In-Situ Resource Utilization: Investigation of Melted Lunar Regolith Simulant JSC-1A

Matthew Kallerud, Brian Nguyen, Timothy Paladin, Anthony Wilson

Department of Mechanical Engineering; Milwaukee School of Engineering, Milwaukee, WI

This study focused on the importance of in-situ resource utilization in the pursuit of space exploration. Experimentation focused on lunar regolith simulant JSC-1A, of which the mechanical properties of melted JSC-1A were to be explored. Specific properties that were tested included compression strength, hardness, density, magnetic properties, and the capability to drill and tap melted regolith. Results showed the compressive strength being greater than that of granite, higher densities in melted regolith versus settled JSC-1A powder, as well as inconclusive hardness and magnetic property testing.

Background

The 2009 Augustine Commission, a group that reviewed the human spaceflight plans of the United States, concluded that "the ultimate goal of human exploration is to chart a path for human expansion into the solar system." It is well known that this exploration and expansion will come at a significant energy cost. Supplying the required energy by transporting material and equipment for power production from Earth's surface to orbit is very costly due to Earth's gravity well. Because of the high costs, utilizing space resources is economically desirable. The utilization of space materials for space exploration is referred to as in-situ resource utilization (ISRU). It is well known in the space exploration community that this concept is the key to an economically feasible expansive human presence in space. ISRU can also reduce the risk of space exploration by reducing the number of necessary Earth launches.

Initially, it was proposed that a study be performed on an energy collection or storage device that can be manufactured in space using in-situ materials found on near-Earth-asteroids (NEA), concentrating specifically on the relevant material properties that lunar and asteroidal materials may have. Early on, the concept of manufacturing an energy collection or storage device using in situ resources was explored. The device that held the most promise, a solar PV cell, was designed. The material that was expected to compose 100% of the cell was to be that of an S-type asteroid, which is composed mostly of olivine and pyroxene. Once the design had been completed and analyzed, it was determined that the system was far too complex to recoup the costs that it would require in order to set the infrastructure in place. In addition to this, the system relied too heavily on controlled environments, similar to Earth in the aspect of requiring gravity and an atmosphere.

The main concept of ISRU was reexamined and it was realized that material for any structures or parts could be processed and developed using in-situ resources. Based on this theory, the new focus was on the properties of the lunar & asteroidal regolith found in space. Upon exploration of lunar simulants, a simulant that was developed specifically for NASA and specialized projects such as this was discovered. The goal would be to perform material property testing of Orbitec's lunar regolith simulant JSC-1A. Because the simulant is intended to mimic the properties of real lunar regolith, the concept of simplistic ISRU was able to be explored.

Funding provided by Wisconsin Space Grant Consortium

Advised by: Professor Michael Swedish, Milwaukee School of Engineering
Dr. Peter Curreri, Marshall Space Flight Center
Dr. Vito Gervasi, Milwaukee School of Engineering

Despite previous complexities and difficulties encountered with ISRU processing, a new attempt to take advantage of the benefits gained with ISRU was envisioned using a simplified concept. This concept was to avoid any unnecessary processing while also producing something useful. In addition, current research suggested that material property testing on melted and formed simulant does not currently exist. In order to determine if the regolith would be a suitable material for a variety of purposes, material testing needed to be completed to quantify the material properties of JSC-1A.

Currently, asteroid regolith simulant is not readily available. Previous studies indicated that the S-type (silicaceous) asteroid examined (99942 Apophis) has an estimated composition of "70% olivine, 22% orthopyroxene, and 8% clinopyroxene," which is very similar to that of the moon (Binzel, et al., 2009). Based on the availability of lunar regolith simulant, it was determined that this was a feasible way in which to pursue the new project focus.

Refocus on Use of JSC-1A in Space. The decision to use lunar regolith simulant JSC-1A was based on the expertise that manufacturing company Orbitec has with the material. It is produced not only for independent projects such as this, but also for NASA's purposes. Based on these criteria, it was deemed to be a suitable material to use.

JSC-1A is produced through the milling and sieving of volcanic ash that is mined from the Merriam Crater of the San Francisco volcano, which is located near Flagstaff Arizona. It is sieved until a particle size of less than 1 mm is achieved, which is important for certain tests as well as for reproducing the nature of real lunar regolith.
The approximate chemical composition can also be seen below in Figure 1. It is important to note that all of the elements are listed in the oxidation state and do not necessarily accurately represent the actual phase or minerals in the simulant.

