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Analysis of a Fire Safe

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Abstract

This study intends to evaluate the characteristics of a SentrySafe Model 1200 Pink fire safe when placed under various heat transfer conditions. Two main analyses were performed, one to test the fire safe's final inside air temperature when heated under UL fire safe specification which governs an ambient temperature of 843°C the safe must withstand for one half hour, and one to test the fire safe's final inside air temperature when heated at 131.3°C in a standard convection oven for 50 minutes. To pass the test, the final inner air temperature of the safe under both conditions cannot be greater than 177.7°C (the published UL standard for when air temperature becomes unsafe for typical documents). By completing this model, we hope to gain a better understanding of heat transfer mechanics and develop a set of data characterizing the fire safe's tolerance to different heat-based scenarios. We first begin developing our study by calculating various parameters of the heat safe such as the insulating material and its thermal conductivity, the thickness of the walls, and the mass of the system. Next, using both a Semi-infinite Wall analysis and a Plane Wall Convection analysis we will calculate the time it takes for the insulation to reach the boiling point of water, 100°C . At this temperature, the water content of the insulation will begin to evaporate and heat transfer to the inside of the safe will cease until all water has been removed from the insulation. For this, a latent heat analysis will be used. Finally, after all the water has been removed from the insulation, heat transfer will resume and again be evaluated through a Semi-infinite Wall analysis and a Plane Wall Convection analysis. These two methods are used as a way to compare and contrast results and analyze which method works better in this application. The general assumptions we make in our analysis are that the calculations are to be performed while neglecting the effects of the plastic shell, all properties are held constant, heat transfer is conducted in one dimension, and the inner air temperature of the safe will have the same temperature as the inner wall of the insulation. At the conclusion of our analysis, we resolved that for the UL case, the final inner air temperature of the safe will be 152.2°C based on the Semi-infinite Wall analysis and 184.7°C based on the Plane Wall Convection analysis. For the convection oven case, we found that the final inner air temperature of the safe will be 80.9°C based on the Semi-infinite Wall analysis and 90.5°C based on the Plane Wall Convection analysis.

Introduction

2020 saw an estimated 356,500 house fires across the United States, according to the National Fire Protection Association (Ahrens & NFPA, 2021). While the loss of memorabilia and personal belongings is hard for anyone to have to deal with, one of the most important sets of non-living belongings that one could lose to fire are their personal documents. Passports, birth certificates, social

security cards, deeds, titles, and more are all extremely sensitive documents that need to be protected from fire-induced harm. Without these documents, it's difficult to prove you are who you say you are and that the things you have are legally yours. In the event of a house fire, families should work to keep their loved ones safe without having to worry about protecting their documents. Fire safes were designed with this purpose in mind. Fire safes are insulated boxes of varying sizes and insulation values that are built to withstand the extreme temperatures of a house fire and protect the contents within. This study will analyze the effectiveness of one of these particular fire safes: the SentrySafe model 1200. In order to make a conclusion about the effectiveness of this particular safe, it is necessary to develop a benchmark of understanding for the varying protection levels of fire safes. Fortunately, a rating scale has been developed to standardize the effectiveness of fire safes and their maximum protection parameters.

Even though the technology behind fireproof safes is continuously improving, the idea of a fireproof safe is nothing new. The first recorded fireproof safe was invented in the early 1800s by British Engineer William Marr. Marr invented a box with two walls of steel and a layer of insulation material sandwiched between the steel. Marr's heat-proof box is regarded as the first "modern-style" fireproof safe (CSG UK, n.d.). Almost a century later on September 17, 1918, Mabel Wupper of Brooklyn, New York filed US1279209A; the first patent for a fireproof safe. This safe was meant to be one of the first safes that were able to withstand a house fire but was also small enough (and inexpensive enough) for a typical home. The description of this safe in the patent describes a heat-treated box with two layers of wood with a layer of asbestos inbetween (Wupper, 1918). Asbestos was used because it is an extremely fire-resistant material. However, as we now know asbestos comes with a number of health risks, and nowadays fire safes are made using non-toxic, safe materials. The fire safe that is being studied for this case has an inner and outer plastic shell with an insulation layer of Gypsum, a common fireproofing material.

Underwriters Laboratories (UL) is one of the many standards organizations around the world on par with ASTM, ISO, IEEE, and ANSI. As stated in the "About Us" section of their website, "[UL] delivers testing, inspection and certification services, together with software products and advisory offerings" (UL Solutions, n.d.). The SentrySafe model 1200 has obtained a UL certification in fire protection from the UL-72 standard. UL-72 is the Standard for Tests for Fire Resistance of Record Protection Equipment. These standard awards products with specific ratings depending on their ability to pass UL's rigorous testing techniques. The standard classifies the effectiveness of a fireproof safe by its ability to withstand temperatures for a specified period of time, as well as to withstand drop and explosion tests of specific intensities. Speaking broadly, UL breaks their certification for fireproof safes into 3 classes: 125, 150, or 350 for 4, 3, 2, 1, or ½ hours. This means that after a specific amount of time being held at a specific temperature, the internal temperature of the product must not exceed 125, 150, or 350 °F in order to be placed in that rating class (UL Solutions, 2015, 6) (KL Security, n.d.). On the SentrySafe product website, the vendor posts a UL rating that states, "UL Classified to protect your valuables in a fire for 1/2 hour up to 1550°F (843°C)" (Sentry Safe, 2018). The website does not state a UL rating of 125, 150, or 350. At the conclusion of this study, the results will be used to determine which UL classification this safe is rated for. The analysis and results section of this study will determine the internal temperature of the safe over a specific period of time at a specific external temperature, so this classification determination will be easy to find.

Methods

The following list of assumptions have been made in order to aid the calculations and provide clarity on the goal of this study:

- 1-Dimensional heat conduction.
- Constant properties.
- Neglect radiation exchange with surroundings.
- Temperature inside the safe chamber is uniform.
- No flowing air inside the container.
- Uniform heat transfer coefficient.
- Perfectly sealed container.
- Perfectly insulated container.
- Neglect kinetic and potential energy.
- Initial temperature of the domain is equal to the ambient temperature.
- The effects of plastic walls can be ignored.

The fire safe being analyzed has been recreated into a 1-Dimensional diagram looking at a cross-section of one of the side walls in order to better understand the wall layers the heat must pass through in order to reach the contents inside the safe. *Figure 1* shows this diagram.

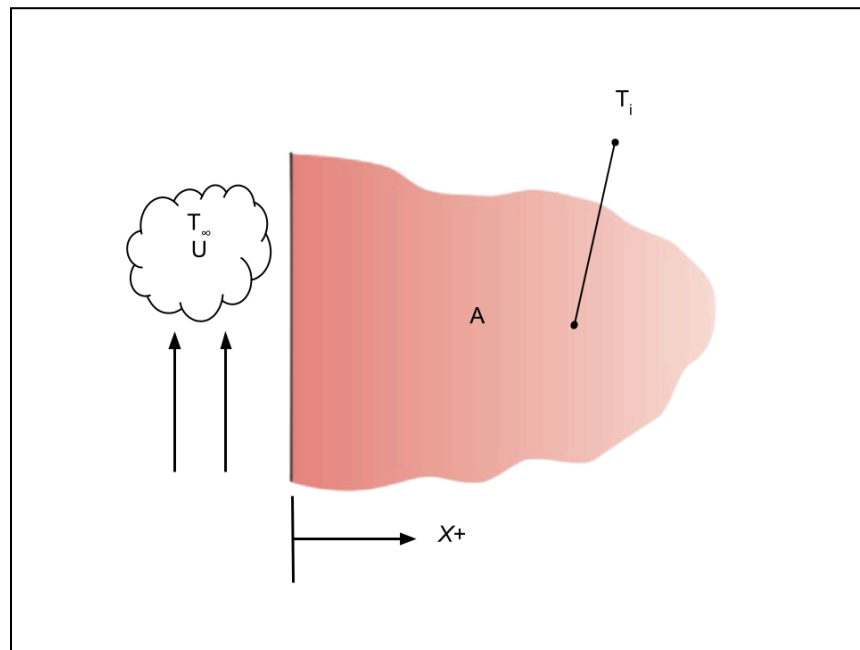


Figure 1: 1-Dimensional Diagram of Semi-Infinite method. Section A is the insulation in the fire safe.

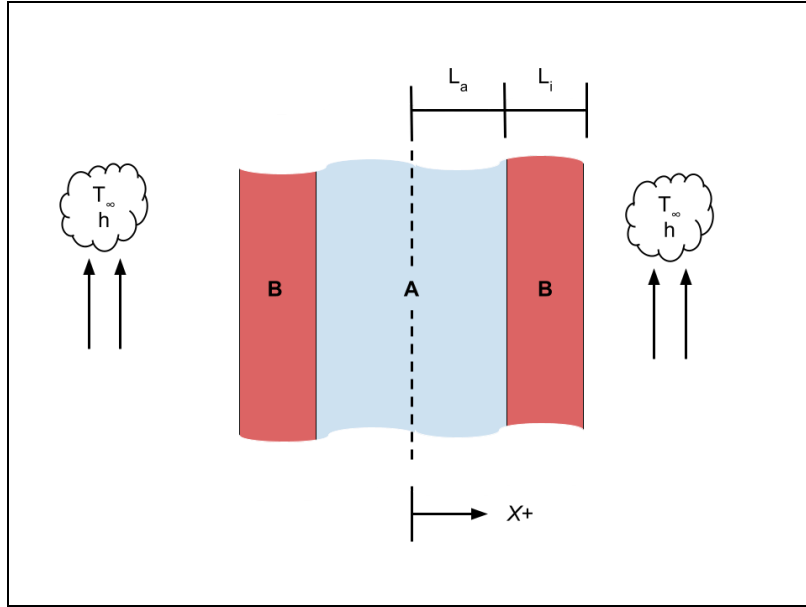


Figure 2: 1-Dimensional Diagram of Plane Wall with Convection method. Section A is the air inside the fire safe and Section B is the insulation inside the fire safe.

