CAE: Design and Analysis of Cookware

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1 Problem Statement

Every year, millions of Americans get together to celebrate Thanksgiving–a holiday that traditionally involves a turkey meal. To elevate this simple dish, a farm owner designed a brand of poultry that combines turkey, chicken, and duck in one. The poultry is designed with a space dedicated for stuffing of choice. The design proposal includes a cooking method in a conventional oven, and custom designed electric resistance skewers which can be placed through the poultry. The skewers are designed to reduce the amount of cooking time and maintain a consistent temperature throughout the bird.

The goal was to cook the turducken as fast as possible with minimal burnt volume. Solid-body modeling of the Turducken was completed on SolidWorks. Finite Element Analysis software (ANSYS Workbench/APDL and Altair Hyperworks) was used to perform a transient thermal analysis to calculate the resulting temperature distributions of a particular cooking process. The set of constraints and parameters of the design process was given to the team for the effective and guaranteed usability of the system.

2 User Manual

Happy Thanksgiving!

You are just a few steps away from treating yourself and your guests to the most unique and delicious Thanksgiving meal of your life! Before we start the cooking process, let's familiarize ourselves with the contents of this kit. We've included 3 carefully engineered components in our kit: the novel bird as the star of the evening, which combines turkey, chicken, and duck meat, along with organic sweet potatoes and mushrooms stuffing - yum!, two electrical skewers to optimize the cooking process and bring Michelin star-level cuisine to the comfort of your home, and a rack to cook the poultry on, ensuring the most even and thorough cook for your enjoyment. All you need is a conventional oven and your loved ones to share this meal with. So let's get to cooking! This instruction will provide you with easy to follow, step-by-step explanation on how to achieve the best cooked Thanksgiving meal.

1. First, preheat the oven to 310 degrees Fahrenheit. To do this, turn on your oven and change the dial to the 310 mark. While the oven heats up, let's prepare the poultry for the cooking process.

2. Unwrap the poultry and the skewers from their packaging. Both the skewers and the poultry are contained in an air-tight, vacuum pack that preserves the food and keeps the skewers clean, so they're both ready to use as soon as you open them!

3. Insert the skewers into the poultry opening. Refer to Figure 4 below to get a clearer idea of where to place the skewers for the most perfect cook.

4. Place the poultry on the rack. Refer to Figure 5.

5. Now your dinner is ready to cook! Turn on the rack and place it inside the oven, and close the oven door. Once turned on, the rack will automatically turn on the skewers at the proper time during the cooking process. Immediately after placing into the oven, set 2 timers for 2 and 5 hours. Only 1 more step left until your perfect Thanksgiving meal is ready!

6. After 2 hours the first timer will go off signaling the chef to turn off the oven but leave the rack, skewers and Turducken in the oven.

7. The second timer will go off at the 5 hour mark, this means your Thanksgiving meal is ready! Bring the perfectly cooked poultry of the future out to your guests - it's time to celebrate!

Thank you for choosing our Thanksgiving kit!

Please find the following components in your Thanksgiving kit!

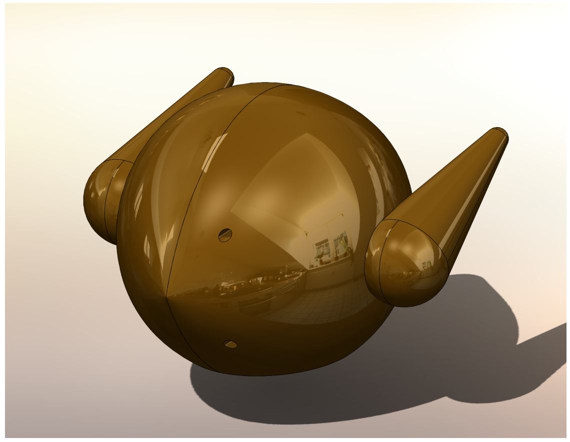

Figure 1: Thanksgiving Bird

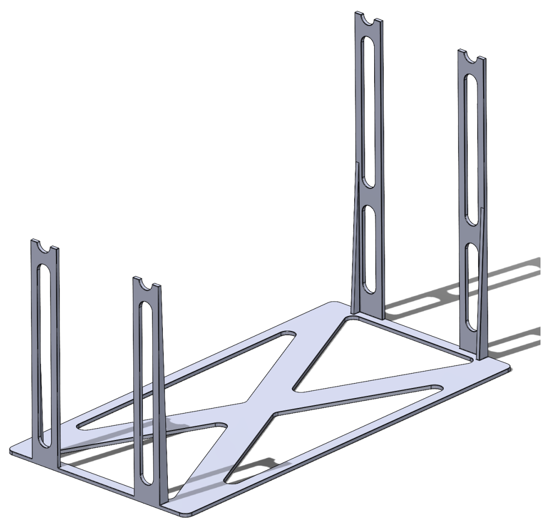

Figure 2: Cooking Rack

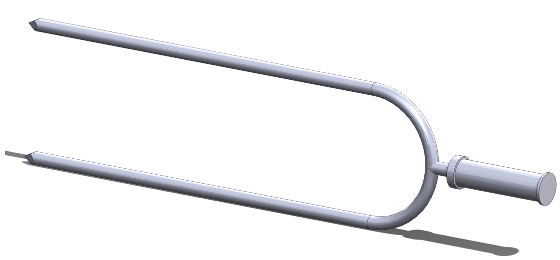

Figure 3: 1 Skewer - Please find 2 in your kit!

Please refer to the illustrations below on how to assemble the cookware and poultry.

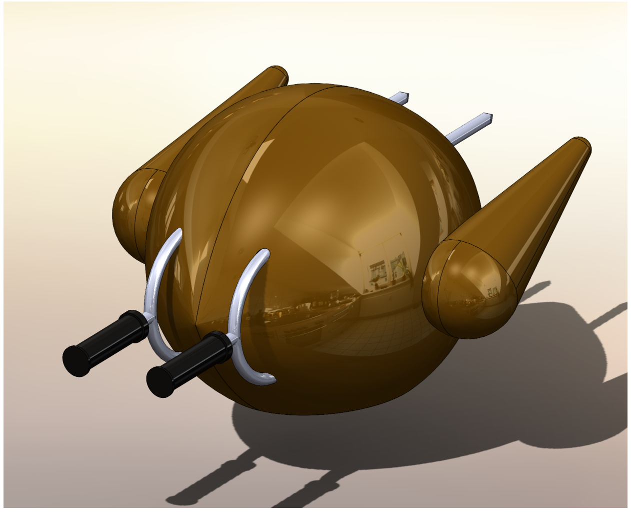

Figure 4: Skewers in the Bird

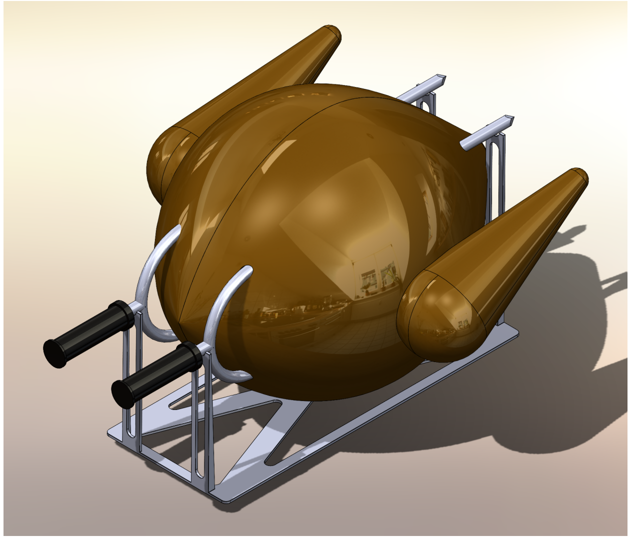

Figure 5: Full Assembly

3 FEA Model Assumptions

The following assumptions were used to analyze and optimize the Turducken meal:

1. All quantities are expressed in U.S. Imperial units.

2. The turducken is initially frozen at 42°F.

3. The turdicken is fully cooked when no temperature in it is less than 165°F.

4. An area is burned when its temperature reaches 281°F. These parts are counted as the burned volume.

5. The oven used is a convection oven that operates between 325°F - 500°F with a single convection coefficient. Two oven temperatures may be used during the cooking process, as long as they are specified to the customer.

