The Turducken Cooking Challenge

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Introduction

The objective of this project is to determine a valid cooking process of a Thanksgiving turkey using a conventional oven and two heating skewers. The dish consists of three parts: The outer layer of turkey, an intermediate layer of ducken and some stuffing on the inside. The goal is to fully cook the meat as fast as possible while minimizing the volume that is burnt. Finite Element Analysis software is used to perform a transient thermal analysis to determine the cooking process necessary to achieve this goal. The parameters that define the cooking process are related to the two boundary conditions: the oven and the skewers.

Design & Model Assumptions

1. All quantities are expressed in U.S. Imperial units (inches, pounds force, Fahrenheit).
2. The whole bird is initially fully refrigerated, which means the temperature at the start of the cooking process is 42°F.
3. The bird is defined as fully cooked when no part has a temperature less than 185°F.
4. At the end of the cooking process, any part of the bird with a temperature above 265°F is considered burned. These parts should be counted as part of the burned volume.
5. The oven is considered to be a typical domestic convection oven that operates uniformly with a single convection coefficient. The temperature of the oven can be changed exactly once by the customer and such a change should be modeled as a step change (i.e. the oven itself has no thermal mass and does not need to be simulated directly).
6. The two electric resistance skewers are identical to each other in every way and are assumed to provide a constant heat flux through their outside surface during operation. The operating state of the skewers can be changed exactly once (from on to off or vice versa) as long as the time when they are switched is specified.
7. All food materials are homogeneous mixtures. The material properties of the mixtures are assumed to be an average of the components that constitute them.
8. The food materials that make up the turducken have non-linear material properties due to
   a. Variations in water content as the food dries during cooking, and
   b. Variations in physical property when the meat burns.
9. A symmetry plane cuts through the turducken so only one half is analyzed for computational efficiency.

Altair HyperMesh and ANSYS Workbench were the Finite Element Analysis software packages chosen for this design project. HyperMesh was used to discretize the turducken geometry into a mesh. ANSYS Workbench was used to analyze the cooking process as a transient thermal simulation involving non-linear material properties, varying boundary conditions and adaptive time-step solving.

Approach

Oven Cooking Approach

At the start of the cooking process, the fully refrigerated turducken is very cold (42°F). In order to achieve the fastest cooking time, the oven should initially be set its maximum temperature setting to quickly bring up the temperature of the bird. This is because convection from the oven on the turkey is directly related to the difference between the temperature of the oven and temperature of the turkey skin. By setting the oven to its maximum setting of 500°F, the turkey will initially heat up rapidly, and therefore minimize overall cook time.

Then, after a period of time when the skin of the turkey begins to burn, the oven should be set at its lowest temperature setting (350°F). This will minimize the total burnt volume in the long term and allow the temperature to distribute more evenly for the duration of the cooking process.

The appropriate amount of cooking time at the high and low oven temperature settings can be determined after running the transient thermal analysis a few times.

Skewer Design Concept

The skewer is intended to help cook the inside of the turducken by providing a direct heat flux that conducts through the interior of the bird. This should help make the overall temperature gradient more uniform during the cooking process and thus help speed up cooking time.

Without any other influence, the convection from the oven will cook the outside (turkey) before cooking the interior (ducken, stuffing). In addition, looking at material properties, the stuffing as a whole should cook faster than the ducken. A hand calculation of the cooking process (described in detail later) verifies this result. Through this process of elimination, the assumed approach is to design the skewer to cook the ducken directly. This approach means the skewer should pierce the turkey and ducken but only provide a heat flux to the ducken directly. The skewer should be switched off when too much of the ducken has burn. The exact placement of the skewer is described in the 'geometry' section.

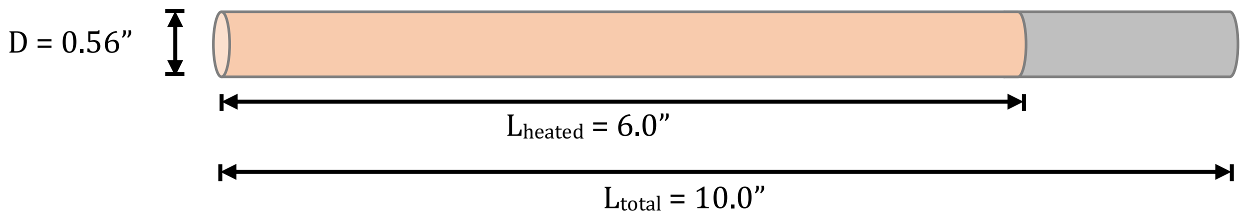
The chosen material for the skewer is silver because it has a very high thermal conductivity, thus maximizing the heat flux through its surface into the turkey. In addition, silver is food-safe. The appropriate magnitude of heat flux can be determined after running the transient thermal analysis a few times.

	Silver
Thermal Conductivity *[BTU/hr.ft.°F]*	247.87
Density *[lbm/in^3]*	0.379
Specific Heat Capacity *[BTU/lb.°F]*	0.057
Melting Point *[°F]*	*1760*

Figure 1: Silver material properties for skewer design

Geometry

Skewer Geometry



	Silver
***Cross Sectional Area** [in²]*	0.25
***Diameter** [in]*	0.282
***Total Length** [in]*	10.0
***Heated Length** [in]*	6.0
***Area of Heated Curved Surface** [in²]*	10.63

The skewer is designed to be a simple cylindrical rod shape with constant cross-sectional area of 0.25”. A circular cross-section is chosen because it maximizes the area of the curved surface that will provide a heat flux to the ducken. In the finite element model the heat flux is only applied to portion of the ducken in direct contact with this outside this curved surface of the skewer. Selecting this portion means the heated length of the skewer is 6.0” The circular area at the tip is negligible and is not included.

Skewer Placement

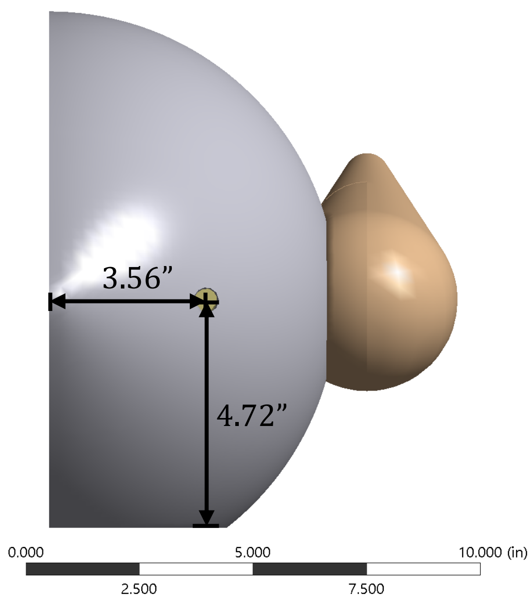


Figure 2: Front view of geometry showing skewer insertion point

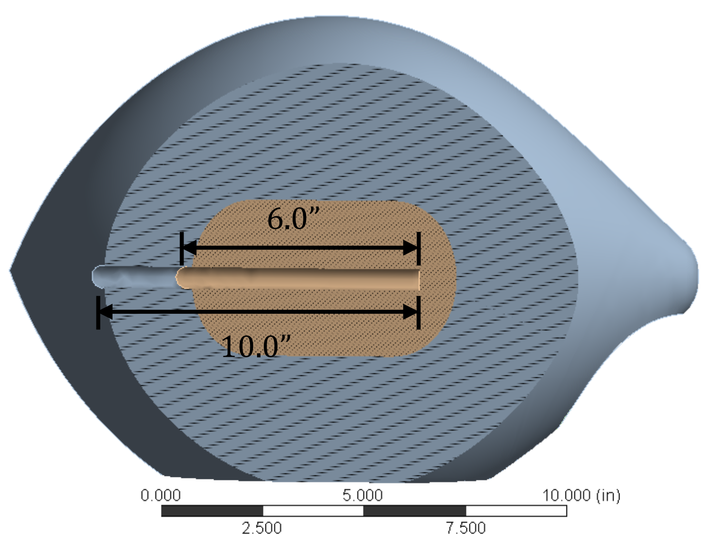
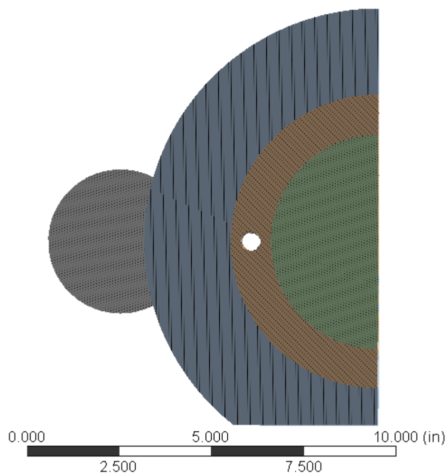


Figure 3: Section view showing depth of skewer insertion



For the purposes of this description, the 'back' of the turducken refers to the region where there is an opening for the stuffing void. As such, the 'front' of the turkey refers to the region diametrically opposite to the back.

From the front of the turducken, the skewer is inserted 3.56" from the plane of symmetry and 4.72" above the plane of the base and parallel to the base, as shown in Figure 2. The skewer is inserted a total depth of 10.63" such that the heated length of 6.0" is contact with the ducken only, as shown in Figure 3. Once the skewer is properly inserted, it should not be touching the stuffing at all (see Figure 4).

Figure 4: Section view showing internal location of skewer

Turducken Geometry

The geometry of the turducken was provided and is considered fixed. It is approximately 18'' in length and width, and approximately 10'' in height. The volume of the turkey is about 1100 in^3.