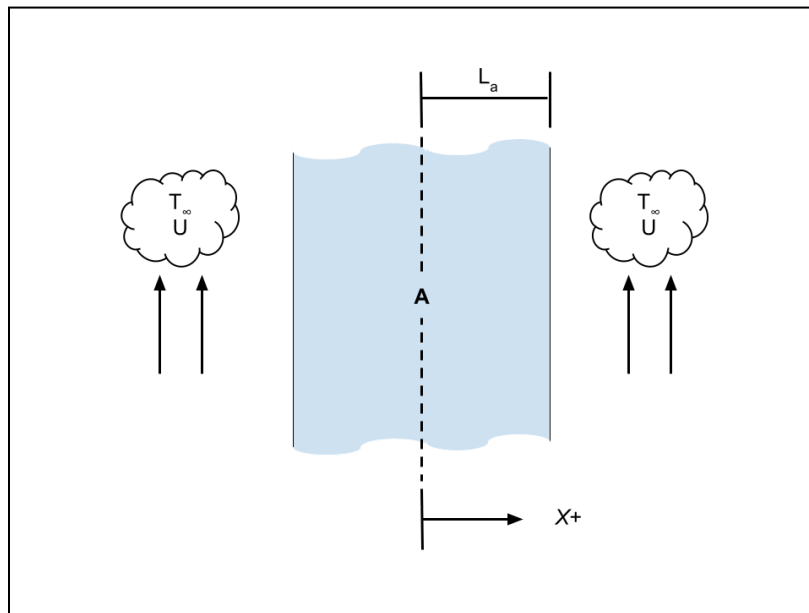


Figure 3: 1-Dimensional Diagram of the Plane Wall with Convection case simplified. Section A is the air in the fire safe.

In addition to a 2-Dimensional diagram, a resistance diagram of the figure above has been created in order to visualize the method that must be used to determine the overall resistance of the system. Figure 2 below shows this resistance diagram.

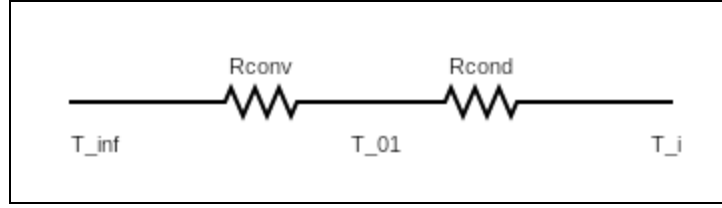


Figure 4: Resistance Diagram of the fire safe system.

Appendix A Table 1 is a Table of Parameters used in the equations and calculations in the sections below.

Governing Equations

$B_i = \frac{L_i * U}{K_i}$	Biot Number
$U = \frac{1}{R_{conv} + R_{cond}}$	U Value
$Fo = \frac{\alpha t}{L_2}$	Fourier Number Calculation
$\alpha = \frac{K_i}{\rho * c_p}$	Alpha Value
$\frac{T(x,t) - T_i}{T_i - T_\infty} = \text{erfc}\left(\frac{x}{2\sqrt{\alpha t}}\right) -$	Semi-infinite Plate Governing Equation
$\frac{T - T_\infty}{T_i - T_\infty} = C_1 * e^{-\zeta^2 * F_o}$	Plane Wall with Convection
$\dot{m} = -k_a A_c \frac{T_\infty - 100^\circ\text{C}}{L_i * h_{fg}}$	Mass Flow Rate of Water Evaporating When T_i is at 100°C
$V_s = D_e - D_i$	Volume of Safe Walls
$m_g = V_s * \rho_g$	Mass of Gypsum in Safe
$m_w = 2 * m_g$	Mass of Water in Gypsum

Table 2: Governing Equations

Analysis

Semi-infinite Wall

Step 1: The first step in the analysis is to determine the U value, then the Biot Number of the system. The U value will be one over the total thermal resistance. Determining the Biot Number will give direction to the next steps in the analysis; if the calculated Biot Number is less than 0.1 ($Bi < 0.1$), the Lumped Capacitance Method may be used for the remainder of the analysis.

$$U = \frac{1}{R_{conv} + R_{cond}} = \frac{1}{\frac{1}{17(\frac{W}{m^2})} + \frac{0.17(\frac{W}{m})}{0.026(m)}} = 4.382$$

$$Bi = \frac{U * L_i}{K_i} = \frac{4.383(\frac{W}{m^2 K}) * 0.026(m)}{(0.16 \frac{W}{m K})} = 0.256$$

Step 2: As the Biot number of the system is greater than 0.1, the Lumped Capacitance Method cannot be used and the Spatial Effects analysis will have to be performed. Within spatial effects there are two cases, Plane Wall with Convection and Semi-infinite Wall. The Semi-Infinite Wall Method was used to find the inside temperature of the safe. The main equation where x is the distance from the heated surface and t is the time elapsed for this method is as follows:

$$\frac{T(x,t) - T_s}{T_i - T_s} = erf\left(\frac{x}{2\sqrt{\alpha t}}\right)$$

$$where \alpha = \frac{k_a}{c_p * \rho}$$

$$So: T(x, t) = erf\left(\frac{x}{2\sqrt{\alpha t}}\right) * (T_i - T_s) + T_s$$

Step 3: As the insulation contains 20% water by weight, if the insulation reaches 100°C the heat transfer will stop until all of the water has evaporated from the insulation. This time is evaluated through a latent heat analysis. First, mass of gypsum and water in the insulation is found, then the mass flow rate of the water evaporating is found. Note that after accounting for the mass of the plastic and locking mechanism, the volume (and thus the mass) of the gypsum will be less than the calculated volume of the safe. We estimate that the mass of these other components is between .5(kg) and 1(kg) and we assume the mass of the gypsum then is roughly 5(kg). The time to completely evaporate the water can be then calculated.

$$\begin{aligned} m_g &= (V_o - V_i) * \rho_g \\ &= ((.15(m) * .36(m) * .29(m)) - (.09(m) * .31(m) * .19(m))) * 557(\frac{kg}{m^3}) \\ &= 5.76(kg) \end{aligned}$$

$$m_w = 20\% * m_g = .2 * 5(kg) = 1(kg)$$

$$\dot{m} = -k_a A_c \frac{T_\infty - 100^\circ\text{C}}{L_i * h_{fg}} = -0.16\left(\frac{W}{m}\right) * 0.407(m^2) * \frac{843^\circ\text{C} - 100^\circ\text{C}}{0.026(m) * (2.26 * 10^{-5})\left(\frac{J}{kg}\right)} = 8.13 * 10^{-4}\left(\frac{kg}{s}\right)$$

$$t_{evap} = \frac{m_g}{\dot{m}} = \frac{1kg}{8.13 * 10^{-4}\left(\frac{kg}{s}\right)} = 1230.01s$$

Step 4: To properly calculate the final temperature of the inner wall of the insulation (and thus the air temperature of the inside cavity) three segments of calculations are needed. The first is the Semi-Infinite Plate Analysis to find the time until the insulation reaches 100°C (Step 2), then a Latent Heat Analysis is used to find the time until the water evaporated out of the insulation (Step 3), then another Semi-Infinite Plate Analysis is used to find the final temperature of the insulation based on the time remaining in the test.

Now that the parameters of the study have been established and the governing equations have been stated and explained, results are now ready to be calculated. The parameters and equations above have been transposed into the software MATLAB for analysis and graphing. *Figure 3* below is a flowchart that shows a visual representation of the code that will be run in MATLAB. The figure shows the inner workings of the numerous “while” loops that were utilized in this analysis. The exact MATLAB code that was used in this analysis can be found in *Appendix B*. The results of the MATLAB script can be found in the Results section of this study.