Major Element Composition	**CAS #**	**% by Wt.**
Silicon Dioxide (SiO_2)	14808-60-7	46-49
Titanium Dioxide (TiO_2)	13463-67-7	1-2
Aluminum Oxide (Al_2O_3)	1344-28-1	14.5 – 15.5
Ferric Oxide (Fe_2O_3)	1309-37-1	3-4
Iron Oxide (FeO)	1332-37-2	7 – 7.5
Magnesium Oxide (MgO)	1309-48-4	8.5 – 9.5
Calcium Oxide (CaO)	1305-78-8	10 – 11
Sodium Oxide (Na_2O)	1313-59-3	2.5 – 3
Potassium Oxide (K_2O)	12136-45-7	0.75 – 0.85
Manganese Oxide (MnO)	1344-43-0	0.15 – 0.20
Chromium III Oxide (Cr_2O_3)	1308-38-9	0.02 – 0.06
Diphosphorus Pentoxide (P_2O_5)	1314-56-3	0.6 – 0.7

Figure 1 - Chemical Composition of Lunar Regolith Simulant JSC-1A

Use of Melted Regolith as a Structural Component. The concept of using the regolith from either asteroids or the moon as a structural component was envisioned because of the mass involved with structural components. Previously, the production of solar PV cells was thought to be very useful, but the complexity and relative mass of a PV cell negated the majority of benefits of ISRU. Looking on the opposite side of the spectrum, structural components tend to be high in mass and are needed to hold most other important components in place. Based on this observation, it was determined that the use of regolith for structural purposes would yield much higher mass cost savings as compared to the production of PV cells.

Intent of Melting Material & Material Property Testing. There is more to bring into consideration aside from the mass penalty benefits when considering regolith for use as a structural material. This includes the mechanical properties of it once melted; specifically the tensile and compressive strength, hardness, impact strength, the ability to machined/formed, and other material properties. These properties will determine first and foremost, what the material is capable of withstanding, as well as give insight as to what uses this might have, either structural or otherwise.

Material Testing to be Performed. Material property testing is needed in order to classify and utilize the melted samples properly. There is a variety of tests that are usually performed on samples in order to measure and quantify these properties. When the JSC-1A is melted it is expected to perform in a similar fashion to a ceramic, as the chemical composition is highly comprised of the ceramic material silicon dioxide (SiO2). As such, the mechanical property testing was tailored for a ceramic material.

Rockwell Hardness Test. Hardness is defined as a means to specify the resistance of a material to deformation, scratching, and erosion. Hardness is a key attribute of ceramics. The test is based on indenting the sample with a hard indenter. Hardness of the ceramic is important for characterizing ceramic cutting tools, wear and abrasion resistant parts, prosthetic hip joint balls and sockets, optical lens glasses, ballistic armor, molds and die and valves and seals (Quinn, 2003).

Hardness characterizes the resistance of the ceramic to deformation, densification, displacement, and fracture. Densification is important because “it relates to the microporosity that is often present in sintered ceramics” (Quinn, 2003).

Though Rockwell indenters are rarely used for ceramics, they were used in this experiment because they are the only hardness testing capability MSOE had available. About 5% of published values use the Rockwell indenter, usually the HRA or superficial HR45N scales. The scale used in this experiment was superficial HR45N. The sample size must be leveled and at least 1/2” thick and ¾” round or squared.

Uniaxial Compression Test. Compression loads occur in a wide variety of material applications. Unlike tension tests, compression tests are not limited by necking. Additionally, compression test specimens are simpler in shape and do not require threads or special ends for gripping. Since the melted samples for this project are difficult to machine, compression test samples are easier to obtain then tension test samples. Samples for compression testing can be obtained by slicing a cylinder section into coin shapes, which can be ground flat on both sides as, shown in *Figure 2*.

Precautions must be taken in order to ensure useful information about failure is obtained, including buckling prevention. Analyses cited in the ASM Handbook Volume 8 predict that specimens with a length-to-diameter ratio less than 5.0 are safe from buckling and can be used for compression testing of brittle materials. When using parallel plates, care must be taken to ensure that the plates are parallel to prevent eccentric loading. For the samples used in this experiment, the length to diameter ratio was less than 1.0, well within the recommended ratio.

