AC 2010-661: NASA SENIOR DESIGN: MINERAL SEPARATION TECHNOLOGY FOR LUNAR REGOLITH SIMULANT PRODUCTION

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NASA Senior Design: Mineral Separation Technology for Lunar Regolith Simulant Production

Abstract

A NASA-ESMD (National Aeronautics and Space Administration-Exploration Systems Mission Directorate) funded senior design project "Mineral Separation Technology for Lunar Regolith Simulant Production" is directed toward designing processes to produce simulant materials as close to lunar regolith as possible. The eight undergraduate (junior and senior) students involved are taking a systems engineering design approach to identifying the most pressing concerns in simulant needs, then designing subsystems and processing strategies to meet these needs using terrestrial materials. This allows the students to, not only learn the systems engineering design process, but also, to make a significant contribution to an important NASA ESMD project.

This paper will primarily be focused on the implementation aspect, particularly related to the systems engineering process, of this NASA EMSD senior design project. In addition comparison of the NASA ESMD group experience to the implementation of systems engineering practices into a group of existing design projects is given.

Introduction

Prior to the discussion of the implementation of system's engineering into engineering design, a brief background on the curricular structure of the Materials and Metallurgical Engineering (MME) department and how the design courses fit into the curriculum is given.

MME Course Stream

The design courses are structured to integrate material learned in core courses with the solution of problems within the field. Typically, students enter the design courses in their junior year having taken two core classes – Introduction to Mineral Processing and Properties of Materials. Both of these are three hour lecture and one hour laboratory courses. During their junior year, MME students primarily take discipline specific classes, usually 7-11 credit hours per semester. The courses and hours taken are variable as the MME department is relatively small, ~20 students per year, and the upper division classes are offered on an every other year basis to ensure that the number of students in each course is of sufficient size to meet minimum size requirements[1].

Design Stream

Beginning in the 2008-09 academic year, the Department of Materials and Metallurgical Engineering (MME) at the South Dakota School of Mines and Technology revamped the design curriculum. The design curriculum consisted of MET 351—Engineering Design I and 352—Engineering Design II for juniors and MET 464—Engineering Design III and MET 465—Engineering Design IV for seniors[2]. The purpose and objectives of these classes can be summarized by the following Accreditation Board for Engineering and Technology (ABET) self-study description[3].

> This is a two-course sequence in Interdisciplinary Senior Capstone Design Project (ISCDP) that involves both lecture and design practice sessions. The course integrates vertically and horizontally concepts from all areas of Metallurgical Engineering into a practical senior capstone design project design to train the students in the design practice. Fundamentals of the design process, specifications, decision-making, materials selection, materials process, experimental design, statistic process control and preliminary design are the focus. The major part of this course consists in the development of the senior capstone design project.

Thus, the students are expected to understand how to perform materials selection and optimally select material processes to accomplish a year-long design project. As stated, the courses are a mixture of lecture and design session. In general, the design portion focused primarily on faculty-mentored design experience[4-7]. In many ways, the overall process is similar to some aspects of axiomatic design[5], as the lectures (and associated assignments) focus on a few basics that are designed to ensure that all students have the requisite knowledge to significantly contribute to the design projects rather than to differentiate students by their abilities and lead quickly to the more active learning areas of the design project. In addition, studying portions of the design process through case studies was used, particularly in the junior design courses (MET 351 and 352), to further understanding of how engineering design works. Overall, a variety of pedagogical techniques are utilized in order to reach all students, as students do not respond equivalently to different teaching strategies.