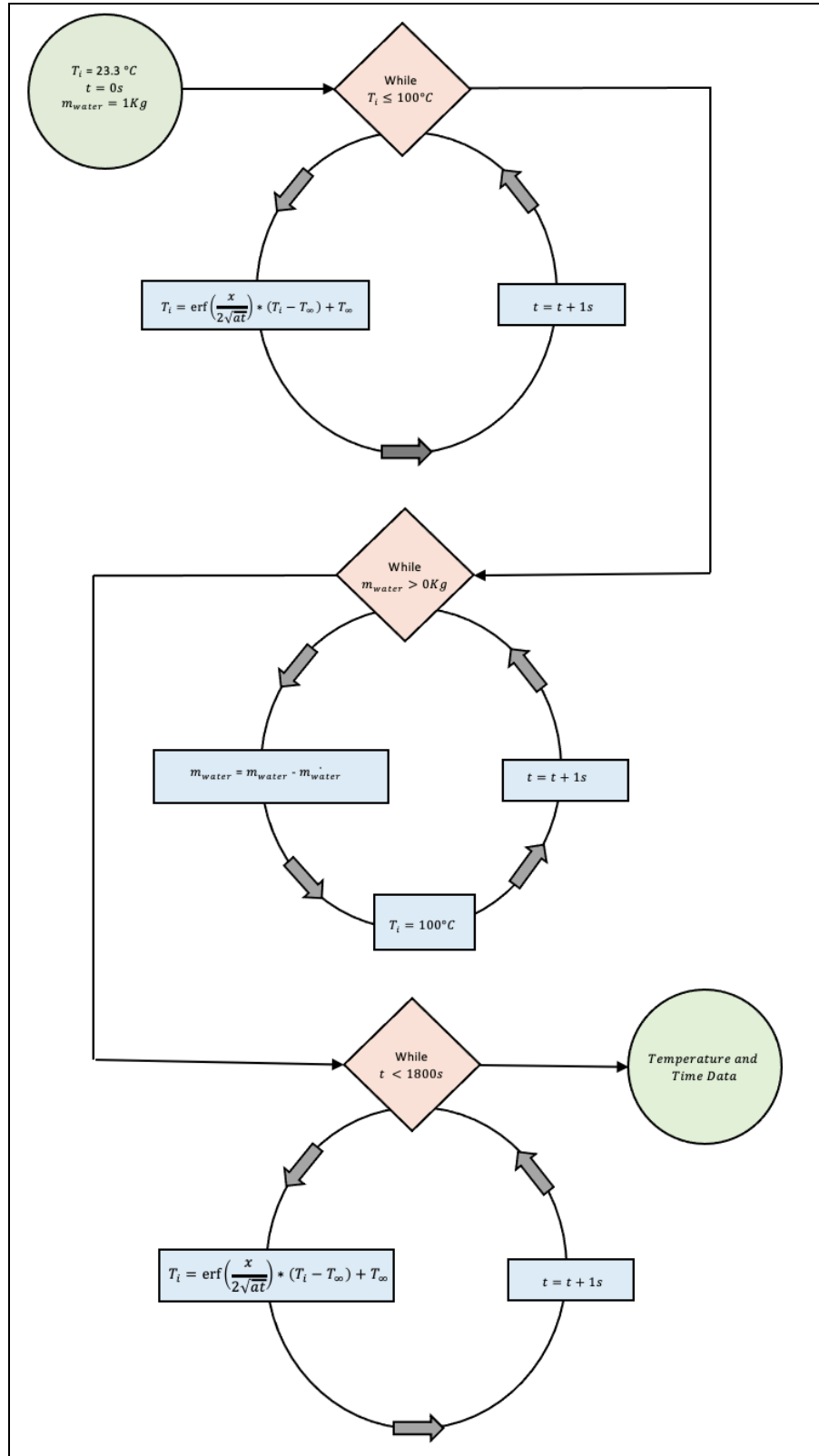


Figure 5: Analysis Flowchart

Plane Wall with Convection

Step 1: The first step in the analysis is to determine the U value, then the Biot Number of the system. Determining the Biot Number will give direction to the next steps in the analysis; if the calculated Biot Number is less than 0.1 ($Bi < 0.1$), the Lumped Capacitance Method may be used for the remainder of the analysis.

$$U = \frac{1}{R_{conv} + R_{cond}} = \frac{1}{\frac{1}{17(\frac{W}{m^2})} + \frac{0.17(\frac{W}{m})}{0.026(m)}} = 4.382$$

$$Bi = \frac{U * L_i}{K_i} = \frac{4.383(\frac{W}{m^2 K}) * 0.026(m)}{(0.16 \frac{W}{m K})} = 0.256$$

Step 2: The other method that can be used is Plane Wall with Convection. The governing equation for the Plane Wall with Convection will be solved to find the internal temperature. On excel time steps of two seconds will be calculated until the inside temperature reaches 100°C.

$$\alpha = \frac{k_a}{c_p * \rho}$$

$$F_o = \frac{t}{\frac{L_a^2}{\alpha}} = \frac{\alpha t}{L_a^2}$$

$$\frac{T - T_{\infty}}{T_i - T_{\infty}} = C_1 * e^{-\zeta^2 * F_o}$$

$$T = [(T_i - T_{\infty}) * C_1 * e^{-\zeta^2 * F_o}] + T_{\infty}$$

Step 3: As the insulation contains 20% water by weight, if the insulation reaches 100°C the heat transfer will stop until all of the water has evaporated from the insulation. This time is evaluated through a latent heat analysis. First, the mass of gypsum and water in the insulation is found, then the mass flow rate of the water evaporating is found. Note that after accounting for the mass of the plastic and locking mechanism, the volume (and thus the mass) of the gypsum will be less than the calculated volume of the safe. We estimate that the mass of these other components is between .5(kg) and 1(kg) and we assume the mass of the gypsum then is roughly 5(kg). The time to completely evaporate the water can be then calculated.

$$m_g = (V_o - V_i) * \rho_g$$

$$= ((.15(m) * .36(m) * .29(m)) - (.09(m) * .31(m) * .19(m))) * 557(\frac{kg}{m^3})$$

$$= 5.76(kg)$$

$$m_w = 20\% * m_g = .2 * 5(kg) = 1(kg)$$

$$\dot{m} = -k_a A_c \frac{T_\infty - 100^\circ\text{C}}{L_i * h_{fg}} = -0.16\left(\frac{W}{m}\right) * 0.407(m^2) * \frac{843^\circ\text{C} - 100^\circ\text{C}}{0.026(m) * (2.26 * 10^{-5})\left(\frac{J}{kg}\right)} = 8.13 * 10^{-4}\left(\frac{kg}{s}\right)$$

$$t_{evap} = \frac{m_g}{\dot{m}} = \frac{1kg}{8.13 * 10^{-4}\left(\frac{kg}{s}\right)} = 1230.01s$$

Step 4: Repeat step 2 and use the derived formula to continue finding the interior temperature for the remaining time until 1800s.

Results

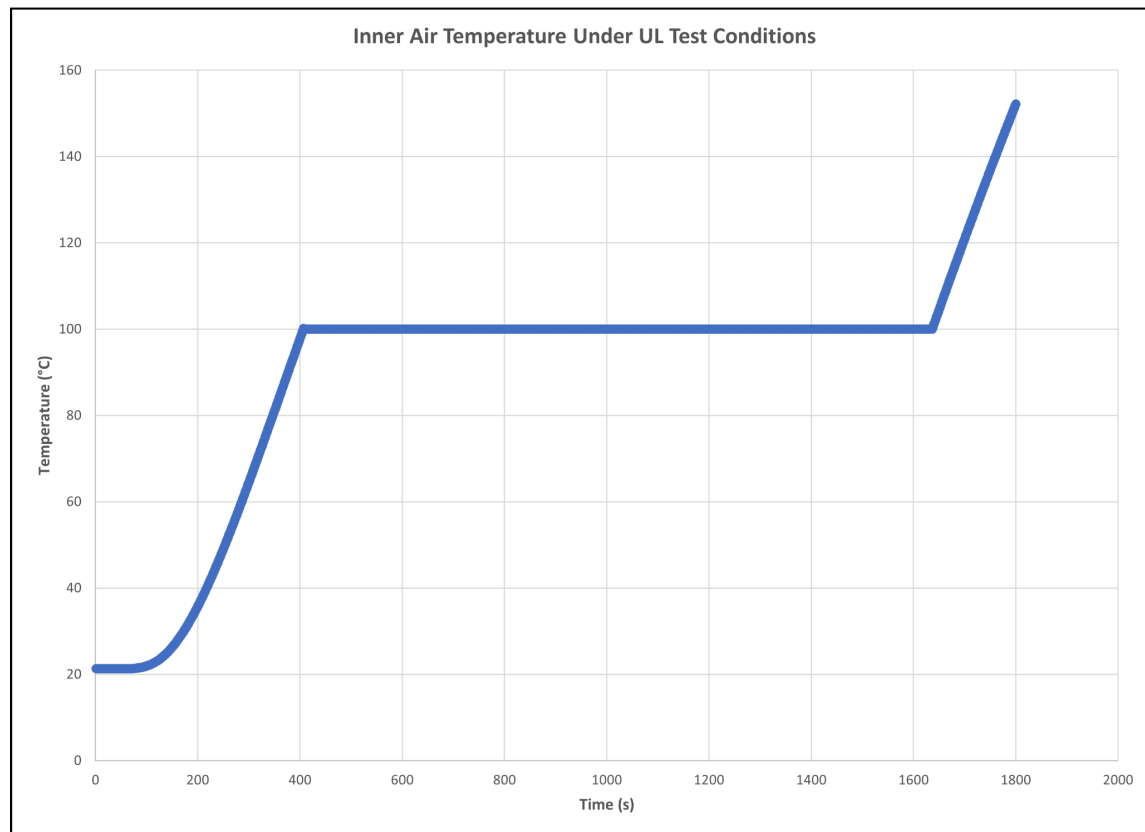


Figure 6: Plot of temperature data from the UL Case, using Semi-Infinite method

The above figure shows the results of the heat transfer analysis of the safe under UL testing conditions using the Semi-infinite Wall method. The two main parameters this set of test procedures outlines are 1), the temperature at the ambient air should be and 2), the amount of time the safe should be subjected to this temperature. These values are 843°C and 1800s (one half hour), respectively. This creates quite an extreme temperature gradient and challenge for the safe. As mentioned in the analysis section, once the insulation temperature reaches 100°C (the boiling point of water), the heat transfer will effectively pause until all the water has evaporated from the insulation. This time is denoted by the large flat line in the center of the graph where the temperature is not changing, this amount of time is 1230s. After the water has evaporated the heat transfer continues to increase the insulation temperature normally. After running the calculation program it was found that the final temperature of the insulation at the inner edge of the insulation after 1800 seconds was 152.2°C. As per our assumption that the inner wall of the insulation is the same temperature as the inner air chamber, the inner air chamber after 1800 seconds is also 152.2°C. Under these conditions, the Sentry Safe model 1200 is predicted to pass the test as the UL published threshold for where the inner temperature becomes unsafe for documents is 177.7°C. It should be noted that this is a conservative estimate as we have assumed that the effects of the plastic walls and inner convection can be ignored. In reality, these components will only decrease heat flux in the safe and decrease the final calculated inner temperature.

