

**Designing, Modeling, Constructing, and Testing a Flat Panel  
Speaker and Sound Diffuser for a Simulator**

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# Designing, Modeling, Constructing, and Testing a Flat Panel Speaker and Sound Diffuser for a Simulator

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## Abstract

The goal of this project was to design, model, build, and test a flat panel speaker and frame for a spherical dome structure being made into a simulator. The simulator will be a test bed for evaluating an immersive environment for human interfaces. This project focused on the loud speakers and a sound diffuser for the dome. The rest of the team worked on an Ambisonics 3D sound system, video projection system, and multi-direction treadmill to create the most realistic scene possible. The main programs utilized in this project, were Pro-E and COMSOL. Pro-E was used for creating detailed figures for the fabrication of a frame that held a flat panel loud speaker. The loud speaker was made from a thin sheet of Plexiglas and 4 acoustic exciters. COMSOL, a multi-physics finite analysis simulator, was used to model and evaluate all stages of the loud speaker, frame, and sound diffuser. Acoustical testing measurements were utilized to create polar plots from the working prototype which were then compared to the COMSOL simulations to select the optimal design for the dome. The final goal of the project was to install the flat panel loud speaker design in addition to a sound diffuser on to the wall of the dome. After running tests in COMSOL on various speaker configurations, including a warped Plexiglas version, the optimal speaker design included a flat piece of Plexiglas with a rounded frame to match the curvature of the dome. Eight of these loud speakers will be mounted into an inch and a half of high performance acoustic insulation, or Thinsulate, that will cover the inside of the dome. The following technical paper discusses these projects and explains the engineering processes used, knowledge gained, and the projected future goals of this project.

## Nomenclature

$dB$	= decibels	$\varphi$	= phase shift from $t=0$ (units rads)
$f$	= frequency (# of oscillations per second)	TL	= transmission loss
$SPL$	= sound pressure level (dB)	STC	= sound transmission class
$c$	= speed of sound through a material (m/s)	$R_f$	= flow resistivity ( $Pa*s/m^2$ )
$\lambda$	= wavelength	rayl	= unit for sound impedance
$\gamma$	= damping constant	F	= force exerted on an object
$k$	= external restoration factor (similar to when vibrations occur in elastic material)	$A_o$	= the area a force is applied to
$RT$	= reverberation time	$\sigma$	= tensile stress
$a_s$	= optimum Sabin value	$\varepsilon$	= tensile strain
$t$	= sound transmission coefficient of material	V	= volume of material
S	= surface area of material	m	= mass of material
E	= Young's Modulus of elasticity (Pa)	D	= density of object
$\rho$	= density of material ( $kg/m^3$ )	$L_o$	= original length of object
$\nu$	= Poisson's Ratio (no unit)	dL	= elongation/compression of object
amp	= amplitude	$\Delta L$	= change in length

## I. Introduction

The Avionic Systems Division and Human Interfaces Branch (EV3) under the National Aeronautics and Space Administration (NASA) at Johnson Space Center, is responsible for supporting, developing, and testing imagery, displays, controls, and audio systems. The Audio Development Laboratory, located within this division, is a key location for analyzing and evaluating electro-acoustic devices utilized in the space program. Located on site, is a dome structure that will be turned into a simulator. This simulator being modeled is referred to as the Dome and shown in Figure A1. It is a sphere; 12 feet in diameter with a section (72 inch in diameter) sliced off the bottom, and

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connected to a rectangular platform. Entering the Dome, the door is about 95.5 inches tall and 48 inches wide. The Dome also has vents along the circumference of the cutout section on the bottom. Across from the door, the vents are 32 inches apart, measuring from the bottom inside corners of the vents. *Figure A1* illustrates the Dome in 3D.

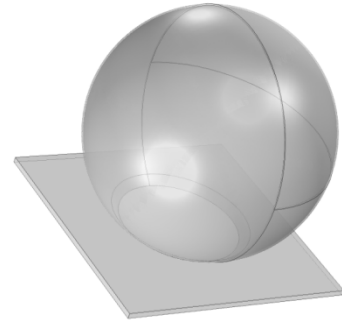


Figure A1: Pro-E model of dome

The idea is that the engineers in EV3 hope to design a projection and acoustic system that has the ability to create a realistic scene on the inside of the dome. The first problem has to do with the reflection of sound on the inside of the dome. How does the group create a sound diffuser that does not take up too much space, but gets rid of the effect of sound pressure focusing towards the middle of the sphere? The second problem discussed in this paper has to do with the speaker system. How do you create a system of 8 speakers that can be connected successfully to the Ambisonics system, but still follow the curvature of the Dome?

