

Characterization of Thermal and Mechanical Impact on Aluminum Honeycomb Structures

Christen M. Robinson¹

Jackson State University, Jackson, MS, 39217

This study supports NASA Kennedy Space Center's research in the area of intelligent thermal management systems and multifunctional thermal systems. This project addresses the evaluation of the mechanical and thermal properties of metallic cellular solid (MCS) materials; those that are lightweight, high strength, tunable, multifunctional and affordable. A portion of the work includes understanding the mechanical properties of honeycomb structured cellular solids upon impact testing under ambient, water-immersed, liquid nitrogen-cooled, and liquid nitrogen-immersed conditions. Additionally, this study will address characterization techniques of the aluminum honeycomb's ability to resist multiple high-rate loadings or impacts in varying environmental conditions, using various techniques for the quantitative and qualitative determination for commercial applicability.

I. Introduction

Since the beginning of recollection, man has been on a mission of great discovery and development. Centuries later, this holds true, as exploration efforts began to expand away from the world on which we live, to the unknowns of outer space. As time continues, we have a better sense of familiarity with our universe, though, as a universal society, we do not have an understanding. The procurement of material knowledge and improved techniques in synthesis has led to an array of multifaceted tunable materials. Alongside of recent developments, we have consequently gained increased scientific and mechanical skills concerning non-synthesized materials. Having orbited the Earth and landed on the moon, the desire for a higher understanding of the soon-to-be misnomer "unknown" has intensified. Permanent space stations and mobile analysis systems; developments are now underway for habitation on the moon.

For this to happen, lightweight, highly durable and cost-effective materials are being developed; materials that can withstand the stress of cryogenic temperatures and interaction with space debris. This study addresses the development of a protocol for the evaluation of the aluminum honeycomb material's behavior within cryogenic temperatures. One of the goals of the study is to observe patterns in the behavior of metallic cellular solids (MCS) due to the varying environmental testing conditions.

II. Background, Materials, and Methods

Aluminum honeycombs are highly useful because of their high strength to weight ratio. This is due to the angles being oriented at 120° which minimizes the surface area for a given volume. This allows a honeycomb to use the least amount of given material to create a lattice cellular network for the given volume. Structurally and mechanically favorable, honeycombs greatly absorb mechanical energy at ambient temperature when crushed out-of-plane. Synthetically, honeycombs are an assemblage of cellular solids made from thinly-walled open prismatic cells filling a plane, which is witnessed in beehives. The design superiority of honeycombs lies in the orientation of the planes. Orienting the planes at 120° minimizes the total surface for a given volume, similar to how three bubbles form a hexagon to minimize their total surface tension^[7]

Industrial synthesis, which is typically used for high-performance sports equipment, aerospace flight hardware, and racing shells, generally comprises an expansion process; which involves partially adhering thin sheets along

¹ NASA Student Research Intern, NASA Engineering, Kennedy Space Center, Jackson State University

specific [desired] lines, then expanding into honeycomb shapes. Another method involves corrugating the sheets into half hexagonal shapes, aligning, stacking and lastly adhering the sheets upon each other.^[11]

Throughout history, honeycombs have had wide commercial application, however little is known about the mechanical behavior of honeycombs under cryogenic temperatures. Cryogenics is a branch of physics that involves the study of temperatures below -150°C (-238°F or 123 K), the methods to achieve such temperatures, and the effects the low temperatures have upon materials. It is important to note the material's performance as being brittle or ductile, where ductile-to-brittle transitions can often occur under cryogenic temperatures.^[8, 11]

For this research effort, nine aluminum honeycomb samples, measuring approximately $\sim 3.5\text{ in.} \times \sim 3.5\text{ in.} \times 3\text{ in.}$ were received from Embry-Riddle Aeronautical University (ERAU). ERAU had performed impact testing on eight of the samples and the ninth sample was used as a reference. The samples were subjected to two impact rates, 50 Joules (J) and 100 J, see Figures 1 and 2, and experienced four environmental conditions: ambient environment, water (H_2O) immersed, LN_2 -cooled and LN_2 immersed. For LN_2 -cooled, the honeycombs were immersed in LN_2 until reaching -196°C , then quickly removed and placed into an insulated container with less than 100 milliliters of LN_2 inside. "Immersed" denotes that the fluid level was slightly above the top of the sample to render it fully submerged. The water used for the H_2O Immersed samples was distilled H_2O .^[1-2, 11]

