Thermal Analysis of a 1 Hour Fire Resistive Joint Design for Architectural Expansion Joints

by

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Nomenclature

A	-	cross sectional area of slab (in)
C_P	-	Heat capacity at constant pressure (J/kg-K)
Gr	-	Grashof Number
h	-	Combined heat transfer coefficient (W/m^2-K)
k	-	Thermal conductivity (W/m-K)
L	-	Slab thickness or characteristic length (in)
Nu	-	Nussault Number
Pr	-	Prandtl's Number
q	-	Heat flux (W/m-K)
Q	-	Energy (W)
r	-	Spatial dimension (in)
t	-	Time (s)
T	-	Temperature (K)
v	-	Kinematic viscosity (m^2/s)
V	-	Control volume (in^3)
α	-	Thermal diffusivity (m^2/s)
β	-	Volumetric thermal expansion coefficient (1/K)
ε	-	Emissivity
ρ	-	Density (kg/m^3)
σ	-	Stefan-Boltzmann constant (W /m^2-K^4)

Acknowledgement

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Abstract

This project develops a thermal model of an architectural expansion joint fire barrier design in order to assess whether it will satisfy the thermal requirements set forth in UL 2079, the industry standard test for resistance of building joint systems. The fire barrier design was for a maximum expansion joint width of 12 inches and has a fire rating of 1 hour. COMSOL Multiphysics was used to develop a thermal stress model of the fire barrier design. The initial proposed fire barrier design did not satisfy UL 2079, as a portion of the surface temperature of the fire barrier cover plate exceeded the requirement. Therefore, modifications were made to the fire barrier design. The analysis concluded that 1 inch thick ceramic fiber insulation, supported by 2"x2" steel "L" brackets and a 3/16 inch thick cover plate will satisfy the thermal requirements of UL 2079.

1. Introduction

1.1 Background

Architectural expansion joints are openings or gaps that are designed into the structure of a building to permit movement between the concrete slabs or other structural members. Building movement can occur for several reasons, including thermal loading (i.e., change of weather season), wind loading, or seismic activity. These openings can vary anywhere between 0.5 inches up to and exceeding 32 inches. Typically, a metal cover plate is installed over the expansion joint to conceal the joint and to permit pedestrian traffic across the joint. An example of an exposed architectural expansion joint can be seen in Figure 1.

Figure 1: Example of an Architectural Expansion Joint

Building codes often require that these expansion joints include a fire resistive system, or fire barrier, to prevent the spread of smoke, heat, and flames in the event of a fire. Underwriters Laboratories (UL) 2079, "Standard for Tests for Resistance of Building Joint Systems" [1], is the standard test method used in industry today to qualify cover plate and fire barrier designs. The thermal acceptance criteria from [1] that is of interest is as follows:

- When exposed to a fire, the transmission of heat through the fire barrier and cover plate assembly must not raise the unexposed side surface temperature more than 250 ^{o}F (~139 K). The fire barrier is then rated as having satisfied this criteria for a stated period of time (0.5 hours, 1 hour, or 2 hours). UL 2079 takes this criteria from American Society for Testing and Materials (ASTM) Standard E1966, "Standard Test Method for Fire-Resistive Joint Systems" [2].

1.2 Project Scope

The goal of this project is to develop a thermal model of a fire barrier design for a maximum expansion joint width of 12 inches in order to assess its thermal performance based on the requirements set forth in UL 2079 for a 1 hour rating. If the proposed configuration does not satisfy the UL 2079 requirement, recommendations will be made to the fire barrier design so that is does meet the requirements.

The fire barrier design of interest is illustrated in Figure 2. The fire barrier consists of the following basic components (from the unexposed boundary to the exposed boundary):

- Two 2 inch by 1 inch galvanized steel "L" brackets - Used to attach the fire barrier the concrete floor slabs and to provide some axial rigidity.
- Ceramic fiber blanket - Used as the main insulation material. Number of layers and the thickness varies based on fire barrier rating.

- Stainless steel foil - Used as an insulation material (radiative shield), to prevent the bulk transport of hot gasses passing through the porous insulation, and to provide some rigidity to the fire barrier assembly.
- High temperature cloth - Used to provide structural support for the fire barrier and as an insulation material.

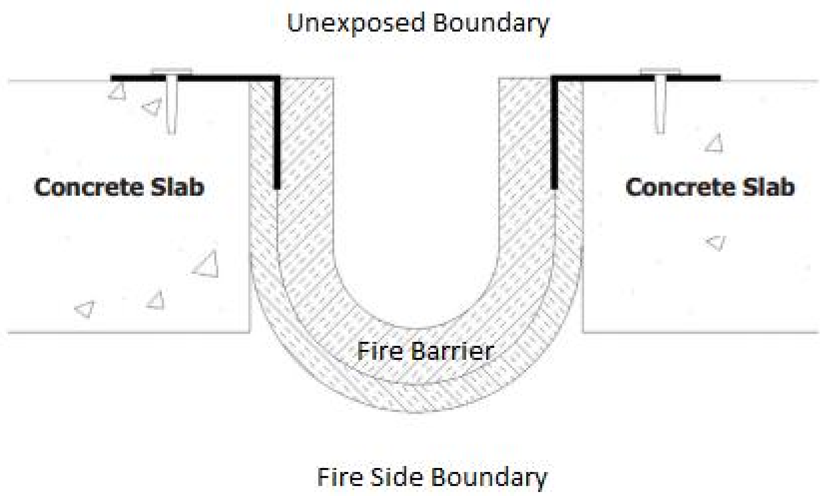

Figure 2: Illustration of Fire Barrier Design (Note: Cover Plate Not Shown)

As part of the fire test portion of UL 2079, a cover plat is installed over the joint. This cover plate is simply a 3/16" stainless steel plate. Note that this cover plate is not shown in Figure 2.

The ceramic fiber blanket is folded into a "U" shape and draped within the expansion joint. This allows the fire barrier to maintain its fire resistive attributes when the expansion joint widens. The analysis performed in this project will be performed with the joint extended to a width of 12 inches such that the fire barrier is stretched to its maximum width.

2. Literature Review

Several investigators have published documents on thermal analysis of fire barriers used for architectural expansion joints. Of particular interest is the American Society of Mechanical Engineers (ASME) paper titled "Transient Heat Transfer for Layered Ceramic Insulation and Stainless Foil Fire Barriers" [3]. This paper aimed to develop a course numerical model and range of thermo physical parameters for a 1-dimensional fire barrier constructed of ceramic insulation and stainless steel foil that accurately represents the real physics of the problem in a standard test situation.

First, this paper first conducted a experimental fire test to gather empirical data. The test was conducted in accordance with ASTM Standard E119, "Standard Methods for Fire Tests of Building Construction Materials" [4], which defines the transient fire temperature/conditions that the fire barrier is exposed to. Then, it developed and applied a numerical model, which was a course finite difference/finite volume formulation of the standard transient conduction energy equation with radiative heat flux and the radiative heat transfer equation. The experimental data was then compared to the thermal model predictions.

The numerical model included radiation effects internal to the insulation, mostly due to the fact that radiation is one of the primary modes of heat transfer in high performance insulation materials, the other being conduction. A parametric analysis was performed, varying such things as insulation thickness and fire temperatures. This paper found that this course finite difference/finite volume formulation agreed well with the experimental data. In addition, one important fact that was identified was that as the insulation thickness was doubled, the benefits of decreased unexposed surface temperature became additive rather than multiplicative, suggesting a diminished return.

While the numerical model was able to predict the thermal performance of the test system, the test setup and subsequent analysis is for a geometrically different fire barrier design and application.

The ASME paper titled "Simulations of Thermal Performance for One- and Two-Dimensional Insulation and Aluminum Foil Fire Barriers" [5] also discusses thermal models of fire barriers. This paper focuses on the thermal interactions of 2-D architectural expansion joint corners (i.e., a 90^{o} directional change), and if "hot spots" form or any degradation in thermal performance occurs at these corners due to the splicing of material. The paper also focuses on the radiative properties of the materials involved, since almost 60% of the heat transfer in ceramic fiber blankets at high temperature is due to thermal radiation [5].