Figure 2 - Grinding of Sample A1

$$\frac{L}{D} = \frac{0.625in}{1.48in} = 0.422 < 5.0$$

"In compression of a brittle… material, fracture occurs catastrophically by shear. The failure either occurs either along one large shear plane, leading to complete separation, or at several sites around the specimen, leading to crushing of the material. In either case, the load-carrying capacity of the material comes to an abrupt halt, and the fracture strength of the material is easily defined as the load at that point divided by the cross-sectional area…in brittle materials the ultimate compressive strength occurs at fracture" (Kuhn, 2003).

Drilling/Tapping Capability. As stated earlier, the melted form of regolith has potential for structural application in space. To fully utilize the regolith as a structural tool, the capability of connecting and interlocking members together is an important aspect that should not be overlooked. A study would be conducted to determine the possibility to drill and install a self-tapping screw in the melted JSC-1A.

Procedure

Compared to metals, most ceramics are brittle in nature with higher hardness and lower ductility. They have great wear resistance and thermal insulation. Due to the physical property of ceramics, careful selection of sectioning, mounting, grinding, and etching procedures are required in-order to achieve the desired shape for testing.

Separating Regolith from Crucibles. One of the biggest problems with melting JSC-1A was its high melting temperature. In order to melt the regolith, the container must be able to withstand temperatures of over 1500C. Another problem was getting the sample out of the crucible without damaging the sample once it was melted and cooled. This would be a challenge considering that the wetting characteristic of the melted regolith was unknown. To ease the removal of the sample from the crucibles, graphite powder was considered as a possible lining to prevent the JSC-1A from bonding to the crucible walls. This would be tested in run 1 by the use of the clay/ graphite jeweler's crucible. Another idea was to machine the crucible off the sample using the MSOE machine shop facility. This method would be dependent on the hardness of the crucible. The final idea was to carefully create small fractures and chips in the crucible using a hammer and a chisel, and then slowly remove pieces of the crucibles off the sample.

Cutting and Sectioning Sample. Generally, ceramics are cut with a lubricated (water or a special cutting fluid), rotating diamond cutting wheel. The cutting speed is dependent on the ceramic type as well as the desired surface finish. The quality of cut is dependent on the cutting speed: low-speed (25 to 500 rpm) and high speed (500 to 5000 rpm) (Taffner, Carle, & Schafer, 2004). Typically a slow cutting speed and low cut pressure produces less cutting and surface damage for most ceramics. The cutting wheel plays a large role in cutting ceramics as well. The higher the contact stress on each of the abrasive particle results in a higher cutting rate. For this reason, low abrasive concentrated blades are used.

Another method for cutting ceramics would be the use of a water jet. Using water and occasionally a garnet abrasive, the fluid is pressurized to 20,000-60,000 psi and forced through a small orifice. This fluid's high velocity thin stream is capable of cutting through much harder materials without generating heat and mechanical stresses (Staff, 2011).

Grinding and Polishing. Once cut, it is important for the both sides of the samples to be leveled. To do this a grinding machine would be used. MSOE's grinding machine was utilized to level all the samples for compression testing. It should be noted that MSOE's grinding machine is not water cooled, so great care while grinding the samples must be taken to prevent fractures.

Results

Density Testing. Mass density is a measure of the mass per unit volume of a material. It is an important property to this particular project due the compacting nature of the regolith simulant. Mass can be calculated using a simple scale and an accurate way to measure volume is through displacement of water.

Density was calculated for several samples from each run. Mass was measured using a digital scale. Propagation of error was performed on each density calculation and graphed against the reported density for JSC-1A according to its MSDS. The density measurements are summarized in Figure 3.