Prior to 2008-09, these courses were separate courses with MET 351 and MET 352 being focused on juniors learning the basics of the design process, particularly with respect to material selection processes, interaction of materials, and materials processing. In addition, teaming, ethics and global/societal concerns were also emphasized. Much of this work was performed through case studies and writing assignments. For MET 464 and MET 465, the seniors generally had two types of experiences, small groups led by an MME faculty member working on a metallurgy-based focus, or individual students working on multi-disciplinary teams, usually with groups sponsored through the Center of Advanced Manufacturing and Production (CAMP)[8]. CAMP projects typically involve vehicles and provide a student-oriented, hands-on design and engineering experience[8]. These projects generally worked well, but individual student experiences varied widely, which was considered to be suboptimal for those students whose experiences were at the lower end and for the continuous improvement in departmental offerings expected by the ABET. In particular, the final design reports and design fair presentations of the students in MET 465 are major contributors to the MME department’s outcome assessments. MET 465 is a primary source for assessment in areas c (optimally select material and design materials treatment and production processes), d (function well on teams), f (know professional and ethical responsibilities and practices), g (communicate effectively), and h (know engineering's global societal context)[9].

The desire to improve the design experience led to revamping how the MME design courses were delivered. Essentially, a large design project composed of multiple parts and combining both the juniors and seniors was developed by the MME faculty. In the first year of the modified design sequence, the overall design project aimed at manufacturing a samurai-type sword from local Black Hills iron ore[10]. Four groups, composed of 5-8 students, were formed. These groups were: 1) agglomeration, 2) furnace manufacturing and steel production, 3) forging and drawing, and 4) forging and quenching. Each group was dependent on the results of the previous group for the final sword production. The experiences of the 2008-09 MME design were enlightening for both the students and faculty[10]. From the faculty perspective, the need for better management of communication between groups as the project structure was such that the primary customer for each group was another of the design groups. The lack of inter-group communication led to many difficulties, particularly with respect to deliverable timelines, material size, shape, composition and quantity. Thus, improving the overall design process was deemed critical to successful future design project implementation.

As the design for 2008-09 was winding down, the author was awarded a National Aeronautics and Space Administration (NASA) Exploration Systems Mission Directorate (ESMD) Faculty Fellowship. This fellowship, which is described in more detail below, included a requirement that NASA systems engineering design be incorporated into the senior design project funded. This requirement offered an excellent method by which the communication issue between groups could be addressed.

ESMD Faculty Fellowship

The stated purpose of the ESMD Faculty Fellowship program *"is to prepare faculty to enable their students to complete senior design projects with potential contribution to NASA ESMD objectives."*[11] When applying for this program, a design project area related to a NASA ESMD program objective is chosen from the list included with the program solicitation and a short proposal for a senior design project submitted.

To develop the design project, the chosen faculty fellow travels to the NASA center of the NASA technical expert who had proposed the NASA EMSD project area and works with this technical expert for six weeks to help focus the design. The design proposal area was lunar and planetary systems and the specific project area being development, characterization and evaluation of lunar regolith and simulants.

As part of the grant, the faculty fellows also were part of the review team for another ESMD Space Grant Education project concerning the development of a fully implementable design course. For the 2009 faculty fellows, the reviewed course was developed by Dr. Stephen Whitmore (Utah State University, Department of Mechanical and Aerospace Engineering). While at the site of the technical expert, the initial portion of the review involved evaluating the slides Dr. Whitmore had developed for his year-long course entitled "Design and Testing of a Demonstration Prototype for Lunar/Planetary Surface Landing Research Vehicle"[12].

Implementation

The implementation phase of the NASA ESMD faculty fellowship began with the MET 351 and MET 464 students ranking their interest in the five design projects, four of the projects were continuations from 2008-09 concerning the samurai-type sword, and the other project was the author's Mineral Separation Technology for Lunar Regolith Simulant Production faculty fellowship project. For the samurai-type sword groups, the agglomeration group has four collegiate members and one high school participant. The furnace group has six collegiate members, the forge-drawing group and forge-hammering group each have five collegiate members. The NASA ESMD group originally had eight collegiate members, but one participant changed majors and decided not to participate further in the project.

General

The first step in implementing NASA systems engineering design principles into the MME design projects was a lecture by the author to acquaint the MME students with the systems engineering process[12-17]. While systems engineering is increasingly becoming a critical part of many engineering disciplines, its scope is also very large. As such, a 50 minute presentation is not sufficient time to cover all of systems engineering. Therefore, this presentation was focused on three main areas: requirements analysis, trade studies and design reviews. The manner in which requirements analysis proceeds is shown in Figure 1. The process begins in the upper right hand corner with determining the design requirements and constraints. These requirements and constraints can come from a variety of areas including the customer and other stakeholders, assumptions inherent in the process, legacy utilization, operational standards and governmental regulations and laws.

