Transient Heater Analysis for Orion Thermal Vacuum Testing

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Abstract

The Space Environments Complex (SEC) at NASA's Plum Brook Station is currently being prepared to perform thermal vacuum testing of the Orion spacecraft. This thermal vacuum, or T-VAC test will be run for a period of 60 days, which will be the longest such test ever conducted at SEC. The Orion Crew Module (CM) and Service Module (SM) will undergo T-VAC testing in SEC's Space Simulation Vacuum Chamber to ensure the functionality of these systems in a high vacuum environment at extremely cold temperatures.

The T-VAC test setup in SEC was modeled and simulated in Thermal Desktop. The initial results from thermal analysis showed areas on the chamber floor to reach very low temperatures, which were below the minimum operating range of certain hardware located on or near the chamber floor. These hardware including elastomeric seals on the GN_2 piping, bearing pads and O-rings are essential to both test and the operation of the SEC facility, and must be kept well above -20°F throughout the duration of the T-VAC test. Thus, further analysis was conducted to include the placement of patch heaters on the chamber floor in an effort to increase the temperature near colder areas on the floor. The results and findings from this analysis showed that using these heaters will result in a favorable temperature distribution on the chamber floor. This paper will discuss the methods used in the analysis, and the results obtained to determine the optimal configuration of these heaters on the chamber floor.

Introduction

The Orion Multi-Purpose Crew Vehicle (MPCV) has been designed and developed by NASA for future spaceflight missions to further push the boundaries of human space exploration. The first flight, EM-1 will be the first test that integrates both the Orion spacecraft and the Space Launch System (SLS). This unmanned mission is projected to launch in 2020, and will fly thousands of miles beyond the Moon, farther than any spacecraft built for humans has ever flown.

Figure 1: Depiction of Orion spacecraft during spaceflight.

Figure 2: Aerial view of the Space Environments Center (SEC).

Early next year, the Orion CM & SM will undergo T-VAC testing in the SEC facility (formerly known the Space Power Facility) at Plum Brook Station in Sandusky, Ohio. SEC includes the Space Simulation Vacuum Chamber, which is located in the center of SEC, as shown in Figure 2. The Space Simulation Vacuum Chamber is the largest and most powerful vacuum chamber in the world, with a height of 122 feet and diameter of 100 feet. The chamber can sustain a high vacuum at a minimum pressure of $2\text{x}10^{-6}$ torr, and is capable of providing a high-emissivity thermal background environment of -250°F to 140°F. Therefore, placing the CM & SM in the vacuum chamber for a 60-day T-VAC test will test its structure and functionality in conditions very similar to the environment that Orion will be exposed to on its deep space missions.

Approach

A diagram of the T-VAC test setup at SEC is shown in Figure 3. The vacuum chamber includes a cryogenic shroud, or cryoshroud, which is enclosed by blue cryowalls as shown in the diagram. During T-VAC, the Orion CM & SM will be placed inside the 40’x40’ cryoshroud, which will maintain a temperature of -250°F as GN_2 flows into the system. The basement contains all of the GN_2 piping that feeds into the vacuum chamber. SEC also includes a platform or walking plate that provides access to the inside of the vacuum chamber. The entire SEC facility is surrounded by a massive outer concrete enclosure, which has an outer diameter of 142 feet and a height of nearly 160 feet. Another part of SEC is the annulus, or the area between the chamber and the outer concrete enclosure, which maintains a pressure of about 10-15 torr during testing.

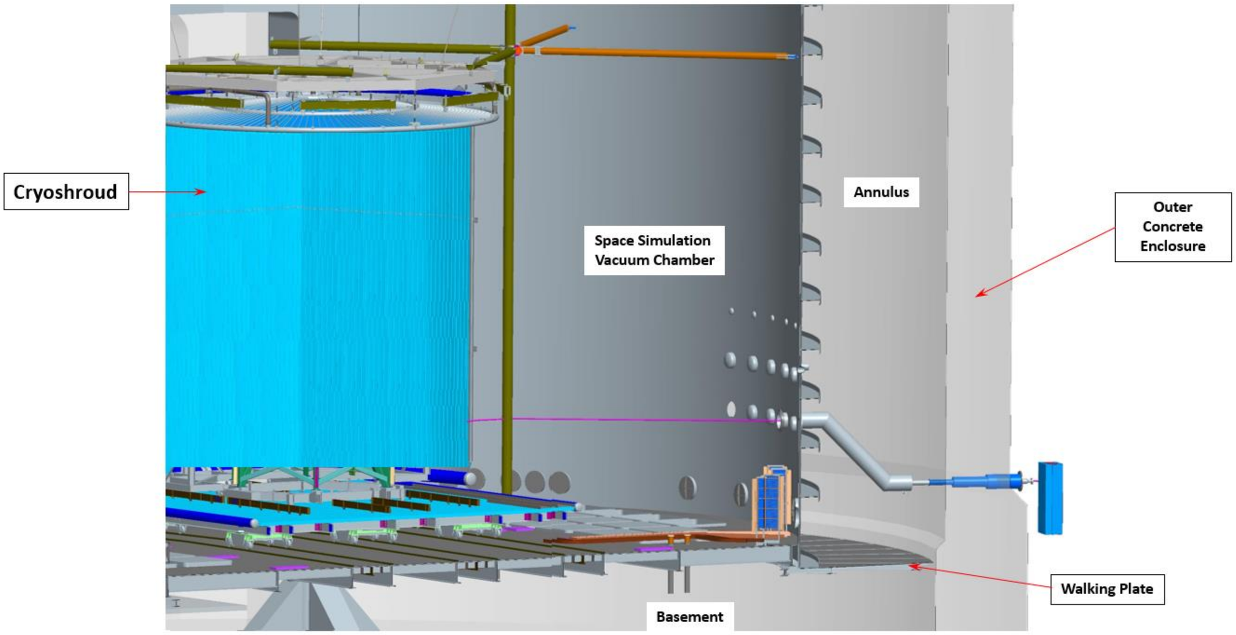

Figure 3: T-VAC test setup at SPF.