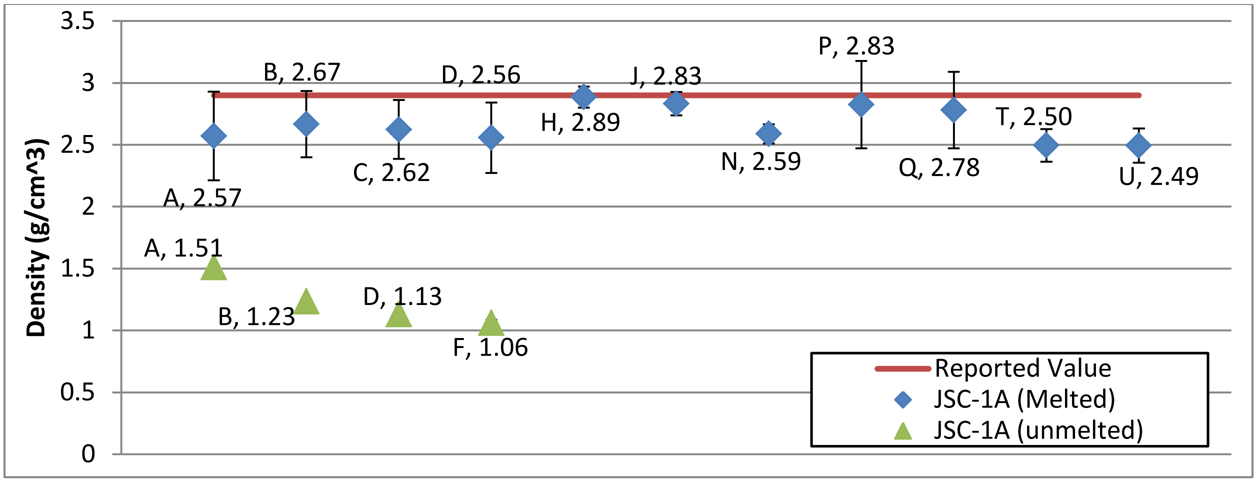

Figure 3 - Density Measurement Summary

The melted samples shown in Figure 3 are from a variety of runs. The MSDS reported value for density is also shown. Select non-melted sample densities are also shown. The accepted value is within the density range for samples B, H, J, P, and Q.

Magnetic Property Testing. Magnetism is a material property that results in having a response to a magnetic field. It is important in many applications, such as use in magnetic, low or no friction bearings. Magnetism of all melted samples was tested qualitatively, with a 0-3 scale created on which to rate the relative attraction to a magnet. The number 0 represented no reaction to a powerful magnet and 3 represented a strong reaction. These data are summarized in Table 1.

Table 1 - Magnetism Summary

Run	Sample	(0=none, 1=weak, 2=med, 3=strong)						
1	**A:**	1	**B:**	1	**C:**	1	**D:**	1
	E:	0.5	**F:**	0.5	**G:**	0		
2	**H:**	0	**I:**	0.5				
3	**J:**	0.5	**K:**	0	**L:**	1	**M:**	0
4	**N:**	1	**O:**	0.5	**P:**	1	**Q:**	1

All but one sample from Run 1 exhibited some level of magnetism. All samples from Run 4 exhibited magnetism. Overall, 4 of 17 samples did not exhibit any level of magnetism. The magnetism was not consistent among samples in the same run, but each sample came from a different crucible.

Compression Testing. Two coin shaped samples from the A crucible of the first melt, A1 and A2, were tested to fracture in a Tinius-Olsen hydraulic tester. The samples were placed between two parallel plates one at a time and loaded until fracture. The first sample, A1, showed failure primarily on one side. The second sample, A2, was similarly placed between the two steel plates and loaded to fracture. This sample took significantly more load to fracture, and failed uniformly across the sample, crushing the sample.

The Tinius-Olsen machine recorded the fracture load on a load curve. Since the fracture load required was unknown prior to testing, scales were changed during the test. Scales of 12,000, 60,000 and 120,000 pounds were used. Sample A1 fractured at around 66,000 pounds and sample A2 fractured at around 98,000 pounds. Samples H3 and H4 from the second run were also tested to failure under compression in the same way. They were pulverized at 67,500 and 48,600 pounds force respectively.

The area of each sample was calculated from the measured diameters, and the ultimate compressive strength of each sample was found. The ultimate compressive strength of the sample is the load at fracture divided by the area of the sample.

The values for diameter and load were measured in inches and pounds-force but were converted to meters and Newtons for calculations. Propagation of error was also performed based on the error in the load and diameter measurements. The error and the calculated ultimate compressive strengths are shown in Figure 4.

