CHAPTER IX. Conclusion

Microwave processing appears to be an appealing substitute for conventional heating of ceramics. However, one of the main problems is controlling the temperature while avoiding thermal runaway. Vogt et al. [9-11] was able to overcome this problem by power control. Using a traveling wavetube, the frequency was adjusted so that the absorbed power remained constant. By this, temperatures were able to exceed the critical temperature which is difficult to do with a constant field strength without some form of hybrid heating. Although successful on a laboratory level, this method is impractical for commercial scale processing. The power is limited in the traveling wave tubes, and the frequency is invariable for other types of microwave generators which produce more power.

A computational model was developed to calculate the temperature profile along a ceramic, cylindrical rod either moving or stationary while being heated volumetrically with microwave energy. The model allows heat conduction axially and radially as a rod is heated in time. It is assumed that the electric field profile is constant along the length of the rod and that microwave energy is heated uniformly within the specimen. Convection and radiation were taken into account for proper heat loss analysis at the surface, and as accurate as possible temperature dependent mullite properties were used in the model calculations.

The model allows for either constant electric field with time or a constant absorbed power with time. Using the constant electric field, temperatures only below the critical temperatures were achieved without thermal runaway. Fixing the power constant with time, temperatures were able to exceed the critical temperature without thermal runaway. This confirms Vogt et al. [9-11] experimental results. By fixing the power constant, the electric field decreases exponentially with time converging at some steady state value. A high initial field strength value is important initially where the dielectric loss is very low; however, to avoid thermal runaway, the field strength must decrease as temperatures increase.

Using a constant absorbed power, steady state surface temperatures of at least 1400^{o}C are obtained for mullite rods. Higher temperatures are also obtainable simply by increasing the absorbed power; however, the center temperatures are hotter than the surface temperatures and are approaching melting temperature of near 1800^{o}C. It was determined that higher powers are required for higher temperatures as expected, and that thicker rods require more power to heat to the same temperatures as heating thin rods at a lower power.

As a ceramic rod is heated initially from the ambient temperature in a 34mm long microwave applicator, a localized temperature maximum appears as the rod becomes hotter. Since the field strength is uniform with length, the only explanation for this effect is heat conduction along the length and convection and radiation losses at the surface. This leads us to conclude that localized hot spots may not be caused entirely by non-uniformities in the electric field. The localized temperature maximum is caused by the short cavity length. Heat is conducted from the center of the rod to the ends. Since the ends are close together in a short applicator, a local hot spot is formed near the center. Longer cavities experience the temperature drop at the ends but a more uniform temperature profile near the center.

The location of the maximum temperature was moved when a velocity was applied. The velocity had to be chosen carefully because a velocity too low would not produce any significant changes over the stationary case, and a velocity too high would carry away the rod before any notable temperature change could occur. The velocity does not play a major role in the magnitude of the maximum temperature, but does change its location. For example, the maximum temperature for the stationary case was located exactly halfway through the applicator. When a velocity was applied, the temperature dropped at that location since the maximum was shifted over with the velocity. Not knowing exactly where along the cavity the actual data were measured made comparison more difficult. From the model it was demonstrated that the thermometer position along the rod makes a difference in the temperature readings even if one thermometer position is within 1mm of another.

The simulated temperature output compared qualitatively well with actual data. Increases in velocity or power produced the same results for both actual and simulated temperatures. The simulated temperatures however were higher. Two explanations are given. The first is the difference in power readings. The model takes into account the absorbed power only; whereas, the actual power considers also the power loss. Assuming that the power loss is significant, the experimental absorbed power is much lower than the model power generating lower temperatures. The other explanation is the emissivity modeled in the simulation. It was shown that small changes in the emissivity create large temperature differences. A range of emissivities is known for mullite, so an average was chosen for the model. If the emissivity is actually higher than the average and the power loss is considered, the experimental and simulated temperatures would correspond more closely.

In conclusion, the model compares nicely to actual data which was the main purpose of this thesis. The model also proves that thermal runaway can be avoided by controlling the absorbed power. Developing microwave applicators that can be power controlled on a commercial level appears to be a promising method for ceramic heating.