## II. Flat Panel Speaker

The first basic step for the flat panel speaker design in the dome was to be able to model everything in COMSOL, meaning a proficient knowledge of the program and how it works was important. Before transitioning to the concept of the warped speaker ideas, a basic flat panel speaker needed to be developed and tested in COMSOL to compare to a prototype. Therefore the steps were:

1. Model flat panel speaker in Pro-E
2. Design, and model a frame for the speaker in Pro-E
3. Run acoustics tests on flat panel loudspeaker plus frame in COMSOL and
4. Check the sound pressure level plots (SPL), and polar plots
5. 3D print prototype of the speaker's frame
6. Mount frame and already built flat panel speaker to a precision turntable and produce polar plots from acoustic measurements to compare to the COMSOL models collected earlier.

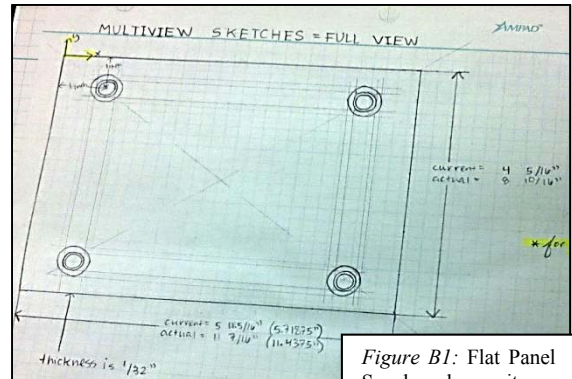


Figure B1: Flat Panel Speaker plus exciters

The basic flat panel speaker the group used had three main parts: an 11 and 7/16<sup>th</sup> ” by 8 and 10/16<sup>th</sup> ” piece of Plexiglas, exciters, and a power source to provide a sufficient alternating electric current to stimulate the exciters. Initially the power source provides an alternating electrical current which the exciters use to allow them to create vibrations. The Plexiglas responds to these vibrations and produces sound. A traditional loudspeaker differs drastically in operation when compared to a flat panel loudspeaker. Traditional loudspeakers rely on piston-like behavior utilizing permanent and electromagnets to produce sound. A flat panel loudspeaker allows sound waves to emit in every direction instead of being focused in just one spot.<sup>12</sup>This frantic vibration created by the exciters is best for high to mid range frequencies, but do not perform as well at lower frequencies.<sup>12</sup> *Figures B1 and B2* are technical sketches of the dimensions of the exciters themselves, and the flat panel loudspeaker with exciters.

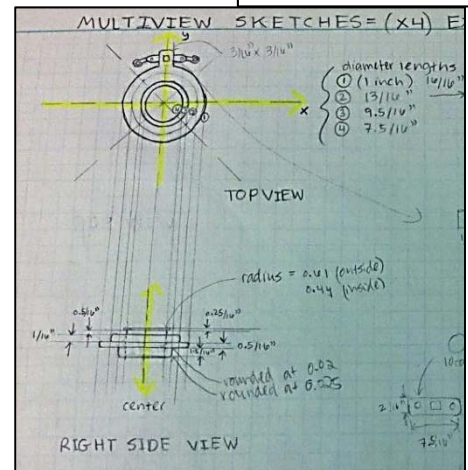


Figure B2: This is the breakdown of one exciter that was used on the flat panel.