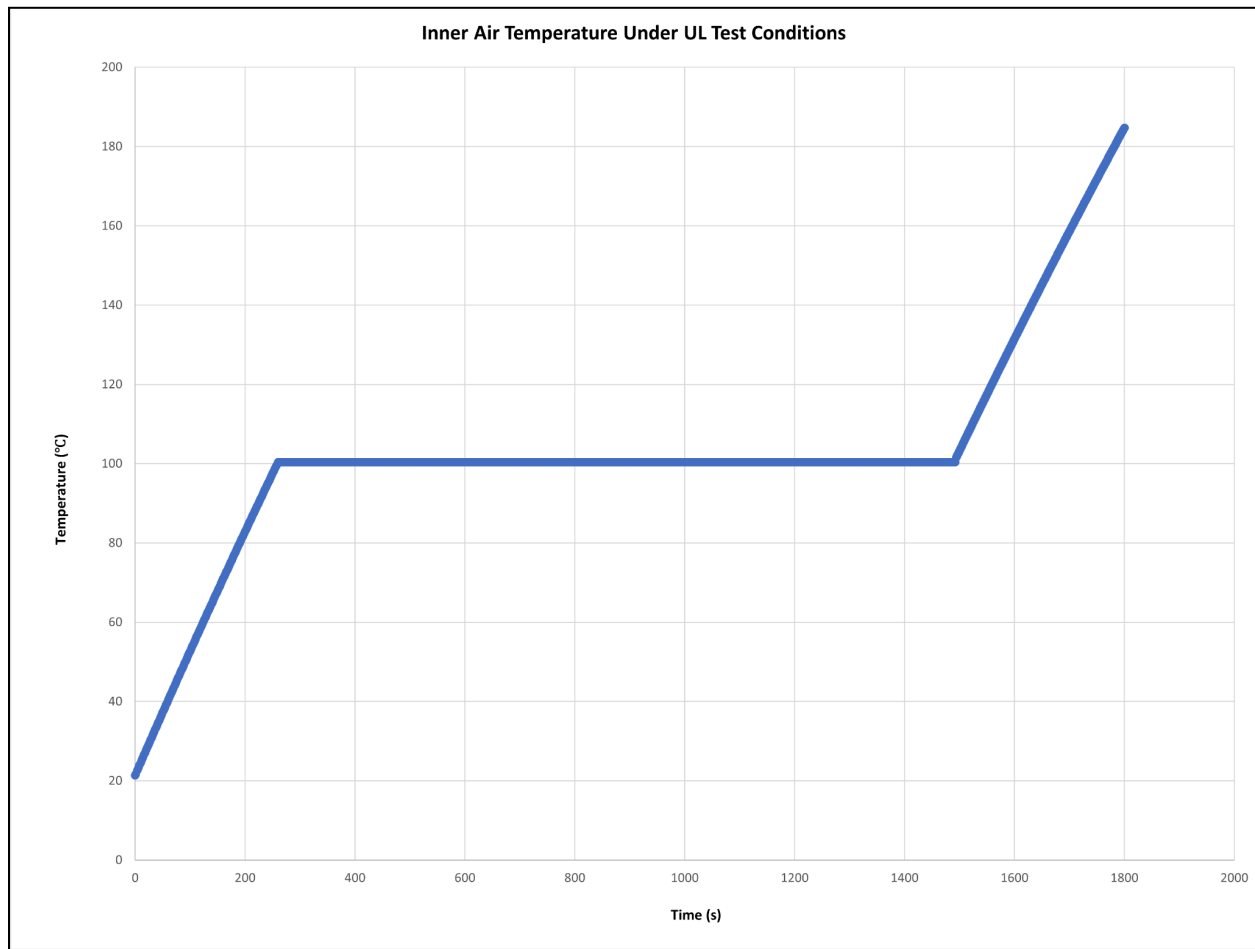


Figure 7: Plot of temperature data from the UL Case, using Plane Wall with Convection method

The above figure shows the results of the heat transfer analysis of the safe under UL testing conditions using the Plane Wall Convection method. The two main parameters this set of test procedures outlines are 1), the temperature at the ambient air should be and 2), the amount of time the safe should be subjected to this temperature. These values are 843°C and 1800s (one-half hour), respectively. After running the calculation program it was found that the final temperature of the insulation at the inner edge after 1800 seconds was 184.7°C. As per our assumption that the inner wall of the insulation is the same temperature as the inner air chamber, the inner air chamber after 1800 seconds is also 184.7°C. Under these conditions the Sentry Safe model 1200 is not predicted to pass the test as the UL published threshold for where the inner temperature becomes unsafe for documents is 177.7°C. It should be noted that this is a conservative estimate as we have assumed that the effects of the plastic walls and inner convection can be ignored. In reality, these components will only decrease heat flux in the safe and decrease the final calculated inner temperature.

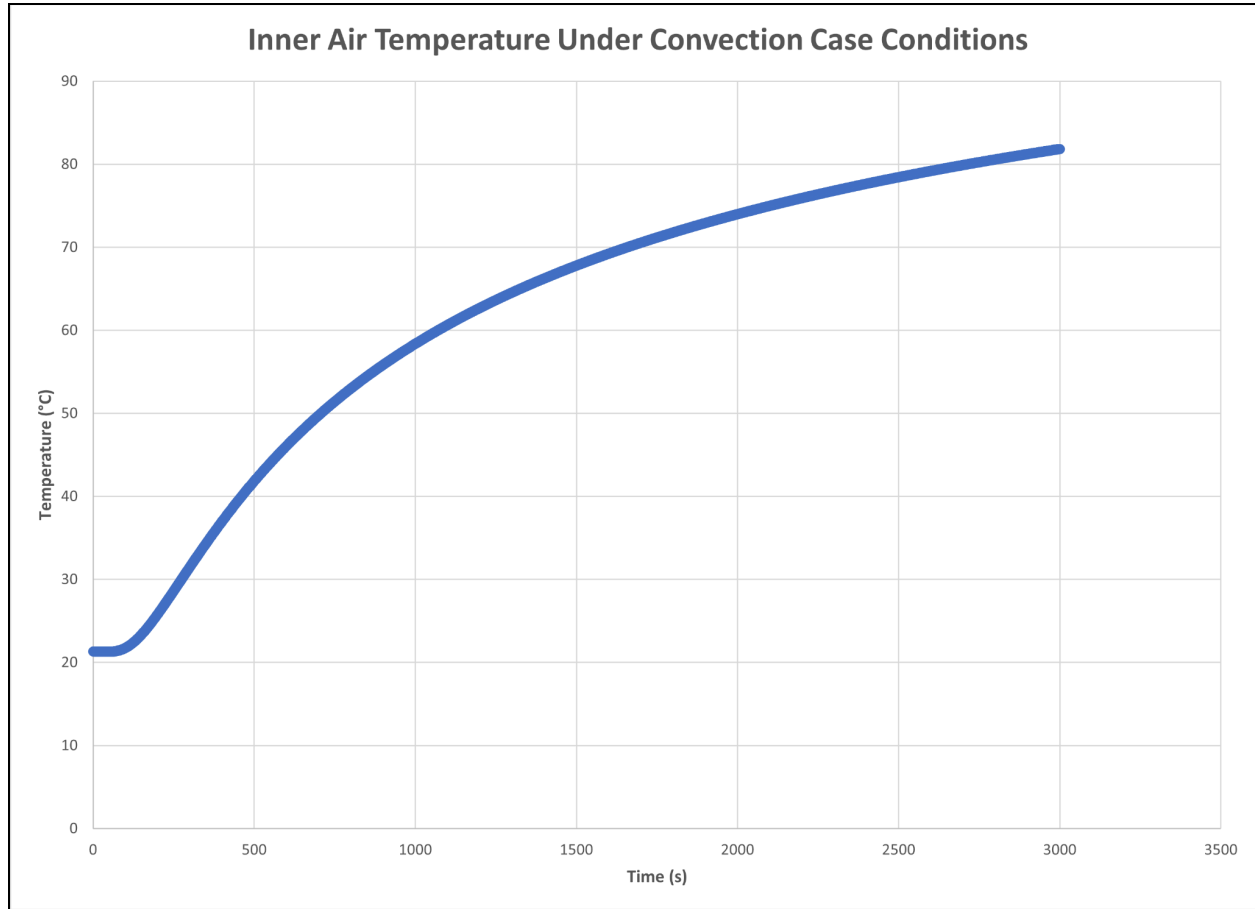


Figure 8: Plot of temperature data from the Convection Oven Case, using the Semi-Infinite method

The above figure shows the results of the heat transfer analysis of the safe under the given convection oven testing conditions using the Semi-infinite Wall method. The two main parameters this case outlines are 1), the temperature at the ambient air should be and 2), the amount of time the safe should be subjected to this temperature. These values are 131.3°C and 3000s (fifty minutes), respectively. As mentioned in the analysis section, once the insulation temperature reaches 100°C (the boiling point of water) the heat transfer will effectively pause until all the water has evaporated from the insulation. However, in this case, it is shown that the temperature of the insulation doesn't reach 100°C during the fifty minutes and thus only the first Semi-Infinite Plate section of our analysis method is required. This difference can be seen in the graph as the curve is an uninterrupted, steady line. After running the calculation program, it was found that the final temperature of the insulation at the inner edge after 3000 seconds was 80.9°C. As per our assumption that the inner wall of the insulation is the same temperature of the inner air chamber, the inner air chamber after 3000 seconds is also 80.9°C. Under these conditions, the Sentry Safe model 1200 is predicted to pass the test as the UL published threshold for where the inner temperature becomes unsafe for documents is 177.7°C. Again, it should be noted that this is a conservative estimate as we have assumed that the effects of the plastic walls and inner convection can be ignored. In reality, these components will only decrease heat flux in the safe and decrease the final calculated inner temperature.