The entire SEC facility was modeled using Thermal Desktop (TD) software and includes all of the aforementioned systems, as well as the piping and other intricacies within SEC. Diffusion nodes were also included in the model to represent the volume of air within the annulus and basement in order to determine how the air within the facility will impact the temperature of various SEC systems during T-VAC testing. Other thermal conditions were also assumed, such as the outer surface of the concrete enclosure being held at ~70°F to represent the outside temperature during testing.

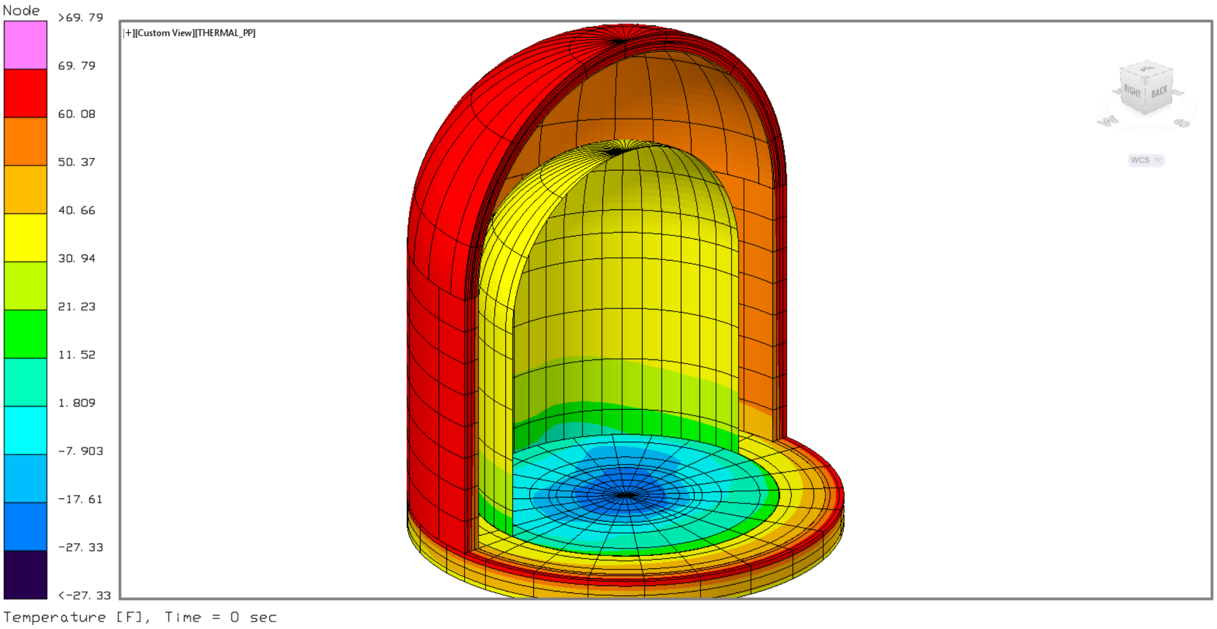

Figure 4: Results from initial thermal analysis for the SEC thermal model.

The main objective of the initial thermal analysis was to investigate the temperature distribution within the facility during the T-VAC test, specifically the chamber, basement, and air within the annulus and basement regions. The plot in Figure 4 shows the results from the initial thermal analysis for the SEC thermal model. The results from this steady-state case provided valuable information on the temperature distribution along the chamber floor. The chamber floor temperature is of particular interest because hardware in SEC that is essential to testing is located very close to the chamber floor.

In order for the T-VAC test to be successful, it is important that hardware such as the elastomeric seals on the basement piping, O-rings and Capralon bearing pads remain above their minimum operating temperatures of -20°F throughout the test. The plot in Figure 4 shows the chamber floor temperature to get as cold as -27°F, which is of course less than the minimum operating temperature of the hardware. The most effective way to address this problem and ensure that the chamber floor remains well above -20°F is to add patch heaters to the chamber floor in areas where the temperature is the lowest. The following section will provide a detailed explanation of how this was done in the TD model.

Model

The patch heaters that were chosen for this particular application are OMEGALUX silicone rubber fiberglass heaters. These heaters were chosen because they are lightweight, thin, insulated, flexible and capable of applying heat evenly to surfaces. They are also equipped with sensors to monitor their temperature during testing. These heaters are each 18”x18” with a watt density of 5 W/in^2, and will be installed in bays located underneath the chamber floor. The heaters also have a power limit of 1620 W, which must not be exceeded during testing.