Understanding the basic wave equation helps with understanding the vibrations created by the exciters, and the sound emitted from the speakers. D’Alembert, a physicist, came up with a one-dimensional un-damped wave equation to describe a general wave which is also a second order linear partial differential equation.<sup>16</sup>To explain this equation, break down a basic wave equation into the general wave equation, the boundaries, and the conditions for an example. The example is a string with negligible weight, fixed ends, no damping, only displacement in the vertical direction, and time starts at zero. When these conditions are plugged in,

several variables turn out to be zero. The following results from D'Alembert's solution of the wave equation, ending with the general wave equation.<sup>16</sup>

(Wave equation)	$a^2 u_{xx} = u_{tt}, 0 < x < L, t > 0,$
(Boundary conditions)	$u(0, t) = 0, \text{ and } u(L, t) = 0,$
(Initial conditions)	$u(x, 0) = f(x), \text{ and } u_t(x, 0) = g(x)$

When designing the frame for the speaker an important factor was the material to be used for the frame itself. The three options were building a frame out of wood, make a frame out of aluminum, or getting it 3D printed. COMSOL was useful in aiding this decision by defining the frame as wood, plastic, or aluminum under the materials tab, running a SPL plot, and comparing the effects of the material change. To be able to define the material properties, listed in the Nomenclature section, there were three important characteristics to define: propagation of sound through a material (c), the material density, the material's Young Modulus (E), and its Poisson Ratio (nu). The material dependency is usually provided through COMSOL. The Poisson ratio is defined as the negative transverse strain divided by the longitudinal/axial strain.<sup>3</sup> Poisson's ratio ranges from 0-0.5 for the most common materials, and it has no units. To find density it's simply the mass of the material divided by the volume. Young's Modulus (E) is used to measure the elasticity of a material or substance. Elasticity is defined as an object's ability to restore itself to its original state. E is measured by dividing the tensile stress by the tensile strain. Strain is the elongation/compression of an object divided by the length of the object. Stress is the force on the object divided by the area of the object.<sup>3</sup>The values (nu, E) used in the COMSOL models, were from the engineering toolbox.<sup>3</sup>Take a look at the following equations for more explanation.

- a)  $D = \frac{m}{v}$
- b)  $Stress = \frac{F}{A_o}$
- c)  $Strain = \frac{\Delta L}{L_o}$
- d)  $E = \frac{\sigma}{\epsilon} = \frac{F/A_o}{\Delta L/L_o} = \frac{FL_o}{\Delta LA_o}$

Going back to the material options, the availability of wood and aluminum is more abundant than the plastic for the 3D printer. Wood and aluminum also cost a lot less. However, physically building the frame takes more time away from other projects, compared to just getting it printed. The preparation for getting something 3D printed involved designing and modeling the frame pieces in Pro-E, setting up the print, and then waiting for it print. It can take all day to print, but that time can be used to work on other projects. With the wood and aluminum models, you would need to draw out all the dimensions and plan of action, and take a day or two building the frame. The other issue with material was how it affected the quality of sound produced by the flat panel speaker. A wood frame, when built correctly, can be very effective as long as there are ports for sound to escape. Wood is very popular in building woofers for acoustic systems. However, since the flat panel is constructed differently compared to traditional speakers, it needs more room for vibration to be effective. Wood and aluminum can be more rigid than plastic. In the end, the frame was 3D printed in two parts and glued together with acetone. The ABS plastic used, allowed the panel more ability to vibrate, and did not take up valuable time (8 hours per half to 3D print the frame). *Figure B3* shows one half of the frame after being printed.



*Figure B3:* Half of the flat panel speaker frame after being 3D printed.

In the next step the team mounted the frame and flat panel loudspeaker on the precision turntable and produced polar plots. Below, *Figure B4 and B5*, are the most recent polar plots of two separate runs. The SPL plots are repeatable and therefore can be trusted as reliable data. Under those figures are SPL surface plots of the flat panel loudspeaker and frame. These plots shows the SPL of the flat panel loudspeaker and frame with a vibration displacement of  $1e-8''$  at frequencies (f) 1600 Hz, 2000 Hz, 4000Hz, and 8000 Hz. The SPL is in dB, and the scale is

on the right side. In Figures B6-B9, the lowest SPL in dB is next to the down arrow below the color scale. The highest SPL in dB is next to the up arrow, above the scale. Notice the change in intensity of SPL as there is an increase in frequency (f).