6. The materials are all homogeneous mixtures with properties that are a weighted average of its components.

7. The food materials have non-linear properties due to evaporation and variations in the physical property when the food burns.

8. A symmetric plane cuts the turducken, assuming the other half cooks identically to the analyzed half for computational efficiency. The surface of the turducken where cut by the symmetry plane is perfectly insulated.

9. The heating loads from the oven and skewer are applied as a step input.

10. The oven temperature and its rising are steady throughout the cooking time.

11. The heat output of the designed heating elements would remain constant throughout the cooking process.

12. The rate of convection within the commercial oven was assumed to be forced and constant.

4 Design Concept

4.1 Design Requirements

The design is required to produce a fully cooked whole turkey. To achieve this, a cooking method will have to be designed including the method of use for the oven and designing custom skewers to insert into the turducken.

The skewers must be designed such that they can be used in a conventional home kitchen. The skewers must not be larger than 0.5in in any one dimension of the cross section; their cross sectional area cannot exceed 0.2 in^2. The skewers are not limited by length and the entire length of the skewers does not need to be actively used. Additionally, the skewers will be designed so that they reject a constant rate of heat. The skewers are allowed to be turned off or on once during the cooking process.

The oven can operate between 300°F and 525°F. It's acceptable to use up to two different temperature settings throughout the cooking process. Each temperature setting and the times at which they're enabled must be reported.

To ensure that the dish is fully cooked, there should be no portion of the turkey that is less than 165°F and to ensure no burning, there should be no portion of the turkey that is 280°F or more.

Skewers Design Constraints	
Maximum Cross-Section Measurement	0.5 in
Maximum Cross-Sectional Area	0.2 in^2

Table 1: Skewers Design Constraints

Cooking Temperatures	
Starting Temperature	42°F
Cooked Temperature	165°F
Burnt Temperature	280°F
Oven Minimum Setting	300°F
Oven Maximum Setting	525°F

Table 2: List of Cooking Temperatures and Oven Settings

4.2 Poultry Properties and Modeling

Thermal Properties of Foods : Poultry								
Food Item	Moisture Content	Protein	Fat	Ash	Initial Freezing Point	Specific Heat Above Freezing	Specific Heat Below Freezing	Latent Heat Of Fusion
Chicken	65.99	18.60	15.06	0.79	27.0	1.04	0.79	95
Duck	48.50	11.49	39.34	0.68	-	0.73	0.59	70
Turkey	70.40	20.42	8.02	0.88	-	0.84	0.54	101

Table 3: Thermal Properties of Foods: Poultry

4.3 Filling Properties and Modeling

Thermal Properties of Foods : Vegetables								
Food Item	Moisture Content	Protein	Fat	Ash	Initial Freezing Point	Specific Heat Above Freezing	Specific Heat Below Freezing	Latent Heat Of Fusion
Mushrooms	91.81	2.09	0.42	0.89	30.4	0.95	0.44	132
Sweet Potatoes	72.84	1.65	0.30	0.95	29.7	0.83	0.50	104

Table 4: Thermal Properties of Foods: Poultry

4.4 Cookware Properties and Modeling: Skewers

According to the design statement, a total of two identical skewers were designed to aid in cooking the poultry. The skewers incorporate two elements: the outer body, and the heating element. The outer body is designed to be a cylindrical shape with a tapered end for easier insertion into the food product. The material used for the outer body is Grade 316 Stainless Steel. This material is food-safe, resistant to corrosion and deformation, and has a high resistivity to heat. On another end, the skewer incorporates a round spherical handle with silicone coating for ease and safety of use. The chosen material has an extremely low coefficient of thermal and electrical conductivity, and is food-safe, making it a great choice to use on skewers. On the inside, the outer body of the skewers incorporates a heating element - a Nichrome Wire coil which is used as a resistor to power the skewers while in use. This high-grade heating element material is commonly used withing the food appliance industry, has a great ductility and weldability, and produces a great heating rate due to a good thermal conductivity. An image and drawing of the skewer concept is provided below:

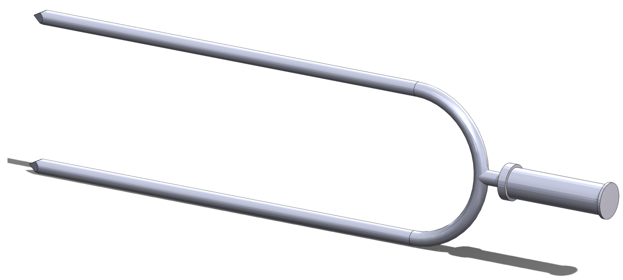

Figure 6: Model of Skewer

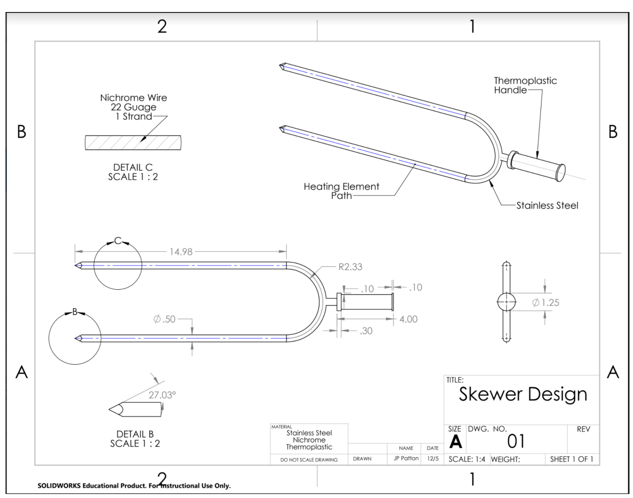

Figure 7: 3-View Drawing of Skewer

4.5 Cookware Properties and Modeling: Rack

A rack was designed to support the skewers and the bird during the cooking process. The rack only contacts the skewers and not the Turducken. The main purpose of the rack is to elevate the entire Turducken above the conventional oven tray. This allows for the Turducken to be modeled with convection heating all around its surface. An image and drawing of the rack concept is provided below:

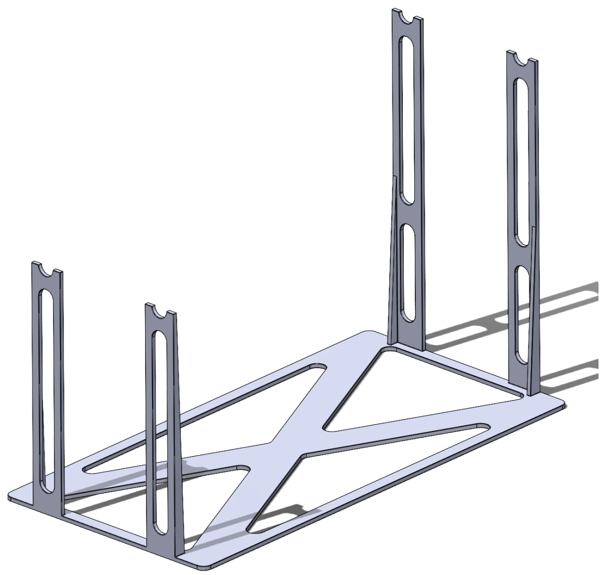

Figure 8: Model of Rack to Support the Skewers and Turducken

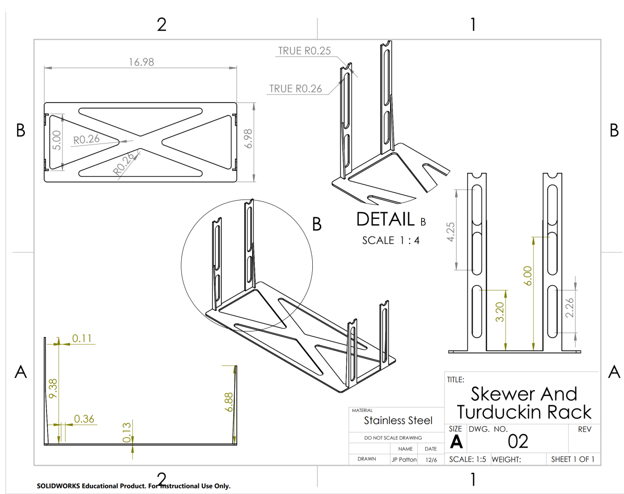

Figure 9: 3-View Drawing of the Rack

4.6 Assembly

The skewer-rack assembly helps the bird get the most even cook by helping the bird avoid contact with other surfaces.