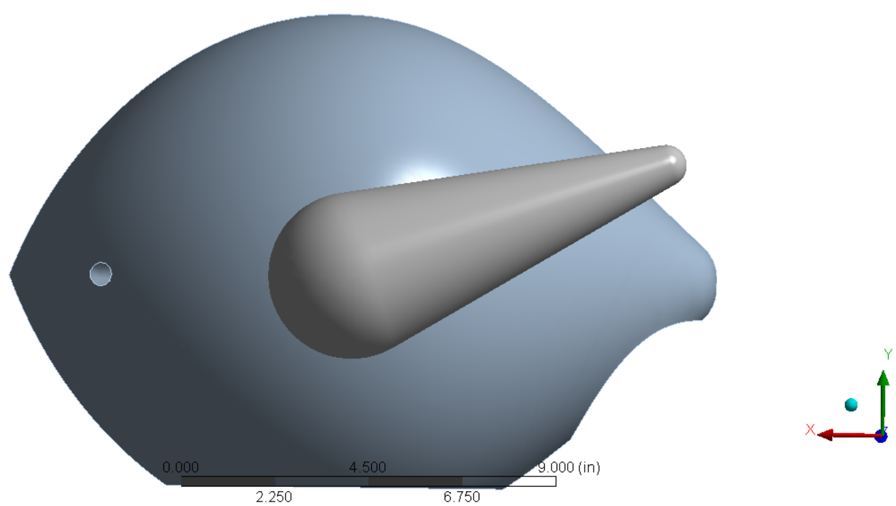


Figure 5: Outside geometry of the turkey and wing

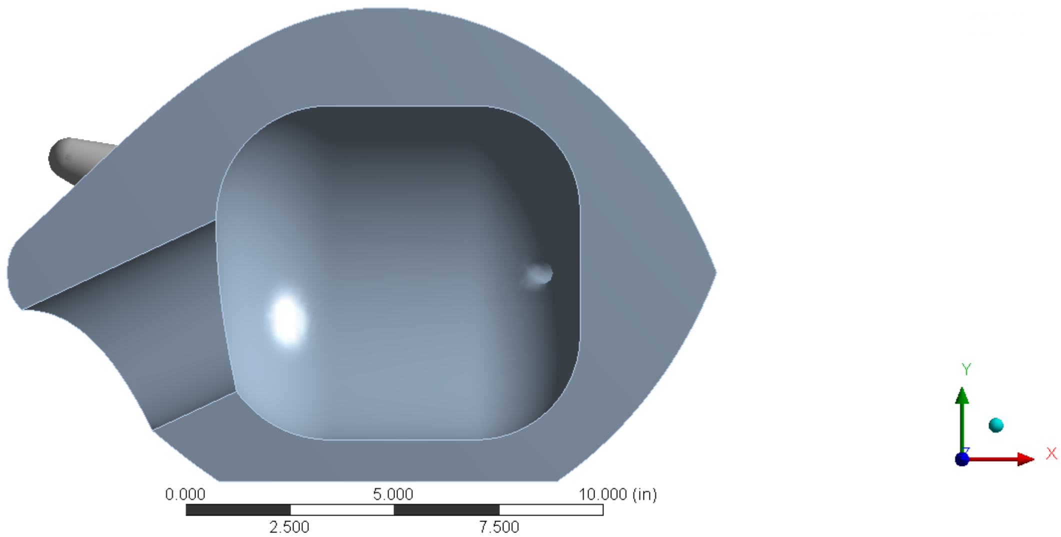


Figure 6: Symmetry plane view of turkey with inside void for ducken and stuffing

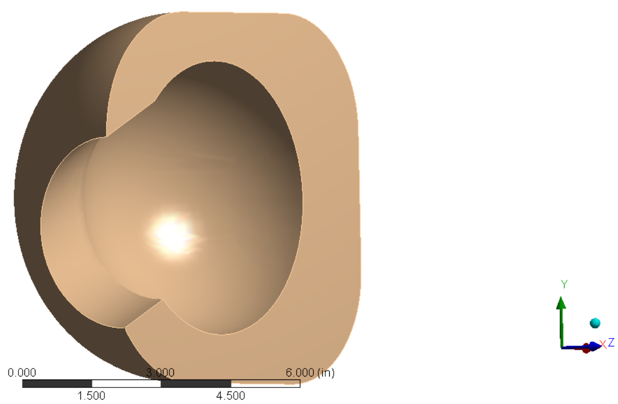


Figure 7: Three-quarters view of the ducken with the void for stuffing

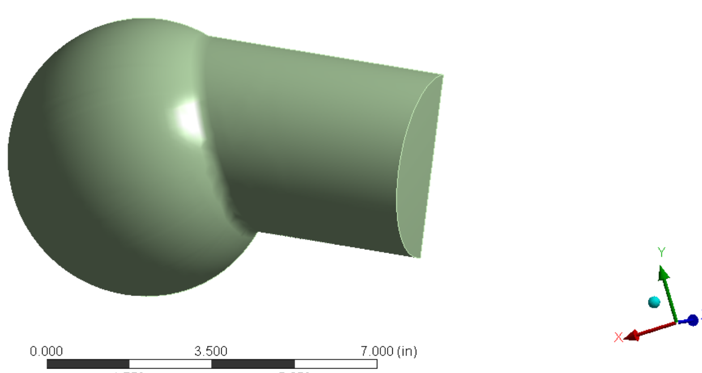


Figure 8: Opposite side view of the stuffing

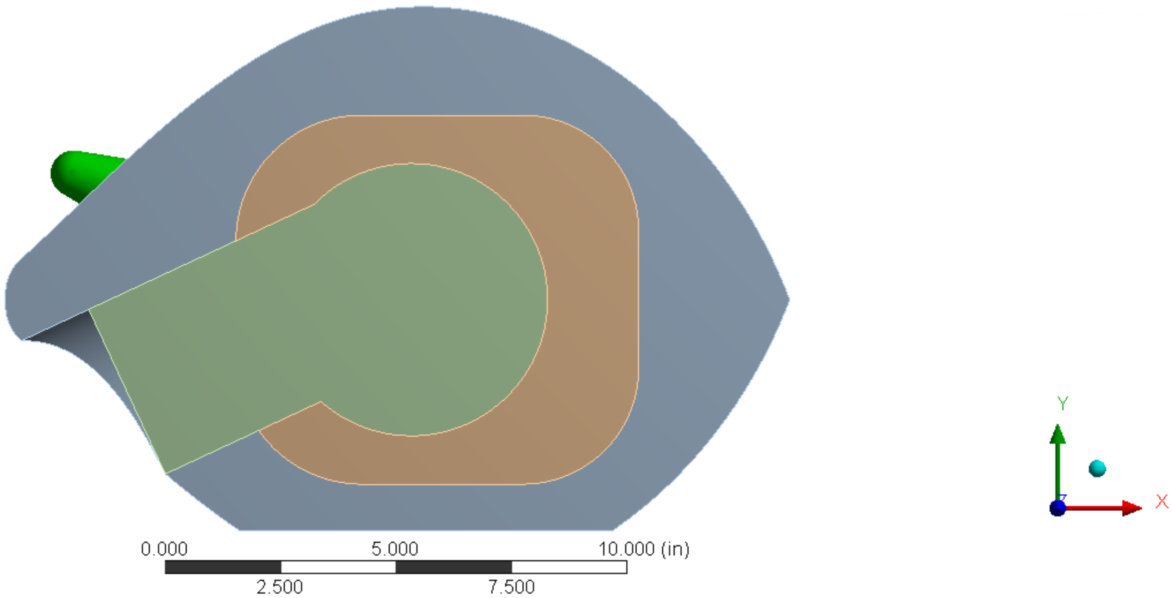


Figure 9: Symmetry plane view of the turducken as a complete assembly

Materials

Properties of Interest

For a transient thermal analysis, the pertinent material properties are thermal conductivity, density and specific heat capacity for each of the food materials in the turducken.

All of these material properties are dependent the proportions of food components: water, protein, fat, carbohydrates, fiber and ash. These material properties also change as temperature increases due to chemical and physical transformations that take place within the material.

Food Components

Figure 10 shows the composition of three turducken materials at 42°F.

	TURKEY	DUCKEN		STUFFING	
% Composition	*100%*	*80%*	*20%*	*50%*	*50%*
Food Components	**-**	**Duck**	**Chicken**	**Peas**	**Potatoes**
Water	0.7	0.485	0.6599	0.7886	0.7896
Protein	0.2	0.1149	0.186	0.0542	0.0207
Fat	0.08	0.3934	0.1506	0.004	0.0001
Carbohydrates	0	0	0	0.1446	0.1798
Fiber	0	0	0	0.051	0.016
Ash	0.0088	0.0068	0.0079	0.0087	0.0089

Figure 10: Nutrient composition of the three turducken materials. Source: 2006 ASHRAE Handbook

Sample Calculation

A sample calculation of the thermal conductivity (k), density (ρ), and specific heat capacity (c) of turkey at 42°F is carried out below.

First, calculate the k_i, ρ_i, c_i values at 42°F for water, which is one component of turkey.

$$k_w = 3.1064 \times 10^{-1} + 6.4226 \times 10^{-4} t - 1.1955 \times 10^{-6} t^2$$

$$\rho_w = 6.2174 \times 10^{1} + 4.7425 \times 10^{-3} t - 7.2397 \times 10^{-8} t^2$$

$$c_w = 9.9827 \times 10^{-1} - 3.7879 \times 10^{-5} t + 4.0347 \times 10^{-7} t^2$$

Similar equations for other food components (protein, fat, …) can be found in the same chapter of the 2006 ASHRAE Handbook.

The overall k, ρ, c for turkey are found by computing the weighted average as follows:

$$k = \sum x_i k_i = x_w k_w + x_{protein} k_{protein} + x_{fat} k_{fat} + x_{carb} k_{carb} + x_{fiber} k_{fiber} + x_{ash} k_{ash}$$

Where x is the fraction of the food component in the material and k is the conductivity of that component only. The density and specific heat capacity is computed in a similar way and shown in Figure 11.

	Nutrient Composition	**k** *(BTU/h.ft².F)*	**ρ** *(lb/ft³)*	**c** *(BTU/lb.°F)*
Water	0.7	0.335706	62.174	0.995697
Protein	0.2	0.107104	76.04782	0.475838
Fat	0.08	0.103528	58.2	0.374638
Carbohydrates	0	0	0	0
Fiber	0	0	0	0
Ash	0.0088	0.002646	151.6	0.26392
	Weighted Average	**0.264721**	**64.72144**	**0.824449**

Figure 11: Material properties for Turkey at 42°F

Temperature choices for tabular material properties

As the temperature increases, chemical and physical transformations take place within the material. It is important to recalculate material properties at these particular temperatures.

Temperature (°F)	***Selection Reason***
42	Initial temperature
212	Water boiling point
213	All liquid water vaporized, thus no water content
265	Last temperature point before the material turns to ash
266	Assume everything besides water turns to ash
2000	Upper limit, assume same properties from T = 266

Figure 12: Temperature points of interest for tabular material property data

Putting it all together, the tabular material data that were input into ANSYS are presented in Figure 13 below.

	Temp. *(°F)*	***Thermal Conductivity k*** *(BTU/h.ft².F)*	***Density ρ*** *(lb/ft³)*	***Specific Heat Capacity c*** *(BTU/lb.°F)*
	42	0.265	64.721	0.824
	212	0.314	58.609	0.814
TURKEY	213	0.038	15.051	0.134
	500	0.040	13.181	0.135
	4000	0.040	13.181	0.135
	42	0.224	63.282	0.710
	212	0.255	59.336	0.708
DUCKEN	213	0.050	26.984	0.203
	265	0.050	25.776	0.204
	266	0.005	72.771	0.156
	4000	0.005	72.771	0.156
	42	0.224	63.282	0.710
	212	0.316	52.218	0.789
STUFFING	213	0.006	3.150	0.022
	265	0.006	2.800	0.022
	266	0.006	1.169	0.022
	4000	0.006	1.169	0.022

Figure 13: Non-linear material data table input into ANSYS

Boundary Conditions

The boundary constraints can be thought of as the methods through which the turducken is cooked. The boundary conditions are therefore chosen in order to meet the stated goals of minimizing total cooking time while also minimizing burnt volume at the end of the cooking process. These boundary condition choices are limited by the real-world capabilities of the cooking tools used. The intent and thought process in selecting boundary conditions are presented in the sections below.