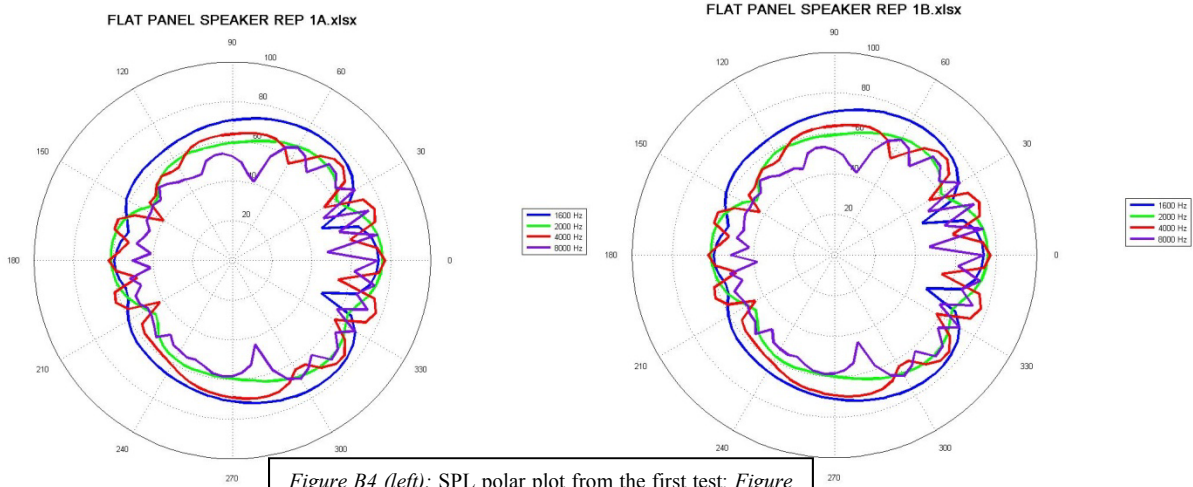


Figure B4 (left): SPL polar plot from the first test; Figure B5 (right): is from the second test.<sup>10</sup>

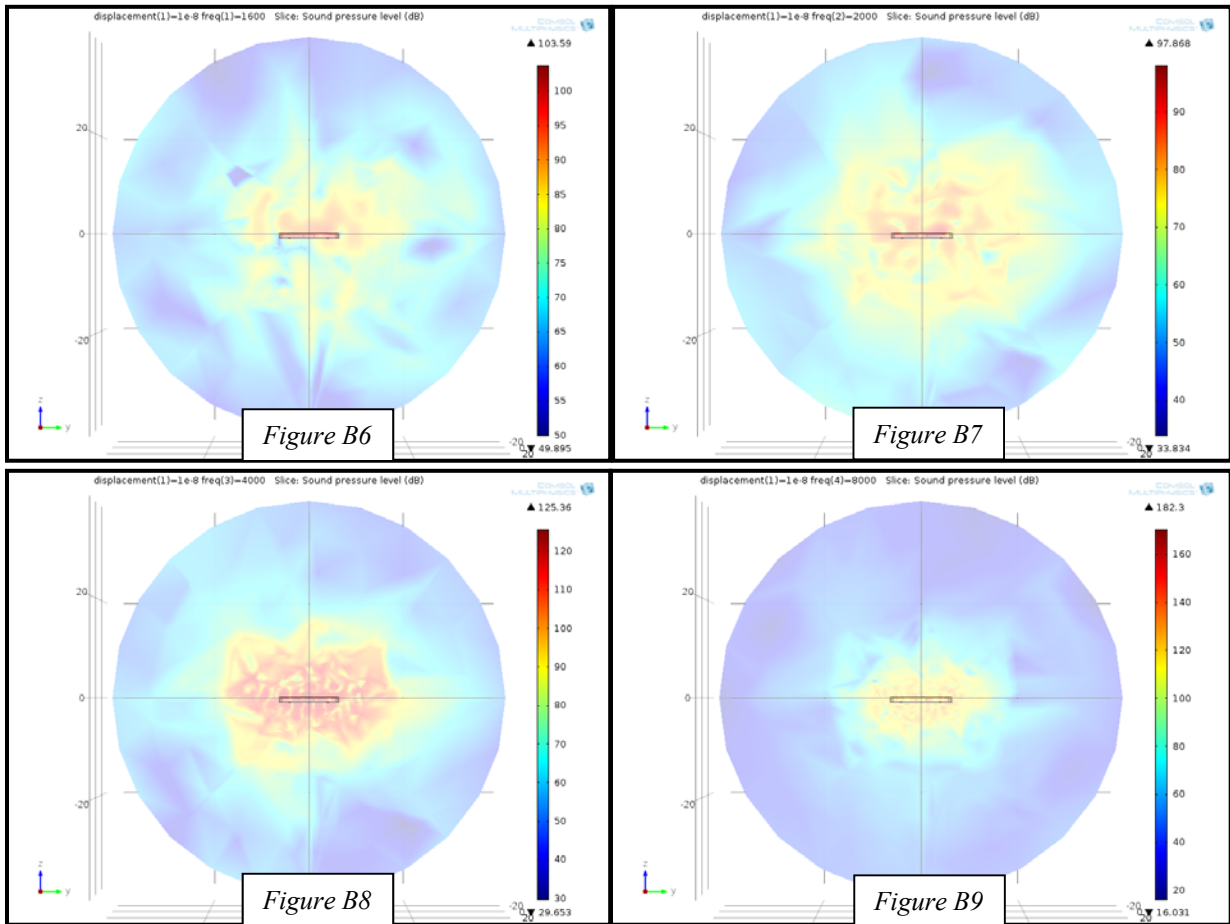
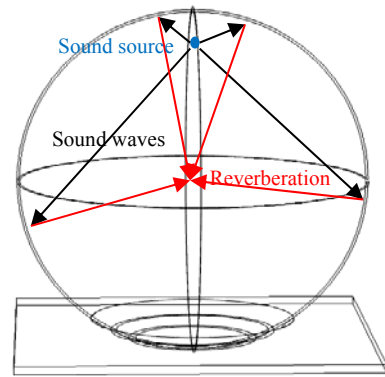


