AC 2008-969: ULTRA-HIGH TEMPERATURE MATERIALS FOR LUNAR PROCESSING

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Ultra-High Temperature Materials for Lunar Processing

Abstract

Because oxygen is essential to both life support and propulsion, the ability to extract oxygen from lunar soil (a.k.a. dust or regolith) is a critical component in the development of space exploration. A lunar factory producing up to 50 times its own weight of oxygen would revolutionize how all countries access and utilize resources available in outer space. Packer Engineering was awarded a Phase I Small Business Innovation Research (SBIR) grant from NASA to design such a device and was successful in its development. In order for the component design to be successful, the Packer Engineering design team needed to find vessel materials that could withstand high temperatures, survive in a highly-reactive environment, and possess the longevity needed for semi-autonomous operation. Out of the 18 students hired under the educational summer intern program at Packer, one student undertook the task to survey the world's best knowledge in ultra-high temperature materials (> 2000^{o}K), and integrated this data into the system model for a device called the "Dust Roaster". In 2007, the Dust Roaster was developed by a diverse team of engineers and scientists under the Space Grant Consortium Fellowship. Through the unique partnership of professors, engineers, and interns, an innovative solution was generated to extract oxygen from lunar soil. The result of this study is a body of information which has not previously been published, and the student is currently working to prepare a seminal paper on the results of her research. This paper will explore how the overall structure of the summer intern program overlapped on-going research projects and led to a deep synthesis of technical information from a senior pursuing a BSE degree in Multidisciplinary Engineering.

Introduction: Intern Programs at Packer

Packer Engineering, Inc. is comprised of 169 employees and hosts four separate intern programs each year. Although a relatively small company, Packer Engineering has been successful in framing management to utilize the talents of its interns and to provide invaluable real-world experiences in engineering. Every facet of the intern program management is effective and contributes to training the students to manage themselves.

The two largest groups of interns are represented by a total of 33 people, divided equally between university students and high school or community college students. Two high school science teachers work full time during the summer to supervise the high school interns. At Packer Engineering the college interns engage in multidimensional learning, as they not only get to experience the types of work engineers do in the real-world, but they are also responsible for organizing and mentoring an assigned group of younger high school interns to work on specific technical projects. The college interns are assigned to staff engineers, and are responsible for balancing paid consulting work for their mentors, with individual and team research and development projects. Hands-on learning is emphasized, in an effort to enable each student to return to school with concrete evidence of their experience. Teamwork is required, and each student is responsible to prepare a final technical report on his or her project. Below is a reduced schematic of Packer Engineering's Summer Intern Program structure (Figure 1). This figure does not represent the exact pairing of interns and engineers to projects, but rather offers a simplified outline for how the internship program was structured at Packer. The red lines represent the major focus projects for the individuals involved. These major projects took up about 60-80% of the intern's time during the summer, while the blue lines represent subsidiary projects that students spend less time on over the summer.