Convection from Oven

The idealized oven in this project has a uniform convection film coefficient (h). To determine a realistic value for h for this analysis, a research paper on "Measurements of heat transfer coefficients within convection ovens" was consulted. The authors of this paper back-calculated from transient temperature data collected empirically to determine a range of convection coefficients that the selected ovens could operate at. The ovens in their study were a typical domestic fan oven and a commercial batch oven. From their results, they found that the typical range of h values was between 15 and 40 W m^{-2} K^{-1}. The idealized oven in this turducken project calls for a single h value, so a number in the middle of this range was chosen: 30 W m^{-2} K^{-1} (1.0192×10^{-5} BTU/s-in^2-°F)

The convection boundary condition is applied only on the surfaces of the turducken that are exposed to the air inside the oven directly. These surfaces are highlighted in Figure 14.

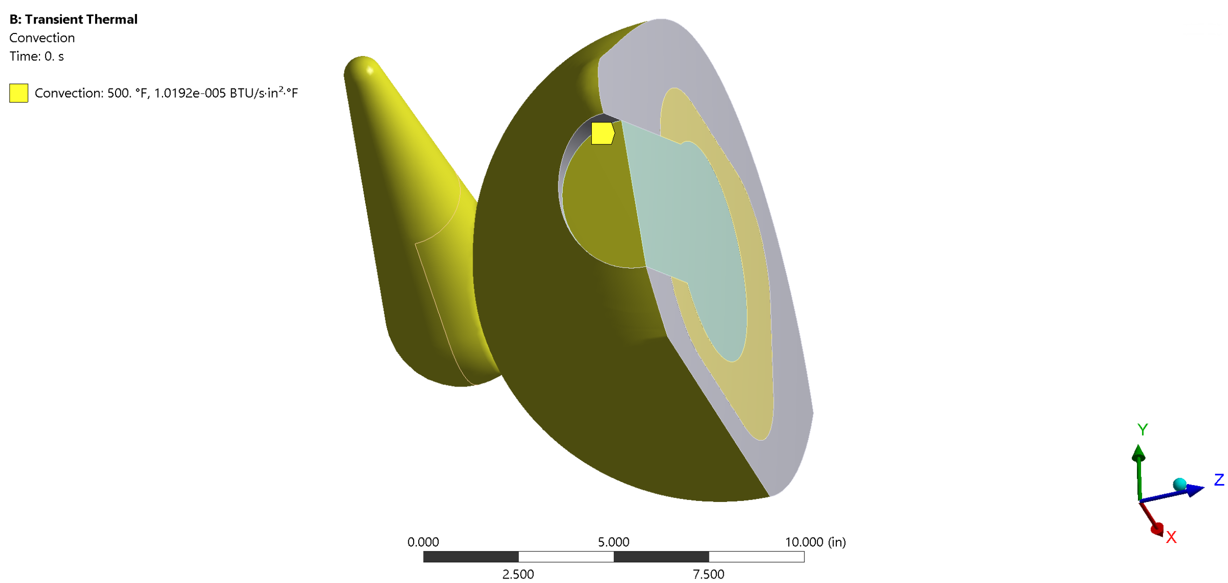


Figure 14: Convection Boundary Condition applied to exterior surfaces of the turducken

Note the red square in Figure 14 highlighting a gap in the boundary condition applied to the exterior. This gap is the result of the fact that this surface is continuous into the interior of the turkey (see Figure 5). Selecting this surface to apply the boundary condition means creating an inaccurate solution where the convection heats up the interior of the turkey. Leaving it unselected is the best choice, however it still does affect the results of the FEA.

The remaining choice is deciding what temperature to set the oven to. As outlined previously in the 'approach' section of this paper, the best choice is to start the cooking process at the highest temperature setting to quickly heat up the refrigerated meat and thus minimize the overall cook time. When the 'skin' of the turkey starts to burn, the oven temperature should be set to its lowest temperature setting to prevent further burning.

After running the transient thermal analysis a number of times, through trial and error, a decision was made:

The optimal convection boundary condition is the oven temperature set to 500°F for the first 30 minutes followed by the oven temperature set to 350°F for the remainder of the cook time. The film coefficient should be 1.0192×10^{-5} BTU/s-in^2-°F throughout.

Heat Flux from Skewer

The purpose of the skewer is to heat up the turducken from the inside, thus helping to keep the temperature gradient more uniform and speed up total cooking time. A microwave is an existing kitchen appliance that heats food with the same idea. Even though a microwave works primarily through radiation (and some convection), the total energy supplied by a microwave can be used as a comparable metric for designing how much energy the skewer should provide through heat flux.

A typical microwave can provide a maximum of 1200 Watts. When cooking refrigerated meat in a microwave, it's a good idea to use the 'defrost' setting [citation needed]. The defrost setting pulses the microwave radiation so that the total power delivered to the food is a fraction of the maximum. The defrost setting for meat can be as low as 10% of the maximum, effectively providing 120 Watts. When defrosting turkey in a microwave, the U.S. Dept of Health and Human Services suggests 6 minutes per pound of turkey. The previously reported approximate volume of the turkey is 1100in^3 and the density at 42°F was computed to be approximately 64.7 lb/ft^3. A Fermi estimation of the total time required to defrost a turkey in a microwave follows:

$$1200\,Watts \times 10\% = 120\,Watts$$

$$6\frac{min}{lb} \times 64.7\frac{lb}{ft^3} \times \left(\frac{1ft}{12\,in}\right)^3 \times 1100in^3 = 247.11\,min \;\approx 240\,min\;or\;(2\;hours)$$

A skewer can be designed to provide an equivalent amount of power through heat flux for an equivalent duration (hence, the same amount of energy). The previously reported heated "active" area of the skewer is 10.63 in^2. Thus, the required power is:

$$\frac{120\,Watts \times \left(3.412\frac{BTU}{hr}\right) \times \left(\frac{1\;hour}{3600sec}\right)}{10.63in^2} = 1.07 \times 10^{-2}\frac{BTU}{s\;in^2}$$

For the same duration of 2 hours.

The skewer design concept calls for the heat flux to only be applied to the surface in contact with the ducken directly, as shown in Figure 15.

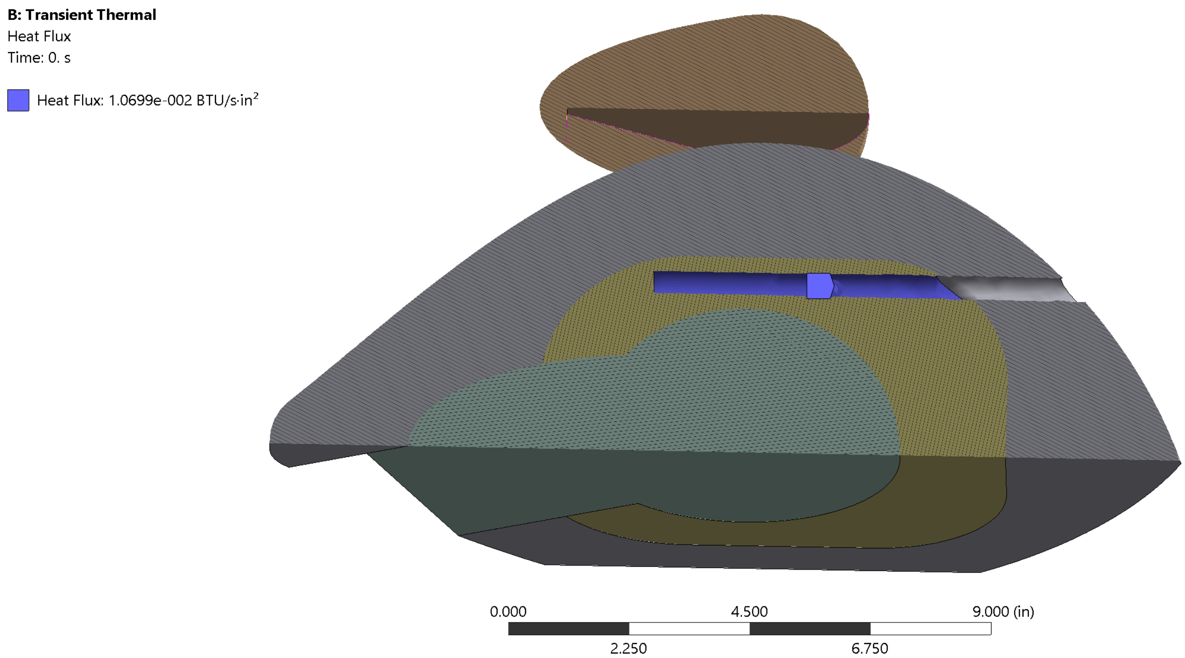


Figure 15: Oblique top section view showing the surface of the ducken where the skewer heat flux BC is applied.

Other Boundary Conditions considered

Radiation

If the turducken is considered as a black body, the total power radiated is proportional to $\sigma(T_{turducken}^4 - T_{oven}^4)$, where σ is the Stefan-Boltzmann constant and is extremely small. Thus radiation is negligible and does not need to be accounted for in the finite element model.