Figure B6: SPL plot in COMSOL Multi-physics, units are dB, of flat panel loudspeaker at 1600 Hz; Figure B7: at 2000 Hz; Figure B8: at 4000 Hz; and Figure B9: at 8000 Hz. Notice the change in dB scale on the side.<sup>10</sup>

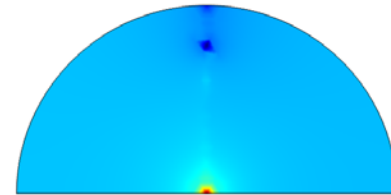
### III. Sound Diffuser

Sound waves are not simply absorbed or stopped when they reach a medium. Depending on the properties of the medium (like reverberation time), the SPL (or level of pressure created from the sound’s oscillations), and the intensity of the sound source, it can reflect, refract/transmit, or diffract. A reflection occurs when a sound wave reaches a medium, bounces off that medium and changes direction. Typically when sound reaches a medium, a portion of the wave undergoes reflection while the rest undergoes transmission across that reached boundary, created by the medium. The reflected portion of the sound wave can either turn into an echo or a reverberation.<sup>6</sup>In the sphere the second phenomenon occurs, reverberation. This is pictured in *Figure C1* to the right. If a person were to stand anywhere in the Dome, and were to speak, the majority of the sound waves would reflect off the aluminum medium and reverberate inside the dome. Since the Dome is shaped in a perfect sphere with only a small portion of the bottom shaved off, the curvature does not drastically change over the sphere. Therefore, the reverberation time is similar throughout the Dome.



*Figure C1:* Sound waves emit from the sound source, and reverberate off the walls of the sphere to focus (SPL) in the middle.<sup>10</sup>

This characteristic creates a feeling of “talking in one’s ear.” In other words the sound pressure level (SPL) created from the voice or sound source reverberates off the walls and focuses back in the middle. This is shown in *Figure C2*. A sound source was placed at the top of the Dome where the dark blue dot is located. Knowing that this is a SPL plot with red being the highest dB level, and dark blue being the lowest dB level, an observer can see that the sound waves reflect off the walls of the Dome and focus back towards the center. To turn this dome into an effective simulator, this effect needs to be decreased by installing a sound diffuser to disperse the sound throughout the air inside the dome.