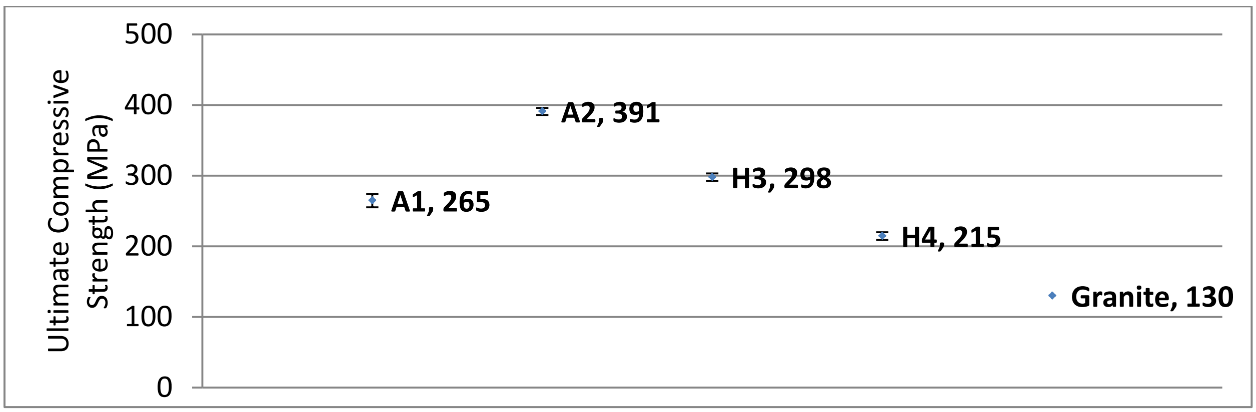

Figure 4 - Ultimate Compressive Strength of Melted JSC-1A Samples

The results indicate relatively low error but immeasurable error exists due to geometry imperfection and the non-homogenous nature of the melt. These errors are hard to quantify and are not reflected in the error analysis. However, the data show that the ultimate compressive strength of the melted JSC-1A is considerably higher than that of granite, which suggests possible application as a structural material.

Hardness Testing. The scale used in this experiment was superficial HR45N. Four samples were tested 10 times each on the same side. The results are summarized in Table 2.

Table 2 - HR45N Hardness Test Summary

Test	H1a	H1b	A1	A2
1	-66.8	2.7	-11.7	47.5
2	9.0	-35.7	-40.9	-12.7
3	25.6	-12.2	-13.5	18.6
4	-20.4	8.0	19.9	34.3
5	63.0	-5.9	23.2	7.8

6	-20.3	14.8	-39	-60.1
7	26.2	24.6	36.7	37.7
8	-18.2	-43.1	17.5	13.1
9	48.3	-23.1	-	-10.6
10	13.7	-35.0	-	-

The data show significantly inconsistent results; values range from -66.8 to 63.0 on sample H1a. The inconsistency of the data may be attributed to the Rockwell indenter or the poor surface quality of the samples. Indentation cracking due to the hardness testing load applied as well as the non-uniform porosity at the surface could have contributed to the inconsistency. A Vickers or Knoops test, better suited to ceramics, should be performed to characterize the hardness of melted and solidified JSC-1A.

Drilling Testing. Being able to drill and tap into materials is an important requirement for fastening materials together or to other materials. After initial difficulty with drilling into the melted JSC-1A samples, three specialty drill bits were acquired. The bits are all ¼ inch: a Vermont American rotary masonry drill bit, a Bosch glass & tile drill bit, and a RIGID diamond tile drill bit. The bits were used to drill into various samples with varying success. The results are summarized in Table 3.

Table 3 - Drilling/Tapping Summary

Sample	Drill? (Yes/No)	Tap? (Yes/No)	Bit
C	Yes	N/A	Diamond Tip
C	Yes	N/A	Glass/Tile
H2	Yes	N/A	Diamond Tip
H2	Yes	N/A	Glass/Tile
B	Yes	N/A	Masonry
H2	Yes. Through? No	N/A	Diamond Tip
H1	Yes. Through? No	N/A	Diamond Tip
A	Yes	N/A	Glass/Tile

All of the samples tested were successfully drilled by at least one of the bits. Qualitatively, the diamond tip drill bit provided the cleanest and quickest cut. Samples H1 and H2 were fractured during drilling, shown in

Figure 55. Other samples were drilled successfully, shown in Figure 6.

Figure 5 - Sample H1 Fracture during Drilling

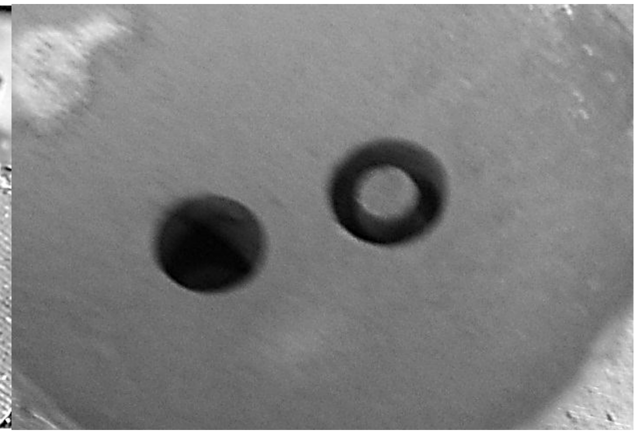

Figure 6 - Successfully Drilled Sample

None of the samples were tested for tapping to this point. Three hex head screws, 2 of 5/16 inch diameter and 1 of ¼ inch diameter were acquired for thread testing of the holes. The ability to drill into the samples creates flexibility in using the material, but the ability to tap will determine if screws or bolts would be used. Also, the best performing drill bit, the diamond tile drill bit, required active water cooling, which would be difficult and unlikely to work in space environments.