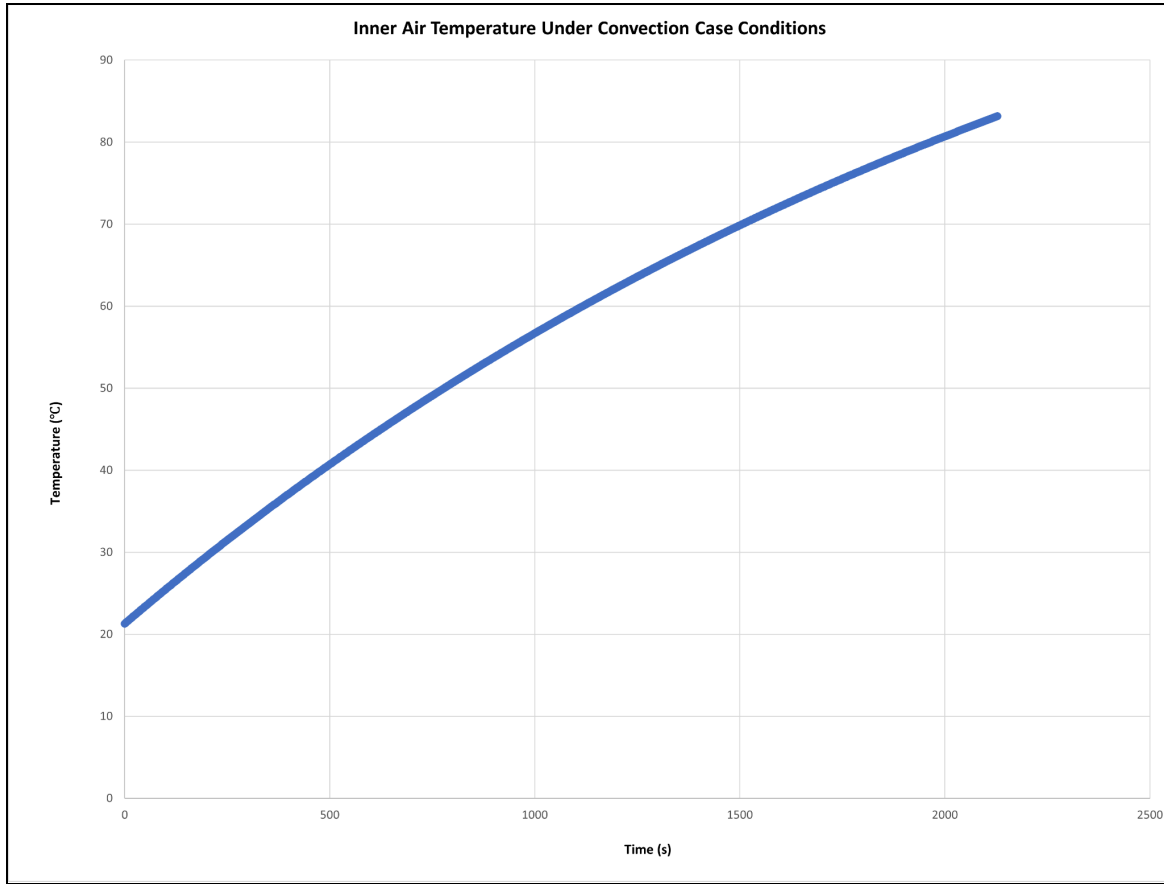


Figure 9: Plot of temperature data from the Convection Oven Case, using Plane Wall with Convection method

The above figure shows the results of the heat transfer analysis of the safe under the given convection oven testing conditions using the Plane Wall Convection method. The two main parameters this case outlines are 1), the temperature at the ambient air should be and 2), the amount of time the safe should be subjected to this temperature. These values are 131.3°C and 3000s (fifty minutes), respectively. As mentioned in the analysis section, once the insulation temperature reaches 100°C (the boiling point of water) the heat transfer will effectively pause until all the water has evaporated from the insulation. However, in this case, it is shown that the temperature of the insulation doesn't reach 100°C during the fifty minutes and thus only the first Plane Wall Convection method section of our analysis is required. This difference can be seen in the graph as the curve is an uninterrupted, steady line. After running the calculation program, it was found that the final temperature of the insulation at the inner edge after 3000 seconds was 90.5°C. As per our assumption that the inner wall of the insulation is the same temperature of the inner air chamber, the inner air chamber after 3000 seconds is also 90.5°C. Under these conditions, the Sentry Safe model 1200 is predicted to pass the test as the UL published threshold for where the inner temperature becomes unsafe for documents is 177.7°C. Again, it should be noted that this is a conservative estimate as we have assumed that the effects of the plastic walls and inner convection can be ignored. In reality, these components will only decrease heat flux in the safe and decrease the final calculated inner temperature.

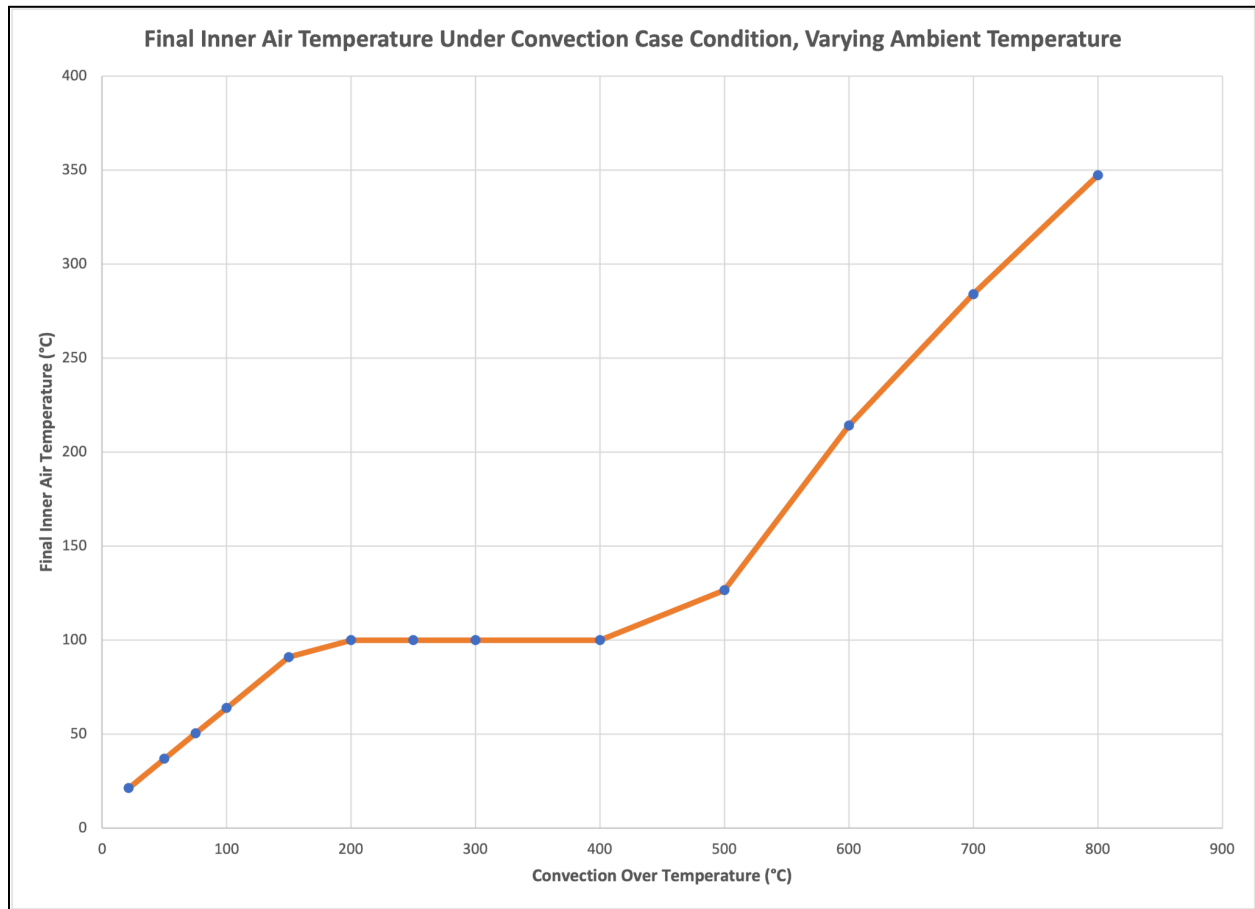


Figure 10: Final inner air temperature of the safe from varying ambient Convection Oven temperatures

The above figure shows what the final inner air temperature of the safe will be under different ambient air cases. This model is based on the convection oven scenario and has a run time of 50 minutes, or 3000s. The data starts out at a convection oven temperature of 21.3°C where there is no temperature change inside the case as the system is already at equilibrium. The first point at which the insulation reaches 100°C and the water in the insulation begins to evaporate is at 166.7°C. From there, there is no change in the final inner air temperature until the convection oven temperature reaches 476.7°C. This flatline is due to the latent heat section of the heat transfer. Another important point to note is the convection oven temperature where the final inner air temperature of the safe crosses the safety threshold of the UL standards. This threshold is 177.7°C, and the inner air temperature will reach this point when the convection oven temperature is 554.5°C. This plot can be very helpful when designing fire-proof safes in the future. It shows how the ambient temperature will influence the final inner air temperature of the safe, and how the content of water in the system can have a major impact on the heat transfer progression of the system.