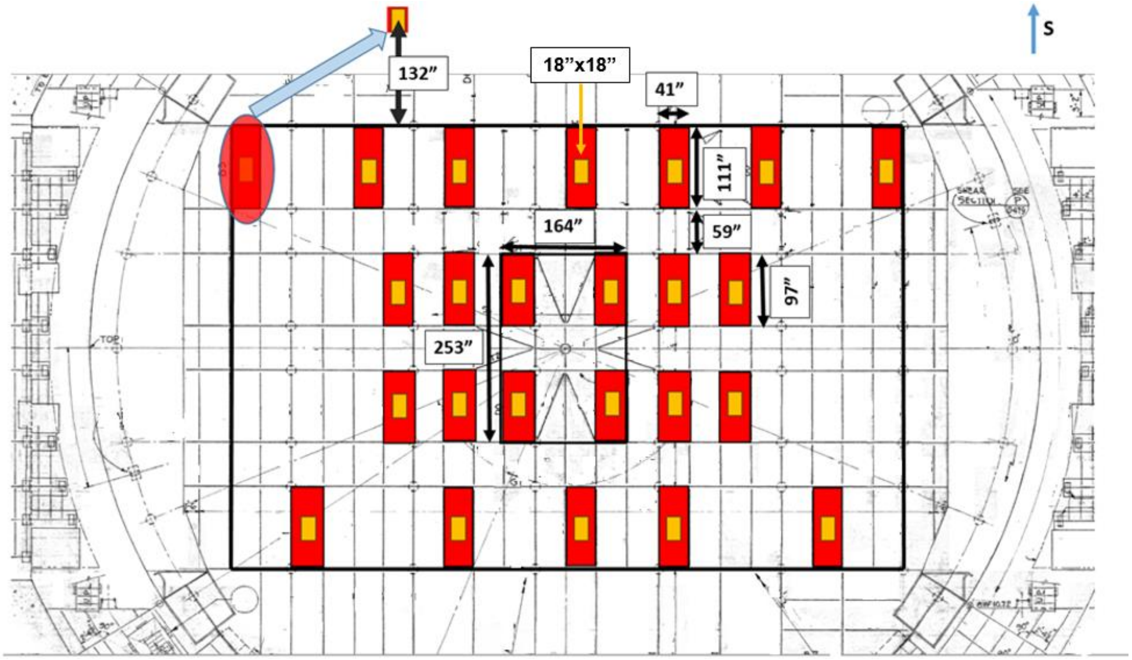

Figure 5: Heater location on SEC Chamber Floor.

The diagram in Figure 5 shows the location of all 24 heaters on the SEC chamber floor. The placement of heaters outlined in this diagram was determined to be the optimal configuration because this will allow heat to be evenly distributed across the entire chamber floor, which will reduce the temperature gradient across the chamber floor. The heaters (light orange) were placed in 4 different rows along the floor, and centered within their respective bay (red). More heaters were grouped near the center of the chamber floor since the initial results showed this particular area to be the coldest on the floor. This is due to the location of the cryoshroud, which is directly above the center of the chamber floor. Heaters were also applied to areas where GN_2 pipes penetrate through the floor, which also caused cold spots on the chamber floor.

The diagram in Figure 6 shows how the heaters were applied to the chamber floor in the TD model, which is the same configuration shown in Figure 5. The thermal analysis was run for a steady-state and transient case, which had a total period of 30 hours. In the model, the heaters were set to 0% power during steady-state (at t=0 s), and then set to run in proportional mode during transient (at t > 0 s). This was done in order to simulate a worst-case scenario in which the chamber is allowed to initially get as cold as possible followed by the activation of the heaters. This allowed us to observe the full capability of the heaters to increase the temperature of the chamber floor, and determine how long it takes for the heaters to reach steady state.

The heaters were modeled to turn on and off based on the temperatures of their respective sensing node, or controller. For instance, the on temperature was set to 40°F, while the off temperature was set to 50°F. Essentially, the heaters are modeled to turn on at the end of steady-state (t > 0 s), and continue operating until their respective sensing node reaches 50°F. When the sensing node drops to 40°F, the heaters will once again turn on.

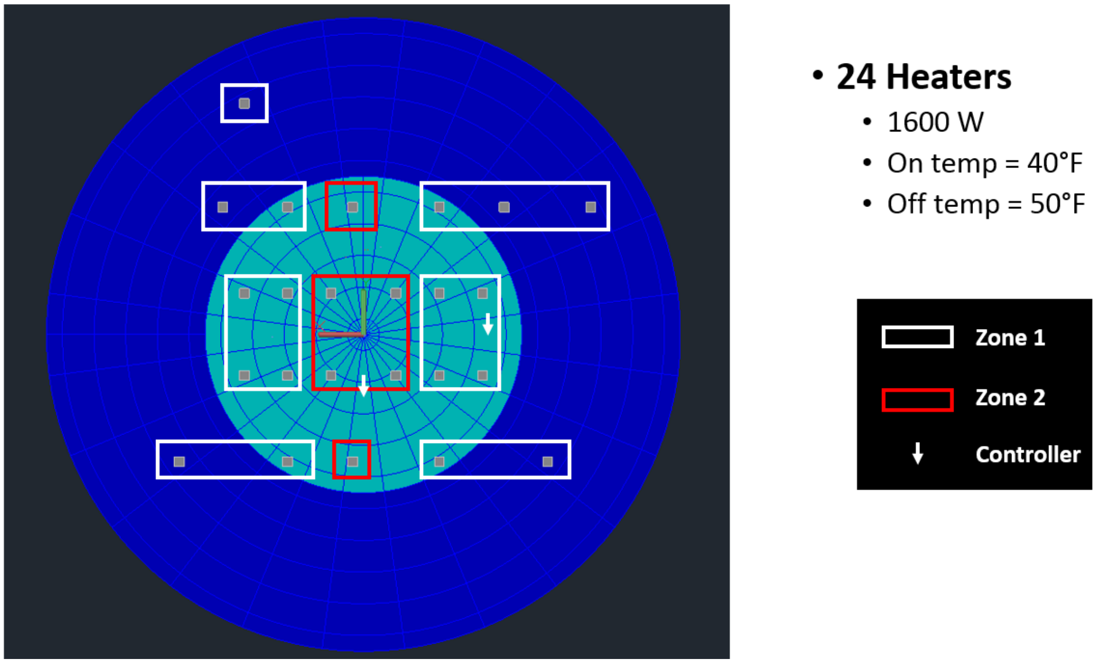

Figure 6: Heater diagram and configuration in TD Model.