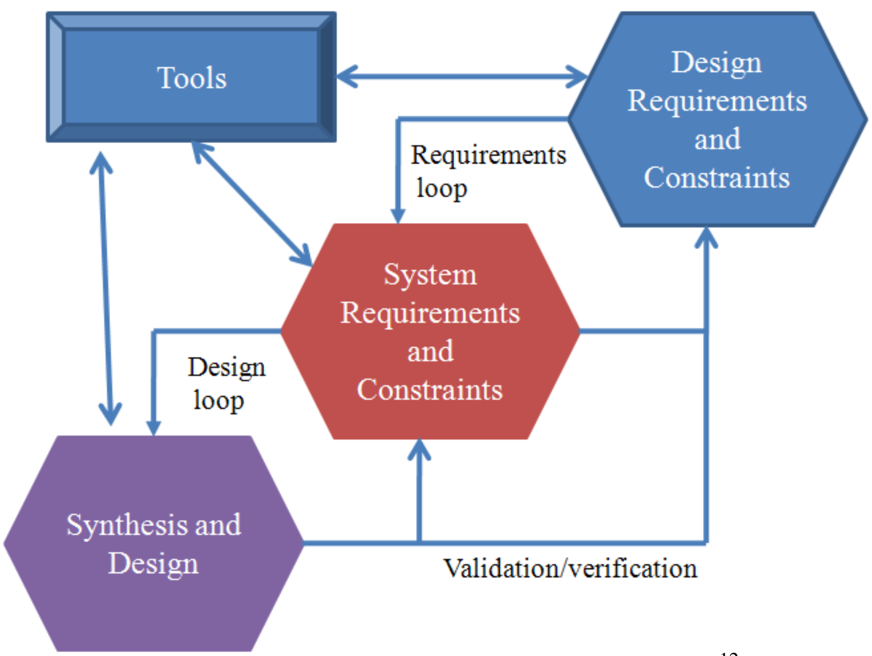

Figure 1. The systems engineering process. After Whitmore[12] and Guerra[13].

The system requirements are derived from the design requirements and are used to understand the design requirements and how these requirements affect the system function. The systems requirements then feed into the design loop to engender possible design solutions. The possible solutions are evaluated by trade studies using design matrices to semi-quantitatively score the various designs. The designs are also validated/verified against the original customer requirements and constraints to ensure that the design fulfills its original goals. The validation and verification is tested through preliminary and critical design reviews. One other key to the satisfactory accomplishment of the systems engineering process is the formal tracking of actions and requests for information within and between groups and customers. Formal tracking is important as without this many tasks don't get finished. Without having a group member in charge of finalizing the task's completion, other priorities occupy all group members and the task never is finished.

Requirements Loop

The first step taken was to identify the primary customer. For the samurai-type sword groups the primary customer was the next group, as defined previously. This created some initial concerns, as the requirements needed to flow from the higher number groups to the lower number groups, so that the requirements loop needed to be iterated several times to include the new system requirements occurring as each customer-group loop iterated. While some iteration was expected, keeping the communications flow between groups was an important task.

For the samurai-type sword groups, the agglomeration group requirements were derived from the furnace group who desired 150 pounds of iron ore pellets able to withstand the weight of the pellets and coke added to the furnace and having fluxing agents compatible with the refractory bricks used. The furnace group requirement, as given by the forging and drawing group, was to produce at least 10 pounds of low and high carbon steel. The primary requirement for the forge-drawing group is to fold and weld the low and high carbon steels produced by the furnace group, such that the forging-quenching group could form, weld and quench the drawn low and high carbon steel blanks into a samurai-type sword. The sword is made so that the ductile low carbon steel core supports the high carbon steel cutting edge. The forging and quenching group's primary customer was the MME faculty who required that the sword have a curve of the type common for samurai swords and have blade patterning similar to samurai swords.