*Figure C2:* Below is the COMSOL SPL plot of the Dome in 2D asymmetric. The color red represents the highest SPL (dB), and it decreases to dark blue.<sup>10</sup>

To determine the sound treatment needed to be installed in the Dome, various calculations can be used. The first method includes reverberation time (RT). Reverberation time is the time required for the sound pressure level in the room to reduce to 60 decibels (dB), or become inaudible to a human ear.<sup>3</sup>This mostly deals with higher frequencies due to the fact that materials, in general, are less absorbent at lower frequencies. To calculate the RT of a sound wave in a room, Sabin values ( $a_s$ ) should be found. Sabin values are similar to decibels in that they are used to describe certain properties of sound, but are typically the unit of choice for creators of theaters, or music halls.<sup>11</sup>The unit is dimensionless and determines how a sound is absorbed by a medium. Sabin values range from 0 to 1; with 1 being a material with 100% absorption. When compared to a decibel, a decibel is the measurement of the sound volume, not absorption.<sup>13</sup>Going back to the reverberation time, the typical RT ranges between 0.7 and 1.2 seconds at 500 Hz; the medium RT being 0.95 seconds. RT is solved for by multiplying 0.05 times the volume of the space (the Dome in this case), and then dividing it by the Sabin value ( $a_s$ ).<sup>11</sup>Therefore, you must either know the  $a_s$  value of the material to solve for the RT or measure the RT with a sound level meter to find the  $a_s$ . The team utilized a sound level meter to measure the SPL/RT in the Dome before sound treatment to compare the SPLs of the COMSOL simulations created with and without sound treatment. Another method to determine the optimal sound diffuser includes the sound transmission class (STC). STC determines the, “airborne isolation properties of a partition,” by finding the transmission level (TL) of the material (chosen sound diffuser in this case) at different frequencies.<sup>11</sup>Typically STL and TL values are used to determine how well the material can keep sound from penetrating an area. However, you can use these calculations to help analyze the effectiveness of the sound treatment by showing how it reacts to sound. To solve for TL, use equation b, below to find the calculated value, and then compare the results to standardized STC contours.<sup>11</sup>For a reliable STC value, around 6 frequencies should be tested to create a STC curve to compare to the standard curve. STC ratings higher on the curve mean the material is blocking most of the sound.<sup>11</sup>These standard curves can be found on the STC ratings website. The following are the two mathematical equations used to aide in selecting the correct sound diffuser.

a) 
$$RT = \frac{0.05V}{a_s}$$



b)

$$TL = 10 \log \frac{\sum S}{\sum tS}$$

While designing an effective sound diffuser, there were also a few physical constraints to consider. One of the limiting factors included the dimension of the availability of space inside the Dome. One of the most popular sound diffusers in planetariums, theaters, and music halls are barrel and pyramidal wall diffusers.<sup>5</sup>The frame of these diffusers are typically made out of high stretch fiber glass and are coated in an acoustic absorbing white gel, or wrapped in fabric.<sup>1</sup>However these diffusers would protrude too far into the inside of the Dome thus reduce the availability of space for people. Another issue would be the uneven surface created from the installation of these wall diffusers. For the simulator, one of the goals was to project a realistic scene onto the inside of the Dome. Surfaces with large sections of uneven portions are not optimal for this, and would hinder the quality of the projection. Another key factor when analyzing the inside a surface of the Dome with sound treatment is: are there any bumps or obscurities on the surface? With such a smooth surface, like the inside of the dome without sound treatment, the sound waves have only one path they can take. This amplifies the sound in a particular location, which in this project is the center in the Dome. If the walls were rough or had uneven surfaces, the sound now has multiple paths possible, and therefore diffuses the sound throughout the area inside the Dome.<sup>3</sup>When choosing a sound treatment, there has to be a middle ground between the two. The surface cannot be too smooth that does not diffuse the sound. However, it has to have enough roughness to allow the sound waves to travel in various paths, diffusing the sound.

After performing research for different materials for sound treatment, Thinsulate was identified as a potential candidate. Thinsulate is typically used in clothing to keep people warm in a cold environment. It can also be used for acoustic insulation, and the 3M Company has a special line for that particular use. To the right is an illustration of a typical Thinsulate sample for clothing.<sup>4</sup> Radiated heat from the body is absorbed by the fabric lining of the Thinsulate material, and then vapors of moisture get omitted from the fabric to keep the body warm. The acoustic insulation version does the same thing, but with sound.<sup>4</sup> In other words, the sound is absorbed by the Thinsulate, and then reflects off the interior of the dome and enters back into the Thinsulate. From layers within the Thinsulate, the sound is then dispersed in various paths. Therefore the Thinsulate is able to effectively diffuse the sound, and reduce the intensity of the reflections in the Dome.