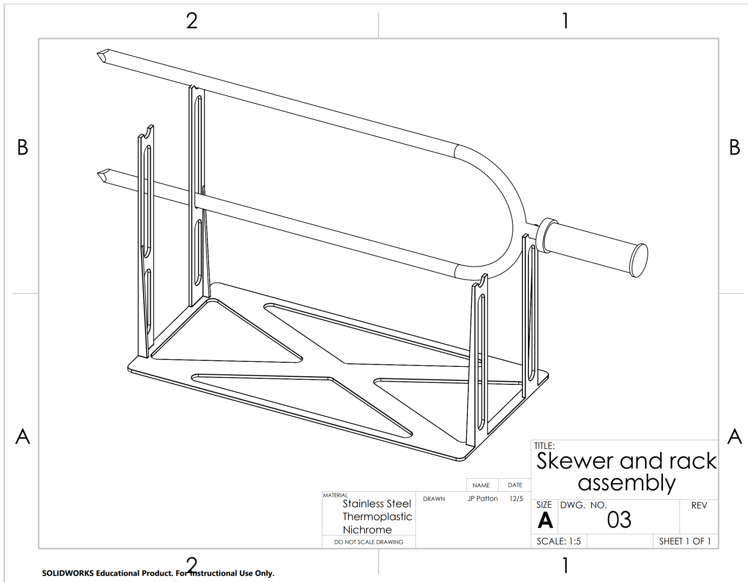

Figure 10: Drawing Demonstrating the mounting of the skewers on the rack

The design is easy to assemble, and produces a convenient and compact way to cook the poultry.

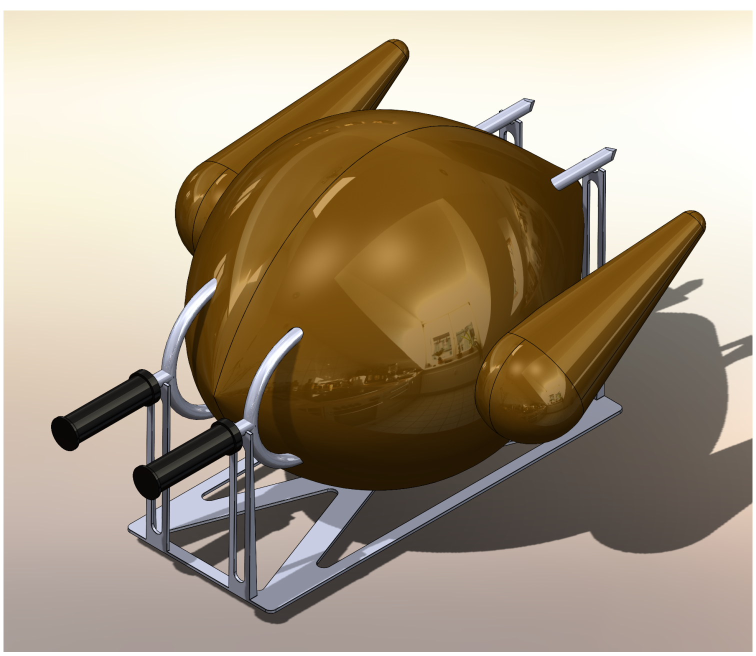

Figure 11: Full Rendering of the Skewers, Rack, and Turducken

5 Hand Calculations

5.1 Produce Properties

To determine the optimal cooking procedure for the poultry and the stuffing, three main material properties were analyzed: density, specific heat, and thermal conductivity. Density of the material is the degree of compactness, or how tightly packed it is. Density is one of the main things that will affect the cooking properties, since the more tightly packed the material, the more energy it requires for the material to heat up and transfer heat. Specific heat is another important property that needs to be considered, since it represents the amount of heat per unit mass required to raise the temperature by one temperature degree. Lastly, thermal conductivity of the material is crucial to consider when designing the optimal way to cook produce since it describes the rate at which heat passes through a specified material.

In order to produce more accurate results, we considered the distribution of various food components, such as proteins, fats, carbohydrates, and others, as a function of temperature. This analysis has been done for turkey, duck and chicken mix, and the stuffing mix separately.

5.1.1 Thermal Property Models

Density Models for Food Components	
Protein	$\rho = 8.3599 \cdot 10^{1} - 1.7979 \cdot 10^{-2} t$
Fat	$\rho = 5.8246 \cdot 10^{1} - 1.4482 \cdot 10^{-2} t$
Carbohydrate	$\rho = 1.0017 \cdot 10^{2} - 1.0767 \cdot 10^{-2} t$
Fiber	$\rho = 8.2280 \cdot 10^{1} - 1.2690 \cdot 10^{-2} t$
Ash	$\rho = 1.5162 \cdot 10^{2} - 9.7329 \cdot 10^{-2} t$

Table 5: Density Models for Food Components, as a Function of Temperature

Specific Heat Models for Food Components	
Protein	$c_p = 4.7442 \cdot 10^{-1} + 1.6661 \cdot 10^{-4} t$
Fat	$c_p = 4.6730 \cdot 10^{-1} + 2.1815 \cdot 10^{-4} t$
Carbohydrate	$c_p = 3.6114 \cdot 10^{-1} + 2.8843 \cdot 10^{-4} t$
Fiber	$c_p = 4.3276 \cdot 10^{-1} + 2.6485 \cdot 10^{-4} t$
Ash	$c_p = 2.5226 \cdot 10^{-1} - 2.6810 \cdot 10^{-4} t$

Table 6: Specific Heat Models for Food Components, as a Function of Temperature

Thermal Conductivity Models for Food Components	
Protein	$k = 9.053 \cdot 10^{-2} + 4.1486 \cdot 10^{-4} t$
Fat	$k = 1.0722 \cdot 10^{-1} - 8.6581 \cdot 10^{-5} t$
Carbohydrate	$k = 1.0133 \cdot 10^{-1} + 4.9478 \cdot 10^{-4} t$
Fiber	$k = 9.2499 \cdot 10^{-2} + 4.3731 \cdot 10^{-4} t$
Ash	$k = 1.7553 \cdot 10^{-1} + 4.8292 \cdot 10^{-4} t$

Table 7: Thermal Conductivity Models for Food Components, as a Function of Temperature

5.1.2 Density

The following formulas were used to model the produce components pertaining to density, as a function of temperature.

Turkey Density Models with Appropriate Constants		
Component	Composition	Equation
Protein	20.42	$\rho = 170.71 \cdot 10^1 - 36.71 \cdot 10^{-2}t$
Fat	8.02	$\rho = 46.71 \cdot 10^1 - 11.62 \cdot 10^{-2}t$
Carbohydrate	0	$\rho = 0$
Fiber	0	$\rho = 0$
Ash	0.88	$\rho = 1.33 \cdot 10^2 - 8.57 \cdot 10^{-2}t$
Total	$\rho = 3.50 \cdot 10^2 - 5.69 \cdot 10^{-1}t$	

Table 8: Turkey Density Models by Components and Total

Chicken and Duck Mix Density Models with Appropriate Constants		
Component	Composition	Equation
Protein	24.35	$\rho = 203.56 \cdot 10^1 - 4.378 \cdot 10^{-1}t$
Fat	27.20	$\rho = 158.43 \cdot 10^1 - 3.939 \cdot 10^{-1}t$
Carbohydrate	0	$\rho = 0$
Fiber	0	$\rho = 0$
Ash	0.74	$\rho = 1.12 \cdot 10^2 - 7.20 \cdot 10^{-2}t$
Total	$\rho = 1.70 \cdot 10^2 - 9.04 \cdot 10^{-1}t$	

Table 9: Chicken and Duck Mix Density Models by Components and Total

Stuffing Density Models with Appropriate Constants		
Component	Composition	Equation
Protein	1.87	$\rho = 15.63 \cdot 10^1 - 3.36 \cdot 10^{-2}t$
Fat	0.36	$\rho = 2.09 \cdot 10^1 - 0.52 \cdot 10^{-2}t$
Carbohydrate	14.45	$\rho = 14.45 \cdot 10^1 - 15.56 \cdot 10^{-2}t$
Fiber	2.1	$\rho = 17.28 \cdot 10^1 - 2.65 \cdot 10^{-2}t$
Ash	0.92	$\rho = 1.38 \cdot 10^2 - 8.92 \cdot 10^{-2}t$
Total	$\rho = 101.66 \cdot 10^3 - 31.01 \cdot 10^{-1}t$	

Table 10: Stuffing Density Models by Components and Total

5.1.3 Specific Heat

A similar analysis has been done with the specific heat models by component.