For the NASA ESMD faculty fellowship group, the primary customer was the NASA technical expert. For this work, the technical expert indicated that processed ore from the Stillwater mine in Montana was of the greatest interest and that the final design should be able to produce up to a few hundred tons of lunar regolith simulant. Ideally, this would be accomplished by producing relatively pure mineral separates of each of the lunar regolith mineral constituents. In addition to the primary customer, possible secondary customers identified included a multi-disciplinary design team participating in the NASA ESMD Lunabotics Mining Competition. This group is interested in obtaining lunar regolith simulant material with which to practice for the competition, and a group of United States Geological Survey (USGS) scientists located in Denver, Colorado are interested in a possible simulant material (road norite) from an area adjacent the Stillwater mine. This material should be similar in composition to the Stillwater

Mill Sand, but has not been processed in the mill, and, therefore, has a larger average particle size. Constraints found include the money available for testing and characterization through the grant and the mineral processing equipment available within the MME department.

System Requirements

For the NASA ESMD project, the most important step toward understanding the system requirements and the tools by which the design can proceed, was obtaining and characterizing the simulant materials. Fifty pound buckets of Stillwater Mill Sand and road norite were obtained from the USGS scientists in Denver. X-ray diffraction and scanning electron microscopy characterization indicated several types of particles including olivine, anorthite, augite and some glass-like and hygrothermally altered materials. Further analysis is underway to identify the amount of each type of mineral in each size fraction. The size distribution of the Stillwater Mill Sand was determined using a nested sieve analysis. Analysis of the sieve data indicated that the five samples tested were quite similar and that the maximum size was approximately 125 μm, which is a little small as compared to the maximum size of lunar regolith which typically is closer to 2-5 mm[18]. With this data, the design loop was begun.

Design Loop

Brainstorming of ideas considering how to use the tools available for mineral separations was performed to begin the process of evaluating the separation process designs. The separations considered were size separation by sieving, dense media separation based on the particle density, magnetic separation based on the magnetic susceptibility, electrostatic separation based on the surface charging in an electric field and flotation based on the ability of the mineral surfaces to be selectively rendered hydrophobic. Separations can be performed to maximize recovery, i.e. the total amount of desired material concentrated in the separation, or grade, i.e. the concentration of desired material separated. In addition, separations can be performed in series to optimize both recovery and grade. Magnetic separation has proved a viable method for separating the main non-magnetic components (anorthite), from the magnetic components (olivine, augite, enstatite). To separate the magnetic components, the most promising method is free-fall triboelectrostatic separation. A separator to perform triboelectrostatic experiments is currently being built.

Comparison of Samurai-Type Sword and NASA ESMD Experience

Initial comparison of the experiences of the five groups shows that using systems engineering practices seems to have improved the design experience for most students. The samurai-type sword groups initially exhibited the greatest benefit as many of the senior students were working on a similar project to their junior year. This allowed the design requirements to be more easily developed and the previous year's experience contributed to more immediate student buy-in to the use of system's engineering principles. Also, members of the samurai-type sword groups being substantially similar to the previous year meant that many group dynamics issues had already been worked through. For the NASA ESMD group, there were only 3 seniors in the eight students and, as the project was new, no prior directly-relevant design knowledge existed within the group. This resulted in longer time for student buy-in to occur and for the group dynamics to become settled. Also, the previous group development in the samurai-type sword groups had led to the natural leader(s) within the group to assert their leadership. This was augmented by having each group designate a member to be part of an overall project group to ensure communication and the timing of deliverables occurred. For the NASA ESMD group, leadership did not emerge organically and, in retrospect, should have been developed by the faculty mentor at the start of the project.

Conclusion

The samurai-type sword design projects have been greatly helped by incorporating systems engineering design principles into the MME design curriculum. The enhanced communication and more explicitly specified requirements and constraints have resulted in the overall design process being 4-5 months ahead of 2008-09, although some of this increase is related to the experience gained by the students during the 2008-09 design. These groups have completed their preliminary and critical design reviews and are currently performing the chosen designs.