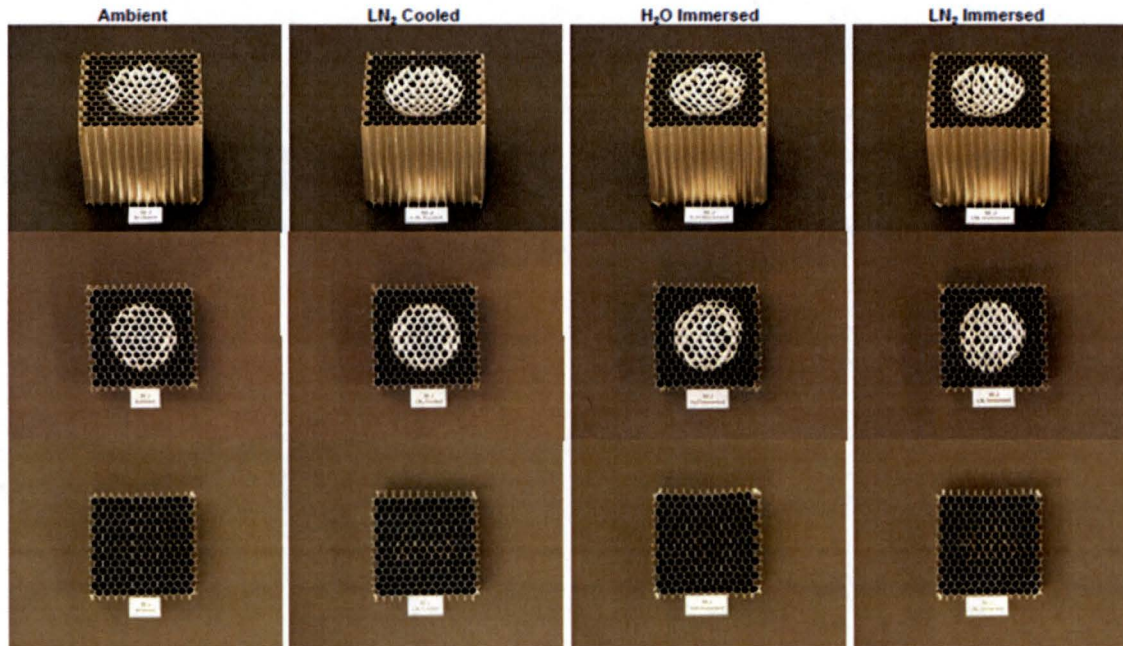


Figure 1: Honeycomb samples impacted at 50 J under different environmental conditions