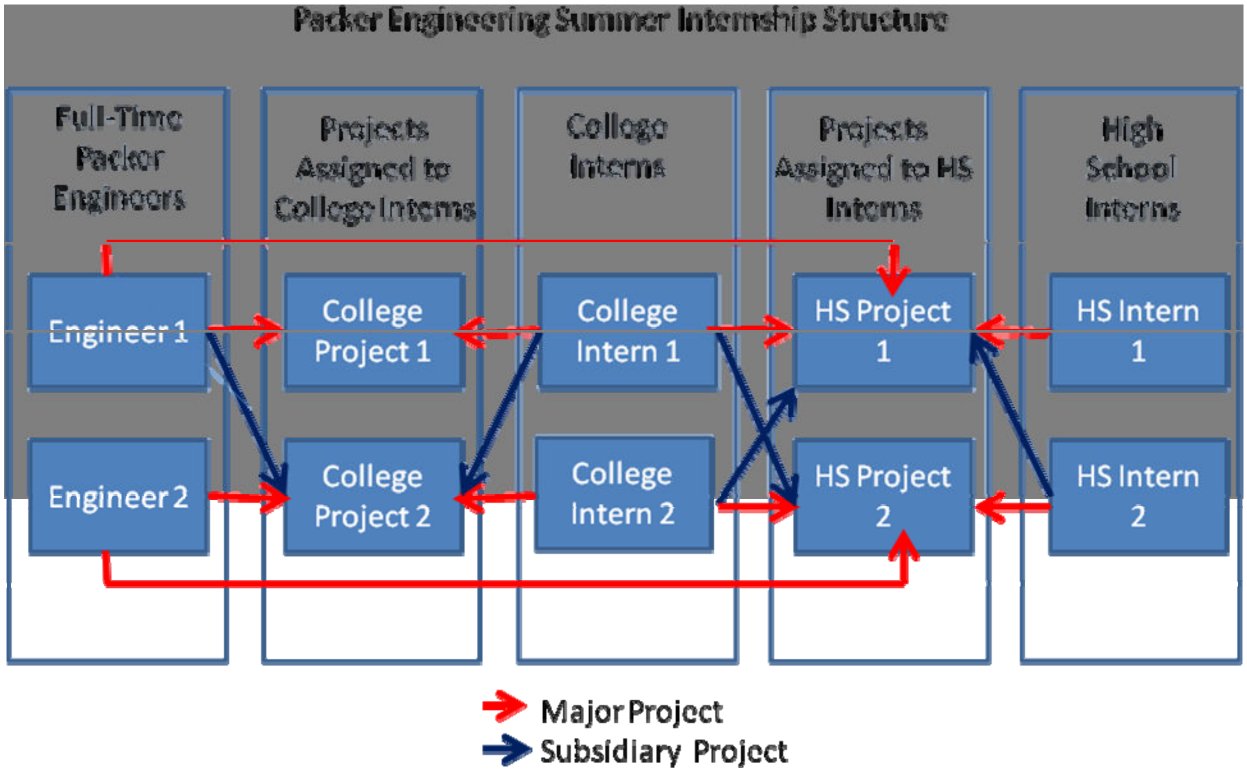

Figure 1: Packer Engineering Internship Structure

This structure cultivates in-depth technical experience in a specific area of study, and also provides the interns with a wider breadth of knowledge of several other subjects gained from their subsidiary projects. Using this framework allowed Packer Engineering interns to maximize their learning by deepening their knowledge through pursuit of their main assigned project, and by providing a broader sense of engineering with the supplementary projects in the program.

Several senior members working at the company were once part of the intern program offered at Packer Engineering. In a program stretching back more than 30 years, students have performed a vast array of tasks here. During building expansions, they plumbed toilets and painted beams. When the neighboring highway construction drained our pond, they mapped out a remediation plan. As new equipment was brought in, students read the manuals, ran experiments, and then developed standard operating procedures. At the same time, they aided consulting engineers in everything from laboratory testing to grueling field work to statistical analysis.

During summer 2007, a confluence of R&D projects produced an unusually rich breadth and depth of results. Practicing engineers give the students overviews of their own fields. In a company covering the gambit of engineering practices, this provides nascent technologists with an unusually broad perspective. Field trips to neighboring businesses and museums sometimes lead to unexpected new projects, such as building a new display on engineering, or recreating a 19th century hand pump used by firemen in an earlier age. Many of our interns have changed majors to pursue a new passion after discovering a newfound interest while working in the intern program. Many others have gone on to graduate school to immerse themselves more deeply in work they find fascinating.

Research is a vital part of a general engineering firm, keeping the staff at the forefront of their fields, and cognizant of the latest developments. A number of disparate R&D efforts became very active in early summer of 2007, and to address the need for additional help, the interns became intimately involved. One project, undertaken by a team comprised of three interns, prepared the first working prototype of a STEM (Science, Technology, Engineering and Math) training tool designed for middle school learners[1]. Another project was staffed by five college interns who retrofitted a plasma cutter to become a plasma torch. The torch is needed to pyrolyze biomass in a project to help farmers become energy independent. A different project aimed to improve the energy harvesting efficiency in a Lorentz force device operating as both a pulse count sensor and a power source for electronics. In a fourth project, three students built a carbon fiber composite rocket body for a test flight which was conducted on the 50th anniversary of the Sputnik launch. In another space-related effort, three teams each having three high school interns (supervised by two college interns) competed to extract the most iron filings from a sandbox using electromagnets of their own design. This was a mock-up for extracting free iron from lunar soil (called regolith) to build structures and rails on the moon for future settlements.