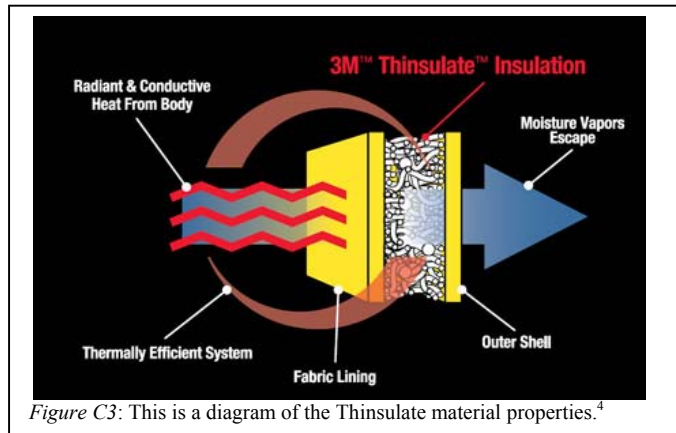


Figure C3: This is a diagram of the Thinsulate material properties.<sup>4</sup>

After selecting Thinsulate as a possibility for a sound diffuser, COMSOL was utilized again for acoustic analysis. The COMSOL models consisted of three main runs: one with just the Dome and no Thinsulate, one with 1 inch of Thinsulate, and one with 1.5 inches of Thinsulate. The geometry was all built in COMSOL. A vertical half circle with a radius of 12 feet and a rectangle located where the sphere cut off, was defined in a 2D work plane. Then the difference was taken of the half circle and rectangle to end up with a slice of the dome. Then the slice was rotated 360 degrees. This was done 3 times with different starting circle radii in order to create the aluminum layer of the Dome (0.5 inches), Thinsulate layer (1 or 1.5 inches), and inside air domain (remaining). To simulate the loudspeakers which were going to be used in the Ambisonics system, a power point source was placed at the corners of a square domain of air dimensioned the same way the Ambisonics was set up. Under the Acoustics-Solid Interaction, Frequency Domain physics in COMSOL, all of the air domains were selected under the first pressure acoustics model, and the aluminum layer of the Dome was defined as linear elastic material. To simulate the characteristics of the Thinsulate material, under pressure acoustics model 2, the Thinsulate layer was selected and defined as a macroscopic empirical porous model. The constants used were defined by the Miki principles, and the flow resistivity ( $R_f$ ) was defined by the units Pascal times seconds, divided by meters squared

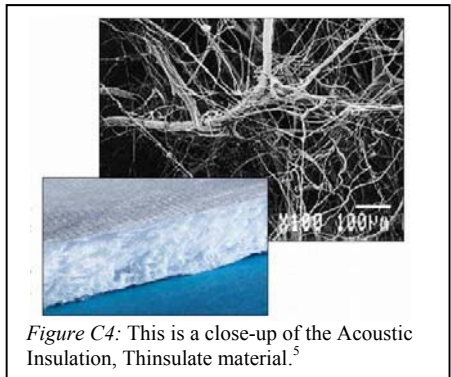


Figure C4: This is a close-up of the Acoustic Insulation, Thinsulate material.<sup>5</sup>

[Pa\*s/m<sup>2</sup>].<sup>13</sup> Finally, the outside boundaries of the aluminum layer of the Dome were selected under spherical wave radiation. COMSOL indicated that the sound waves would travel in a spherical like fashion and would not pass the boundaries selected. The following are the examples of the two runs done in COMSOL. As shown, the 1.5” Thinsulate model diffused the sound the most, and decreased the sound pressure level about 6 dBs more than the model with only 1 inch of Thinsulate in the Dome.