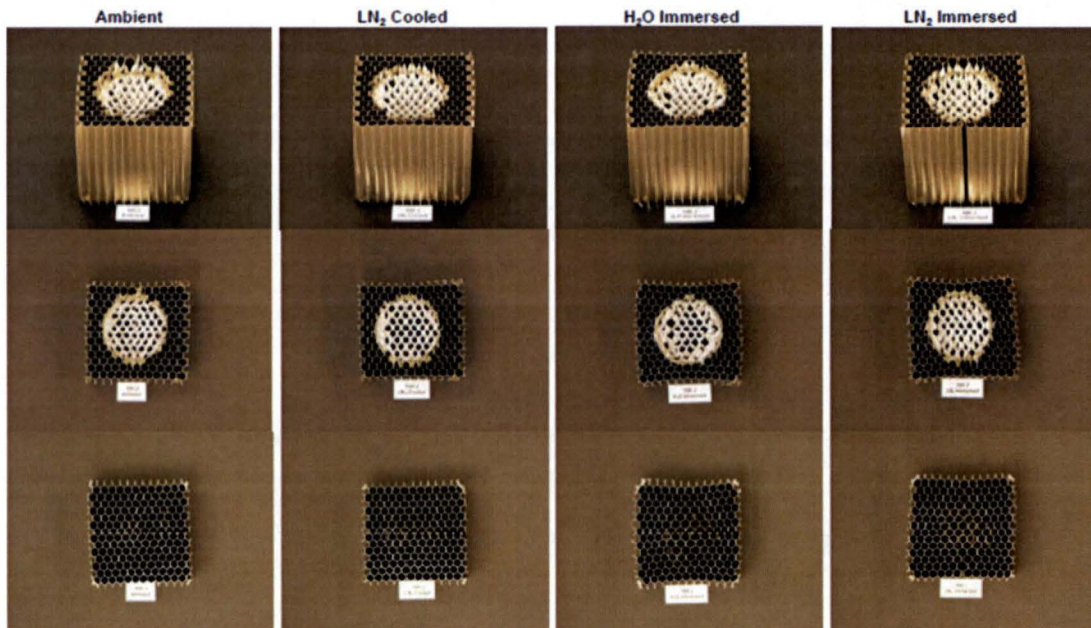


Figure 2: Honeycomb samples impacted at 100 J under different environmental conditions

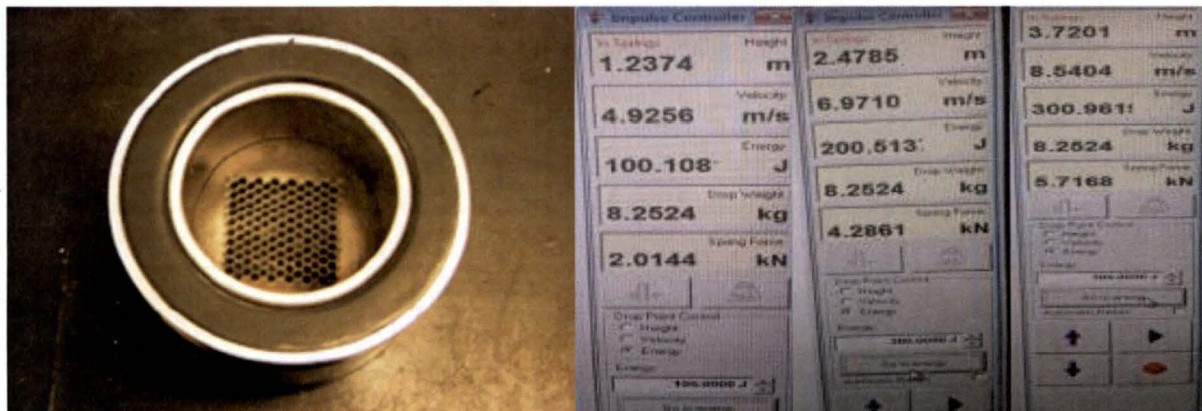


Figure 3: Insulated impact container and the settings for various load rates of the impactor

A. Impact Testing

Impact testing was carried out with a spring-assisted, Instron 9250 HV impact test system using a 2 in. diameter, hemispherical drop-weight impactor, equipped with a temperature control chamber and a pneumatic rebound brake (Figure 4), and placed into the insulated steel container and impacted under the four environmental conditions at 50 J and 100 J. [1, 3, 11]

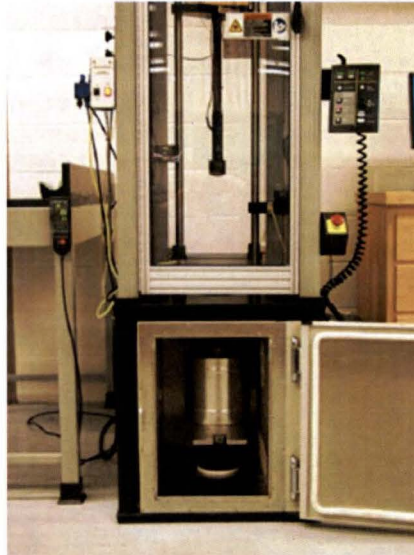


Figure 4: Instron 9250 HV impact test system at ERAU.