Two controllers were used to control the operation of the heaters; therefore, each heater was divided into 2 zones as shown by the white and red boxes in Figure 6. In TD, two particular nodes on the chamber floor were chosen as the sensing nodes, and the temperatures of these sensing nodes were used to control the response of the heaters. So the heaters cycle on and off based on the temperature of their particular sensing node, represented by the white arrows in the diagram. An iterative process was done in order to determine which sensing nodes enabled a favorable, cyclic response of the heaters.

Figure 7 shows the heater position relative to the GN_2 piping configuration in the SEC basement. This diagram provides further justification for the placement of the heaters, which were placed closer to areas near pipe penetrations. The heaters in Zone 2 are controlled by one sensing node, and are placed in areas with more pipe penetrations, as shown in Figures 6 and 7. As a result, these heaters will be kept on for a longer period of time than the heaters in surrounding areas (i.e. Zone 1 heaters).

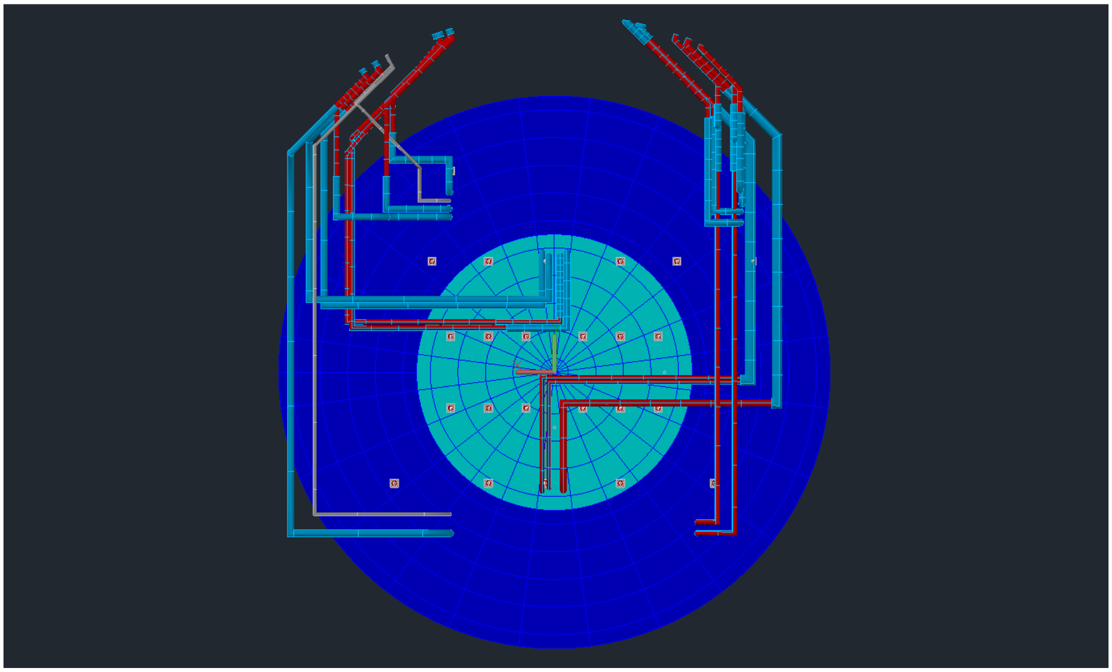

Figure 7: Heater diagram with GN_2 piping configuration.

Results

The post-processed plots from the transient analysis are shown in Figures 8 and 9. Figure 8 shows the temperature distribution across the chamber floor for the steady-state case, which shows very cold temperatures as expected. Figure 9 shows results at the end of the transient case, at t = 30 hours. As expected, the chamber floor temperature is noticeably warmer, especially near the heaters. The minimum temperature of the chamber floor, underneath the cryoshroud, increases from -32.5°F to 12.5°F, which shows that the heaters have a significant impact on the chamber floor temperature, and can effectively raise its temperature well above -20°F.