The NASA ESMD design project is slightly behind this pace due to the difficulties encountered in the characterization of the mineral samples. Despite this delay, utilization of systems engineering design principles has made implementing the new design project easier as compared to the 2008-09 projects. Also, the students have a better understanding of what is required of the design and of them.

Overall, regardless of the structure of the design projects, the utilization of system's engineering principles has proved a valuable addition to the MME design courses and will likely continued to be utilized.

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Bibliography

1. South Dakota School of Mines and Technology, pages 159-162, accessed April 1, 2010, http://resources.sdsmt.edu/catalog/metallurgical-engineering.pdf.

2. South Dakota School of Mines and Technology, pages 93-94, accessed January 8, 2010, http://resources.sdsmt.edu/catalog/courses.pdf.

3. Department of Materials and Metallurgical Engineering, South Dakota School of Mines and Technology, accessed April 1, 2010, http://www.abetmeteng.org/SD/Reports/SelfStudy/SelfStudyInventory.htm

4. S. Campbell and C.L. Colbeck, "Teaching and Assessing Engineering Design: A Review of the Research", ASE Conference, Session 3530, 1997.

5. C. A. Brown, “Teaching Axiomatic Design to Engineers – Theory, Applications and Software”, Looking Forward: Innovations in Manufacturing Engineering Education, CIMEC (CIRP International Manufacturing Education Conference), 2005.

6. J. A. Parcover and R. H. McCuen, “Discovery Approach to Teaching Engineering Design”, Journal of Professional Issues in Engineering Education and Practice, pp. 236-241, October 1995.

7. C. L. Dym, A. M. Agogino, O. Eris, D. D. Frey and L. J. Leifer, “Engineering Design, Thinking, Teaching, and Learning, Jurnal of Engineering Education, pp. 103-120, January 2005.

8. Center for Advanced Manufacturig and Processes, South Dakota School of Mines and Technology, accessed January 8, 2010, http://camp.sdsmt.edu/index.php.

9. Department of Materials and Metallurgical Engineering, South Dakota School of Mines and Technology, accessed January 8, 2010, http://abetmeteng.org/SD/index.htm.

10. J. Kellar, S. Howard, M. West, W. Cross, D. Medlin, and S. Kellogg, “**The Samurai Sword Design Project and Opportunities for Metallurgical Programs**”, presented at MS&T ’09, Materials Science and Technology 2009 Conference and Exhibition, October 25-29, 2009, Pittsburgh, Pennsylvania.

11. National Aeronautics and Space Administration, Exploration Systems Mission Directorate, accessed January 8, 2010, http://education.ksc.nasa.gov/esmdspacegrant/2010_Faculty_Solicitation.htm.

12. S. A. Whitmore, Department of mechanical and Aerospace Engineering, Utah State University, accessed January 8, 2010, http://www.neng.usu.edu/classes/mae/5900/frameset_for_design_class_webpage.

13. L. A. Guerra, National Aeronautics and Space Administration, Exploration Systems Mission Directorate, accessed, January 8, 2010, http://spacese.spacegrant.org/.

14. J. Seller, W. Astore, R. Giffe and W. Larson, **Understanding Space: An Introduction to Astronautics + Website (Space Technology)** McGraw-Hill; 3 edition (May 25, 2007)

15. National Aeronautics and Space Administration, accessed January 8, 2010, http://education.ksc.nasa.gov/esmdspacegrant/Documents/NASA%20SP-2007-6105%20Rev%201%20Final%2031Dec2007.pdf.

16. Federal Highway Administration, accessed January 8, 2010, http://ops.fhwa.dot.gov/publications/seitsguide/index.htm.

17. Department of Defense, accessed January 8, 2010, http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA387507&Location=U2&doc=GetTRDoc.pdf .

18. D.Vaniman, R. Reedy, G. Heiken, G. Olhoeft and W. Mendell, “The Lunar Environment”, in **Lunar Sourcebook, Chapter 3**, pp. 27-60, Cambridge University Press, New York, 1991.