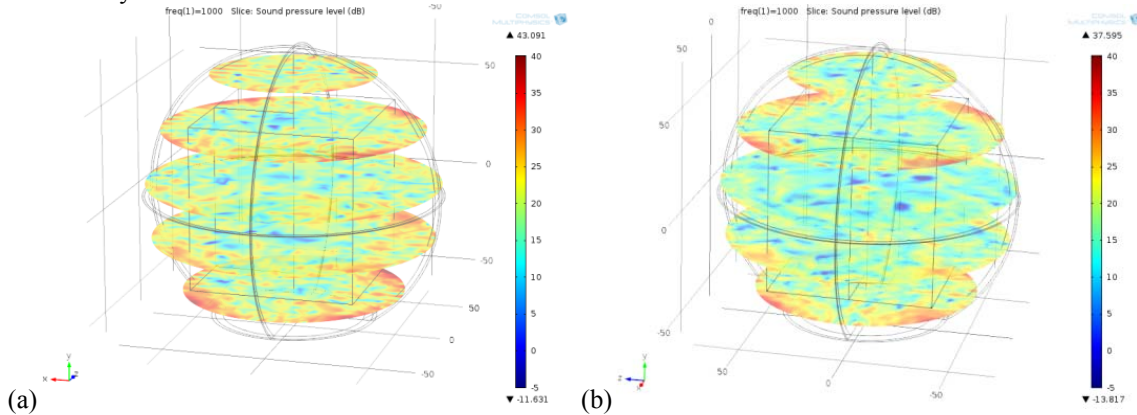


Figure C5: Above are SPL plots of the Dome in COMSOL; (a) is the Dome with 1 inch of Thinsulate on the walls; and (b) is with 1.5 inches on Thinsulate on the walls.<sup>10</sup>

#### IV. Conclusion/Future Goals of Project

The primary contributions to this project included the acquiring of knowledge and the mastering of COMSOL through the analysis of the flat panel loudspeakers, warped speakers, and sound diffusers. The design, model, and testing of prototypes have been completed, so the next step is to create the final system to install into the Dome. A layer of 1.5 inches of Thinsulate will be installed into the interior of the Dome and secured by a metal skeleton of 20, 0.5 inch radius curved tent poles connected at the top by a ring system. Refer to figure D1 for this diagram. The Thinsulate will have a layer of gray material quilted over the top to get the optimal color for the projection system. The metal skeleton will be attached to the Thinsulate and quilted by strips of gray material along the inside of Dome to hold the poles in place. The bottom of the poles will have a thicker, heavier duty material, similar to a tent that will let the poles slip into a secure pocket. The eight flat panel loudspeakers will be aligned in a square shape and inserted into the Thinsulate and quilt material to complete the projection system. The speakers will be connected the computer running the Ambisonics and projection system. A future goal is to stream real time data, from a camera and audio feed, to assess the system performance, and then go back and create an interactive virtual scene. A Multi-directional treadmill will then complete the simulator, and allow it to be used as a training tool or educational tool for the space program.

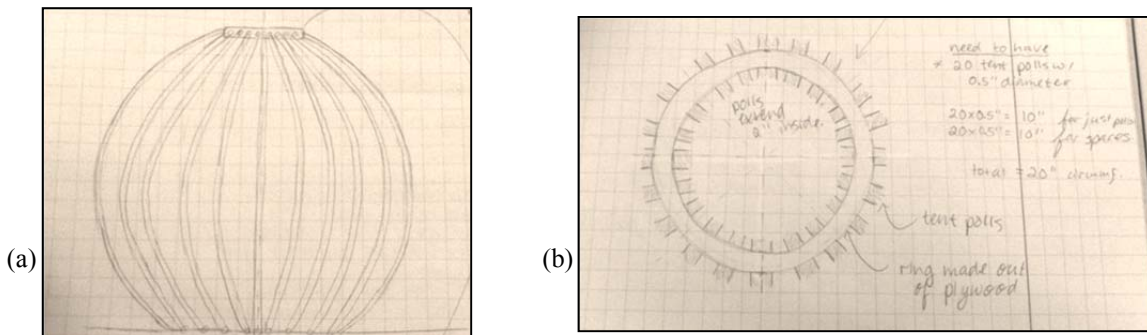


Figure D1: These are technical drawings. (a) This is the side view of the metal skeleton that will be used to hold the Thinsulate in place; (b) is top view of the ring that will be used to connect all the tent poles together at the top.<sup>10</sup>



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