The NASA SBIR research had the effect of galvanizing nearly the entire intern group. The plasma torch, intended for terrestrial work, was based on capsule re-entry research conducted by NASA in the 1960s. The module developed for the STEM training tool introduced the basic physics underlying both the pulse counter and the free iron sweeper projects. Almost inadvertently, an incredible synergy developed. Having seen the result, Packer Engineering intends to have a similar thematic overview for subsequent intern programs.

Dust Roaster Overview

The space race between the USA and the USSR began 50 years ago last October, was won in 1969 with the first manned lunar landing, then went dormant in 1972 after Apollo 17. The Space Transportation System, commonly called the Space Shuttle, provided human access only to low earth orbit, and fell far short of the hopes for cheap and frequent access to space. No humans have been farther than 500 miles from the earth in 36 years.

Then, in 2004, President Bush announced a manned return to the moon, leading to a permanent lunar base. Suddenly the space race was underway once again. Now, more than a dozen countries have space programs, and half of them have visited the moon via spacecraft, and three have plans for manned missions to our nearest celestial neighbor, 240,000 miles away.

Every one of these missions has a need for oxygen, serving both as one half of a bi-propellant propulsion system (technically an oxidizer for propellant fuel) and as breathing air for life support.

Recognizing the critical need for lunar sources of oxygen, NASA awarded our company a Phase I SBIR grant to study the problem. The "Dust Roaster" was developed during the summer of 2007 and the calculations predict high output which exceeds all other known methods of oxygen extraction from regolith. Understanding how this unique research and development effort progressed provides insight into student motivation, undergraduate research, and how university, government and industry interaction can successfully accomplish an important technical objective. Team members included a university professor, an industrial researcher, a post-doctoral student, a junior consulting engineer, an undergraduate student operating under a Space Grant Consortium Fellowship, and a summer intern sponsored by Packer Engineering. Together the team of five developed a breakthrough method of oxygen production with calculated system metrics, exceeding those of any other method studied to date. However, to operate effectively, a material capable of withstanding the extreme temperatures needed to coax oxygen out of rock-hard minerals needed to be identified. The pursuit to satisfy this need took us to the forefront of refractory (high-temperature) materials.

To understand the requirements, and to determine if a suitable material even exists, the SBIR research team enlisted the aid of an undergraduate senior student participating in the college intern program. The specific advance in materials science, developed by the intern, enabled the remainder of the team to confidently design a novel device which is currently patent pending with the US Patent and Trademark Office. By combining information available in published literature with published patents, and through collaboration with a 63 different companies providing high-temperature materials, the student intern was able to determine the material necessary for building the Dust Roaster. However, the breadth of knowledge gathered during this three month effort provided sufficient information to cover a much wider variety of ultra-high temperature applications. The result of her study not only identified several candidate materials suitable for oxygen extraction from lunar soil, but also demonstrated how the Packer Engineering intern program prepares students to work on and solve real-life engineering problems.

Problem: Ultra-High Temperature Processes

Oxygen makes up 40% of the mass of the moon, but every single atom is tied up in a mineral. Common minerals like sand, granite and limestone are also mostly oxygen. Energy is required to remove this oxygen. Simple heating has been proposed as a means to force oxygen from lunar regolith,[2,3] but this is a messy process, requiring continuous maintenance and need of spare parts, making it more practical to just bring oxygen to the rocket. Lunar oxygen is so precious due to the staggering cost of a space launch. Each kilogram of material delivered to the moon from earth carries a cost of over $100,000[11]. The most economical approach is to launch a factory capable of delivering many times its own weight in oxygen produced.