Turkey Specific Heat Models with Appropriate Constants		
Component	Composition	Equation
Protein	20.42	$c_p = 96.88 \cdot 10^{-1} - 33.91 \cdot 10^{-4}t$
Fat	8.02	$c_p = 37.45 \cdot 10^{-1} - 17.48 \cdot 10^{-4}t$
Carbohydrate	0	$c_p = 0$
Fiber	0	$c_p = 0$
Ash	0.88	$c_p = 2.22 \cdot 10^{-1} - 2.35 \cdot 10^{-4}t$
Total	$c_p = 136.55 \cdot 10^{-1} - 53.74 \cdot 10^{-4}t$	

Table 11: Turkey Specific Heat Models by Components and Total

Chicken and Duck Specific Heat Models with Appropriate Constants		
Component	Composition	Equation
Protein	24.35	$c_p = 115.42 \cdot 10^{-1} - 40.42 \cdot 10^{-4}t$
Fat	27.20	$c_p = 127.02 \cdot 10^{-1} - 59.29 \cdot 10^{-4}t$
Carbohydrate	0	$c_p = 0$
Fiber	0	$c_p = 0$
Ash	0.74	$c_p = 1.85 \cdot 10^{-1} - 1.98 \cdot 10^{-4}t$
Total	$c_p = 244.29 \cdot 10^{-1} - 101.69 \cdot 10^{-4}t$	

Table 12: Chicken and Duck Specific Heat Models by Components and Total

Stuffing Specific Heat Models with Appropriate Constants		
Component	Composition	Equation
Protein	1.87	$c_p = 8.86 \cdot 10^{-1} + 3.10 \cdot 10^{-4}t$
Fat	0.36	$c_p = 1.68 \cdot 10^{-1} + 0.78 \cdot 10^{-4}t$
Carbohydrate	14.45	$c_p = 52.16 \cdot 10^{-1} + 41.62 \cdot 10^{-4}t$
Fiber	2.1	$c_p = 9.07 \cdot 10^{-1} + 5.46 \cdot 10^{-4}t$
Ash	0.92	$c_p = 2.32 \cdot 10^{-1} + 2.47 \cdot 10^{-4}t$
Total	$c_p = 74.02 \cdot 10^{-1} + 53.61 \cdot 10^{-4}t$	

Table 13: Stuffing Specific Heat Models by Components and Total

5.1.4 Thermal Conductivity

A similar analysis has been done with the thermal conductivity models by components.

Turkey Thermal Conductivity Models with Appropriate Constants		
Component	Composition	Equation
Protein	20.42	$k = 183.78 \cdot 10^{-1} + 84.54 \cdot 10^{-4} t$
Fat	8.02	$k = 8.61 \cdot 10^{-1} - 68.65 \cdot 10^{-4} t$
Carbohydrate	0	$k = 0$
Fiber	0	$k = 0$
Ash	0.88	$k = 1.54 \cdot 10^{-1} + 4.24 \cdot 10^{-4} t$
Total	$k = 330.48 \cdot 10^{-1} + 20.13 \cdot 10^{-4} t$	

Table 14: Turkey Thermal Conductivity Models by Components and Total

Chicken and Duck Thermal Conductivity Models with Appropriate Constants		
Component	Composition	Equation
Protein	24.35	$k = 220.44 \cdot 10^{-1} - 43.12 \cdot 10^{-4} t$
Fat	27.20	$k = 28.61 \cdot 10^{-1} - 187.34 \cdot 10^{-4} t$
Carbohydrate	0	$k = 0$
Fiber	0	$k = 0$
Ash	0.74	$k = 0.98 \cdot 10^{-1} - 3.55 \cdot 10^{-4} t$
Total	$k = 249.46 \cdot 10^{-1} - 144.82 \cdot 10^{-4} t$	

Table 15: Chicken and Duck Thermal Conductivity Models by Components and Total

Stuffing Thermal Conductivity Models with Appropriate Constants		
Component	Composition	Equation
Protein	1.87	$k = 15.34 \cdot 10^{-2} + 8.41 \cdot 10^{-4} t$
Fat	0.36	$k = 0.76 \cdot 10^{-1} + 3.09 \cdot 10^{-5} t$
Carbohydrate	14.45	$k = 15.53 \cdot 10^{-1} + 73.95 \cdot 10^{-4} t$
Fiber	2.1	$k = 19.17 \cdot 10^{-2} + 9.24 \cdot 10^{-4} t$
Ash	0.92	$k = 1.56 \cdot 10^{-1} + 3.78 \cdot 10^{-4} t$
Total	$k = 51.38 \cdot 10^{-1} + 98.28 \cdot 10^{-4} t$	

Table 16: Stuffing Thermal Conductivity Models by Components and Total

5.1.5 Critical Values

To summarize our findings, the density, specific heat, and thermal conductivity models were evaluated at a few critical temperature points, including initial point, cooked temperature, boiling water, and burnt temperature:

Density of Produce at Critical Temperatures lb / ft^3			
Temperature	Turkey	Duck and Chicken	Stuffing
42°F	66.34	65.39	69.17
165°F	66.16	64.88	69.55
213 °F	66.05	64.73	69.41
280 °F	74.09	79.23	63.92

Table 17: Stuffing Thermal Conductivity Models by Components and Total

Specific Heat of Produce at Critical Temperatures Btu / lb * F			
Temperature	Turkey	Duck and Chicken	Stuffing
42°F	0.84	0.78	0.90
165°F	0.83	0.78	0.89
213 °F	0.50	0.34	0.49
280 °F	0.51	0.35	0.51

Table 18: Stuffing Thermal Conductivity Models by Components and Total

Thermal Conductivity of Produce at Critical Temperatures Btu / h*ft*F			
Temperature	Turkey	Duck and Chicken	Stuffing
42°F	0.27	0.25	0.31
165°F	0.31	0.30	0.37
213 °F	0.20	0.16	0.21
280 °F	0.21	0.18	0.26

Table 19: Stuffing Thermal Conductivity Models by Components and Total

To get a better understanding of how the three materials interact and change over the applied temperature loading, visual representations of the three tables above were created for the three materials. Density, Specific Heat, and Thermal Conductivity were plotted against the change in temperature. The vertical axis is a log scale to better fit the 3 types of data in one graph.