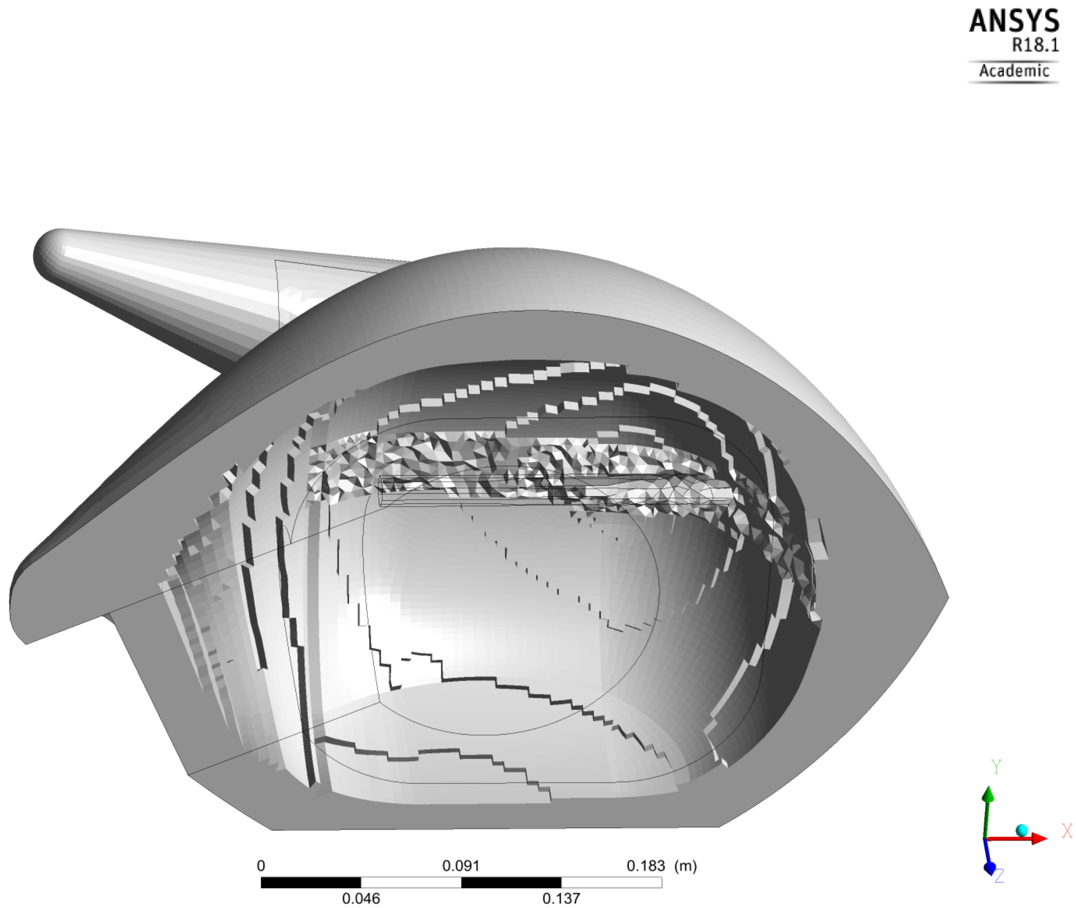
Furthermore, the research paper on convection in ovens suggests that the range of the convection coefficients actually already includes the effects of radiation inside the oven. The h value effectively includes the total net effects of both radiation and convection together.

Conduction through oven rack

In real life, the turducken would be placed on a metal rack in the oven. However, the surface area of the turducken that would be in contact with the metal would be relatively small. Furthermore, if the rack is made of stainless steel, then the limited thermal conductivity of the steel means that very little heat conducts through the rack. In effect, it is not necessary to model this boundary condition in this thermal analysis.

Heat Flow

No heat flows through the symmetry plane of the turducken.



Summary

Graphical timeline for cooking temperatures and skewer operation.

Meshing

Since the transient analysis will be run at many, many time steps, it is important to reduce the total element count so that the simulation is computationally efficient. In terms of meshing, the goal should be to create as many mapped regions as possible since mapped volumes have up to four times fewer elements than tetrahedral meshed ones.

To ensure an adequate element density, it was decided that there needs to be at least 20 elements through the diameter of the stuffing opening. Since this diameter is 0.1 units, the chosen element size is 0.005 units. For consistency in meshing, this element size is held constant throughout the turducken mesh.

To create mappable volumes, the turducken geometry was sliced using the solid edit tool in HyperMesh. The goal was to great prism-like volumes that can be mapped one after another. The yellow, translucent volumes in Figure 16 show that the after careful solid editing, it is possible to make the vast majority of the turducken volume mappable.

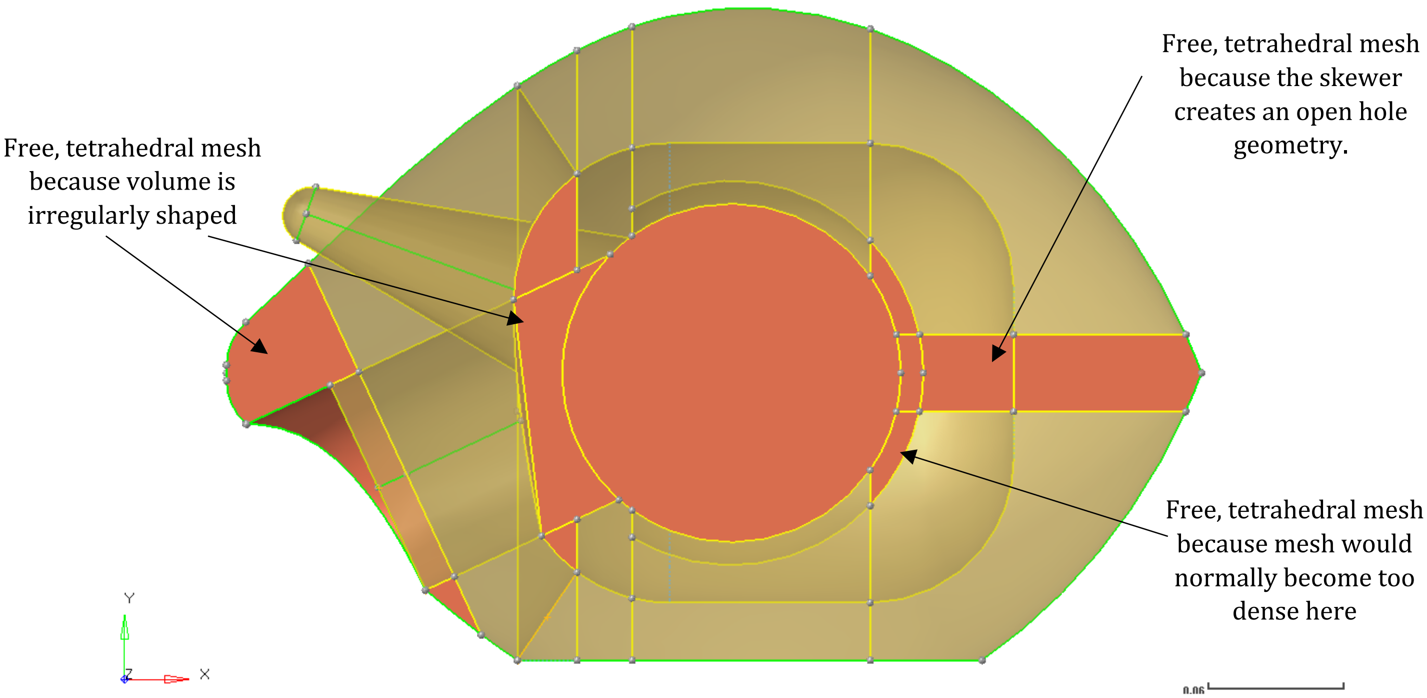


Figure 16: Mappable volumes shown in HyperMesh after solid editing. Translucent yellow means mappable.

The meshing approach was to start at the outside (turkey layer) and work towards the center. When the mesh gets inevitably gets too dense, the idea was to switch to a free tetrahedral mesh for a small, thin volume to return to an adequate element size (0.005).

Lastly, the hemisphere at the center of the stuffing was meshed using hexacore because it is over-constrained by the mapped meshes surrounding it and it's too large to only use tetrahedral mesh. Instead, the hexcore method allows some mesh efficiency to be regained.