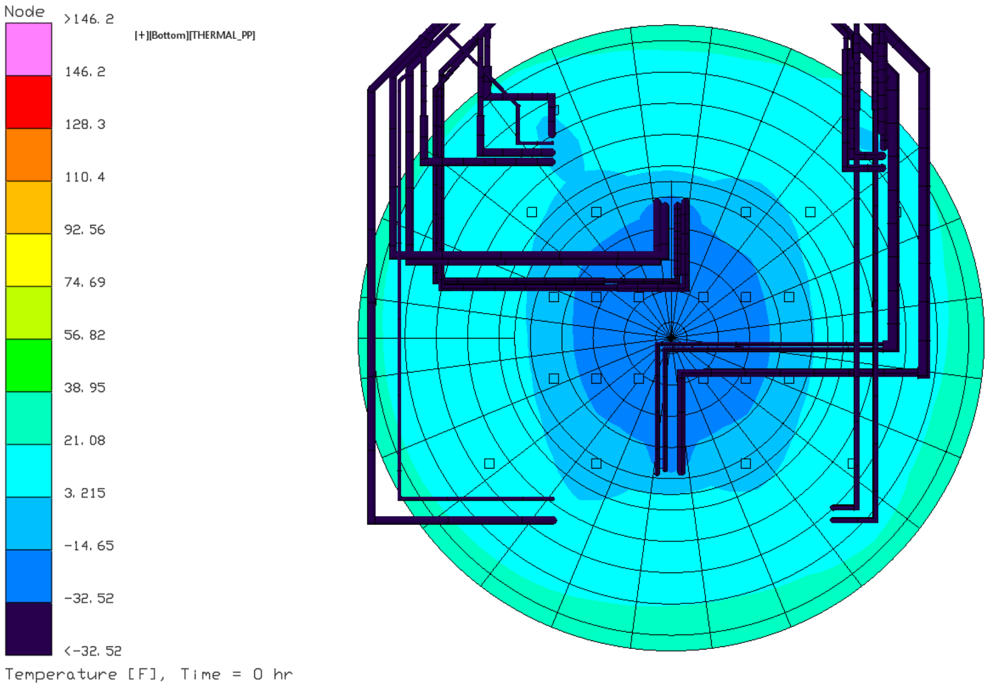

Figure 8: Chamber floor temperature distribution at t = 0 s.

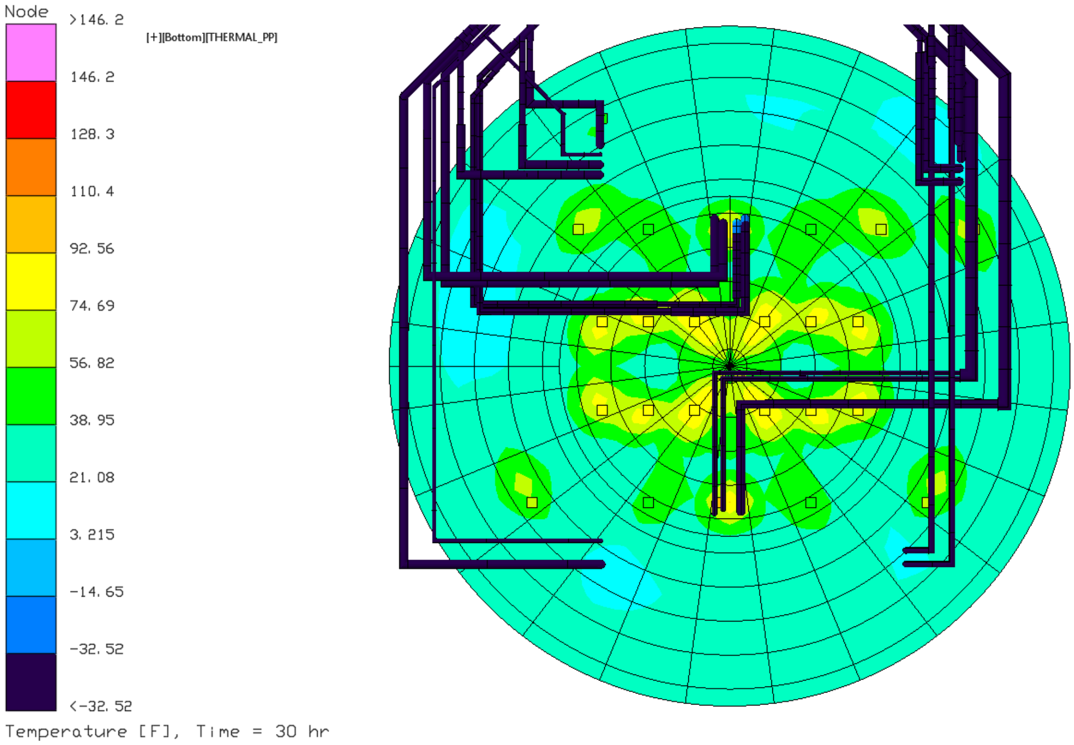

Figure 9: Chamber floor temperature distribution at t = 30 hrs.