Impact-testing concerns gauging an object's ability to withstand high-rate loading before fracturing or deformation. The energy absorbed is measured visually, and more importantly, numerically, where impact force is measured. Various parameters can be assessed as a function of time; force, displacement, absorbed energy, and velocity, which can disclose strain-rate sensitivity. Values of interest include maximum load, energy required to reach maximum load, total absorbed energy, and deflection to maximum load. Plot shapes yield insight to impact dynamics, structural, and mechanical performance (brittle or ductile behavior). It is noted that jagged patterns that end with a steep drop are characteristic of brittle failures, while smoother, more rounded patterns and drops are indicative of ductile failures. Geometry has fittingly played a great hand in the production of materials possessing high strength-to-weight ratios, ranging from arches and triangles to cylinders and hexagons.^[11]

B. Non-Destructive (NDE)

The following non-destructive evaluation (NDE) methods were used to evaluate the impacted samples. As lunar missions are extremely costly, timely, and aerospace materials and parts are relatively expensive, it holds great importance to be able to examine aerospace constructs non-destructively.

a. Computed Tomography (CT) Scanner

The CT scanner, also known as a CAT (Computer Axial Tomography) scanner, is a technique whereby various views can be obtained, internally, and externally, generating data unable to be obtained visually. Tomography is the process of three-dimensional (3D) image fabrication via penetration from ionized waves. This is achieved by the capture and combination of hundreds and thousands of sectioned 2D images, rotating either the sample or the X-ray 360° about a single axis, to form a comprehensive 3D image. From this, with the aid of 3D graphical software, CT can be performed to obtain cross-sectional information, depth analysis, and at times volumetric data.^[4-5, 9-11]

With the aid of the modeling software, it was expected that the dimensions of the separate compressions from impact, as well as the volume of the impact area, could be measured, providing plausible conventional material behavior and characteristics of failures in defined environments. A trial assessment was run upon an impacted sample using a *Northstar NSI X-5000* scanner. Though the CT scanner is generally excellent for NDE, specifically 3D modeling for cross-sectioning, the method was inconclusive in the timeframe of this study.

b. X-Ray Analysis

X-ray machines are commonly used to inspect equipment and luggage for commercial travelling companies. It is also used within industry to detect imperfections and possible defects within materials. It was hoped that this machine would show deformation characteristics; however, the x-ray images were not clear; the stress points and compressions of the impact area were not clearly distinguishable from the outer walls.

c. Coordinate Measuring Machine (CMM)

A CMM is an imaging device that uses points about an imposed plane to measure various parameters of an object. Employing all three axes, the measurements taken by a probe can be mechanical, optical, laser, visible light (generally white). A CMM reads measurement about six degrees of freedom. The LN₂-cooled 50 J honeycomb was selected for evaluation to shed insight upon material behavior under cryogenic conditions. At 82x magnification, the sample showed splitting at the adherent (Figure 5), indicating that the honeycombs were corrugated sheets glued together, also leading to believe that the adhesive was not conducive to high-rate loading resistance in cryogenic atmospheres.^[6]

For the depth analysis of each impact, each sample was measured using an 18mm hemispherical stylus on a Brown & Sharp Global Image 9128 CMM (Figure 6), which has an accuracy of up to ± 0.0002 in. The probe took measurements at four corners of the top face of the cube to gain a value for the flatness of the surface, creating a plane. From the acquired plane, three separate points were taken relative to the lowest point of impact to quantify the maximum depth of impact. Results are listed in Table 1. Though visually undetectable, the orientation of the plane is generally subject to change after impact. "Flatness", as seen in the table, is a correction measurement that describes (in inches) how vertically offset the measured plane is with respect to a non-raised surface. It is the distance the actual plane is vertically offset with respect to a completely flat surface. After the flatness was obtained, three depth measurements were taken with respect to the measured surface plane in order to more accurately measure the lowest point of impact within the damage area.^[6]

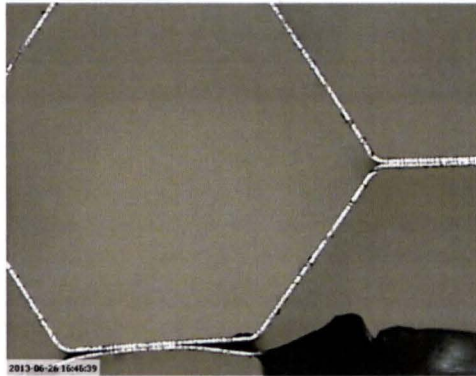


Figure 5: Using the Micro-Vu Excel 654 UC, the 50J LN₂-cooled sample was observed at 20x magnification. The cell walls can be seen splitting apart from each other.