In order to quantify this, a numerical simulation of the fire barrier is developed. This is accomplished using the energy and radiative heat transfer equations. The energy equation is in the following form:

$$\nabla[\nabla T(r,t) - q(r,t)] = \frac{1}{\propto}\frac{1\partial T(r,t)}{\partial t} \qquad \text{[Eqn. 1]}$$

A computer code was generated to solve the above equation along with the radiative heat transfer equation iteratively, and the results were compared with the results from [3] and showed good agreement. The analysis suggested that a fire barrier at a 2-D architectural expansion joint corner is thermally less robust than a standard 1-D straight architectural expansion joint.

3. Methodology and Approach

COMSOL Multiphysics [6], an engineering finite element analysis software, is used to develop the two dimensional thermal model. Two concrete slabs, 4.5 inches thick, are placed with a 12 inch opening between them. A 1 inch thick piece of ceramic fiber insulation, as shown in Figure 3, is draped in the opening and supported by two steel "L" brackets. The "L" bracket extends 1 inch downward. A steel cover plate is placed horizontally across the top of the fire barrier. There is an air gap between the ceramic fiber insulation and the steel cover plate. For simplification purposes, the steel cover plate and "L" brackets are modeled as one piece.

The thermal resistive properties of the stainless steel foil and high temperature cloth will be neglected in this analysis for conservatism and simplicity. This assumption is valid for the stainless steel because since it is on the fire side of the barrier, [3] predicts that it will reach 96.4% of the fire temperature within 0.01 hours. This assumption is valid for the high temperature cloth because it is assumed to have a thermal conductivity similar to the ceramic fiber blanket.

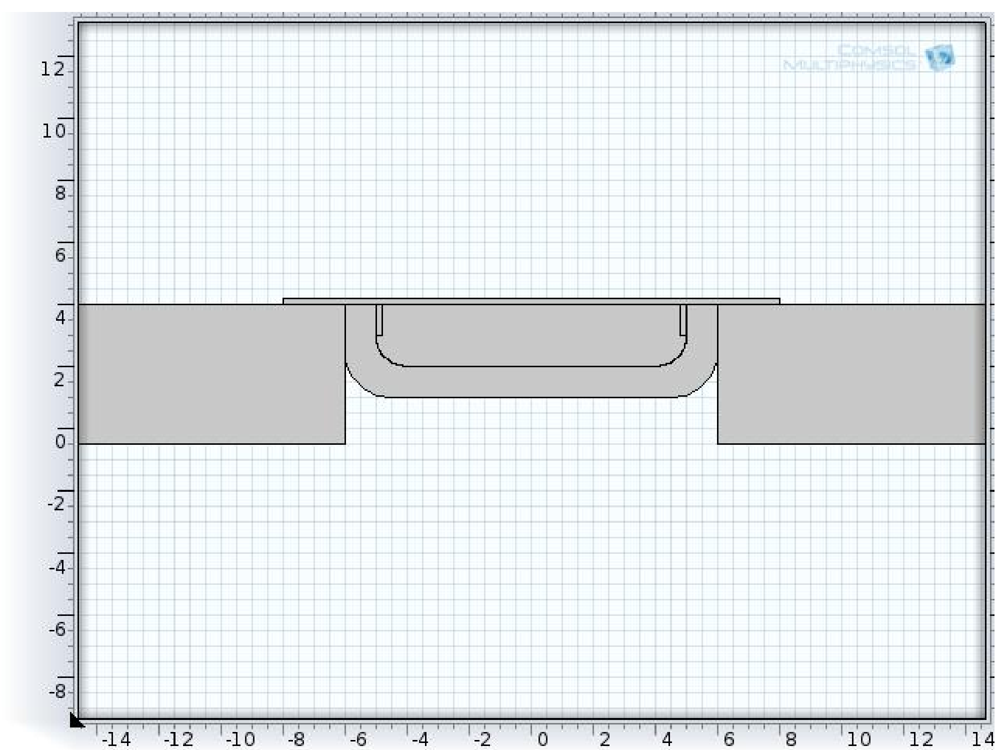

Figure 3: COMSOL Model Geometry

The material properties for the concrete slabs and fire barrier material are summarized in Table 1. All material properties for concrete and steel were obtained from the COMSOL material library. The properties for the ceramic fiber insulation were taken from [5].

Table 1: Material Properties

	Density [kg/m^3]	Thermal Conductivity [W/(m×K)]	Heat Capacity [J/(kg×K)]
Concrete	2300	1.4	880
Ceramic Fiber Blanket	128	0.2	1130
Steel AISI 4340	7850	44.5	475

An extra-fine physics-controlled mesh was applied to the COMSOL model. A physics-controlled mesh was used in lieu of a user-controlled mesh because it was deemed to provide sufficient resolution throughout the model. Extra-fine was used because courser meshes impacted the model thermal results. Figure 4 illustrates the mesh used for this analysis.

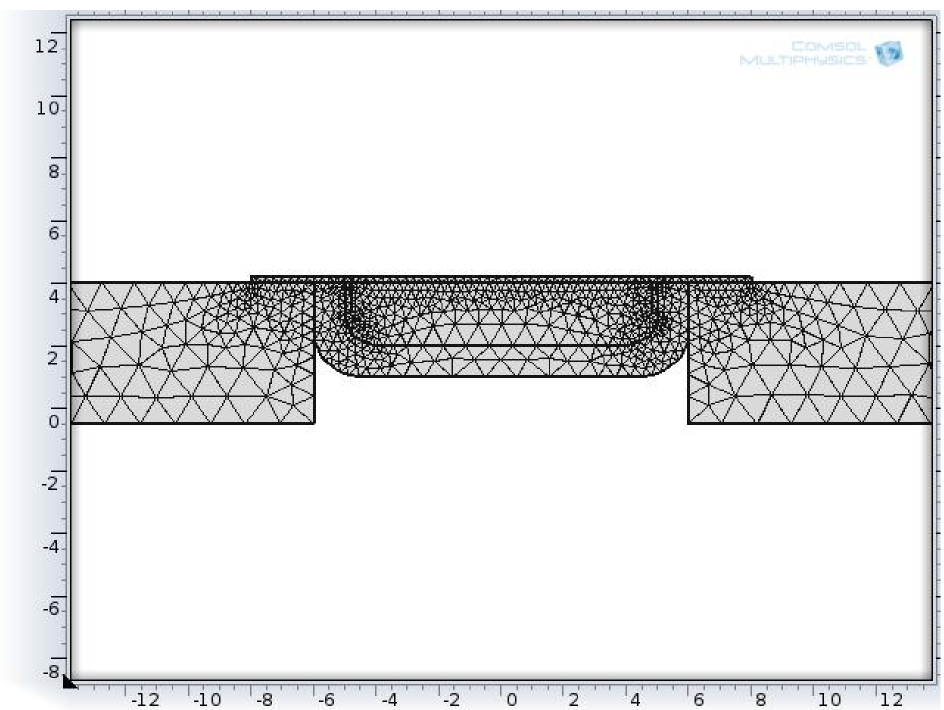

Figure 4: Physics Controlled COMSOL Mesh

3.1 COMSOL Physics

While the thermal performance of the fire barrier is of particular interest, the thermal stress physics COMSOL physics model was applied, allowing to solve for both the thermal characteristics of the system as well as the stresses involved. The model developed for this project will focus on the thermal characteristics.

COMSOL uses the following equation to solve for the heat transfer through the fire barrier:

$$\rho C_P \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q + Q_r \qquad \text{[Eqn. 2]}$$

3.2 Analysis Parameters and Boundary Conditions

The following paragraphs discuss the boundary conditions used on the COMSOL model. Each boundary condition are part of the thermal stress physics model in COMSOL.