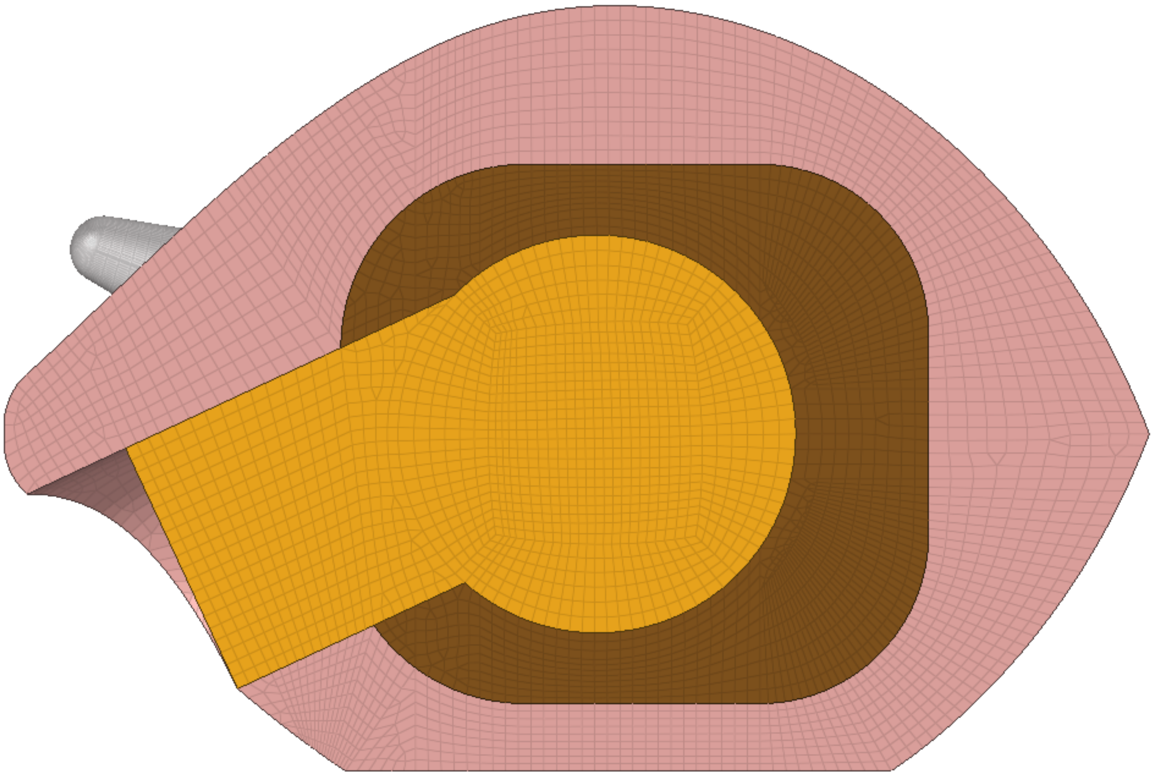


Figure 17: Symmetry plane view of meshed turducken

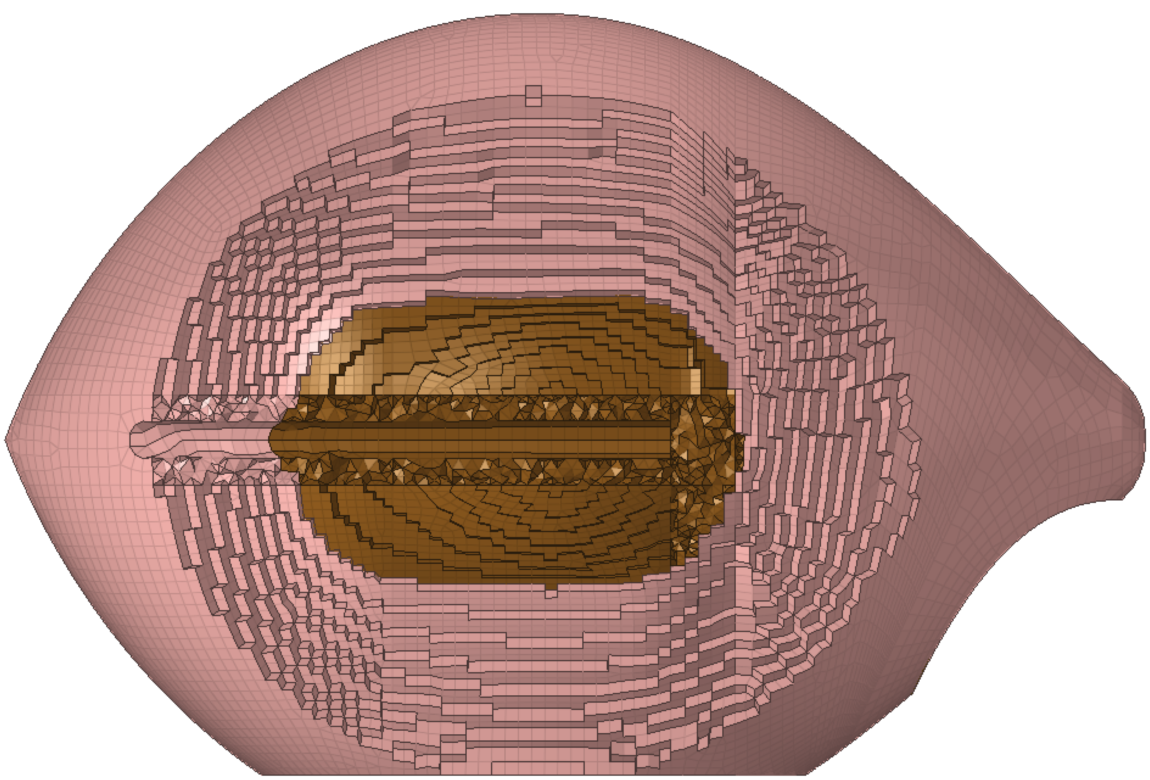


Figure 18: Opposite to symmetry plane view with cutaway to show mesh around the skewer

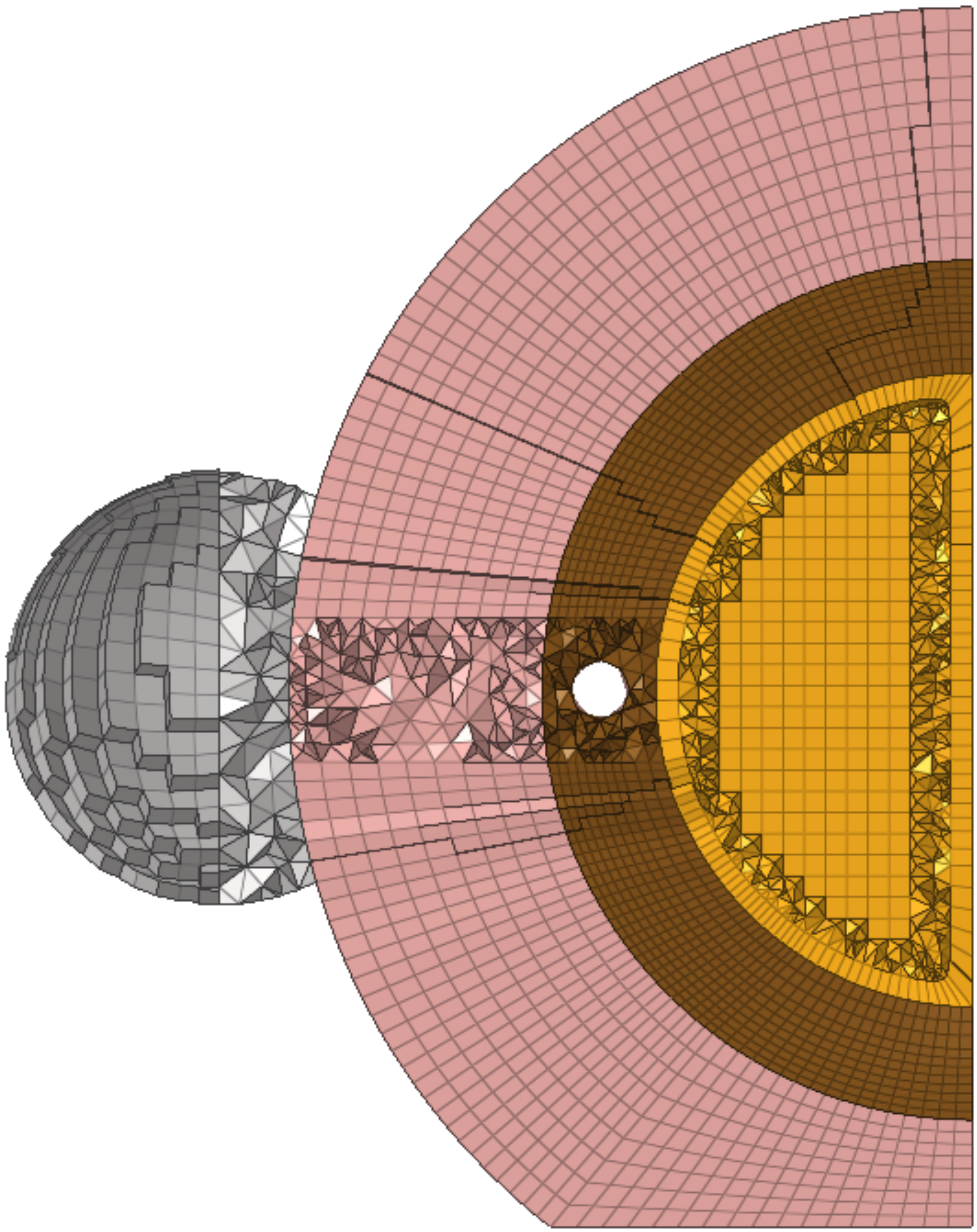


Figure 19: Section view from 'back' of turducken showing mesh

The total counts are <u>355,158 elements</u> and <u>159,417 nodes</u>. All elements are exported as <u>SOLID185</u> type.

Mesh Quality

The quality of the mesh is assessed by the metrics like element Jacobian and aspect ratio.

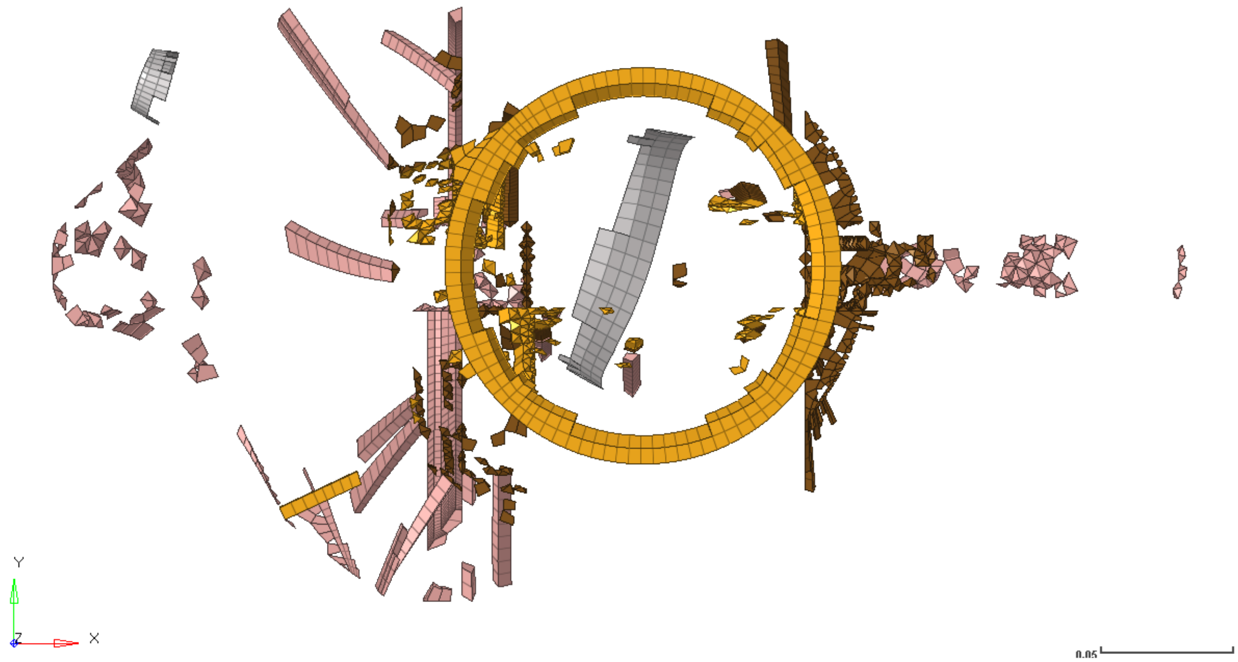


Figure 20: A masked plot of all elements with Jacobian < 0.7

There are 2,560 elements (0.7%) that have a Jacobian less than 0.7. Figure 20 shows a masked plot of only these elements. Figure 21 is a histogram of all elements by Jacobian.

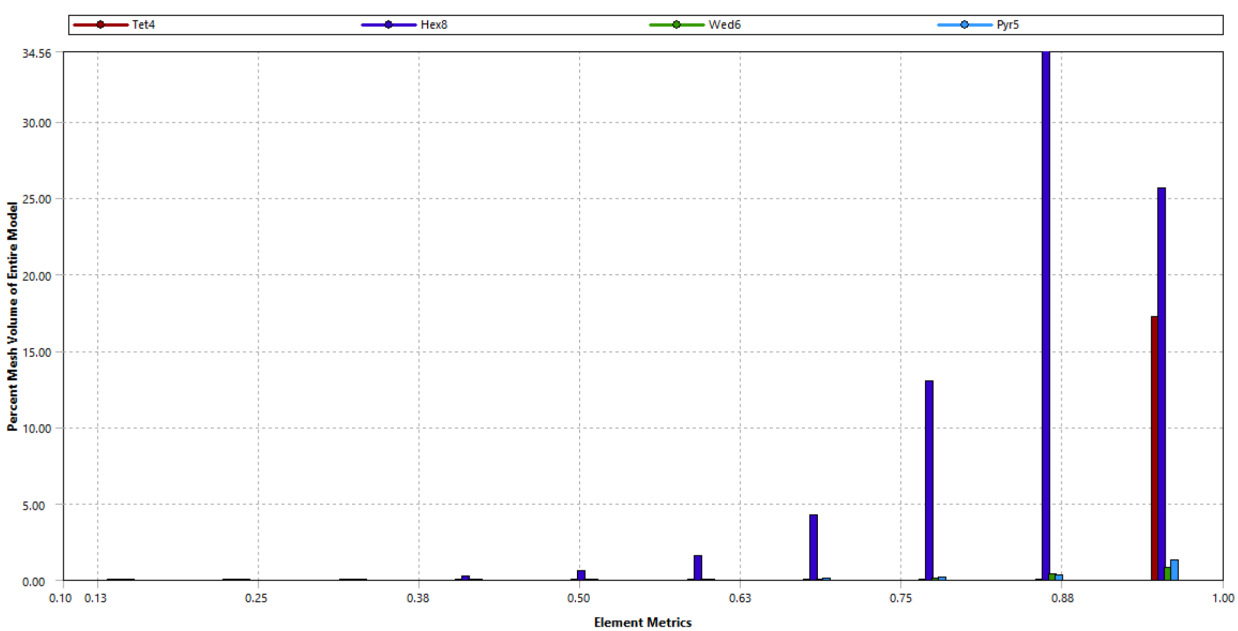


Figure 21: Histogram of element Jacobians, grouped by element shape.
The vast majority of the volume is meshed with elements that have a Jacobian greater than 0.7 or even 0.75.