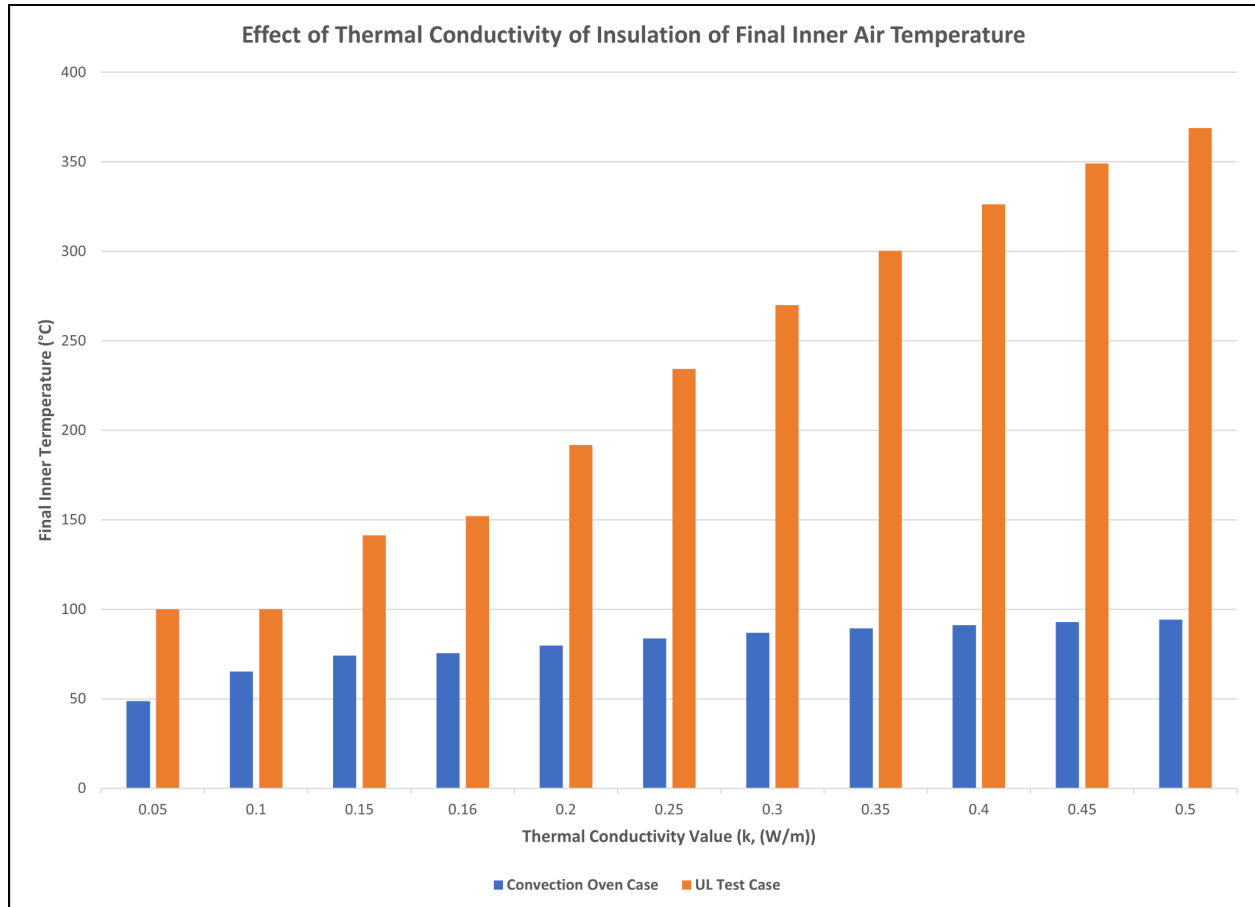


Figure 9: Effect of k value on final inner air temperature of safe in both Convection Oven conditions and UL test conditions

The above figure shows how changing the k value of the insulation of the safe impacts the final inner air temperature of the safe. The k value drastically affects the final inner air temperature of the safe as it directly changes the heat transfer characteristics of the insulation. It can be seen in the figure that this is especially true for the UL Test Case. The reason there is a growing discrepancy between the Convection Oven Case and the UL Test is that as the k value increases the Convection Oven Case is approaching the Latent Heat section of the analysis (where the temperature of the insulation hits and maintains a temperature of 100°C) and the rate of heat transfer is slowing as the temperature gradient decreases. As can be seen in the chart, the UL Test Case surpasses the latent heat analysis section once the k value of the insulation is greater than 0.1. Thus, the final air temperature inside the safe under the UL Case Analysis increases greatly after the water has been evaporated out of the system. Similar to Figure 6, this chart can be quite helpful when designing safes. It gives a general view of how the insulation of the safe will affect the inner temperature, and what values correlate to which temperature.

Conclusions

For this case study we analyzed two scenarios involving a SentrySafe 1200 Pink fire safe. One scenario involves predicting the inside of the SentrySafe 1200 initially at 21.3°C then placed in a convection oven with an average temperature of 131.3°C for 50 minutes. The second scenario consists of predicting the inside temperature of the safe with the conditions defined by the UL standards which are a temperature of 843°C and duration of 1800 seconds. Spatial Effect cases were used because the Biot number was greater than 0.01, which consisted of a Plane Wall with Convection and Semi-Infinite wall.

The SentrySafe Model 1200's website advertises that the safe is UL Certified against fire protection. While the website details the conditions that the safe was tested in (time and ambient temperature), the specific UL Standard 72 classification rating is not stated. Using the results of the analysis above, the specific UL classification rating can be determined. According to the SentrySafe website, the safe was tested to withstand ambient temperatures of 843°C for half an hour (Sentry Safe, 2018). According to *Figure 6*, after 1800 seconds (30 minutes) of an external temperature of 800°C, the final internal temperature of the safe is 152.2°C as determined using a Semi-Infinite Method. Under the same conditions, analysis using the Convection method determines an inner temperature of 184°C, roughly a 21% increase. Regardless, it is reasonable to expect this safe model to have a UL classification rating of "Class 350 - 1/2 h" because the inner temperature of the safe is over the Class 150 maximum temperature of 150°F (66°C) but within the maximum temperature of Class 350: 350°F or 177°C after 30 minutes of testing. The physical safety in the MECE main office has a specific UL classification rating that was not available on the SentrySafe website. The safe is rated "Class 350 - 1/2 h". The same rating between our theoretical analysis and the true UL rating proves the methodology of this study, confirms the calculations are correct and demonstrates that the assumptions made in our methodology section do not impact the final results to an extent where they greatly affect the results.

For this case study, we used two methods to find the inside temperature, Plane Wall with Convection and Semi-Infinite Solid, to find the final internal temperature of the two cases. For the case using UL standards, the initial temperature of 21.3°C, ambient temperatures of 843°C and for time of 1800s the final temperature for the Semi-Infinite was 152.2°C and for the Plane Wall with Convection was 184.71°C. This is a 19.3% percent difference between the methods. For the oven case, the initial temperature of 21.3°C, ambient temperatures of 131.3°C, and a time of 3000s the final temperature for the Semi-Infinite was 80.9°C and for the Plane Wall with Convection was 96.97°C. This is a 18.07% percent difference between the methods. The Semi-Infinite method is the more desirable method of analysis for this case study. The Semi-Infinite method does not take into account more variables compared to the Plane Wall with Convection like the Coefficients and Eigenvalues that was found in tables.

One of the main characteristics we discovered regarding the insulation is how the water affects the heat transfer. Initially, it was not thought that the water would significantly alter the final inner air temperature of the safe, however, we discovered that the greater the water content of the insulation the lower the air temperature will be, as long as the insulation reaches at least 100°C. This is due to the latent heat effect of the water where all heat transfer through the insulation stops when the water is evaporated when it reaches 100°C. This is what causes a "flatline" effect (seen in figures 6 and 7) and a decrease in the slope of the temperature increase (seen in figures 8 and 9). Concluding from this, water content is an important variable when designing a fire safe. If the insulation is anticipated to reach 100°C, it would be a good idea to ensure that the water content of the insulation is relatively high.

Ansys Analysis

As an extension to this study, the SentrySafe was modeled in the Ansys analysis software in order to further certify the accuracy of the calculations in the analysis section. Ansys was prepared to run a Fluent Fluid Flow simulation. After modeling the safe in Ansys, the properties of Gypsum that were used in the original analysis were entered into the solid material properties of the Setup window. The appropriate parameters from *Appendix A Table 1* were also entered into Ansys.

Originally, the simulation was set to run 3600 steps at 0.5 seconds between each step. The outcome of this simulation would analyze the temperature of the safe for the entire half-hour period that was being analyzed. Unfortunately, the step interval had to be shortened because the time it would take to run the simulation was estimated to be eight hours. The simulation was modified down to 180 steps at 10 seconds; shortening the simulation time to 2 hours. The following figure, *Figure 10* shows the result of the Ansys Analysis.