1. The thermal insulation boundary condition, as well as the prescribed displacement boundary condition (stress), are placed on the outside ends of the concrete (internal to the concrete) as shown in Figure 5. This ensures that the heat flux is in the y-direction only (1-dimensional), and that the ends of the concrete are not displaced outward due to the thermal stresses. COMSOL uses the following equations for these boundary conditions:

$$-n \cdot (-k \nabla T) = 0 \qquad \text{[Eqn. 3]}$$

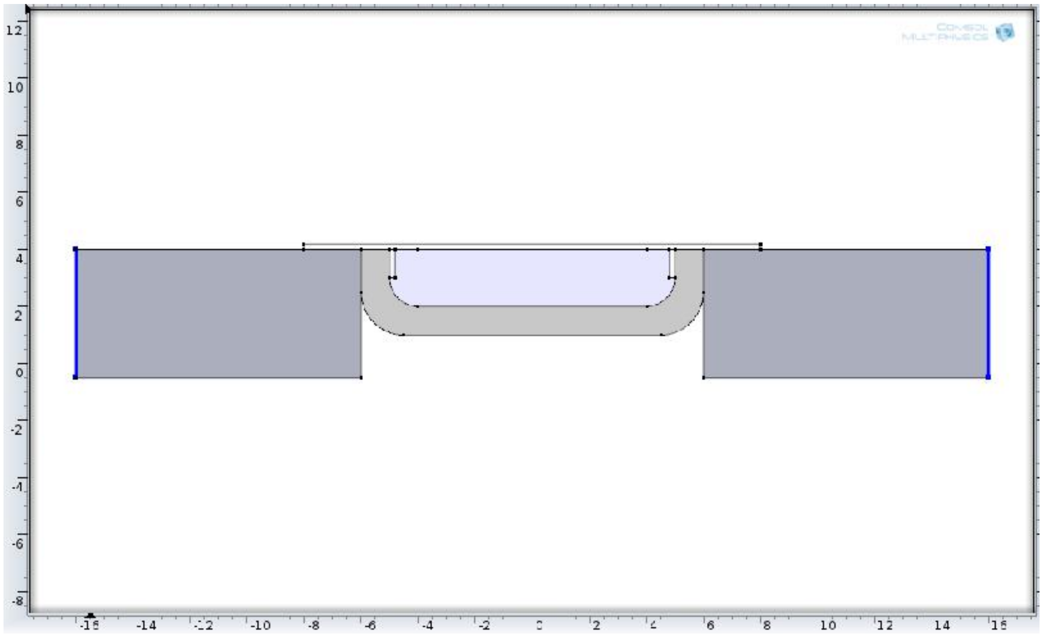

Figure 5: Thermal Insulation and Prescribed Displacement Boundary Condition

2. The free boundary condition was applied to both the exposed and unexposed surfaces, as shown in Figure 6. This boundary condition will allow the material to deform and move in the y-direction due to the thermal stresses.

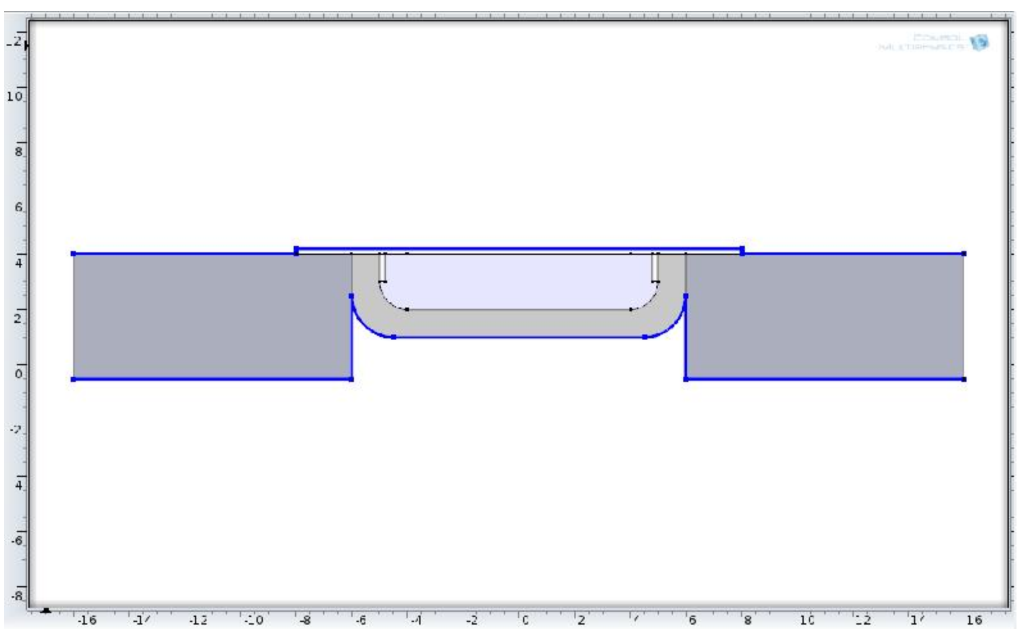

Figure 6: Free Boundary Condition

3. The convective cooling boundary condition is applied to the unexposed side of the model as shown in Figure 7, thereby applying a heat flux via the following equation:

$$-n \cdot (-k\nabla T) = h(T_s - T_\infty) \qquad \text{[Eqn. 4]}$$

The radiation and convective heat transfer coefficients are manually applied to the boundary and are calculated as follows:

$$h_{rad} = \sigma\varepsilon(T_s + T_\infty)(T_s^2 + T_\infty^2) \qquad \text{[Eqn. 5]}$$

$$h_{conv} = \frac{Nuk_{air}}{L_C} \qquad \text{[Eqn. 6]}$$

Where

$$Nu = 0.15(GrPr)^{1/3} \qquad \text{[Eqn. 7]}$$

$$Gr = \frac{g\beta(T_s - T_\infty)L_C^3}{v} \qquad \text{[Eqn. 8]}$$

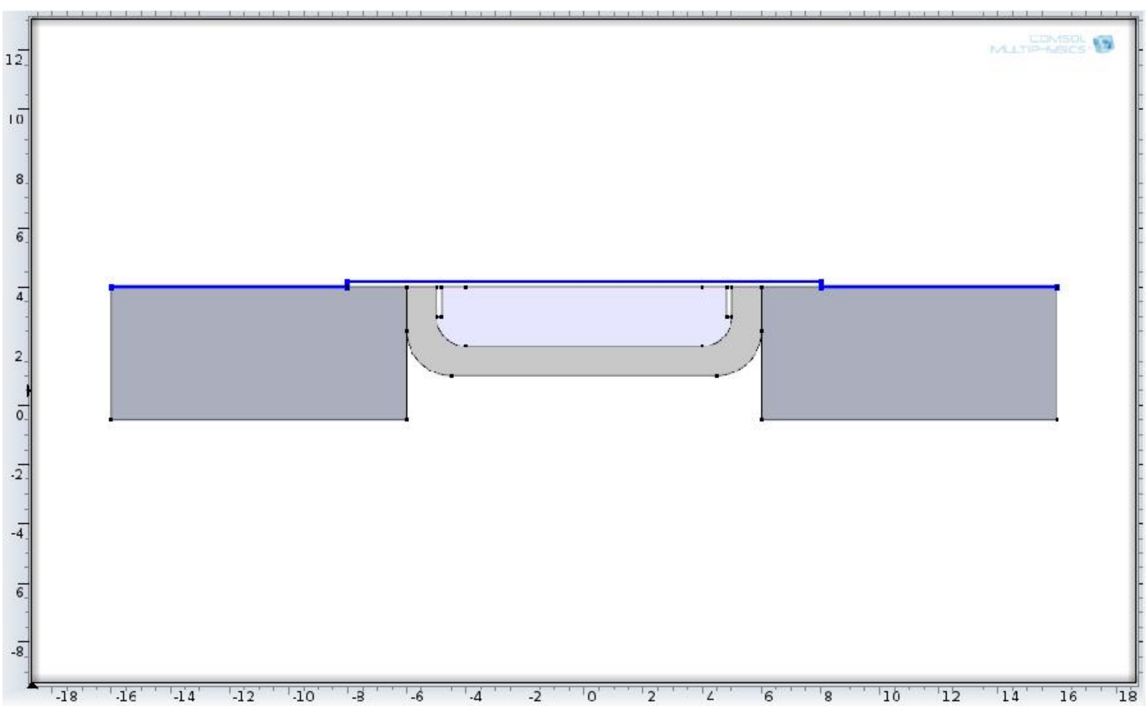

Figure 7: Convective Cooling Boundary Condition

The thermal conductivity (k), Prandtl's Number (Pr), and kinematic viscosity (υ) of air are taken from [6] and are plotted in Figure 8 against temperature in order to obtain a best fit curve. The equations are as follows:

$$Pr = (2.82 \times 10^{-7})x^2 - (3.65 \times 10^{-4})x + 0.797 \qquad \text{[Eqn. 9]}$$

$$k = (-2.18 \times 10^{-8})x^2 - (8.95 \times 10^{-5})x + 1.19 \times 10^{-3} \qquad \text{[Eqn. 10]}$$

$$v = (9.31 \times 10^{-5})x^2 + (3.51 \times 10^{-2})x + 2.93 \qquad \text{[Eqn. 11]}$$