	Flatness (inches)	Depth 1 (inches)	Depth 2 (inches)	Depth 3 (inches)
Ambient (50 J)	0.0029	0.3736	0.3768	0.3754
LN₂ Immersed (50 J)	0.0019	0.3621	0.3617	0.3567
LN₂-cooled (50 J)	0.0018	0.3634	0.3646	0.3638
H₂O-Immersed (50 J)	0.0018	0.3489	0.3491	0.3481
Ambient (100 J)	0.0015	0.7230	0.7213	0.7257
LN₂ Immersed (100 J)	0.0027	0.6036	0.5973	0.5945
LN₂-cooled (100 J)	0.0028	0.5674	0.5689	0.5689
H₂O-Immersed (100 J)	0.0099	0.5831	0.5849	0.5841

Table 1: A table of coordinate data collected from the probing CMM

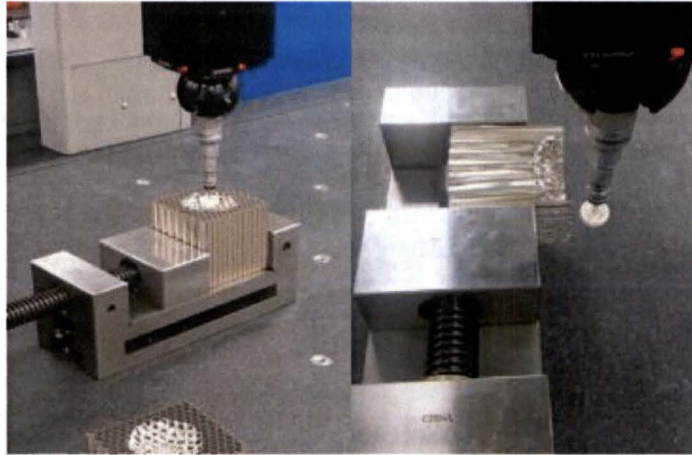


Figure 6: Depth analysis was performed on a NDE sample and a cross-sectioned impacted sample using a Brown & Sharp Global Image 9128 CMM

d. Cryogenic Thermocouple Testing

A developmental experimental test method (Figure 7) was set up to evaluate the temperature response at cryogenic temperatures in the vertical direction (parallel to the honeycomb structure) of impacted aluminum honeycomb compared to non-impacted honeycombs. To allow for more isolation and thermal control of the test specimen thermocouples were strategically placed (see Figures 8-9) across the projected impact boundary on the test samples to try and measure present minor differences. The samples were either virgin (metal alone, non-insulated), or were filled with insulating aerogel beads (see Figure 10). The data was tested as a transient thermal performance of cellular solids over time (seconds) versus temperature (Celsius).

For the experimental set-up, a 3.5 x 3.5 x 3 in. virgin aluminum honeycomb was placed in a 4x4x4 cardboard frame, open on the top and closed on the bottom by a sheet of aluminum tape. The sample was centered inside the box, allowing for approximately a 1/2" gap between the edge of the sample and the side of the frame (see Figure 6)—this gap was filled with aerogel beads for test #2 (Figure 10). The bottom of the sample was secured to the adhesive side of the aluminum tape (see Figure 9). This surface was placed in LN₂ during testing, effectively establishing a 77 Kelvin (-321°F) isothermal boundary along the bottom of the honeycomb sample. Six thermocouples were employed to record the transient performance: four placed diagonally on the top (warm side) of the sample from the middle to the outer corner, and two affixed on opposite sides, toward the bottom (cold side) of the sample (see Figure 7).