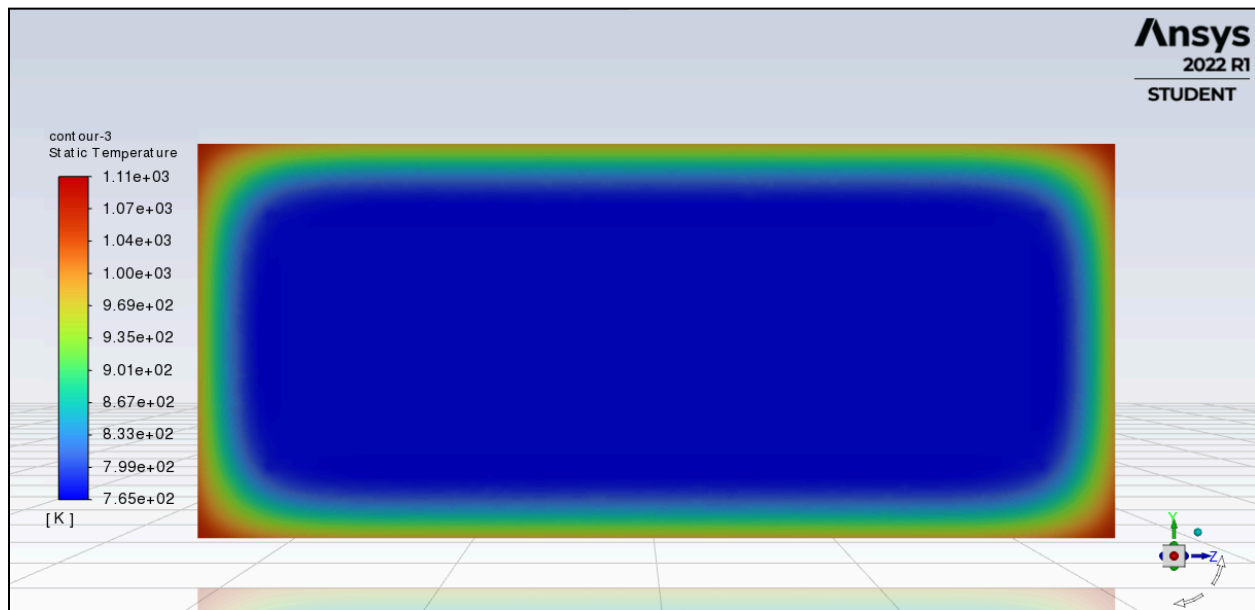


Figure 10: Ansys Analysis Heat Map
This is a section view of the safe

As can be seen from the legend, the final internal temperature of the safe has been simulated to be 765 K (491.95°C). This value is much higher than the analysis calculations predicted. Additionally, even though the hollow inside of the safe was modeled in the safe geometry, that open space is not visible in this heat map, which raises concerns over the accuracy of the simulation and the correctness at which it was set up. It is entirely possible that the simulation was prepared incorrectly, which would explain the unexpected result of the final inner temperature.

An interesting aspect that this simulation revealed was that the hottest parts of the safe after half an hour are at the exterior edges. One reason that the edges could be so much hotter than the rest of the safe is that they are exposed to high temperatures from multiple directions within the oven.

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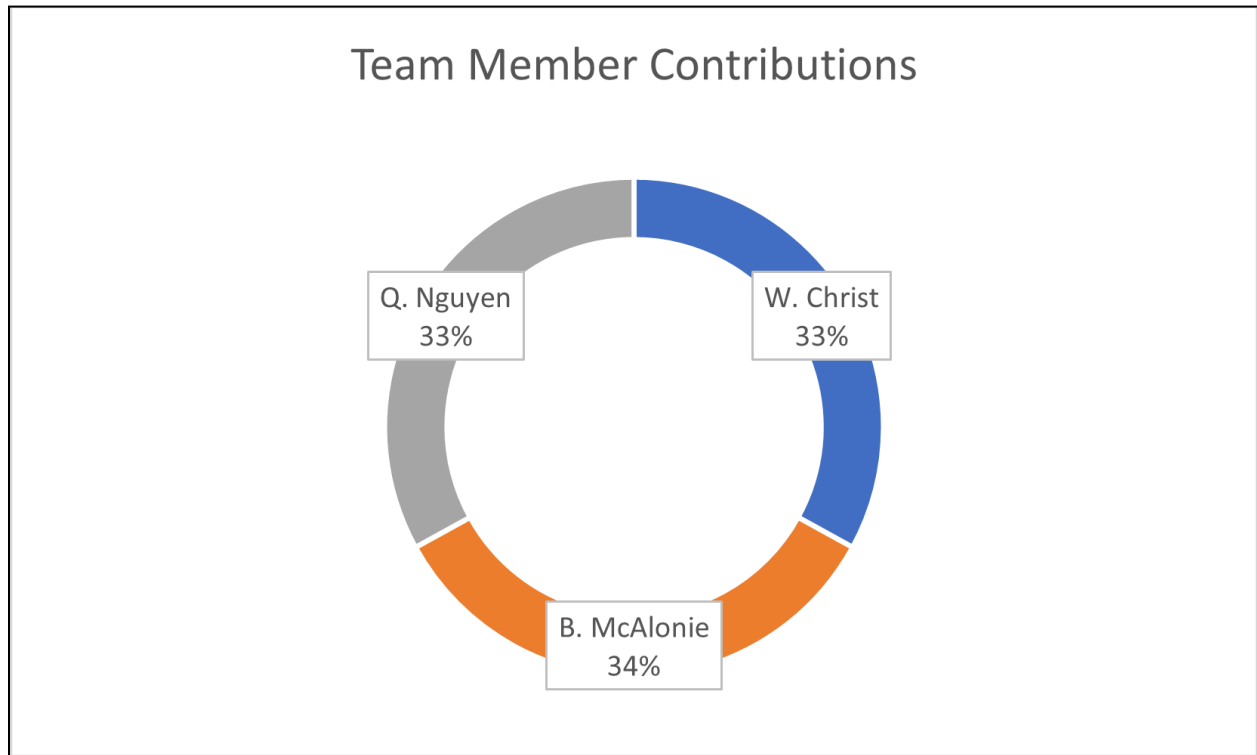
Feedback given to other teams

Team #	Positive Aspect 1	Positive Aspect 2	Negative Aspect 1
11	Figures are very well done and are described well.	Table of properties makes the known values and variables clear and organized.	Abstract needs values and conclusions. Show equations and calculations in the Analysis section.
12	Very thorough introduction that introduces the study and its significance.	The included figures are of a very professional quality and are relevant to the study.	Include a discussion on why you chose the h value that you did.
13	<i>Figure 4</i> contents look very good and justify the claims of the study.	Very informative and well-written introduction.	Need more assumptions that determine which method to use. Export figures as PNG instead of MATLAB screenshots.

Feedback received from other teams

Team #	Positive Aspect 1	Positive Aspect 2	Negative Aspect 1
3	Assumptions are thorough and listed well.	Plots show relevant information and we like how you compared different insulations.	Need to work on theory and governing equations in order to understand what results were acquired.
4	Introduction has excellent flow, really well written and rationalized.	Governing equations well formatted and described.	I would make sure you write out the assumption that T_i is equal to the wall of the safe. If you don't, you need to account for radiation.
13	I like that you do not assume the cement material but test for what it is.	Good introduction and description of the problem and relevance.	Dive deeper into the first term approximation equation and how it calculates the temperature.

Pie-chart



Appendix

Appendix Contents

- A. Table of Parameters
- B. MATLAB Code
- C. Excel

A. Table of Parameters

Symbol	Description	Value	Units
L_i	Thickness of the insulation	0.026	Meters (m)
k_i	Thermal conductivity of the insulation	0.16	Watts per Meter Kelvin $\left(\frac{W}{mK}\right)$
t_{UL}	Time UL analysis	1800	Seconds (s)
t_c	Time case analysis	3000	Seconds (s)
t_{evap}	Time of Evaporation	1230	Seconds (s)
T_{iUL}	Initial temperature UL analysis	21.3	Celcius ($^{\circ}C$)
$T_{\infty UL}$	Atmospheric temperature UL analysis	843	Celcius ($^{\circ}C$)
T_{iC}	Initial temperature case analysis	21.3	Celcius ($^{\circ}C$)
$T_{\infty C}$	Atmospheric temperature case analysis	131.3	Celcius ($^{\circ}C$)
D_e	Dimensions of Safe Exterior	.15 x .36 x .29	Meters (m) H, W, D
D_i	Dimensions of Safe Interior	.09 x .31 x .19	Meters (m) H, W, D
ρ_G	Density of Gypsum	557	Kilogram per Cubic Meter $\left(\frac{kg}{m^3}\right)$
c	Specific Heat of Gypsum	950	Joules per Kilogram Kelvin $\left(\frac{K}{kg K}\right)$
h	Convection Coefficient of Air	17	Watts per Meter Squared $\left(\frac{W}{m^2}\right)$
C_1	Coefficients	1.0382	Dimensionless
ζ_1	Eigenvalues	0.4801	Radians (rad)