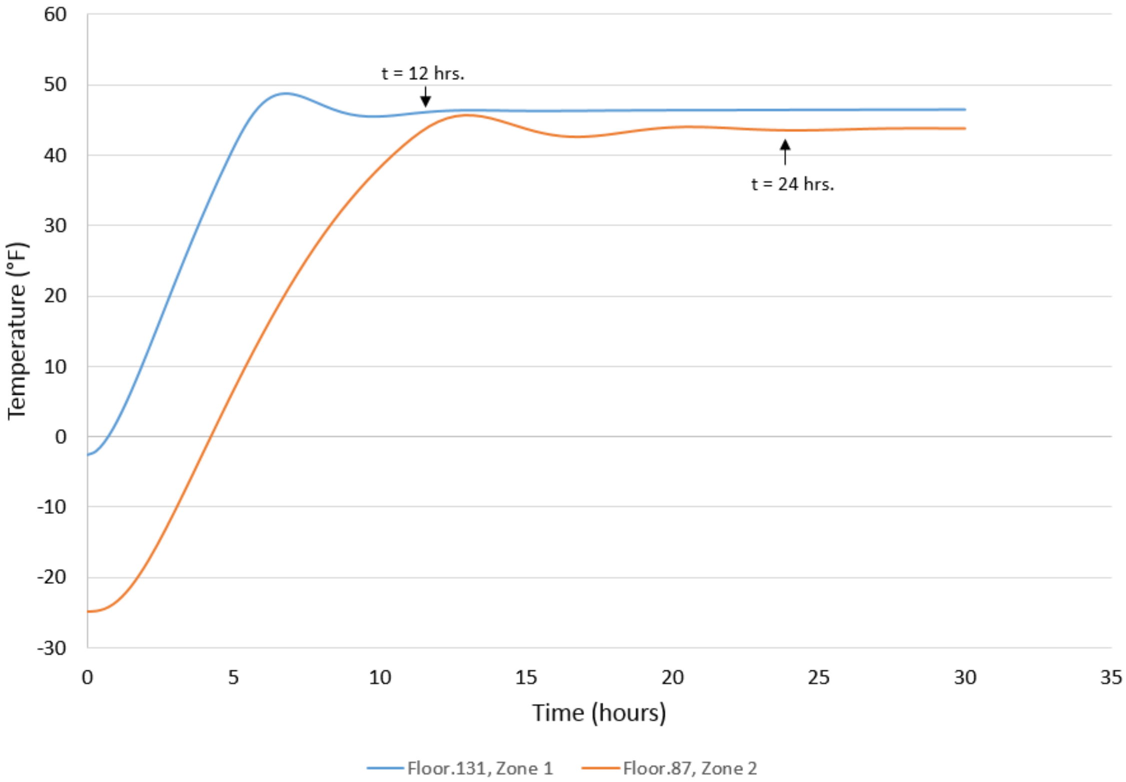

Figure 10: Transient response of the sensing nodes.

The transient response of the sensing nodes is shown above in Figure 10. The sensing node temperature is initially very low since the heaters are turned off for steady state (t=0 s). There is a similar response for both sensing nodes, which consists of a fairly quick increase in temperature, followed by slight oscillations due to the sensing node approaching the on and off temperatures, 40°F and 50°F, respectively. The sensing node temperature for Zone 1 increases faster than that for Zone 2 since the Zone 2 sensing node is placed in a colder area on the chamber floor near more pipe penetrations. At about t = 12 hours, the Zone 1 sensing node reaches steady state, while the Zone 2 sensing node reaches steady state within about 24 hours.

Figure 11 shows the transient response of the heaters in the top row on the chamber floor. The trend in the plots for each heater matches that of their designated sensing node, which involves a quick increase due to all the heaters turning on at the end of steady state, and then cycling as their sensing node reaches the on and off temperature. Heater 4 starts out with the coldest temperature in this row since it is located near more pipe penetrations than the other heaters. Heater 4 also takes the longest amount of time to reach steady state, due to the temperature of its sensing node. The responses for the heaters in subsequent rows follow very similar trends shown in Figure 11, and therefore, are included in the Appendix section.

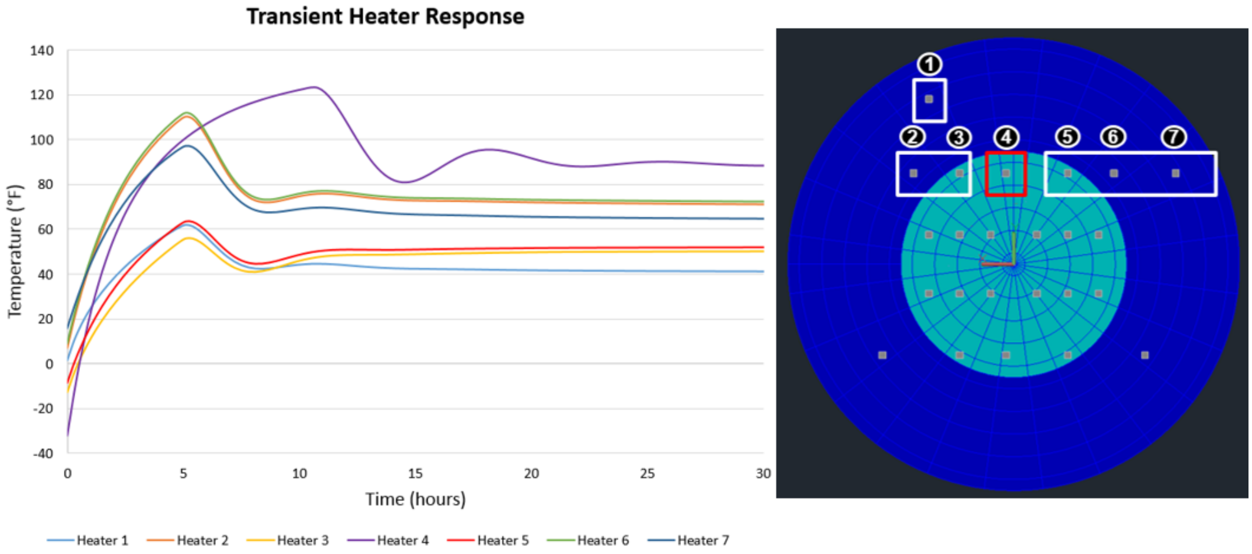

Figure 11: Transient response of heaters in the top row on the chamber floor.

The plot in Figure 12 shows the power output per heater in each zone over the 30-hour period. The heaters are shown to reach a maximum of 1600 W when they are initially turned on, which is followed by a cyclic response, as they turn on and off based on their sensing node temperature. As shown in the previous plots, the power output steadies faster for the Zone 1 heaters than those for Zone 2, indicating the heaters reaching steady state.