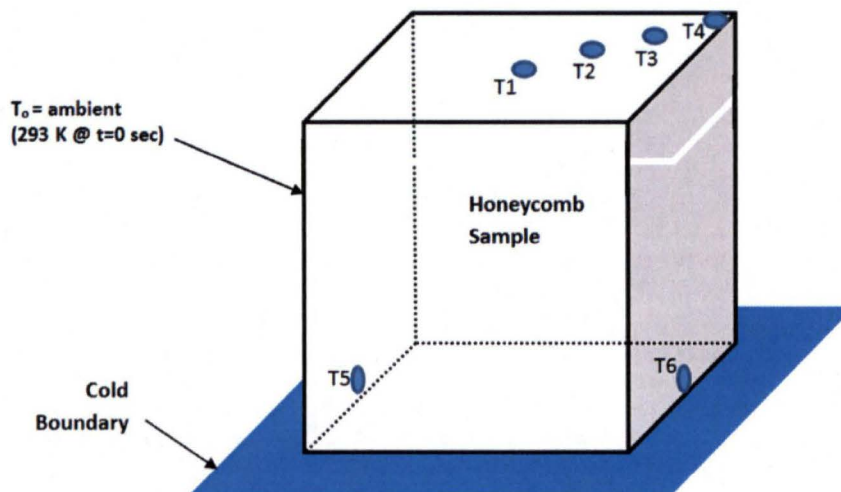


Figure 7: Experimental set up for thermocouple cryogenic testing. Bottom of the test set-up is the cold boundary.

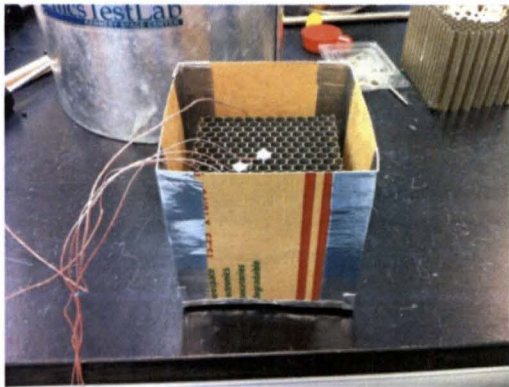


Figure 8: Honeycomb sample inside the test container



Figure 9: The bottom of the test container

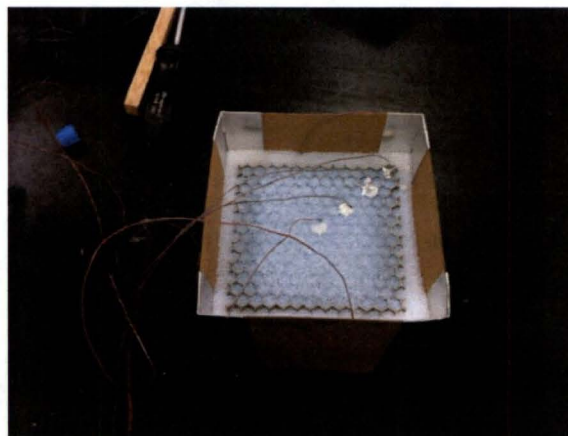


Figure 10: Aerogel-filled and surrounded honeycomb. The box was completely filled with aerogel before testing

Test 1 was conducted with the virgin honeycomb, where data logging (at a rate of 1 reading every 5 seconds) began on thermocouples 1-4. The bottom of the test set-up (aluminum tape side) was held in LN_2 until the temperature readings bottomed out and remained stable for a number of minutes. This was defined as the steady state condition, and the test was terminated after an adequate number of data points were taken.

The second test was conducted with aerogel filled around the sample and inside the honeycomb cells (see Figure 10). The test followed the same procedure as the honeycomb testing. Below is a time vs. temperature graph comparing the aerogel-filled and virgin samples. Time restraints did not allow for testing of all samples, but preliminary results on one impacted sample does indicate some differences in heat flow in the axial (vertical) direction. Further examination would be required, but it is expected a comparison of virgin sample to impacted samples could potentially give valuable information of thermal performance behavior differences due to changes in impacted cellular structure.