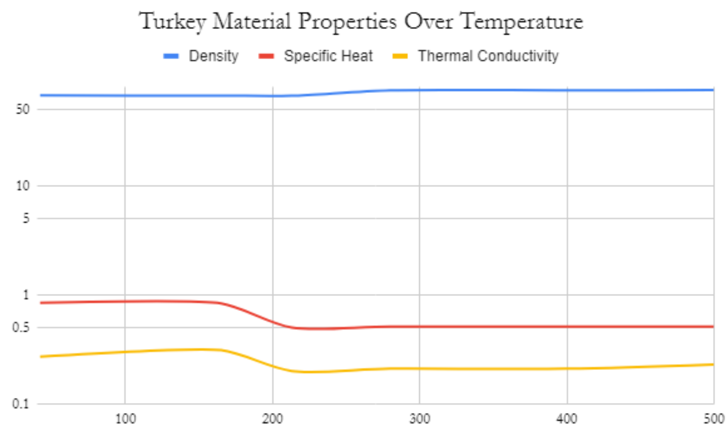

Figure 12: Turkey Material Properties Change with Temperature

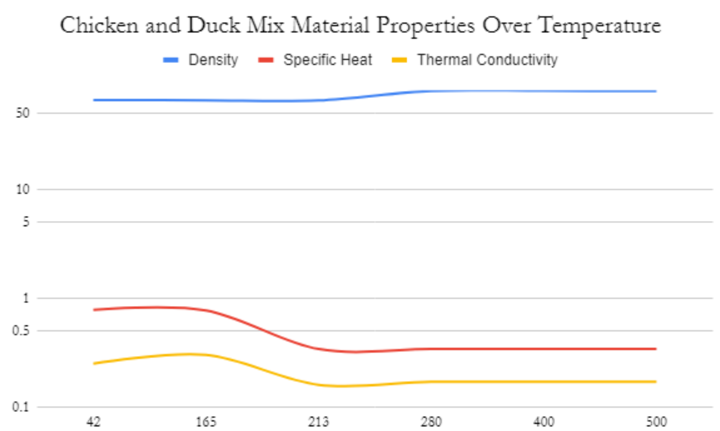

Figure 13: Chicken and Duck Mix Material Properties Change with Temperature

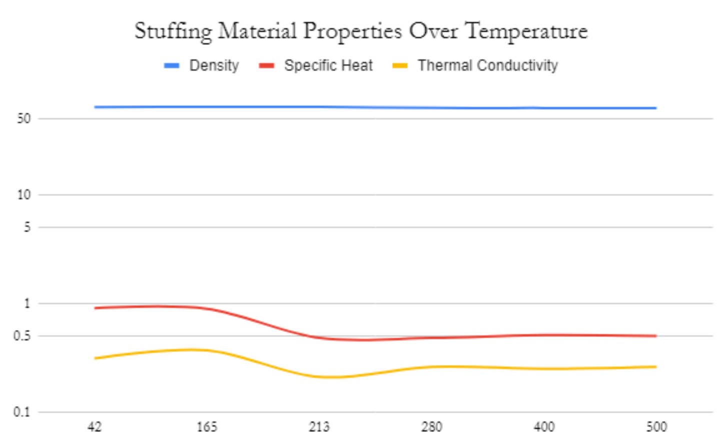

Figure 14: Stuffing Material Properties Change with Temperature

5.2 Heating Element Design

To ensure a proper and even cook on the poultry, electric skewers were designed to heat up the bird from the inside. The main component in the skewers is the heating element - a resistor designed from 20 gauge Nichrome wire. This material provides an average resistivity of 0.924 Ω/foot. Each skewer's heated element is designed to be 20 inches long. Through numerous simulations analyzing different skewer power outputs, power of 205 Watts (over 2 skewers) resulted in the best performance. Based on this configuration, Ohm's law is applied to solve for the current running through the wire:

$$P = V * I$$

$$P = I^2 * R$$

$$R = \rho * A/L = (0.924\,\Omega/foot) * (1.7\,feet) = 1.571\,\Omega$$

$$I = (P/R)^{1/2} = (200\,Watts)/(1.571\,\Omega)^{1/2} = 10.36\,Amps$$

Most American homes run on 120 Volt alternating current with 15 Amp output. Our skewer design uses 10.36 Amps, staying well within the safety limit. Solving for voltage yields:

$$V = I * R = (15\,Amp) * (1.571\,\Omega) = 23.56\,Volts$$

5.3 Thermal Analysis

Within the frame of thermal analysis, the two most important properties of produce to analyze are resistance and capacitance, as they can be used to model the cooking of the turkey over time.

5.3.1 Material Convection

Prior to analyzing the behavior of poultry under certain thermal loading, some thermal properties of the material. The focus of this analysis is the film coefficient h, Reynold's number Re, and Nusselt number. First estimation we can make is the Reynold's number for the elements of the bird that are exposed to air. A simplified version of the Reynold's number equation can be used, which only considers velocity and viscosity of the fluid, and diameter of the body. For this calculation the bird can be approximated to be a sphere with a radius of 9 inches.

$$Re = VD/\mu = (9 * 2/12\,feet) * (10\,ft/s)/(0.000323\,ft^2/s) = 37,500$$

Next estimation is the Nusselt number, the calculation of which stems directly from the Reynold's number. The formula below is applied since the fluid has a Reynold's number of less than 100,000 and the fluid flow is around a sphere.

$$Nu = 2 + 0.43Re^{1/3} = 2 + 0.43 * (37,500)^{1/3} = 7.985$$

Finally, we are able to calculate the film coefficient for the poultry. The film coefficient represents the proportion between the heat flux and the temperature difference. The film coefficient is used in analyzing convection and phase transitioning, typically between liquids and solids. Two separate film coefficients were calculated, for the turkey and the chicken-duck mix, since they come in direct contact with the air flow within the oven.

$$h = Nu * k/D$$

Film Coefficient of Produce at Critical Temperatures **Btu / h*ft$^2 * F$**			
Temperature	Turkey	Duck and Chicken	Stuffing
42°F	2.66	3.21	5.32
165°F	2.95	4.02	5.14
213 °F	2.01	2.39	4.75
280 °F	1.97	2.64	5.20

Table 20: Film Coefficient of Produce at Critical Temperatures

5.3.2 Governing Equations

A set of differential equations that relate temperature, capacitance, and resistance over time, were solved in order to obtain separate capacitance and resistance relationships. The following governing equation was used over a range of materials throughout the produce, separately: turkey, chicken and duck, stuffing.

$$\frac{dT}{dt} = \frac{1}{C_{region}} * [\frac{T_\infty - T_{region}}{R_{region}} - \frac{T_{region} - T_{boundary}}{R_{boundary}}]$$

5.3.3 Capacitance

After solving the governing differential equations, the following result (relating density, specific heat, and volume was obtained for determining capacitance of different materials within the produce:

$$C = \rho V c_p$$

5.3.4 Resistance

Along with the relationship for capacitance, the following equation relating heat transfer coefficient and the surface area was obtained for convective resistance:

$$R_{convection} = \frac{1}{h * A_{surface}}$$

The derived differential equations were separated by material (turkey, chicken and duck mix, stuffing), and input into Matlab to be solved for temperature distribution in material. The following graph shows the temperature change in turkey, chicken and dux mix, and stuffing over a 10-hour time graph under the lowest oven setting. From this graph, initial estimates about the required simulation time. Radiation effects were added and analyzed in the same way. The results yielded that radiation effects are negligible.

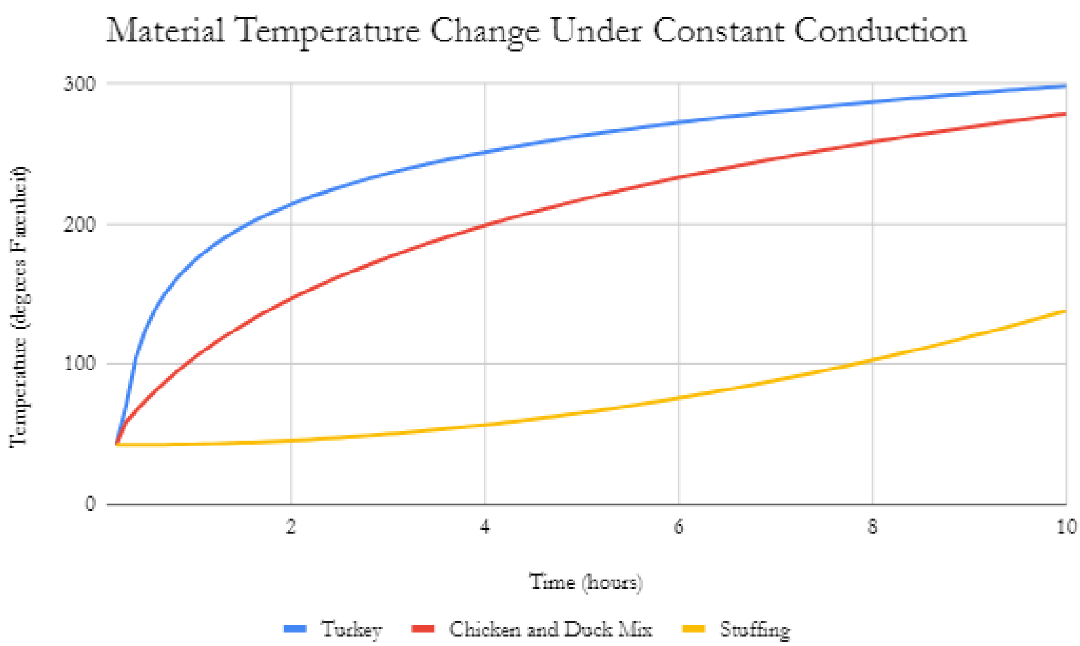

Figure 15: Material Temperature Change

6 Computer Simulations

6.1 Meshing Technique

Prior to meshing and FEA analysis, the Turcucken and skewers were modeled on SolidWorks. A model of the Turducken without the skewers was exported and meshed in Hypermesh.