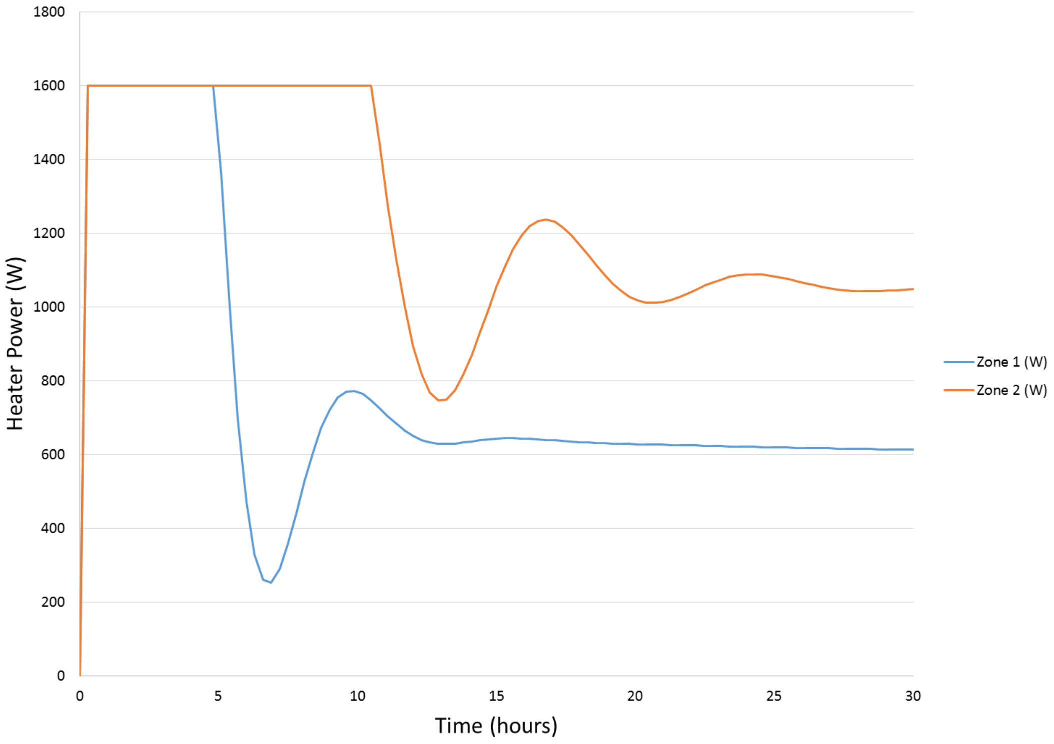

Figure 12: Power output per heater over time

Conclusions

The T-VAC test setup for the Orion spacecraft was modeled and simulated in Thermal Desktop. This TD model includes patch heaters that were applied to the chamber floor in an effort to increase its temperature. The results from the transient analysis show that the heaters were able to significantly increase the chamber floor temperature, especially in the colder areas near GN_2 pipe penetrations. The results from the transient run also showed the chamber floor to have a minimum temperature of 13°F at the end of the run when the heaters reached steady state, which is well above -20°F. Thus, these results helped to ensure that certain SEC hardware will remain fully functional during T-VAC testing.

This analysis also made it possible to determine the optimal configuration and placement of the heaters on the chamber floor. Each heater was modeled to output a maximum power of 1600 W, which is slightly less than its limit of 1620 W. Even with this condition, the heaters were still able to effectively warm the chamber floor, which shows that the heaters can remain well within their operating limits to increase the chamber floor temperature, especially when they output less power when reaching steady state. The temperature gradient in different areas across the chamber floor was also kept within a reasonable range, which results in less thermal stress on the chamber floor.

Finally, each heater was able to reach steady state within a period of 30 hours. Since this case represented a worst-case scenario in which the heaters are initially turned off, this can be considered a very favorable response shown by the heaters. During actual testing, the temperature of the vacuum chamber will start from atmospheric temperature (60-70°F) and the heaters will only be turned on when the chamber floor reaches extremely low temperatures. Therefore, these heaters will be more than sufficient for maintaining the chamber floor temperature within an acceptable temperature range throughout the duration of the test.

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Appendix

The following figures show the transient response of the heaters in the second, third and bottom rows on the chamber floor. The trends in these plots are very similar to those shown in Figure 11 for heaters in the first row on the chamber floor. The heaters all turn on at the end of steady state, and then proceed to cycle as their respective sensing node approaches the on and off temperature. The heaters in Zone 1 all have the same cycle. Similarly, the plots for the Zone 2 heaters also follow the same trend.

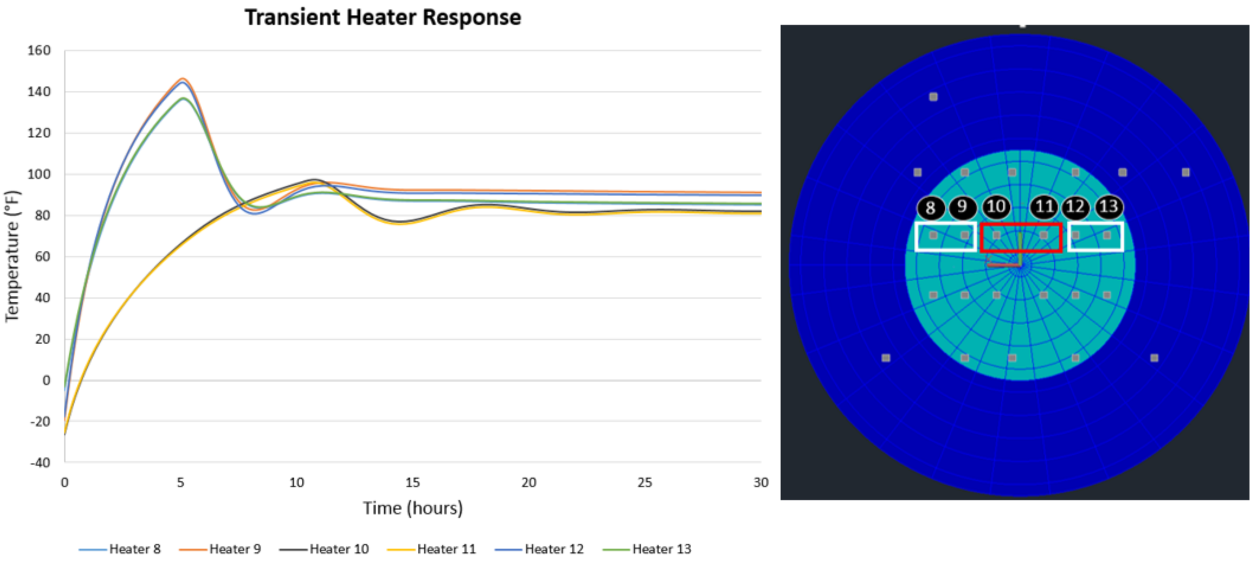

Figure 13: Transient response of heaters in the second row on the chamber floor.