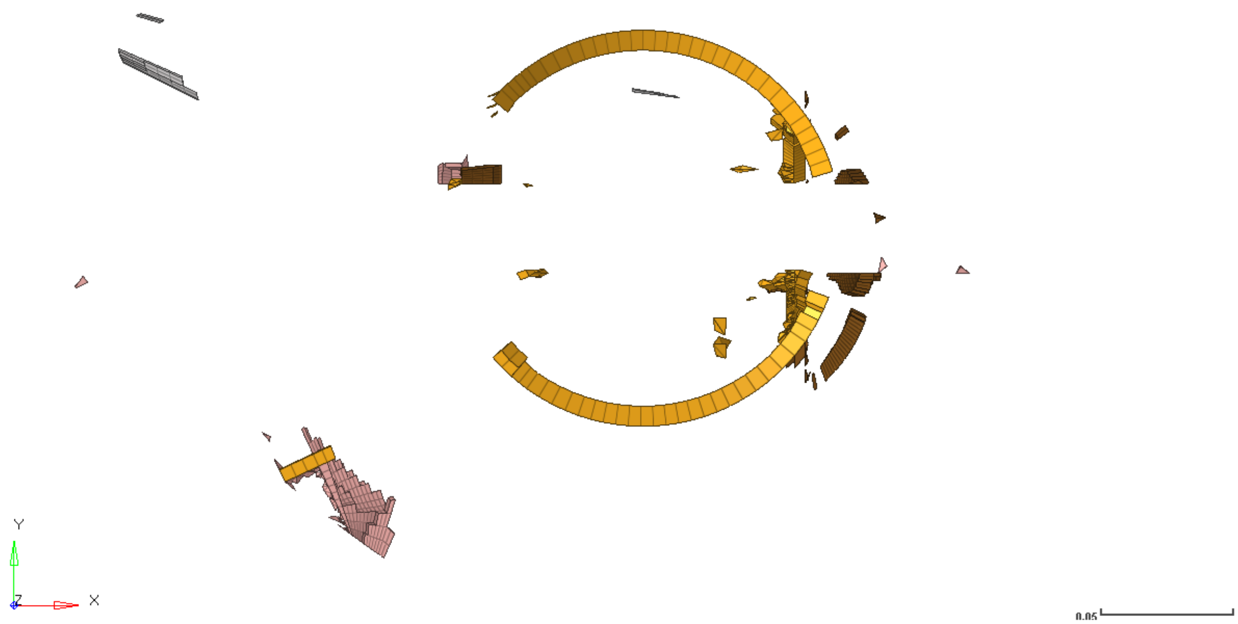


Figure 22: A masked plot of all elements with aspect ratio > 5.0

There are 1,183 elements (0.3%) with an aspect ratio greater than 5.0. Figure 22 shows a masked plot of only these elements. Figure 23 is a histogram of all elements by aspect ratio.

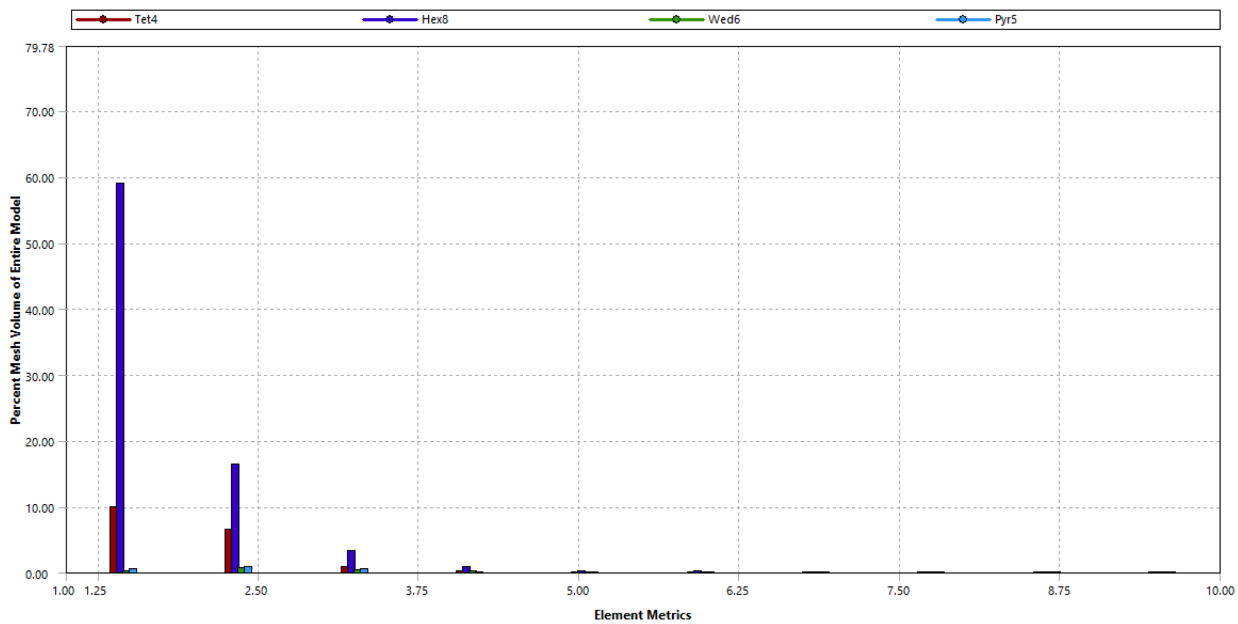


Figure 23: Histogram of elements by aspect ratio.
The vast majority of the volume is meshed with elements with aspect ratio less than 5.0.

Overall, the mesh metrics (Jacobian and aspect ratio) show that the quality of the mesh is very high. The element shapes (tetrahedral, pyramid, wedge and hexhedral) are all compatible with the chosen element type: SOLID185.

Results

With the previously reported boundary conditions and material data, the transient finite element model gives the following results:

The total cooking time was 6 hours and 6 minutes. At the end of the cooking time, approximately 41% of the volume was burned.

Summary of Plots

Figure 24 is a table summary of the result plots in the rest of this section.

Elapsed Cook Time (hh:mm)	***Oven Temp. (°F)***	***Skewer On?***	***Figure***	***Description***
0:00	500	On	-	Initial set-up, turkey fully refrigerated
0:30	500 → 350	On	24	Turkey 'skin' starts to burn
1:15	350	On	25	Skewer region is way too hot
2:00	350	On → Off	26	Skewer region is way, way too hot
4:00	350	Off	27	Cooked region has started to grow
6:00	350	Off	28	Almost done cooking
6:06	350	Off	29	Fully cooked, 41% burned volume