The meshed Turducken is composed of six parts:

1. Turkey Boundary Layer : With outer and inner edge sizes of 0.25.
2. Turkey Tetramesh : Element size of 0.25.
3. Ducken Boundary Layer : With outer edge size of 0.25 and inner edge size of 0.125.
4. Ducken Tetramesh : Element size of 0.125.
5. Stuffing Boundary Layer : With outer and inner edge sizes of 0.125.
6. Stuffing Tetramesh : Element size of 0.125.

Mesh Size	
Total of Nodes	195822
Total of Elements	736673

Table 21: Mesh Size

Mesh Quality Analysis	
Elements with Aspect Ratio 1-4	736673
Elements with Aspect Ratio 5 and Above	0

Table 22: Mesh Quality Analysis

Figure 16: 6 Parts of the Turducken from Hypermesh

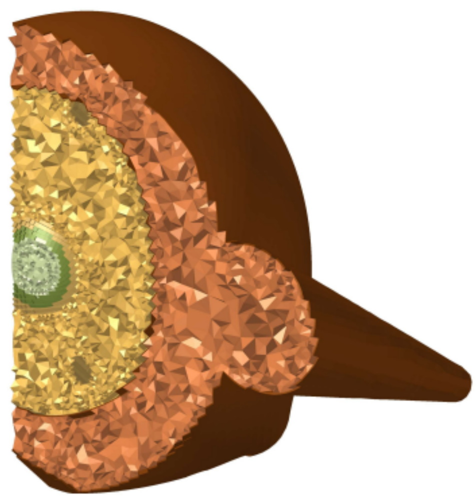

Figure 17: Section View of Mesh

6.2 Thermal Analysis Setup

The mesh was then used in the FEA analysis in Workbench. The following are conditions used in the Workbench model to simulate the Turducken cooking:

1. Convection on outer Turkey boundary layer : Representing the heat from the oven onto the Turkey.

2. Heat flow on outer Skewer boundary layer : Representing the heat from the skewers into the Turducken.

3. Convection on outer Stuffing boundary layer : Representing the heat from the Ducken to the Stuffing.

In order to run the transient model within a reasonable amount of time for each method iteration, the auto-time stepping was turned off, then the time step value was half of the end time for each step. The maximum time step value was set to be 2500 seconds to ensure that for the larger time steps, the simulation's accuracy didn't decline.

6.3 Cooking Time

A thermal analysis was conducted over a period of 5 hours for the Turducken. A total of 6 time steps were modeled in the FEA analysis. The Turducken reaches a cooked state at the 5 hour mark. In this state, the outside of the Turducken and elements nearby the skewers are burnt. However, overall, all temperatures reach above the 165°F threshold and are deemed cooked.

6.4 Thermal Gradient

Completing a thermal FEA analysis on Workbench yielded the following simulated thermal gradient temperatures inside the turkey as a function of time:

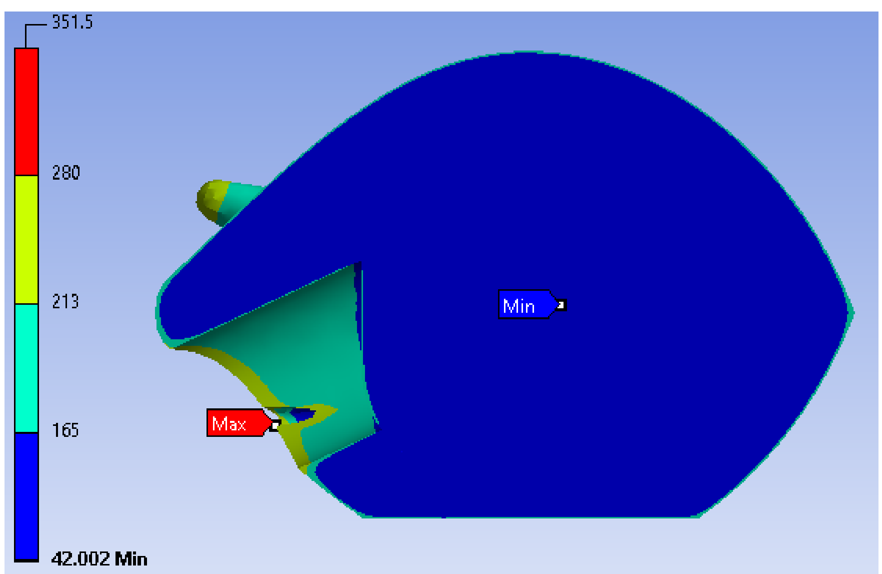

Figure 18: Thermal Gradient at Time 0 Hours

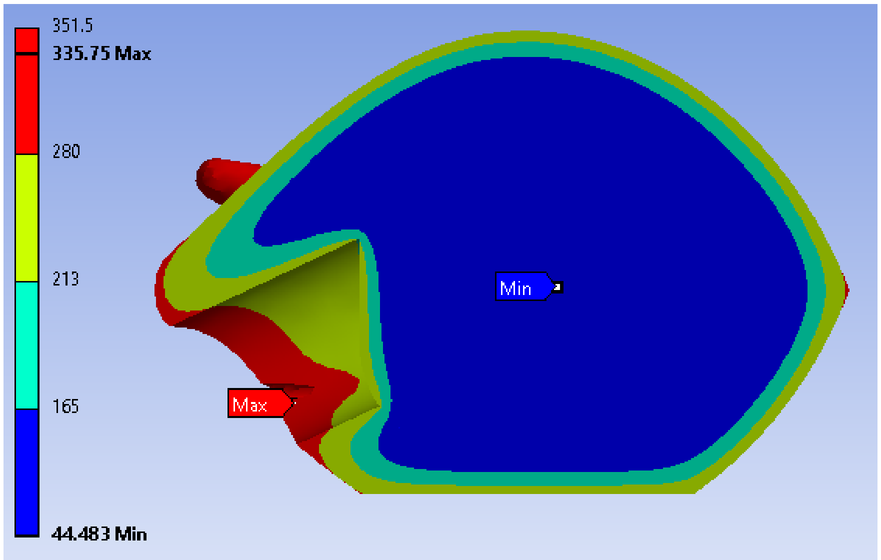

Figure 19: Thermal Gradient at Time 1 Hour

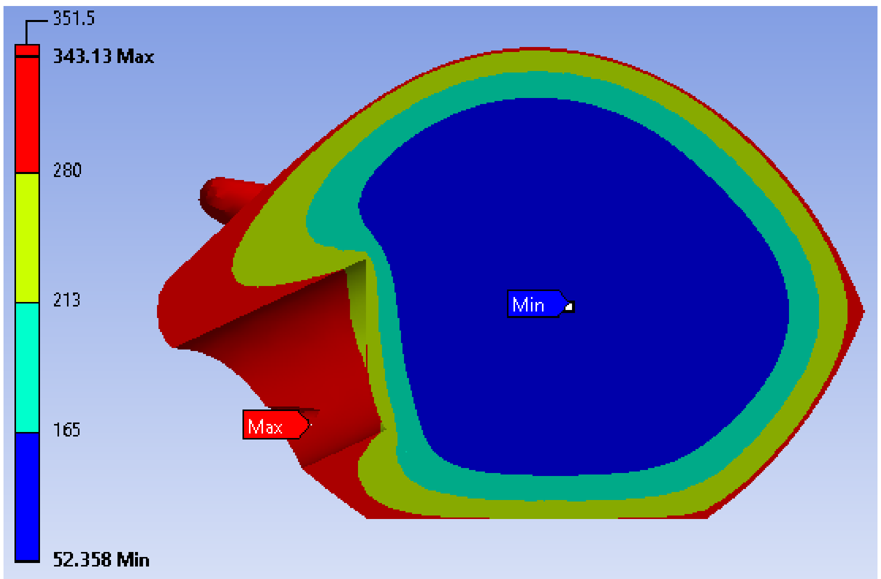

Figure 20: Thermal Gradient at Time 2 Hours

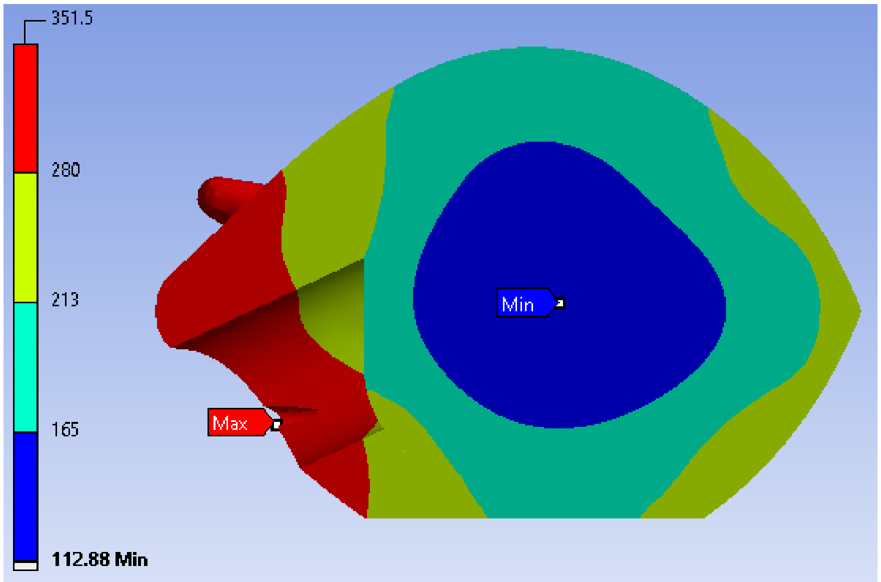

Figure 21: Thermal Gradient at Time 3 Hours

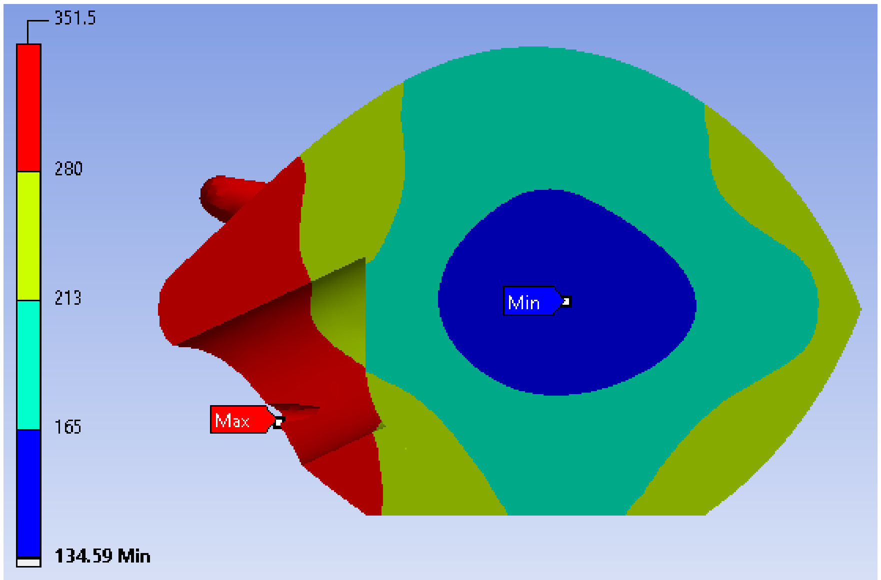

Figure 22: Thermal Gradient at Time 4 Hours

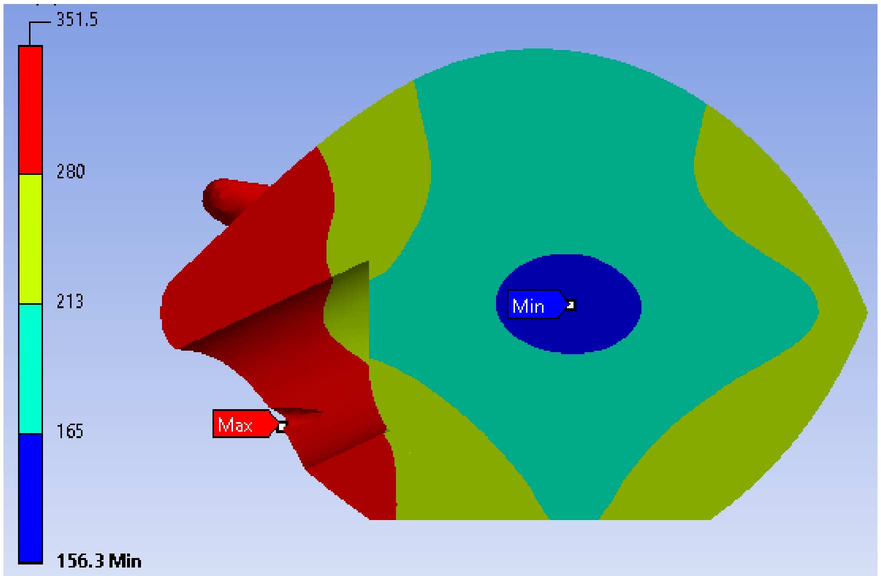

Figure 23: Thermal Gradient at Time 5 Hours

6.5 Maximum Temperatures

As expected, the surfaces which directly contact the heating elements such as the oven and skewers exceed the burnt temperature of 281 °F. It was determined that the max temperature of the Turducken was 317 °F. Maximum and minimum temperature spots are highlighted in the image below