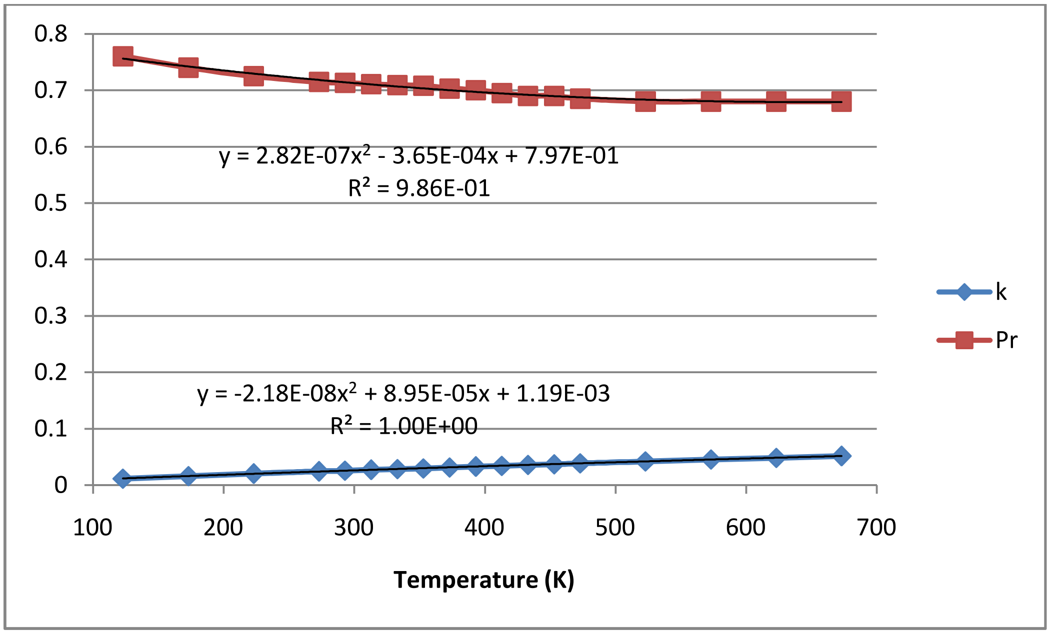

Figure 8: Thermal Conductivity and Prandtl's Number for Air

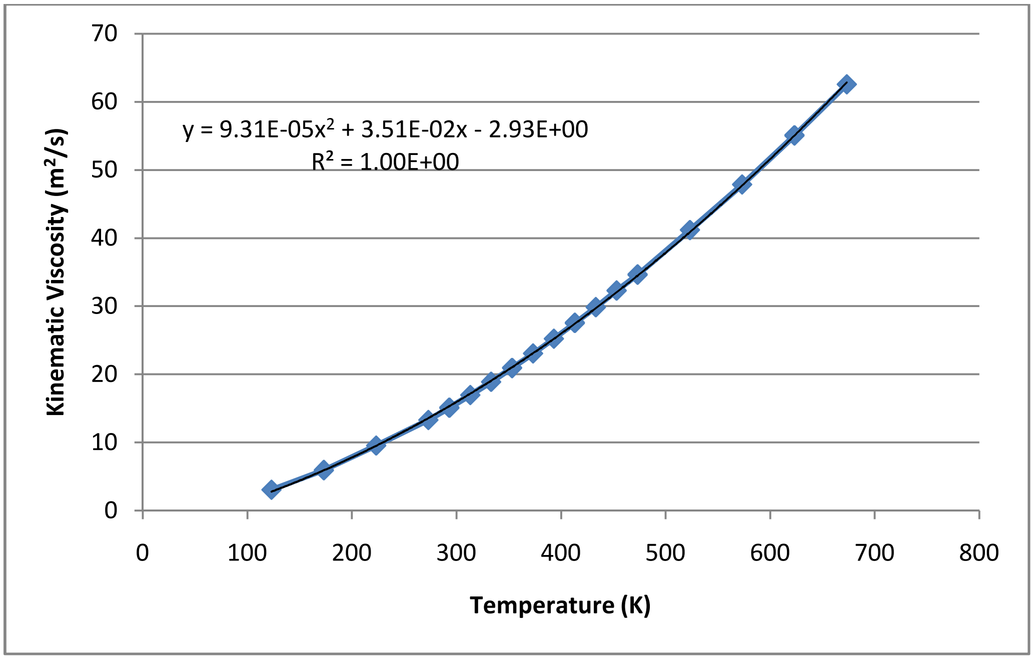

Figure 9: Kinematic Viscosity of Air

4. The entire system is set to initial values as follows: displacement field (u) = (0,0), structural velocity field (du/dt) = (0,0), and temperature = 300 K.

5. The inward heat flux boundary condition is applied on the fire side of the model as shown in Figure 10 in order to simulate the heat transfer effects of the fire. The fire temperature is in accordance with [4]. An equation is generated to approximate the fire side temperature to be similar to the [4] required temperature at each time interval. Table 2 below shows the standard time-temperature table for fire resistance tests per [4], as well as the approximation temperature. COMSOL uses the following equation for this boundary conditions:

$$-n \cdot (-k\nabla T) = h\left(T_{fire} - T_{\infty}\right) \qquad \text{[Eqn. 12]}$$

Similar to the convective cooling boundary condition, the heat transfer coefficient for the heat flux is also applied manually and includes radiation and convection.

Table 2: Time-Temperature Curve for Fire-Resistance Tests per ASTM E119

Time		Temperature (K)		% Difference
Minutes	Seconds	ASTM E119	Approximation	
0	0	293	293	0.00%
5	300	811	874	7.77%
10	600	977	957	-2.05%
15	900	1033	1011	-2.13%
20	1200	1068	1051	-1.59%
25	1500	1094	1085	-0.82%
30	1800	1116	1113	-0.27%
35	2100	1135	1138	0.26%
40	2400	1151	1160	0.78%
45	2700	1165	1180	1.29%
50	3000	1178	1198	1.70%
55	3300	1189	1214	2.10%
60	3600	1200	1230	2.50%

The fire temperature starts at time = 0 seconds is equal to ambient air temperature; after which point the temperature increases to a maximum temperature of approximately 1,200 K (1,700 ^{o}F). The fire temperature approximated by the following equation and plotted in Figure 11 versus time:

$$T[K] = t^{\frac{1}{5.2}} \times 194 + 293 \qquad \text{[Eqn. 13]}$$

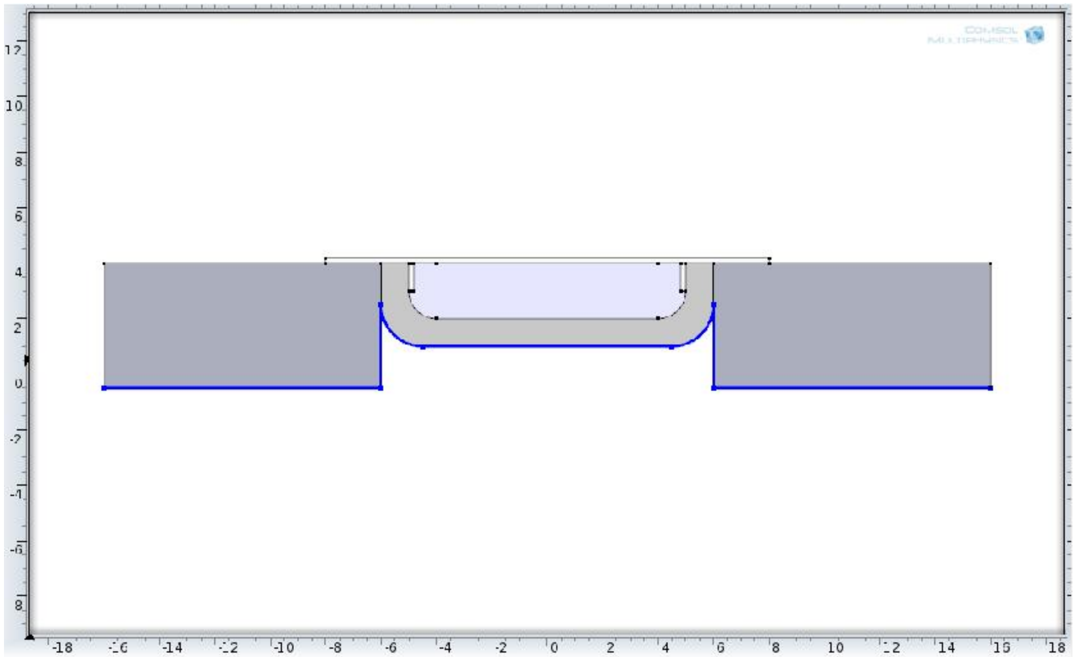

Figure 10: Heat Flux Boundary Condition

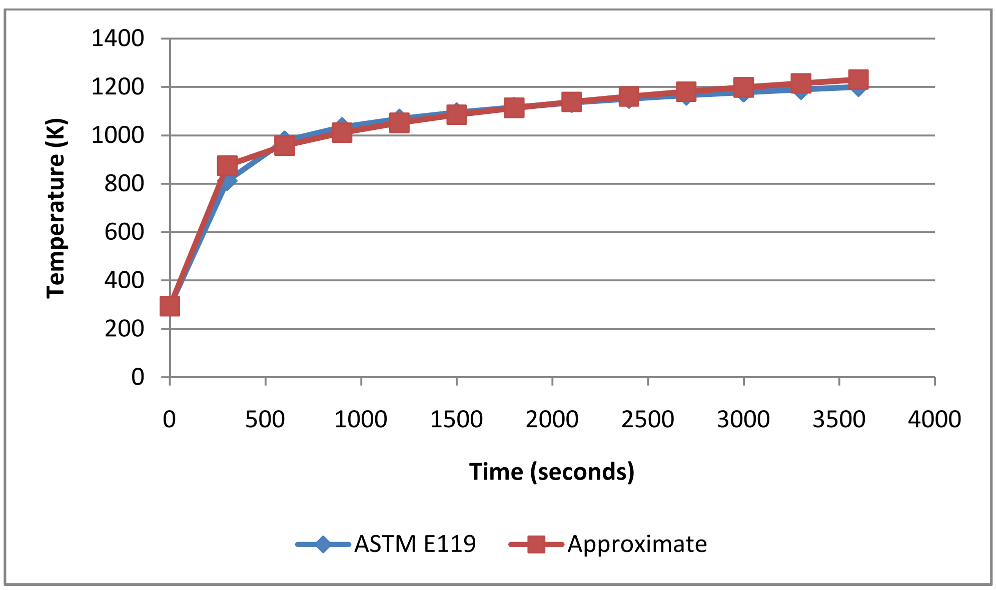

Figure 11: ASTM E119 and Approximate Fire Temperature vs. Time

6. Continuity on interior boundary is the default boundary condition that is applied to all internal boundaries. This condition enables intensity conservation across each internal boundary.

7. The heat transfer in fluids is applied to the air in the air gap internal to the fire barrier and cover plate, as shown in Figure 8. This node adds the heat equation for conductive heat transfer in fluids. The equations above for Pr, k, and v for air are used, and the COMSOL model library properties are used to for the specific heat capacity, density, and ratio of specific heats.

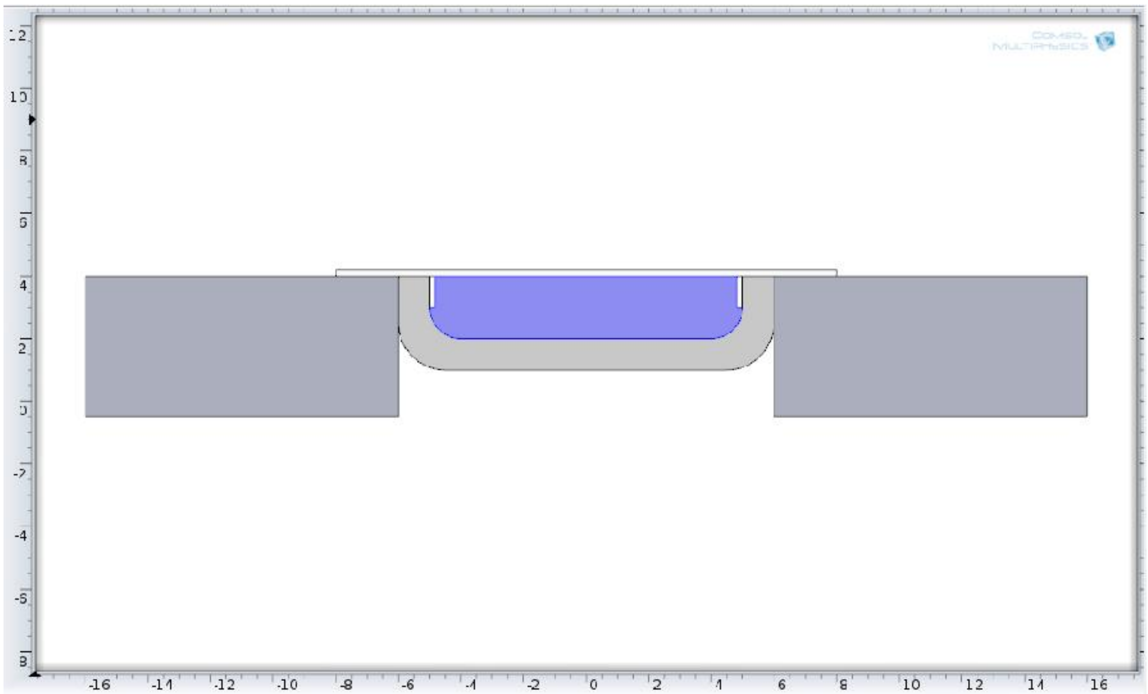

Figure 12: Heat Transfer in Fluids

8. The COMSOL time dependent solver is used with default settings. The time step is chosen to be 100 seconds with an ending time of 3,600 seconds (1 hour).

4. Results

Figure 13 shows the surface temperature of the unexposed side of the fire barrier assembly as a function of time. The average, maximum, and minimum temperatures of the cover plate surface after 1 hour was calculated to be 441 K (333 ^{o}F), 483 K (409 ^{o}F), and 407 K (271 ^{o}F), respectively. The concrete surface temperature far from the fire barrier rises to 393 K, or 48 K less than the cover plate surface average temperature. The starting temperature of the system was 300 K. Therefore, the maximum temperature rise for the fire barrier assembly is calculated to be 183 K, while the average temperature rise is 140.5 K. The maximum and average temperature rises are 44 K and 1.5 K, respectively, above the UL 2079 temperature rise acceptance criteria of 139 K.