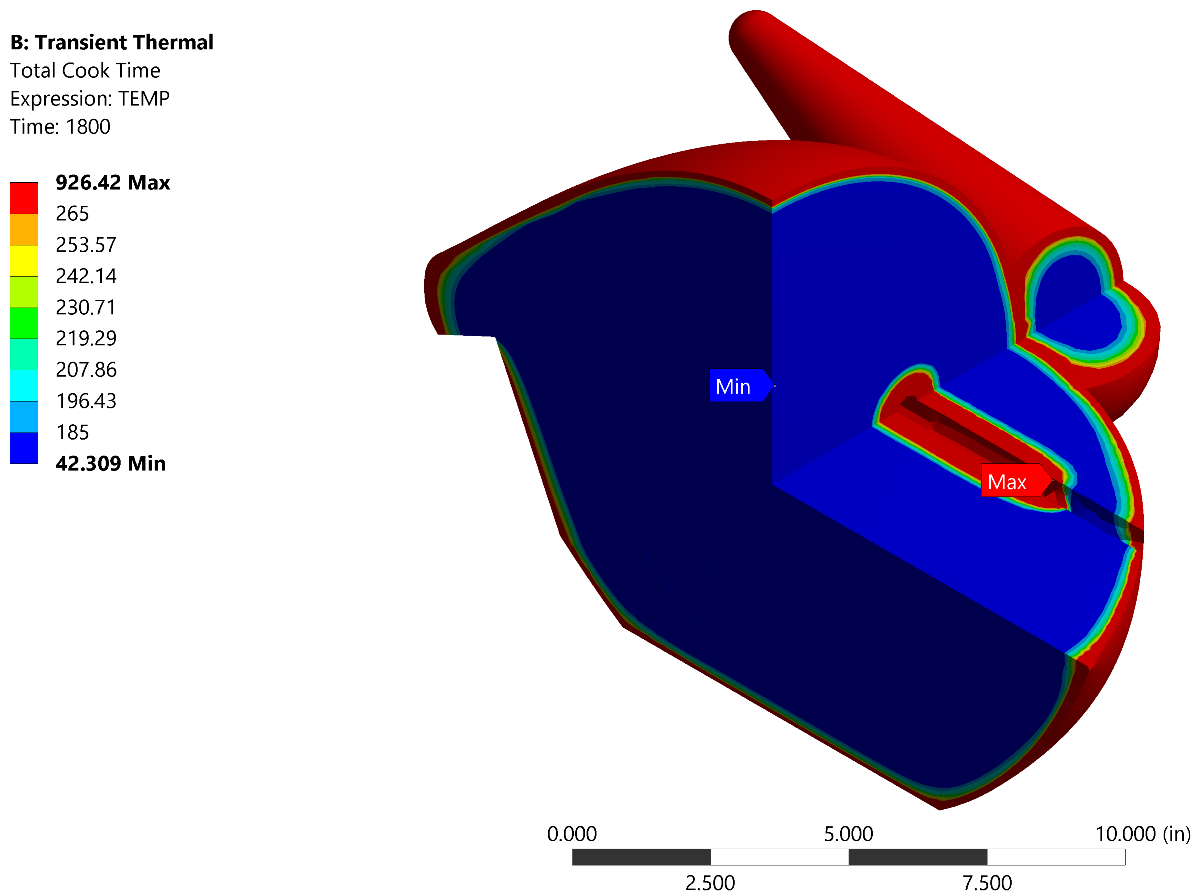


Figure 24: (above) t = 0h 30m

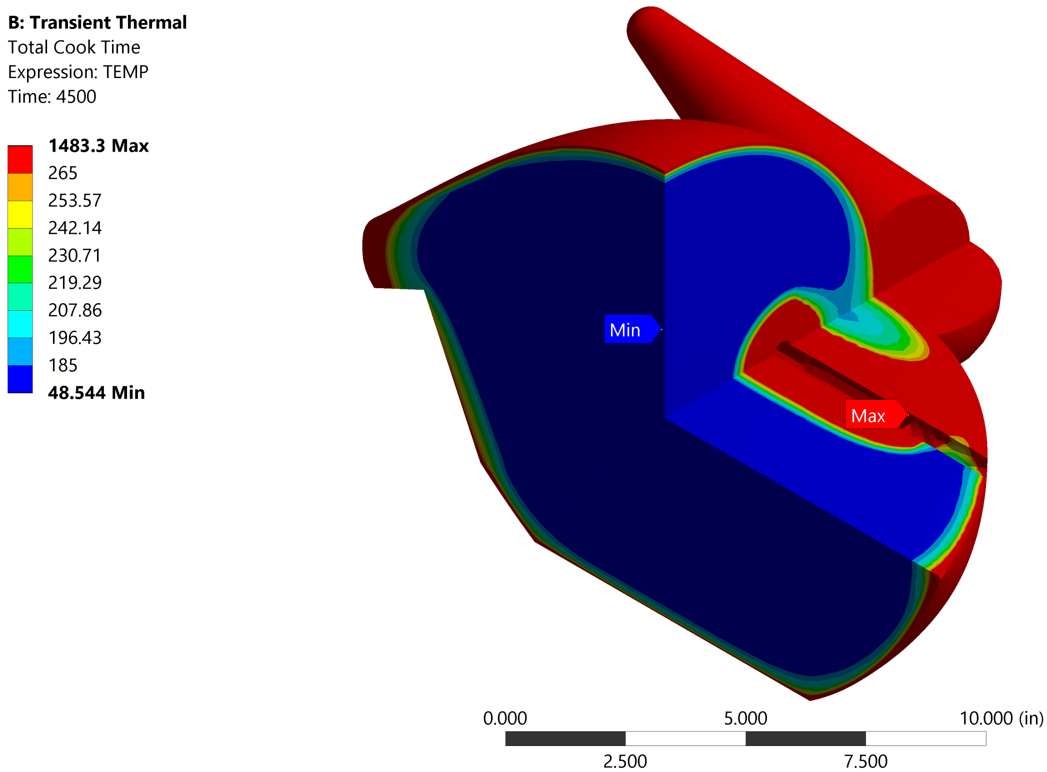


Figure 25: (above) t = 1h 15m

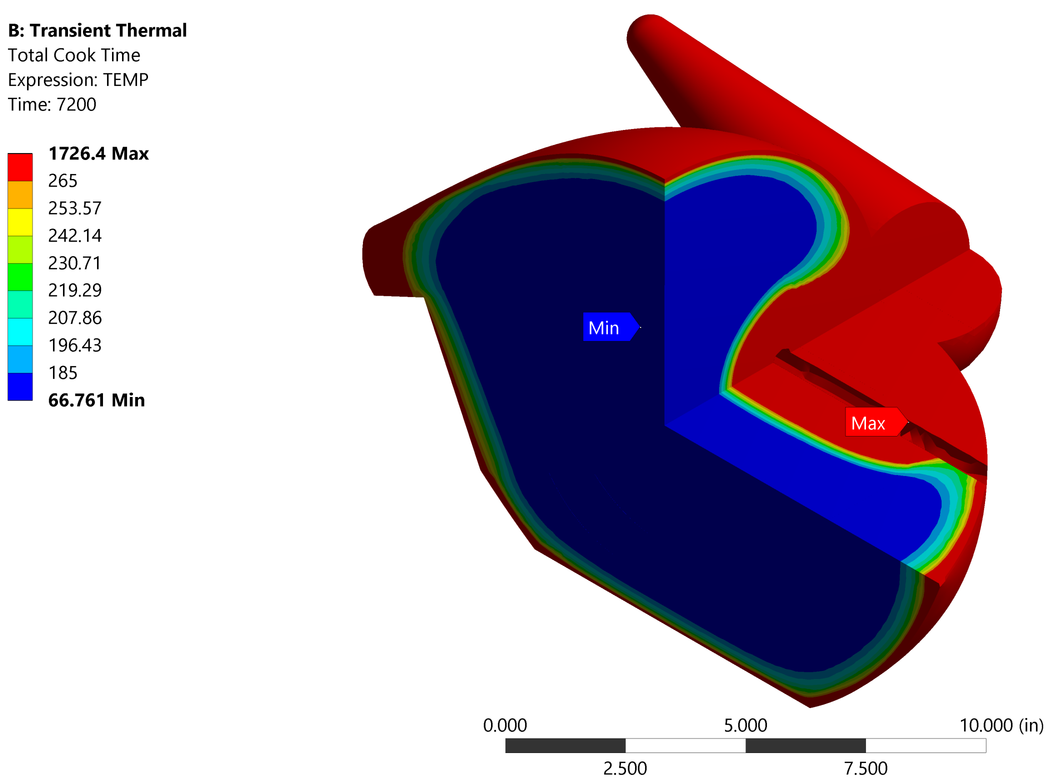


Figure 26: (above) t = 2h 00m

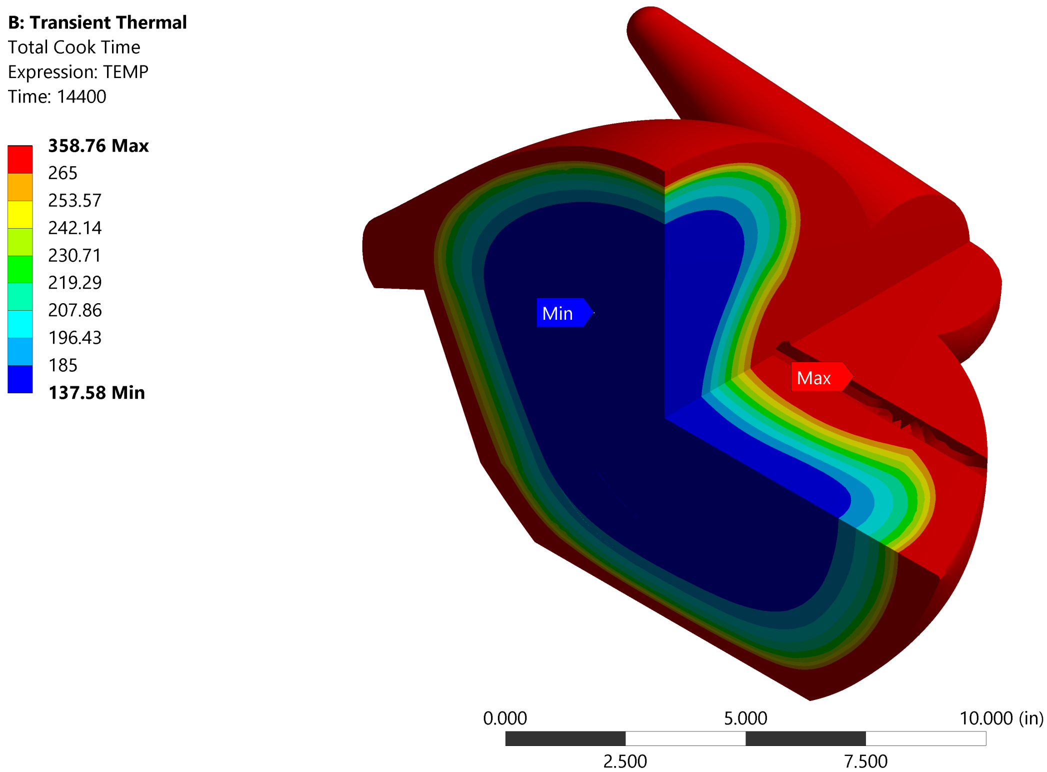


Figure 27: (above) t = 4h 00m

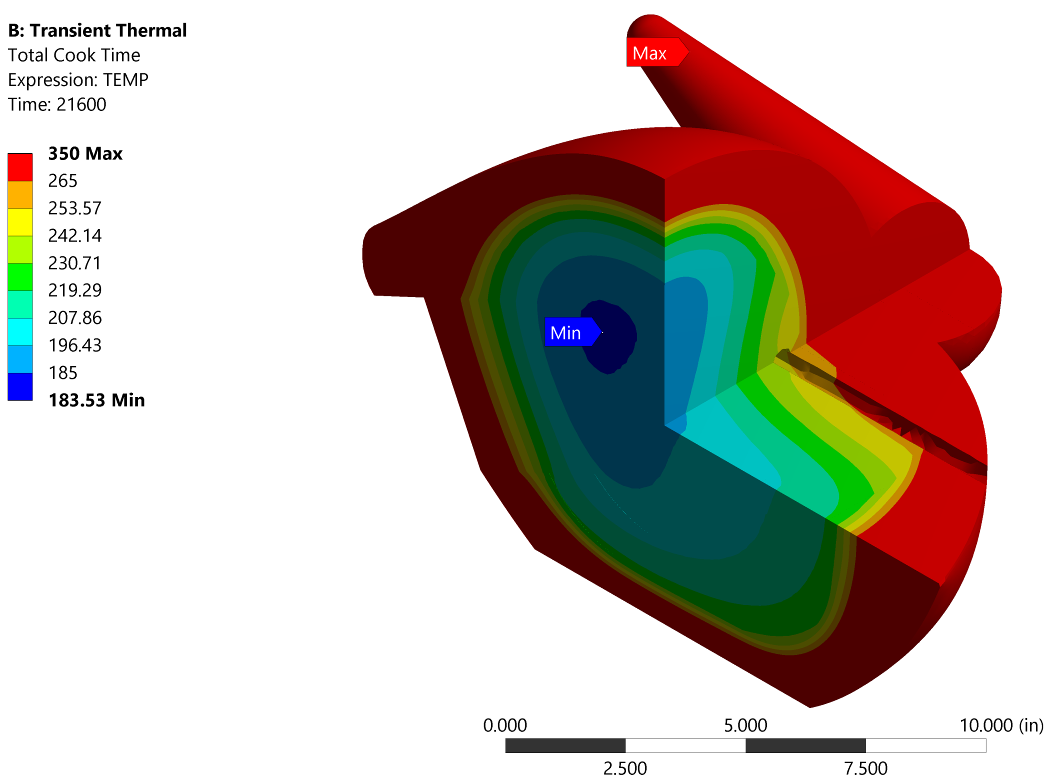


Figure 28: (above) 6h 00m

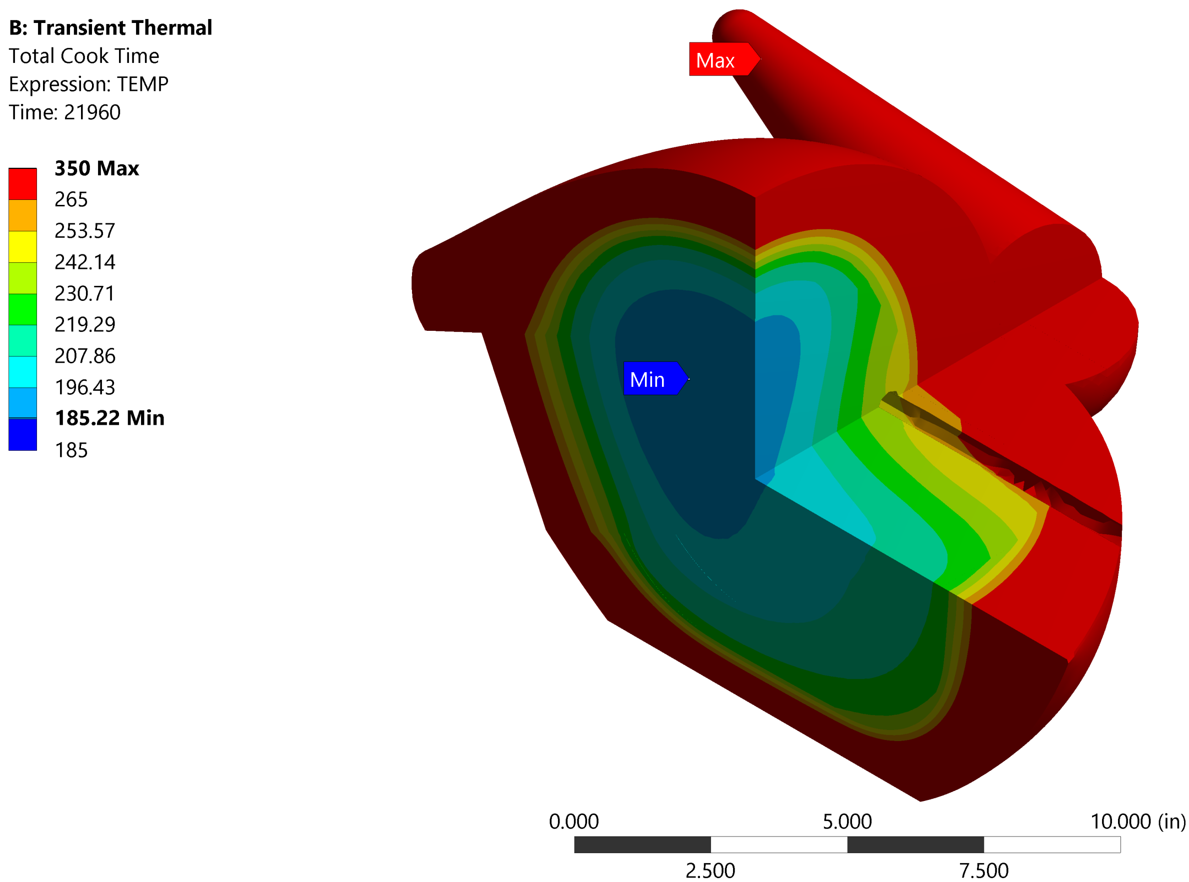
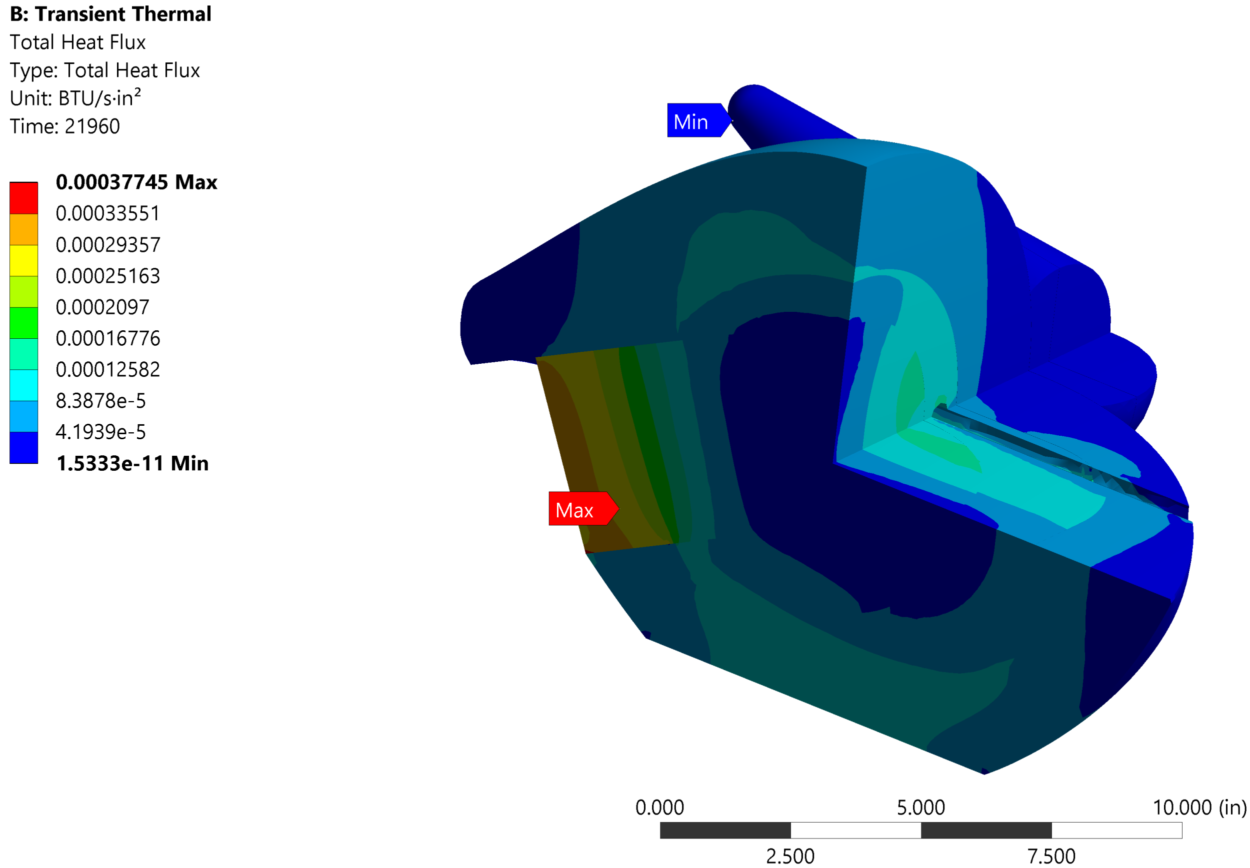


Figure 29: (above) t = 6h 06m

Thermal Gradient



Burned Volume

To calculate the percent burned, the volume of turducken above a certain threshold temperature needed to be calculated. This was accomplished by exporting the temperature at each node, the volume of each element, and which nodes correspond to each element from ANSYS (for the result at the last time step only). Using a MATLAB script the average temperature in each element was calculated by taking the mean temperature of the nodes in each element. Next the elements over the burning temperature (265 F) were sorted and the total volume of all elements over the burning temperature was calculated. The quotient of the total volume burned divided by the total turducken volume represents.