The concept developed during the NASA SBIR is called the Supersonic Dust Roaster, and operates as follows. Regolith (pulverized minerals) is heated resistively in a crucible until it melts and becomes conductive. Inductive heating raises the temperature to 3000^{o}K, at which point the vapor pressure over the melt reaches approximately 100 kPa,[4,5] and includes a large fraction of molecular and atomic oxygen. A de Laval nozzle fitted to an aperture into the vapor chamber creates a supersonic flow of the vapor. As the superheated vapor passes down a drift tube, it cools to the point where suboxide minerals condense and flocculate into agglomerates. As these accrete further their supersonic inertia turns them into ballistic particulates, disengaged from the gas flow. Oxygen, which remains a gas until a frosty 90^{o}K, can be culled out of the stream with molecular skimmers and captured into praseodymium cerium oxide adsorbate beds. This patent pending system works great in calculations[6], but what material can withstand such temperatures with an atmosphere containing highly-reactive monatomic oxygen?

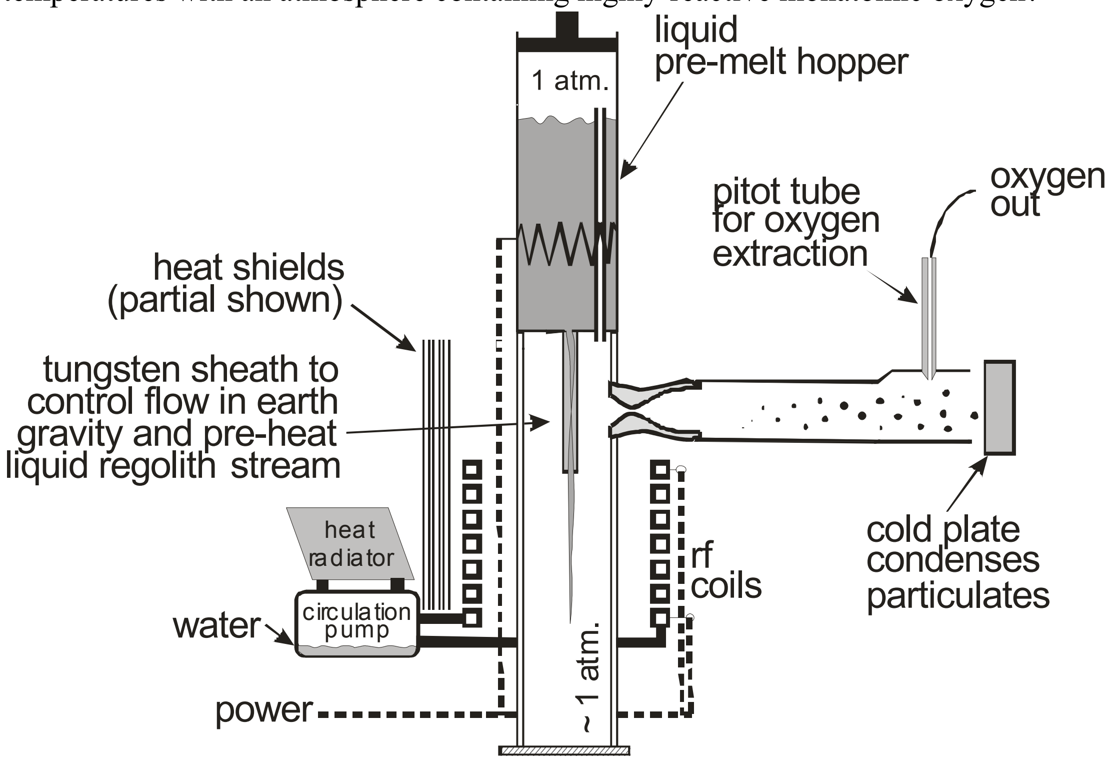

Figure 2. Supersonic Dust Roaster for oxygen extraction from lunar regolith.