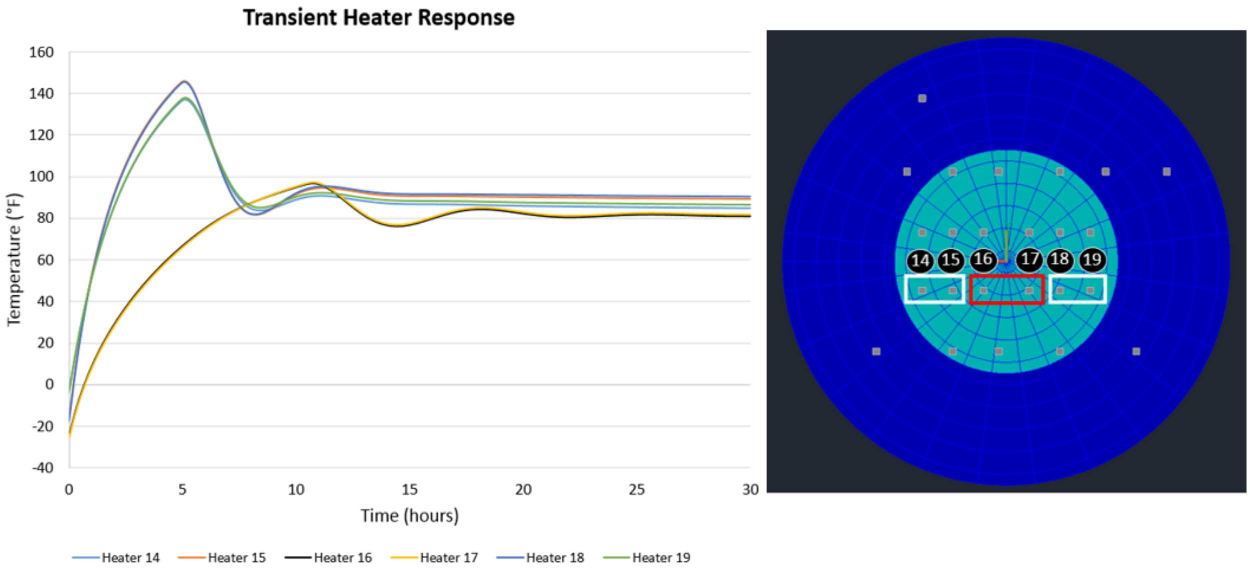

Figure 14: Transient response of heaters in the third row on the chamber floor.

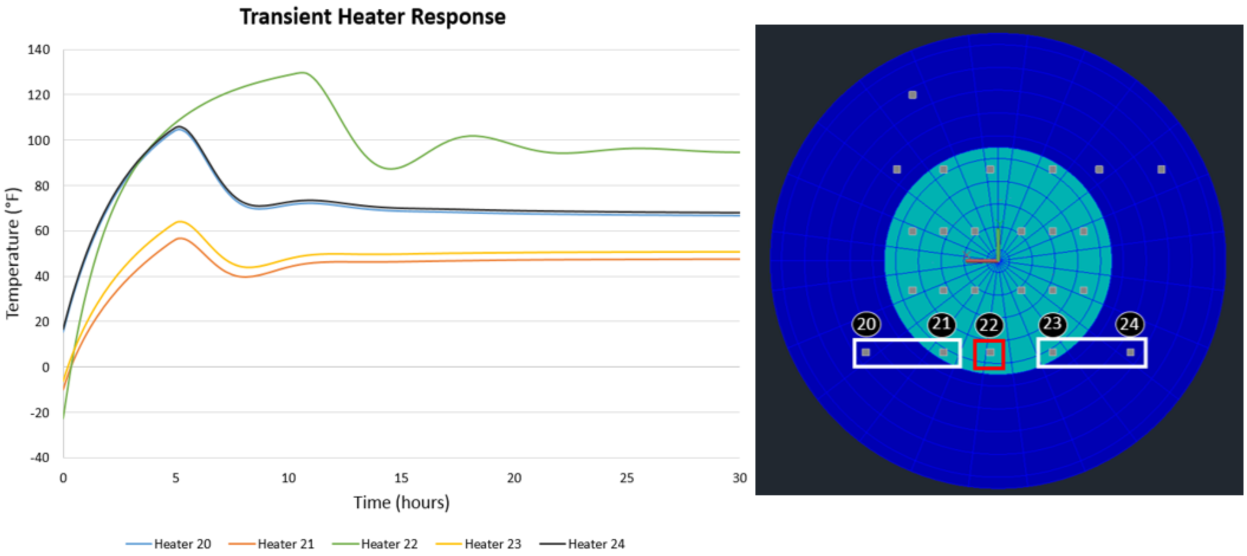

Figure 15: Transient response of heaters in the bottom row on the chamber floor.