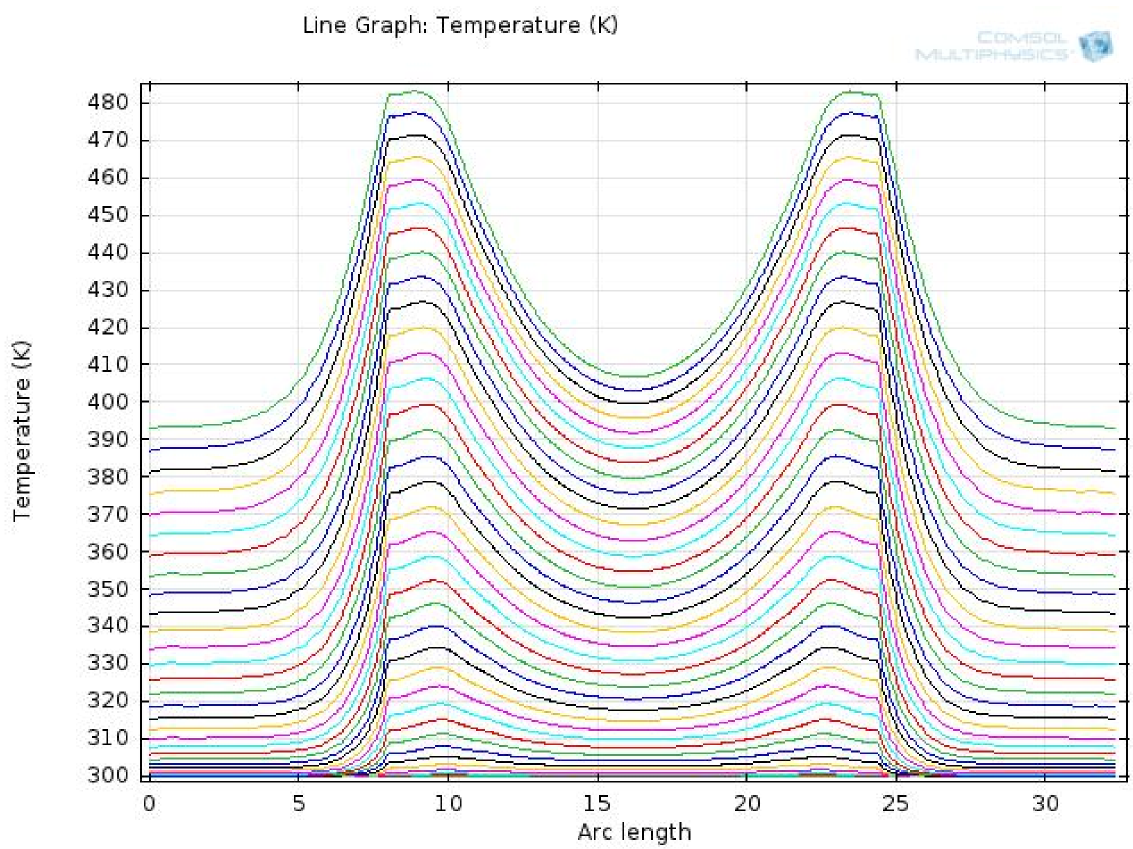

Figure 13: Unexposed Side Surface Temperature

Figure 13 shows that the minimum cover plate surface temperature is achieved at the centerline of the fire barrier assembly. Figure 13 suggests that the maximum temperatures are observed at the edges of the fire barrier in the vicinity of the steel "L" brackets. To confirm this, a surface temperature gradient plot is generated of the fire barrier assembly edge (Figure 14). Figure 14 shows that large temperature gradients exists near where the insulation meets the concrete on the fire side, as well as the bottom face of the "L" bracket.

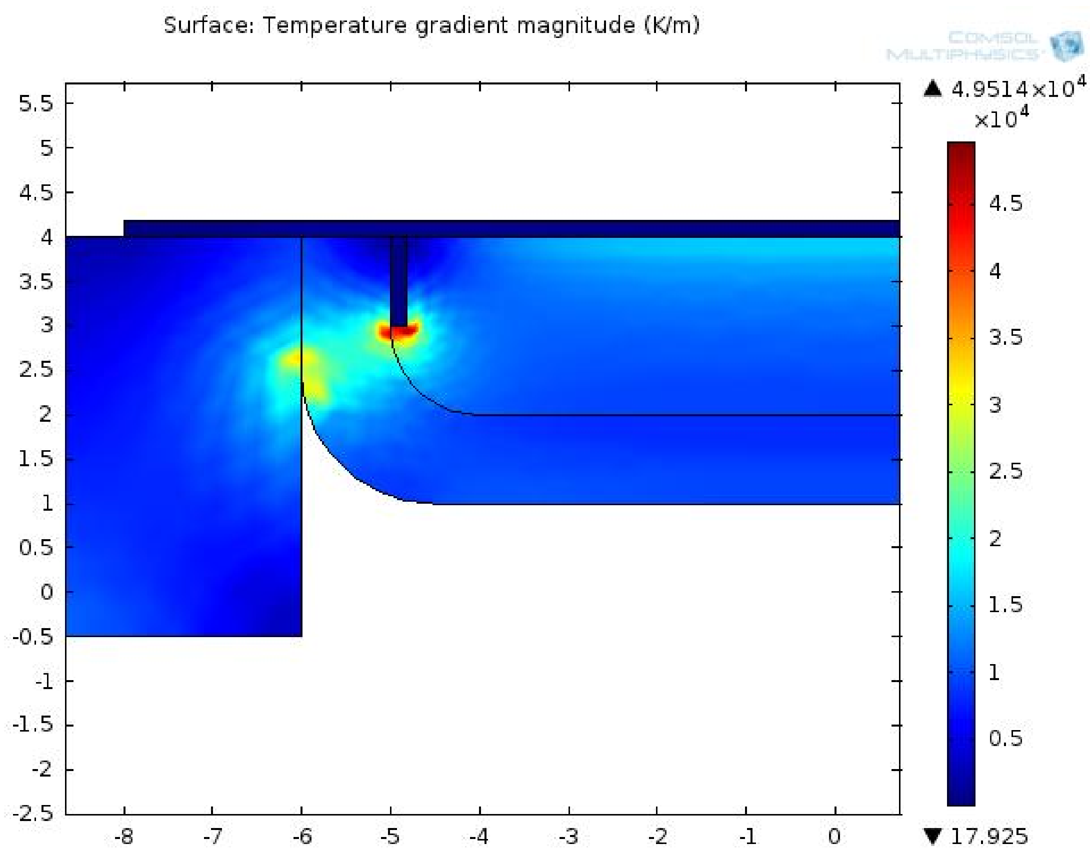

Figure 14: Surface Temperature Plot of Fire Barrier Assembly Edge at 1 Hour

Figure 15 illustrates the average temperature of the fire side of the insulation, air side of the insulation, air gap, and the cover plate surface temperature. From Figure 14, the fire barrier assembly reduces the temperature 1,228 K (fire side of insulation average temperature) to 441 K (cover plate surface average temperature), a reduction of 787 K.

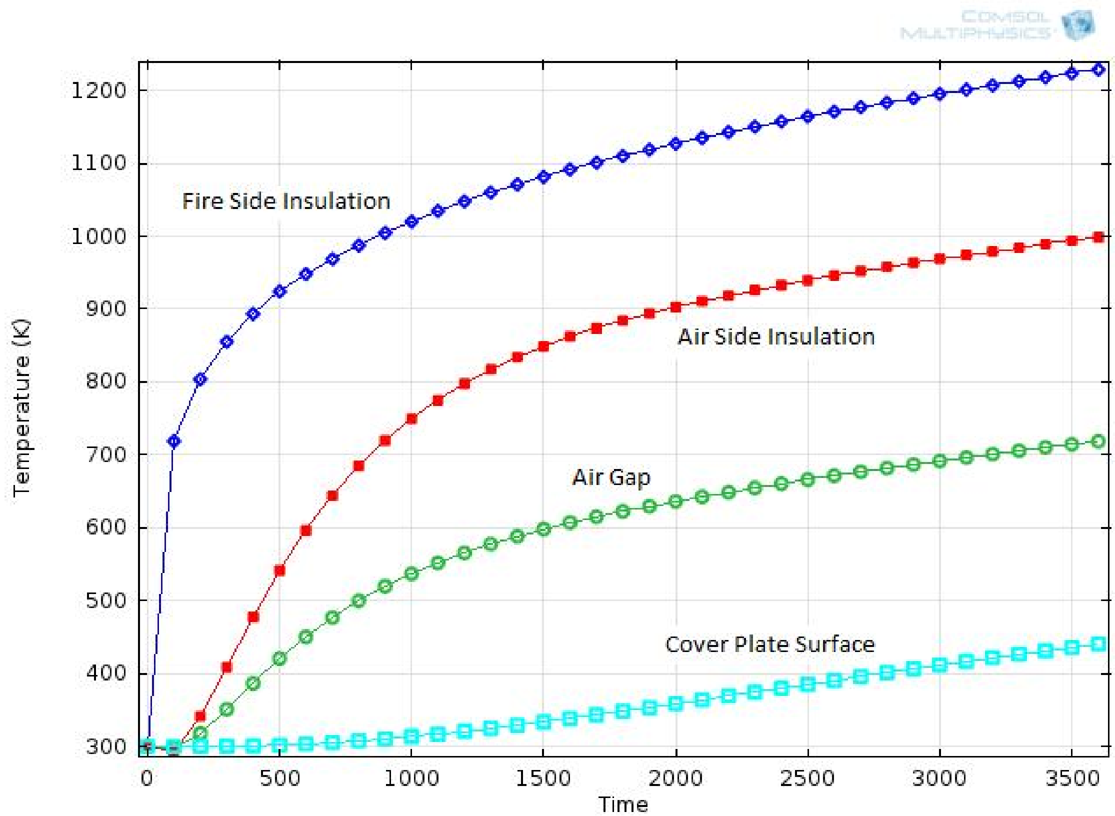

Figure 15: Average Temperatures of Various Surfaces as a Function of Time

The proposed fire barrier assembly does not satisfy the UL 2079 temperature rise criteria, as the maximum surface temperature of the cover plate exceeded 139 K temperature rise by 44 K. As a result, changes to the fire barrier design must be made.