Answering this question became of paramount importance for the SBIR research, yet the team members were already overwhelmed with the other activities involved. The team decided to utilize one of the college interns, a senior in Multidisciplinary Engineering, in order to help find the appropriate materials needed for this extraction process.

Solution: Determining Potential Ultra-High Temperature Materials

Refractory materials can be either metallic (W, Mo, Nb, Ta, Rh) or ceramic – typically oxides, borides or carbides of certain metals, such as MgO, TiB_2 and SiC. Applications for refractory materials include metallurgy, welding, rocket nozzles and heat shielding. When monatomic oxygen is present, the refractory metals are ruled out. Even though tungsten does not melt until 3400^{o}K, in the presence of oxygen it will burn at a much lower temperature. The intern assigned to this project identified that the Dust Roaster produces abundant O^- in the system atmosphere and refractory ceramic components were needed to avoid oxidation.

Refractory ceramics have been used in cruise missile nozzles.[7] In this application, they must survive for an hour or so, but for long-term operation on the moon, a much greater lifetime is needed. Solid rocket motors, such as those used in cruise missiles burn their propellant upstream of the de Laval nozzle. The intern learned that particulates from the combustion chamber abrade the throat of the nozzle, limiting their useful service life. In the Dust Roaster, the particulates are formed downstream of the nozzle, so abrasion is much less of a concern. Armed with this set of requirements, she began her search for the best ultra-high temperature material.

Beginning with a search of available literature, she found that most of the research work done on refractory ceramics was conducted 35 to 70 years ago.[8,9] At that time, there was great interest in the oxide of thorium. Thorium oxide has the highest temperature of any ceramic, melting at 3300°K. It is already oxidized, and can withstand the energetic monatomic oxygen, making it ideally-suited to the Dust Roaster's need. However, thorium is mildly radioactive. Because of this, thorium oxide production worldwide has dropped dramatically starting about 15 years ago. Thorium is now used almost exclusively in breeder reactor research. The super-bright mantles of a Coleman™ lantern were once made of thorium oxide. Today, such mantles use the oxide of yttrium (MP 2963°K), which became our next candidate material to investigate.

Several other materials arose from the initial literature search, such as hafnium oxide, the second highest melting point ceramic. Hafnium oxide is not as mechanically stable as thorium oxide, and is often stabilized (mixed with) with other refractories, such as zirconium oxide or silicon carbide. An interesting patent, granted in 1998, identified several tertiary combinations of refractory ceramics having excellent properties like a rocket nozzle.[10] The search was expanded to include companies offering materials or processing of refractory ceramics, a total of 63 potential suppliers worldwide were identified and contacted.

As a result of this research effort, the team was able to identify three candidate materials for the Dust Roaster. Thorium oxide could not be entirely discounted. The radiation dose received from an astronaut working on the Dust Roaster is far less than that received due to background radiation from the sun and from highly-energetic galactic cosmic rays. Oxides of hafnium or yttrium would be a good second choice, and when properly stabilized, provided a modicum of cooling is included in the Dust Roaster design. As a third choice, a mixed ceramic based on zirconium oxide is readily available, inexpensive, and there is an abundance of experience working with this material. Keeping this material cooled below its softening point will require a thermal management system, a challenge since the thermal conductivity is quite low.

Summary

Within the context of a substantial engineering intern program, a number of synergistic activities converged to create a summer of great progress and enthusiasm among the students. Exemplary of these results is the work performed on a NASA SBIR, making possible a novel approach to the important problem of oxygen production in space. Through this unique collaborative, it has been described how one intern was able to gain experience and insight into engineering applications that occur in industry. In turn, the host company for the internship program was able to utilize the technical and innovative strengths of the individual and incorporate them in designing the Dust Roaster. Each of the members participating in the Dust Roaster design group also gained insight into the dynamics that emerge when working in a multidisciplinary team. Open and clear communication among group members is essential in multidisciplinary environments and is the main contributor to the success of Packer's SBIR collaboration team. This paper was written so that companies can refer to Packer Engineering's internship organizational model and employ a similar framework to their internship programs in order to maximize learning and innovation.

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