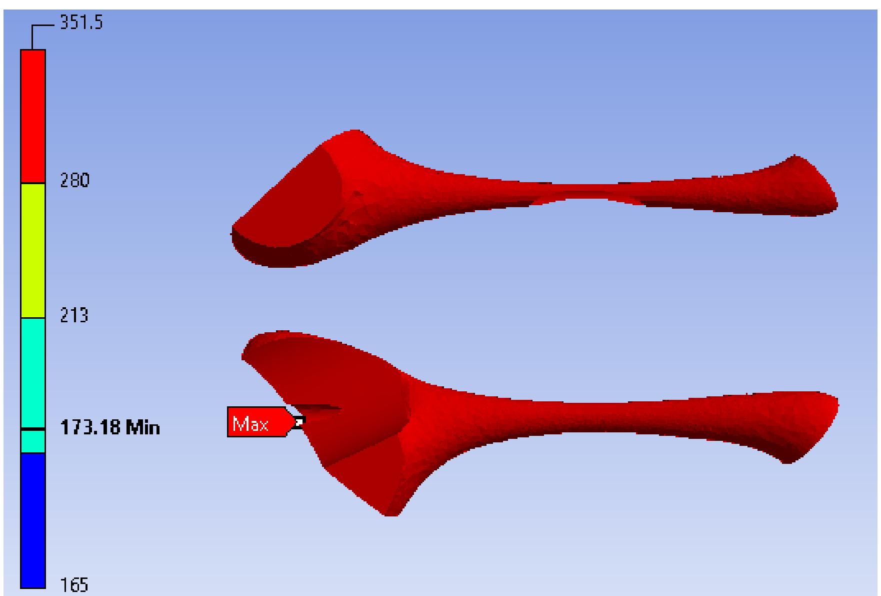

Figure 24: Burn Volume Surrounding Skewers at 5 Hour Mark

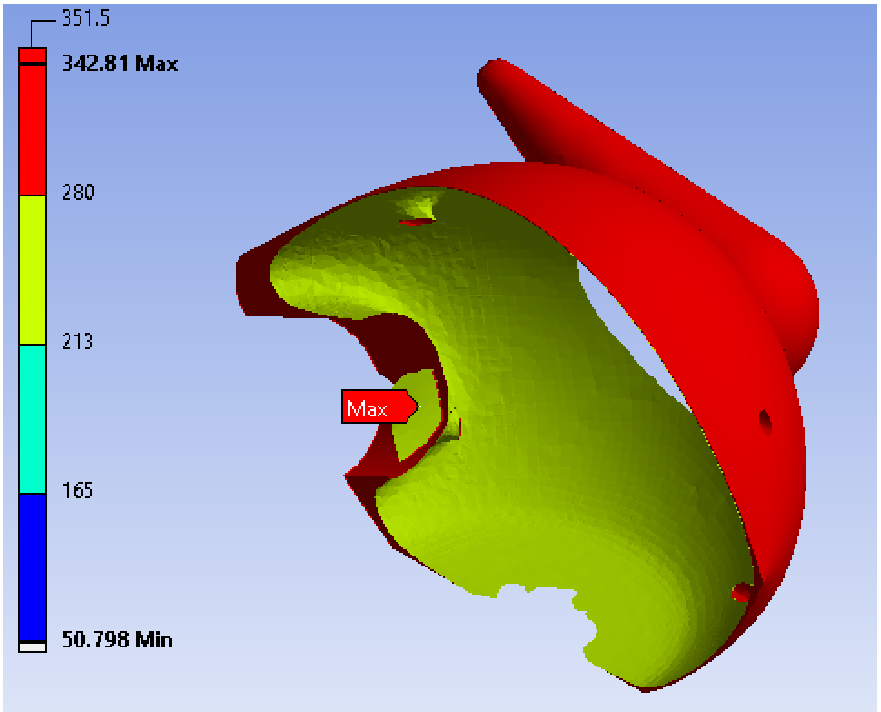

Figure 25: Burn Volume Surrounding Outer Turkey at 2 Hour Mark

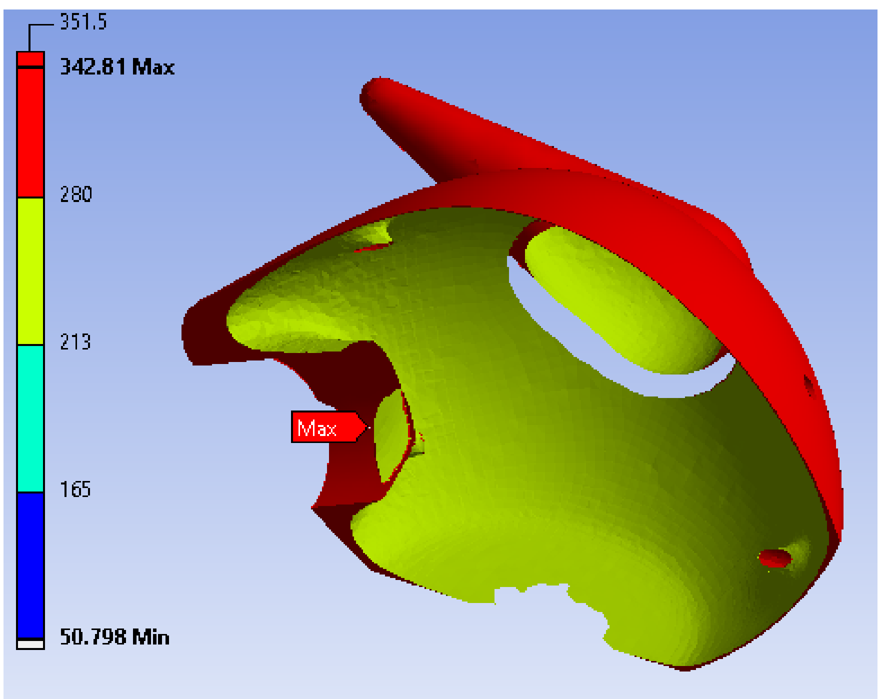

Figure 26: Burn Volume Surrounding Outer Turkey at 2 Hour Mark Alternate View

There were two determined burn volumes during the thermal analysis due to the nature at which the simulation was run. The first max burn volume was reached during the second hour of the simulation which includes the outer Turkey skin. The second max burn volume was reached during the fifth hour of the simulation which includes the parts of the Turducken surrounding the skewers.

A summation of the two burn volumes excluding the overlapped regions was taken to determine the final burn volume described in the subsection below.

6.6 Burned Volume

To estimate the volume burned during the cooking process, the elements that have a temperature above 280 degrees were filtered out using Workbench command Capped IsoSurfaces and its bottom cap feature. This process was done twice for both the 2 hour and 5 hour mark of the simulation as one yielded the burn volume of the outside of the Turkey before turning the oven off and the other yielded the burn volume of the elements near the skewers at the end of the cooking time at the 5 hour mark. The data was then exported for all the burnt elements: the element number, location, and the volume of the element. A calculation completed in Excel combined volume of the burned elements and divided it by the total volume. The result obtained a 7.42% burned volume. Below is a sample of the dataset from the Excel.

	Entity - Element	Volume (ft^3)	Average [°F]
1	1436	0.000087665	281.1823
2	99676	0.000156979	282.7885
3	33970	0.000197526	284.1632
4	70341	0.000226294	285.4351
5	27999	0.000248609	286.6487
6	43253	0.000266841	287.8245
7	85103	0.000282256	288.9741
8	85416	0.000295609	290.1041
9	75958	0.000307387	291.2192
10	43317	0.000317923	292.3224

Figure 27: Element Spreadsheet (from Excel)

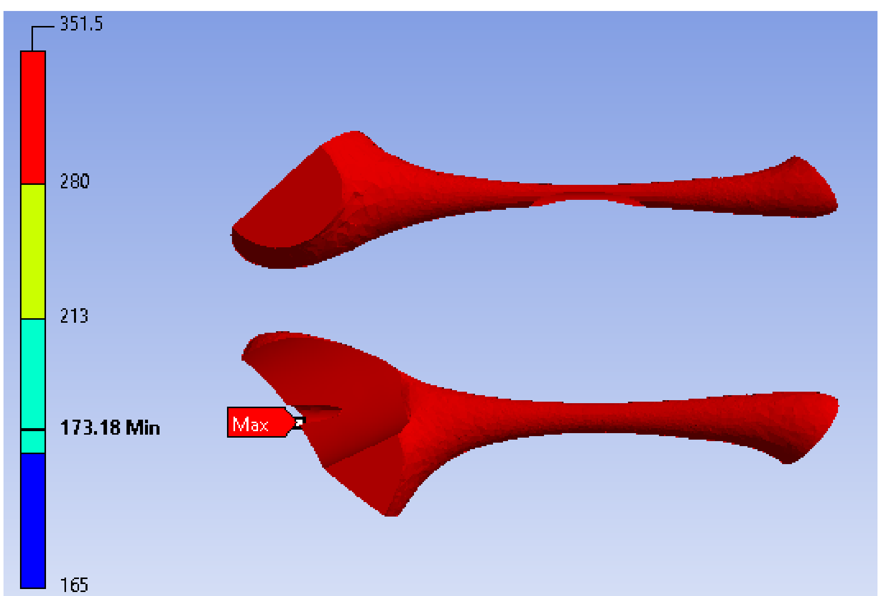

Figure 28: Burned Volume

7 Summary

Through incorporating well-functioning skewers in our design, we were able to optimize the cooking operation and results. We designed prong-style skewers that were easy to use and effective in heating up the poultry. The bird was meshed using tetra-mesh with varying element size from 0.25 to 0.125 of an inch, and boundary layers with edge sizes of 0.25 of an inch. We were able to achieve a relatively short cooking time of 5 hours, and minimize the burned volume percent of the poultry to 7.42%.

8 Design Time Estimate

The work for this project was split up evenly among the four members of our group, on which we worked all at the same time.

For the preliminary research part, we spent a total of 4 hours each on researching thermal analyses, food preparation, food appliances and their design, and on thinking about the design for our skewers.

For the hand calculations part, we spent a total of 3 hours each on defining appropriate equations, making lists of material properties, and calculating the necessary values by hand.

For the modeling and meshing part, we spent a total of 23 hours each. Work in this part consisted of designing the skewers, analyzing and fixing the poultry design file, and meshing the parts accordingly in HyperMesh.

We spent 6 hours each compiling and editing the report, which included formal write-ups, creating tables, and incorporating useful images in our paper.

The cumulative time spent on this project is **144 hours** .