5. Recommendations

Figures 13 and 14 suggest that the large temperature gradient observed on the cover plate surface is due to the fire barrier configuration near the concrete walls. Figure 13 also suggests that the center region of the fire barrier assembly has sufficient thermal resistance to keep the unexposed surface temperature in this area below the requirement. Adding an additional layer of insulation may prove to be costly, and is not recommended because that thermal resistance is not needed near the centerline.

Adding additional thermal resistance can be accomplished by changing the 2x1 inch "L" bracket (original configuration) to a 2x2 inch "L" bracket (modified configuration). Additional ceramic fiber insulation would be added to accommodate the extra space.

To confirm this recommendation, the geometry modifications were made to the COMSOL model. All of the same analysis parameters and boundary conditions (mesh, time step, etc.) were applied to the modified configuration. Table 3 below summarizes the findings and compares the results after 1 hour to the original proposed configuration.

Table 3: Summary of Results for Original and Modified Fire Barrier Configurations After 1 Hour

Configuration	Cover Plate Temperature (K)			Concrete Temperature (K)
	Maximum	Average	Minimum	
Original	483	441	407	393
Modified	417	389	368	393

The temperature rise of the modified fire barrier is 117 K, which is less than UL 2079 temperature rise criteria of 139 K. Therefore, the modified fire barrier configuration satisfies the temperature rise criteria of UL 2079.

Table 3 also shows that the minimum surface temperature of the fire barrier cover plate is actually less than that of the concrete surface temperature far away from the fire barrier. Figure 16 illustrates the surface temperature of the unexposed side of the fire barrier assembly as a function of time.

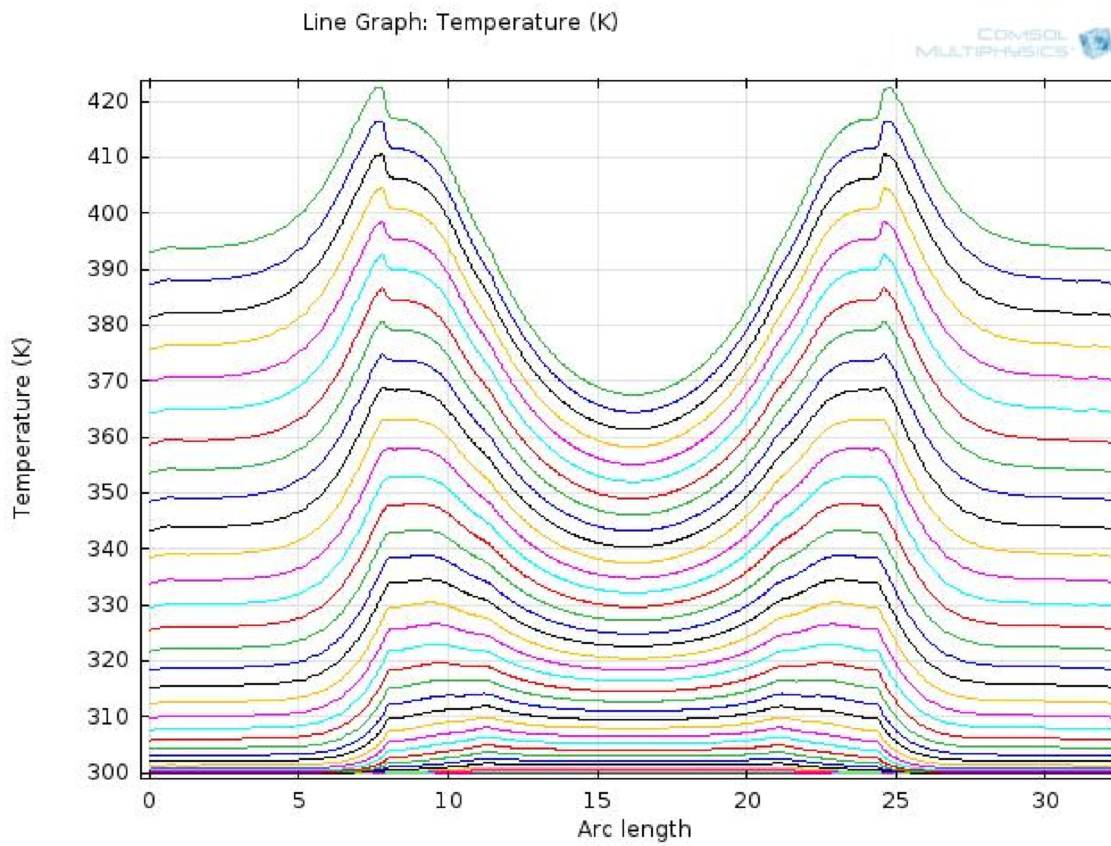

Figure 16: Modified Configuration - Unexposed Side Surface Temperature

Additional COMSOL plots and figures for the modified configuration can be found in Appendix A.

6. Conclusions

The purpose of this project was to develop a thermal model of an architectural expansion joint fire barrier design in order to assess whether the surface temperature of the fire barrier cover plate on the unexposed side would be equal to or less than required by UL 2079. The proposed fire barrier design did not satisfy this requirements, as the temperature rise was 183 K, 44 K above the maximum allowable.

Investigation of the thermal model results revealed that the high temperature was observed near the edge of the fire barrier where it was in contact with the concrete slab. It was concluded that additional insulation was required in this area. To achieve this, the steel "L" bracket was lengthened to a 2"x2". This added inch of steel forced the insulation further down into the expansion joint, requiring slightly more insulation to fill the opening. The modified fire barrier design satisfied the UL 2079 requirements as the temperature rise was 117 K, which is 22 K less than the required.

7. References

[1] Standard for Tests for Resistance of Building Joint Systems, UL 2079

[2] Standard Test Method for Fire-Resistive Joint Systems, ASTM E1966

[3] Caplinger, G. D.; Sutton, W. H.; Spindler R.; Golke, H.; "Transient Heat Transfer for Layered Ceramic Insulation and Stainless Foil Fire Barriers"; Journal of Heat Transfer, Vol. 121, pp. 1059-1066, dated 1999

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8. Appendix A: Detailed Results of Modified Fire Barrier Design

