 FIELD3 : LEAVE BLANK

SOL : SOLUTION METHOD FOR THE TIME-DEPENDENT DATA
 (INPUT IN ALPHA-NUMERIC "FLAW" FIELD)

0 : MEDIAN VALUE LEAST SQUARES REGRESSION
 1 : LEAST SQUARES REGRESSION
 2 : MEDIAN DEVIATION ITERATION

STAT : STATIC FATIGUE (CONSTANT STRESS) SPECIMEN DATA

FIELD1 : MAGNITUDE OF FATIGUE STRESS
 FIELD2 : LEAVE BLANK OR TIME TO FAILURE (SECONDS)

TEMP : TEMPERATURE OF SET (ONE ASSIGNMENT PER DATA TABLE)

FIELD1 : TEMPERATURE
 FIELD2 : LEAVE BLANK
 FIELD3 : LEAVE BLANK

TPARAM : DIRECT INPUT OF TIME-DEPENDENT PARAMETERS

FIELD1 : FATIGUE CRACK GROWTH EXPONENT N
 FIELD2 : FATIGUE CONSTANT B SUB W,

(STRESS**2*SECOND) OR (STRESS**2*CYCLE)
 FIELD3 : LEAVE BLANK OR WALKER R-RATIO
 SENSITIVITY EXPONENT
 VAGTIM : TIME-DEPENDENT EFFECTIVE VOLUME OR AREA
 FIELD1 : EFFECTIVE VOLUME OR AREA
 FIELD2 : LEAVE BLANK
 FIELD3 : LEAVE BLANK
 VAGAGE : FAST-FRACTURE EFFECTIVE VOLUME OR AREA
 FIELD1 : EFFECTIVE VOLUME OR AREA
 FIELD2 : LEAVE BLANK
 FIELD3 : LEAVE BLANK
 \$ENDD : END OF DATA MARKER FOR THE DATA TABLE

FLAW : FRACTURE ORIGIN (ONLY FOR FAST, STAT, CYCL, AND
 DYNA KEYWORDS)
 : BLANK CHARACTER DEFAULTS TO FLAW TYPE INDICATED BY
 THE ID4 KEYWORD
 S : SURFACE FLAW
 U : UNKNOWN FLAW (COMPETING FAILURE MODE OR RUN OUT)
 V : VOLUME FLAW

DTABLE : DATA TABLE (FAST-FRACTURE, STATIC OR DYNAMIC FATIGUE)
 -TEST-I-FLAW-I-----FIELD1-----I-----FIELD2-----I-----FIELD3-----I

TEMP		0.296E+03	
SOL	2		
RANGE		1.00	200.00
DYNA	S	0.030	179.91
	S		155.91
	S		175.04
	S		175.71
	S		159.92
	S	0.30	157.51
	S		184.28
	S		180.55
	S		179.08
	S		185.00
	S	30.0	226.43
	S		229.64
	S		224.06
	S		244.58
	S		186.59
	S		243.68
	S		247.06
	S		238.38
	S		241.09
	S		237.93
	S		241.45
	S		127.21
	S		230.99
	S		229.89
	S		238.50
	S		239.98

\$ENDD

-TEST-I-FLAW-I-----FIELD1-----I-----FIELD2-----I-----FIELD3-----I
END OF DATA FOR THE ABOVE TEMPERATURE

*****

\$ENDT : END OF DATA FOR THE ABOVE MATERIAL

*****

Appendix F: FORTRAN program power.f

```
      program power
c This program is to calculate the total amount of power
c dissipated in the window

c open files
      open(unit=68,file = 'flux.dat', status='unknown')
      open(unit=70,file = 'vol.dat', status='unknown')

c initialize variables
      power = 0.0
      volume = 0.0

c calculate power
      do 10 i = 1, 3470
        read(68,99) el,flux
        read(70,*) eln,vol
        ptet = flux * vol    !wattts
        power = power + ptet
        volume = volume + vol
10      continue

99      format(1x,i4,12x,E14.9)
c write output
      write(*,*) 'total power = ',power, ' watts'
      write(*,*) 'total volume = ',volume, ' M^3'

c close files
      close(unit=68)
      close(unit=70)

      stop
      end
```

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