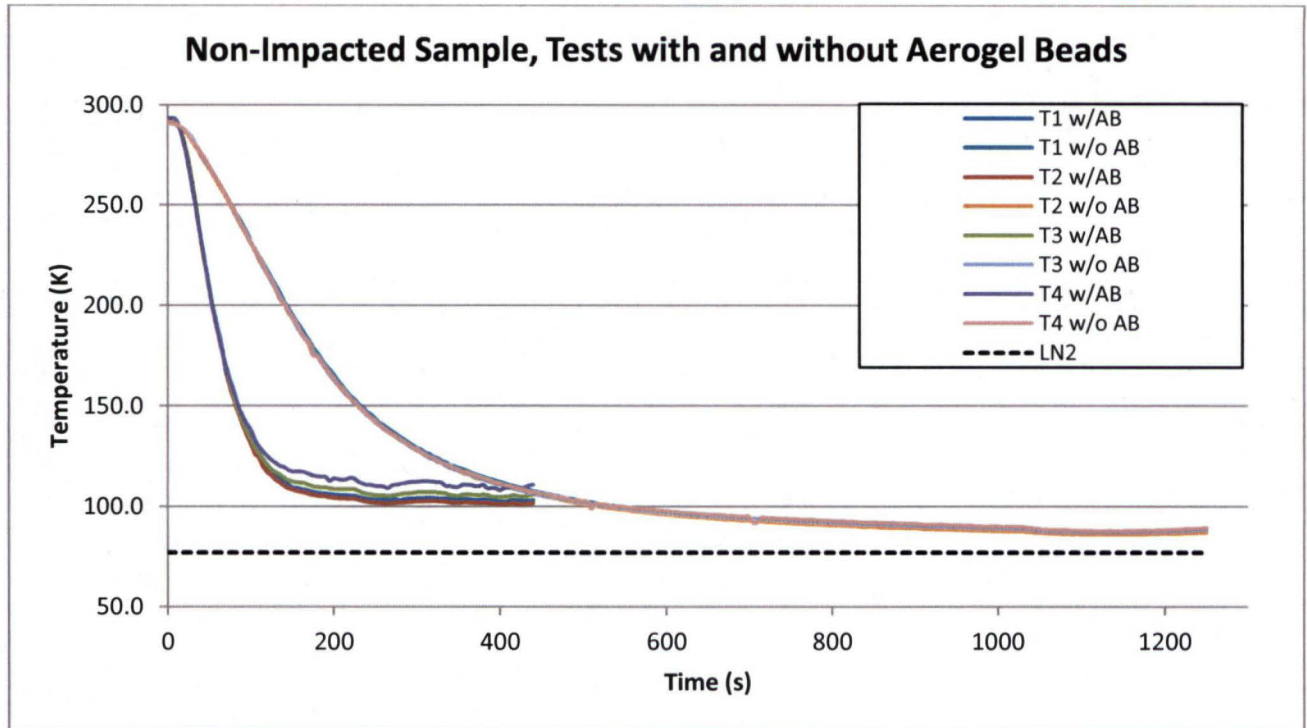


Figure 11: Time versus temperature plot of for tests 1 and 2 (virgin and aerogel-filled honeycomb)

	Test #1	Test #2
Initial Sample Temp.	293.2 K	291.1 K
Avg. Steady State (SS) Temp.	101.8 K	86.1 K
Approx. Time to Reach SS Temp.	250 sec	1105 sec
Avg. ΔT Between Thermocouples	3.3 K	0.9 K
ΔT Between T1 and T4	7.2 K	0.7 K

Table 2: A table of comparative test data of the virgin and aerogel filled honeycombs

III. Conclusions

As referenced in literature there are various non-destructive ways to evaluate the mechanical and thermal performance of honeycomb, and other metallic structures. Ultimately, the tests conducted here show the potential to develop evaluation methods for the examination of materials non-invasively; and with such a wide variety of structural systems employed in the aerospace industry, it is important that such procedures possess general applicability. X-ray radiation, including CT scanning, though effective for NDE in many contexts, yielded inclusive results when applied to the aluminum honeycombs. X-ray images showed a superimposed cell wall that was barely distinguishable from the impact area. X-ray imaging would probably be more applicable with honeycombs and the addition of added face sheets or insulation to the honeycomb. Though CT scanning is an effective technique, inconclusive results were shown for usage as a suitable NDE technique for the empty honeycombs. Further testing with CT scanning will hope to prove more conclusive results. CMMs have proven to be an effective method for the NDE of aluminum honeycombs as coordinates obtained effectively provide depth analysis. The measuring system also has the ability to measure spherical coordinates, showcasing the ability for not only depth, but volumetric analysis as well. Characterization of thermal performance by using cryogenic thermocouple testing shows promise as a potential novel NDE test. Preliminary, comparative thermal tests of impacted and non-impacted honeycomb samples has produced promising results, yet further examination is required to fully understand the behavior.

Future studies will deal with the applicability of blue light and white light scanning techniques, terahertz scanning, shearography, and thermography for potential usage in honeycomb NDE protocol. This study has thus far shown great promise for cryogenic aerospace NDE, bridging the gap between theoretical usage and commercial employment.

IV. Acknowledgements

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