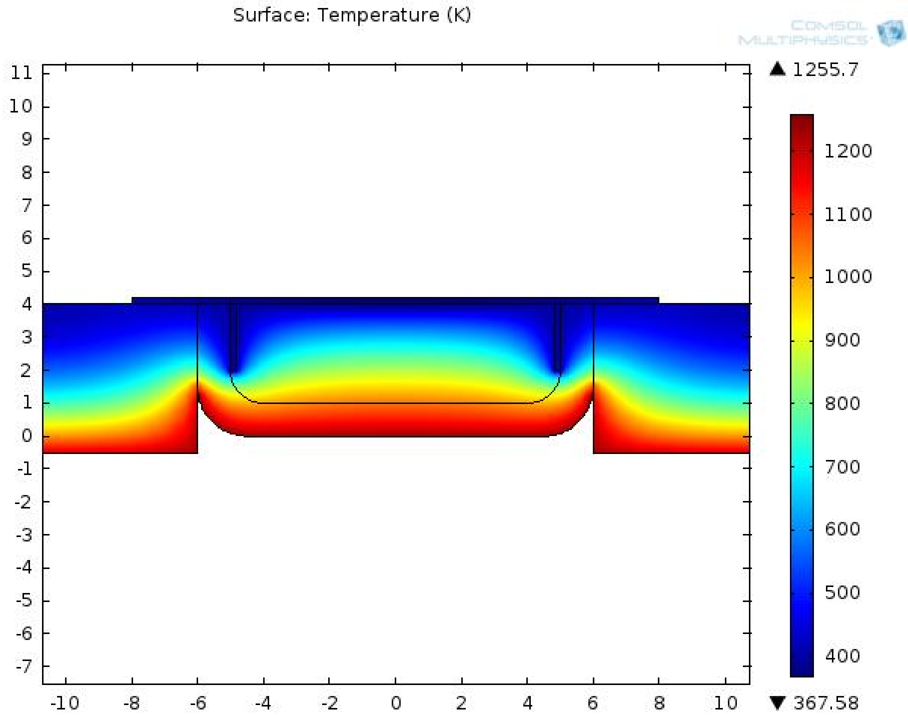

Figure 17: Surface Temperature Plot

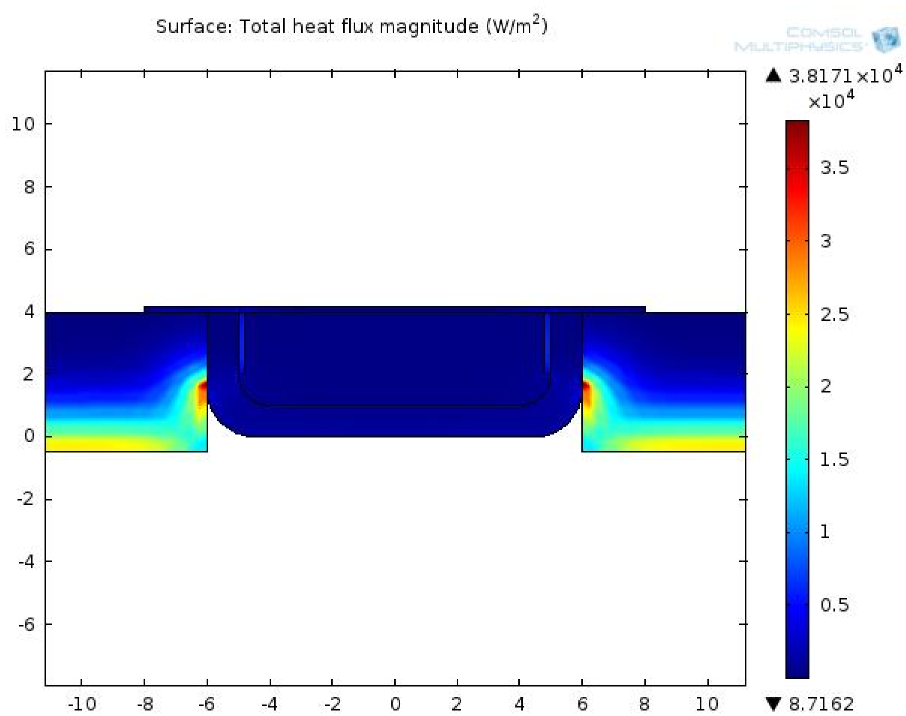

Figure 18: Total Heat Flux Plot

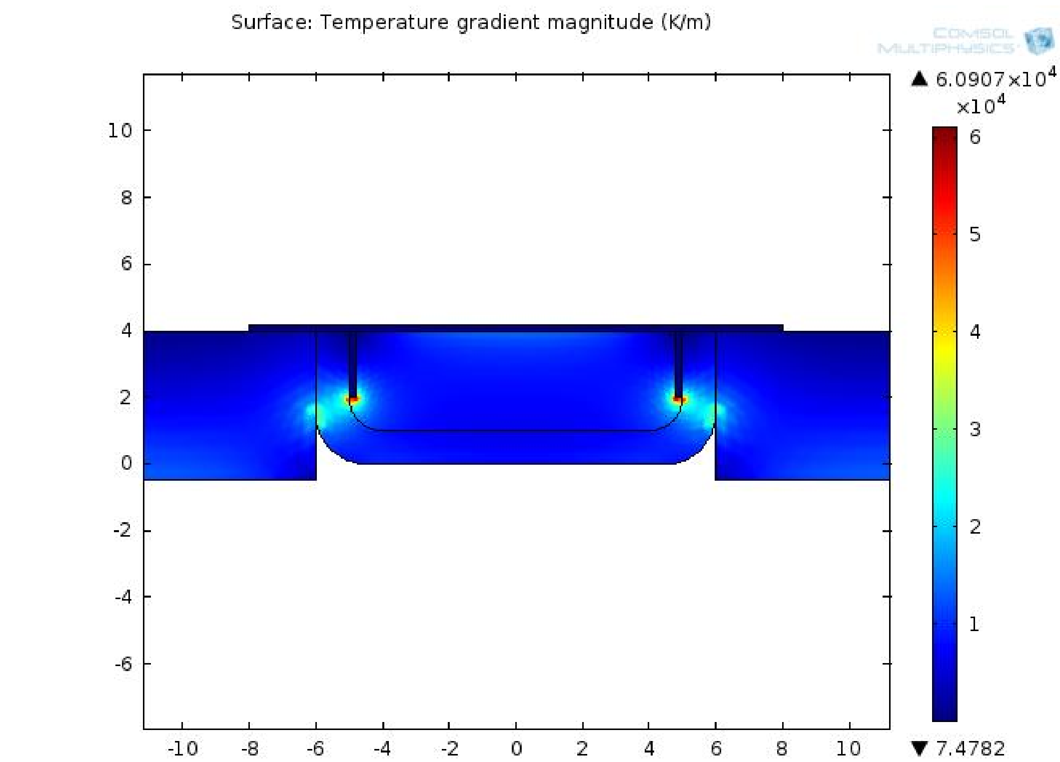

Figure 19: Temperature Gradient Plot

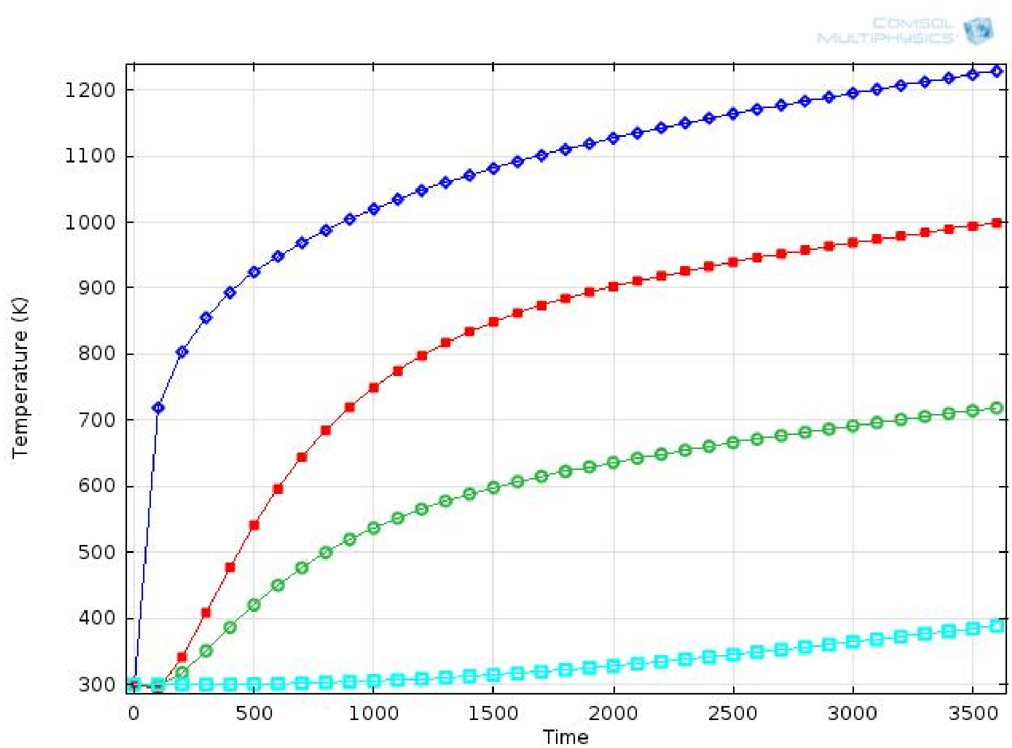

Figure 20: Average Temperatures of Various Surfaces as a Function of Time