Contract No:

This document was prepared in conjunction with work accomplished under Contract No. DE-AC09-08SR22470 with the U.S. Department of Energy.

Thermal Cycling on Fatigue Failure of the Plutonium Vitrification Melter

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INTRODUCTION

One method for disposition of excess plutonium is vitrification into cylindrical wasteforms. Due to the hazards of working with plutonium, the vitrification process must be carried out remotely in a shielded environment. Thus, the equipment must be easily maintained. With their simple design, induction melters satisfy this criterion, making them ideal candidates for plutonium vitrification.

However, due to repeated heating and cooling cycles and differences in coefficients of thermal expansion of contacting materials fatigue failure of the induction melter is of concern. Due to the cost of the melter, the number of cycles to failure is critical. This paper presents a method for determining the cycles to failure for an induction melter by using the results from thermal and structural analyses as input to a fatigue failure model.

PROCESS DESCRIPTION

The body of the induction heated melter is cylindrical. Thus, it is referred to as a Cylindrical Induction Melter (CIM). The bottom has the form of a truncated cone from which a tube, used to drain glass from the melter, extends. Glass flow in the drain tube is controlled by cooling the tube to increase the glass viscosity. Air jets within the cavity surrounding the drain tube are used to provide additional cooling, and to stop the flow of glass. Thus, the drain tube functions as a freeze valve. The melter is inductively heated using separate coils for the cylindrical part, the conical bottom, and the drain tube. The melter is supported at the base by refractory material and is allowed to freely expand in the vertical direction, while its radial expansion is limited by the allowed displacement of the fiberfrax blanket along its vertical sides. The drain tube is located within a cylindrical tube composed of refractory material, having sufficient diameter such that there is no restriction to its radial expansion. At the end of the cycle, some glass is left in the tube, which functions as a stopper for the next cycle.

As the melter is heated, it experiences stresses associated with thermal expansion arising from temperature gradients within the melter, expansion of the melter against support structures and the difference between the thermal expansion of solidified glass adhering to the internal surface of the melter and the Pt/Rh alloy. The latter phenomenon contributes significantly to stresses in the drain tube, where the Pt/Rh alloy expands and contracts while in contact with the cylinder of glass contained in the tube. Below its melting temperature, the glass is fairly rigid and has a much lower coefficient of thermal expansion than the Pt/Rh alloy. Operation in this regime occurs during the transition of the CIM from ambient temperatures to its high-temperature hold point, when the drain tube is heated to discharge the melter and again when the system is cooled to ambient temperature to receive a new charge.

THERMAL ANALYSIS

The thermal analysis was performed using MSC.Thermal® software. It includes transient effects of the simultaneous heating and cooling of the melter body and cone regions separated by a steady-state high-temperature hold stage. The transient temperature profile of the drain tube includes heating the drain tube towards the end of the high-temperature hold stage of the melter body and cone regions followed by rapid cooling aided by the air jets. The melter body and cone regions cool under ambient conditions. The importance of the thermal model lies in its ability to calculate temperatures at locations that cannot be monitored during the actual process for input to structural model of the melter under nominal operating conditions. The thermal model is semi-empirical as it utilizes experimental data of the temperatures at points that can be measured. The output from the thermal analysis matched the experimental data at specific points and times during the heating and cooling process.

STRUCTURAL ANALYSIS

The output from the transient thermal analysis was input into the structural model as temperature profiles for each node in the model. The mechanical loads present – gravitational load of the melter, weight of the glass, stresses from the glass/drain tube interaction – were applied and the model was evaluated for rupture failure as well as failure due to fatigue from cyclic thermal stresses. During the heating phase, the stresses in the melter were highest in the drain tube near the glass transition point. At the end of a thermal cycle, the stresses were highest in the region where the drain tube connects with the melter bottom. The strains were highest throughout the thermal cycle at the drain tube/melter joint. Due to the elevated stresses and strains, this region is the critical region for failure of the melter. Over one cycle, the predicted strain is much less than the ultimate strain, so the melter is not expected to fail by rupture during the first operation cycle. Due to the elevated temperatures and resulting plastic strain, the expected fatigue failure mechanism is low-cycle plastic strain fatigue rather than high-cycle elastic stress fatigue.

FAILURE ANALYSIS

To evaluate fatigue failure, the plastic strain components determined from FEA were used to calculated principle plastic strains in the critical region for four consecutive heating and cooling cycles. The hoop strain was the only cyclic strain determined from this analysis. Then, using the Manson-Coffin equation[3-5] for high-temperature low-cycle fatigue, it was determined that failure would occur within 330-345 cycles. This modeling technique can be applied to investigate the effect of design modifications to increase the number of cycles to failure.

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