Conclusions

Potential Applications of Melted In-Situ Resources Based on Observations of Melted JSC-1A. Based on the material property testing that was accomplished, along with the observations made along the way, it is certain that there are constructive space applications for in-situ resources similar to simulant JSC-1A. One application that had initially sparked interest in the testing of JSC-1A was its use as a structural material. In an attempt to lower the mass penalty of shuttle launches, parts or structural members that undergo high compressive forces can be manufactured or replaced while in space, rather than needing to bring them along.

Planetary and space based habitats are also a target market for this concept. Rather than needing to bring all of the structural material along to begin or continue human expansion into space, these habitats can be built and expanded in space through ISRU of lunar or asteroidal material. If roads are involved, such as on a planetary habitat, the observed compressive properties of JSC-1A suggest that ISRU would be an appropriate option in the construction of these roads.

Alternative to structural uses, these materials can potentially be used for radiation protection. Many of the samples that were manufactured had glossy or glasslike finishes, and therefore can help reflect or redirect electromagnetic waves. Additionally, the material can act as a particle shield to protect from the various micrometeorites and similar threats found in space.

Downsides to the application of ISRU of lunar or asteroidal material based on JSC-1A include the relatively high temperatures required to melt and form it, the brittleness that was observed in a variety of property tests, and the difficulty involved in machining and forming it into the desired product.

Future Testing. If this project was allotted time and resources for further testing, it would be beneficial to explore other material properties of the simulant JSC-1A. Two of the more important tests would be tensile testing and 3-point bending testing, to further evaluate its potential use as a structural material. Additionally, more accurate hardness testing via the Vickers or Knoops methods would help in evaluating the potential failure modes of the material when it might affect mission safety. Further exploration of the magnetic capabilities could prove beneficial for use in low friction magnetic bearings or electric generators. Lastly, microstructural analysis of the various phases of the melted material could help determine which phase would be best in each application, be is structural, shielding, or other.

Limitations. Given that this project was intended to explore the properties of regolith simulant JSC-1A in the hopes of better understanding lunar and asteroidal material properties, there exist several fundamental limitations on what can properly be tested. In the tests performed, the induction furnace used requires a medium through which the heat can be transferred. Additionally, the medium that was used was standard Earth air, which has a specific chemical composition that can allow for chemical reactions that may not occur in open space where there is no atmosphere.

Another fundamental limitation encountered was the gravity applied on the samples by the Earth. In space there is a variety of gravitational forces but most are very faint or practically non-existent. That said, the formation of the samples was capable only in an environment with gravity. Low or no gravity environments will require a closed system to form the material into the desired product, which can require complex mechanical systems.

References

Binzel, R. P., Rivkin, A. S., Thomas, C. A., Vernazza, P., Burbine, T. H., DeMeo, F. E., et al. (2009). Spectral properties and composition of potentially hazardous Asteroid (99942) Apophis. *Elsevier Icarus*, 400-485.

Kuhn, H. A. (2003). Uniaxial Compression Testing. *Vol. 8 ASM Handbooks, 8*.

Lawrenz, A., Manning, B., Kilroy, K., & Larson, P. (2010). *Engineered Compact Lunar Interchangeable Power Systems.* Milwaukee: Team ECLIPS.

Price, S., Phillips, T., & Knier, G. (2001, March 21). *Staying Cool on the ISS*. Retrieved November 7, 2010, from NASA Science: Science News: http://science.nasa.gov/science-news/science-at-nasa/2001/ast21mar_1/

Quinn, G. (2003). Indentation Hardness Testing of Ceramics. *Vol 8. ASM Handbook, 8*.

Shapiro, E. (2003). Three-Point and Four-Point Bend Tests. *Vol.8 ASM Handbook*, 640-647.

Staff. (2011). *waterjet.org*. Retrieved May 24, 2011, from Joomla: http://www.webcitation.org/5nWaNTDGA

Taffner, U., Carle, V., & Schafer, U. (2004). Preparation and Microstructural Analysis of High-Performance Ceramics. *Vol. 9 ASM Handbook*, 1057-1066.