The result of the MATLAB script is 41% of the turducken volume is burned at the end of the cooking process. Figure 30 is a visual representation of this volume using the isovolume feature in ANSYS Result Viewer.

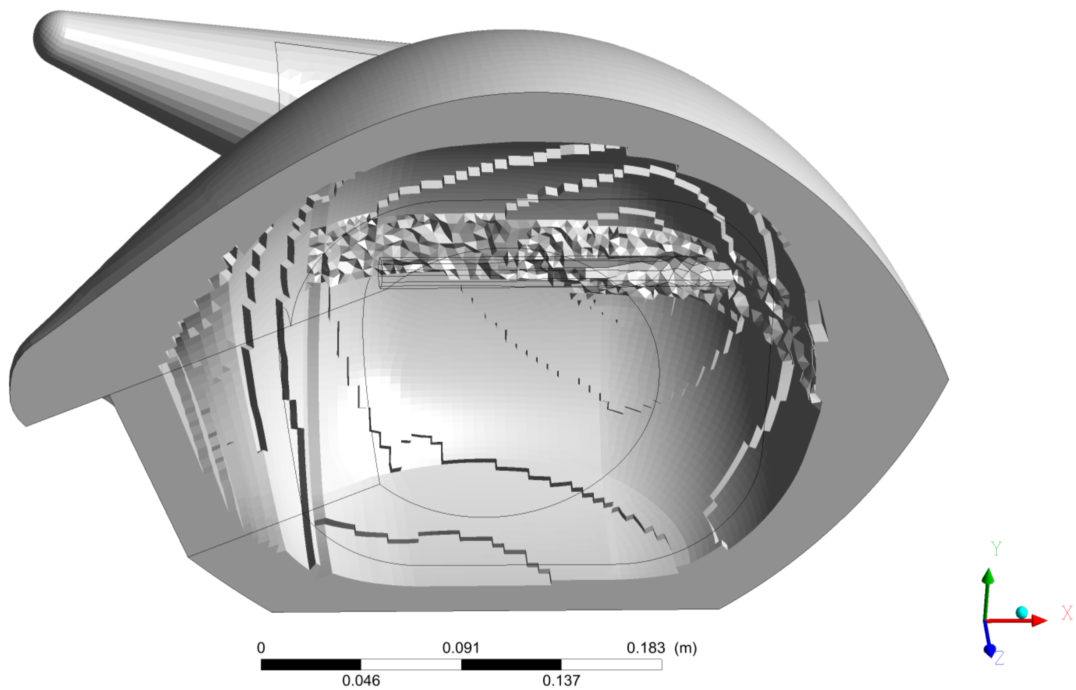


Figure 30: A visual representation of the burned volume of the turducken (isosurface with only elements with temperature greater than 265°F)

It's important to note that the burned volume calculation is carried out for the results of the last time step only. This means that any elements that 'burned' and then cooled off below the threshold temperature *during* the cooking time are not counted. For example, the elements around the skewer in Figure 24-25 (t = 1h to 2h) are shown to be well above the threshold temperature, but they cool off by the end of the cooking process and are not counted as 'burned' in this calculation.

Lacking an automatic way to compute burned volume at every time step within ANSYS, it is unfeasible to export each of the time steps individually for this MATLAB computation.

Hand Calculation

Evaluation

Simplified Cooking Process Instructions for Customer

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