Table 1: Parameters

B. Matlab Code

```
% clear windows
clc
%% oven case
% constants and properties
lp = .00175; % thickness of plastic walls in m
li = .026; % thickness of insulating material in m
kp = .51; % thermal conductivity of plastic walls in W/mk
ki = .16; % thermal conductivity of insulation in W/mk
ri = 557; % density of insulation in kg/m3
ci = 950; % specific heat of insulation in j/kgk
ka = .03; % thermal conductivity of air
tic = 21.3; % initial temperature of system in celsius
tac = 131.3; % ambient temperature in celsius
hc = 2; % convection coefficient in W/m^2k
% calculate bi, alpha, fo
rcvc1 = 1/hc; % convection resistance of air on plastic
rcdc1 = lp/kp; % conduction resistance of plastic
rcdc2 = li/ki; % conduction resistance of insulation
uc = 1/(rcvc1+rcdc1*2+rcdc2); % u value
bic = (lp*uc/ka); % biot number
a = ki/(ri*ci); % alpha number
% initialize variables
tc = 0; % time in seconds
toc = 21.3; % initial temperature
toctest = toc; % initialize loop condition
nc = 1; % counter

%% oven Case
% constants and properties
lp = .00175; % thickness of plastic walls in m
li = .026; % thickness of insulating material in m
kp = .51; % thermal conductivity of plastic walls in W/mk
ki = .16; % thermal conductivity of insulation in W/mk
ri = 557; % density of insulation in kg/m3
ci = 950; % specific heat of insulation in j/kgk
ka = .03; % thermal conductivity of air
tic = 21.3; % initial temperature of system in celsius
tac = 131.3; % ambient temperature in celsius
hc = 17; % convection coefficient in W/m^2k
tfc = 3000; % time limit

% initialize variables
tc = 0; % time in seconds
tcl = 0; % latent heat counter
toc = tic; % initial temperature
toctest = toc; % initialize loop condition
nc = 1; % counter
mwc = 1; % initial mass of water in insulation
acc = .407; % outer surface area in m2
qconvc = ki*acc*((tac-100)/li); % convection
hfwu = (22.6*10^5); % latent heat of water in kg/s
mdsu = qconvc/hfwu; % mass rate change of water in gypsum
ncw = 1;
tuc = 0;
```

```

while tc < tfc
while toctest <= 100 && tc < tfc
    % equations
    termc = erfc(li/(2*sqrt(a*tc)));
    toc(nc) = (tac-tic)*(termc)+tic; % output temperature vector
    toctest = (tac-tic)*(termc)+tic; % temperature loop condition
    tuc(nc) = tc+1; % output time vector
    tc = tc + 1; % time loop condition
    tcl = tcl + 1;
    nc = nc+1; % advance counter
end
while mwc > 0 && tc < tfc
    mwc = mwc-mdsu;
    toc(nc) = 100;
    tuc(nc) = tc+1; % output time vector
    tc = tc + 1; % time loop condition
    tcl = tcl;
    nc = nc+1; % advance counter
end
    termc = erfc(li/(2*sqrt(a*tcl)));
    toc(nc) = (tac-tic)*(termc)+tic;
    tuc(nc) = tc+1; % output time vector
    tc = tc + 1; % time loop condition
    tcl = tcl+1;
    nc = nc+1; % advance counter
end
plot(tuc,toc) % plot time vs inside temp
figure;

%% UL Case
% constants and properties
lp = .00175; % thickness of plastic walls in m
li = .026; % thickness of insulating material in m
kp = .51; % thermal conductivity of plastic walls in W/mk
ki = .16; % thermal conductivity of insulation in W/mk
ri = 557; % density of insulation in kg/m3
ci = 950; % specific heat of insulation in j/kgk
ka = .03; % thermal conductivity of air
tiu = 21.3; % initial temperature of system in celsius
tau = 834; % ambient temperature in celsius
hu = hc; % convection coefficient in W/m^2k

% initialize variables
tu = 0; % time in seconds
tul = 0; % latent heat counter
tou = 21.3; % initial temperature
toutest = tou; % initialize loop condition
nu = 1; % counter
mwu = 1; % initial mass of water in insulation
acu = .407; % outer surface area in m2
qconvu = ki*acu*((tau-100)/li); % convection
hfwu = (22.6*10^5); % latent heat of water in kg/s
mdsu = qconvu/hfwu; % mass rate change of water in gypsum
nuw = 1;
tuu = 0;

```



```

while tu < 1800
while toutest <= 100
    % equations
    termu = erfc(li/(2*sqrt(a*tu)));
    tou(nu) = (tau-tiu)*(termu)+tiu; % output temperature vector
    toutest = (tau-tiu)*(termu)+tiu; % temperature loop condition
    tuu(nu) = tu+1; % output time vector
    tu = tu + 1; % time loop condition
    tul = tul + 1;
    nu = nu+1; % advance counter
end
while mwu > 0
    mwu = mwu-mdsu;
    tou(nu) = 100;
    tuu(nu) = tu+1; % output time vector
    tu = tu + 1; % time loop condition
    tul = tul;
    nu = nu+1; % advance counter
end
    termu = erfc(li/(2*sqrt(a*tul)));
    tou(nu) = (tau-tiu)*(termu)+tiu;
    tuu(nu) = tu+1; % output time vector
    tu = tu + 1; % time loop condition
    tul = tul+1;
    nu = nu+1; % advance counter
end
plot(tuu,tou) % plot time vs inside temp

toc(3000)
tou(1800)

```

C. Excel

UL Case

Properties			Up to boiling							Boiling Time	
Lp	0.00175		Ti-tinfi	Alpha	Time	Fo	B	Temp	in cel	1230.01	
Li	0.026		-821.7	2.49169E-05	0	0	1	294.45	21.300		
La	0.3048				2	0.00054	0.99922	295.09	21.939		
Kp	0.51	W/m*k			4	0.00107	0.99845	295.73	22.577		
Ki	0.18	W/m*k			6	0.00161	0.99767	296.36	23.215		
Ka	0.03	A4 at 350K			8	0.00215	0.99689	297.00	23.852		
t	1800	s			10	0.00268	0.99612	297.64	24.489		
Ti	294.45	k			12	0.00322	0.99535	298.27	25.125		
Tinf	1116.15	k			14	0.00375	0.99457	298.91	25.760		
T	?				16	0.00429	0.9938	299.55	26.396		
C1	1.0382				18	0.00483	0.99303	300.18	27.030		
ζ1	0.4801				20	0.00536	0.99225	300.81	27.665		
ρ	1.204	kg/m3			22	0.0059	0.99148	301.45	28.298		
c	1000				24	0.00644	0.99071	302.08	28.932		
h	15				26	0.00697	0.98994	302.71	29.564		
e	2.71828				28	0.00751	0.98917	303.35	30.197		
					30	0.00805	0.9884	303.98	30.828		
1) Find Bi of the problem					32	0.00858	0.98764	304.61	31.460		
Rconv	0.0666667				34	0.00912	0.98687	305.24	32.091		
Rcond1	0.0034314				36	0.00966	0.9861	305.87	32.721		
Rcond2	0.1				38	0.01019	0.98533	306.50	33.351		
Rcond3	0.0034314				40	0.01073	0.98457	307.13	33.980		
U	5.7627119				42	0.01126	0.9838	307.76	34.609		
					44	0.0118	0.98304	308.39	35.237		
Bi	0.3361582				46	0.01234	0.98227	309.02	35.865		
					48	0.01287	0.98151	309.64	36.492		
Approximation					50	0.01341	0.98075	310.27	37.119		
α	2.492E-05				52	0.01395	0.97999	310.90	37.746		
Fo	0.4827667				54	0.01448	0.97922	311.52	38.372		
					56	0.01502	0.97846	312.15	38.997		
					58	0.01556	0.9777	312.77	39.622		
					60	0.01609	0.97694	313.40	40.246		
					1795	0.15154	0.80279	456.50	183.351		
					1796	0.1518	0.80247	456.76	183.608		
					1797	0.15207	0.80216	457.01	183.864		
					1798	0.15234	0.80185	457.27	184.120		
					1799	0.15261	0.80154	457.53	184.376		
					1800	0.15288	0.80123	457.78	184.632		

Oven Case

Properties			Up to boiling					Boiling Time	
Lp	0.00175		Ti-tinfi	Alpha	Time	Fo	B	Temp	in cel
Li	0.026		-109.9	2.49169E-05	0	0	1	294.45	21.300
La	0.3048		tevp-tinfi		2	0.00054	0.99922	294.54	21.385
Kp	0.51	W/m*k	-100.031		4	0.00107	0.99845	294.62	21.471
Ki	0.18	W/m*k			6	0.00161	0.99767	294.71	21.556
Ka	0.03	A4 at 350K			8	0.00215	0.99689	294.79	21.641
t	699	s			10	0.00268	0.99612	294.88	21.726
Ti	294.45	k			12	0.00322	0.99535	294.96	21.812
Tinf	404.35	k			14	0.00375	0.99457	295.05	21.897
T	?				16	0.00429	0.9938	295.13	21.982
C1	1.0382				18	0.00483	0.99303	295.22	22.066
ζ1	0.4801				20	0.00536	0.99225	295.30	22.151
ρ	1.204	kg/m3			22	0.0059	0.99148	295.39	22.236
c	1000				24	0.00644	0.99071	295.47	22.321
h	15				26	0.00697	0.98994	295.56	22.405
e	2.71828				28	0.00751	0.98917	295.64	22.490
					30	0.00805	0.9884	295.72	22.574
1) Find Bi of the problem					32	0.00858	0.98764	295.81	22.659
Rconv	0.0666667				34	0.00912	0.98687	295.89	22.743
Rcond1	0.0034314				36	0.00966	0.9861	295.98	22.828
Rcond2	0.1				38	0.01019	0.98533	296.06	22.912
Rcond3	0.0034314				40	0.01073	0.98457	296.15	22.996
U	5.7627119				42	0.01126	0.9838	296.23	23.080
					44	0.0118	0.98304	296.31	23.164
Bi	0.3361582				46	0.01234	0.98227	296.40	23.248
					48	0.01287	0.98151	296.48	23.332
Approximation					50	0.01341	0.98075	296.57	23.416
α	2.492E-05				52	0.01395	0.97999	296.65	23.500
Fo	0.1874744				54	0.01448	0.97922	296.73	23.583
	295.07723				56	0.01502	0.97846	296.82	23.667
	FALSE				58	0.01556	0.9777	296.90	23.751
					60	0.01609	0.97694	296.98	23.834
					2984	0.80032	0.31344	369.90	96.753
					2986	0.80086	0.31319	369.93	96.780
					2988	0.80139	0.31295	369.96	96.807
					2990	0.80193	0.31271	369.98	96.834
					2992	0.80247	0.31246	370.01	96.860
					2994	0.803	0.31222	370.04	96.887
					2996	0.80354	0.31198	370.06	96.914
					2998	0.80407	0.31174	370.09	96.940
					3000	0.80461	0.31149	370.12	96.967