AC 2010-1733: INNOVATIVE CONCEPTUAL ENGINEERING DESIGN -- A TEMPLATE TO TEACH INNOVATIVE PROBLEM SOLVING OF COMPLEX MULTIDISCIPLINARY DESIGN PROBLEMS

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Innovative Conceptual Engineering Design—A Template to Teach Innovative Problem Solving of Complex Multidisciplinary Design Problems

Abstract

The NASA Engineering and Safety Center (NESC), in conjunction with the National Institute for Aerospace (NIA), CIBER, Inc. and faculty from NASA, Georgia Tech, MIT, and Penn State recently developed and taught a short five-day course entitled: "Innovative Engineering Design." Unlike previous NESC Academy courses, which stressed discipline knowledge capture and transfer from past NASA experiences (e.g., developing complex hardware for programs like *Apollo*), this course teaches techniques for conceiving innovative concepts to solve complex multidisciplinary problems. The methodology used for this course was one that evolved from experiences working several NASA and joint NASA and DOD advanced development programs.

The processes for rapidly conceiving, evaluating, and developing concepts are explained as well as methodologies for accelerating the maturation of said concepts. The formulation of a five-day short course was a collaboration of faculty and organizations mentioned above. The course centered on the solution of a current critical problem facing NASA: the contingency land landing of the *Orion* capsule. The *Orion* capsule is a four-to-six-person spacecraft launched atop the Ares I rocket as part of the Constellation Program (CxP). The current *Orion* design would result in injury to the crew in the event of a land landing.

This paper is an overview of the format, teaching methodology, and resultant ideas/concepts that students conceived and developed by analysis and, in some cases, both analysis and test in only five days. Several of the ideas were novel and had not been pursued by the CxP. Several of the ideas are currently being pursued by commercial space launch companies. Viable solutions conceived by the students received funding by NASA and are currently under study by several of the faculty and students of Penn State and MIT.

The paper presents an overview of the course philosophy and format as well as some of the concepts that were presented by the five student teams on the last day of the course.

Introduction

NASA is currently struggling to develop innovative solutions to human spaceflight challenges that the Agency had solved successfully over thirty years ago. The development of a new launch system that mimics much of the technologies developed for the *Apollo* Program has been beset with program delays, technical design problems, and cost overruns. While the Vision for Space Exploration's (VSE) requirements include a larger crewed vehicle and different objectives than the *Apollo* Program, the new vehicles (Ares I launch vehicle, *Orion* Capsule, Ares V launch vehicle, etc.) are supposed to take advantage of Shuttle-derived systems such as the solid rocket boosters (SRBs). The bureaucratic morass of rules, processes, and procedures developed for a once-thought "operational" vehicle such as the Space Shuttle are still evident and have dimmed the spark of creativity and innovation, which was once the hallmark of a once great and highly innovative organization. Glimpses of innovation and creativity are seen occasionally; however, the energy and perseverance required to overcome the cultural inertia and cognitive biases can be overwhelming at times. It is hoped this course would serve as a potential example of what could be accomplished with minimal resources in a timely manner and possibly have a positive effect on a real design problem facing the Constellation Program (CxP). Toward that end, the course focused on a relevant problem facing the CxP: the assurance of crew safety in the event of a contingency land landing of the *Orion* crew return vehicle.

This paper presents a methodology for inspiring the creative solution of complex multidisciplinary problems. The techniques used were developed and have evolved over the years to solve critical problems such as the on-orbit repair of reinforced carbon–carbon wing leading edges on Shuttle[1]; the design of a new launch abort system for the CxP; and for other complex vehicles such as the National Aerospace Plane (NASP) and the X-33 single-stage-to-orbit vehicle. The format for teaching design presented in the current paper was utilized to teach a five-day short course for the NASA Engineering and Safety Center (NESC) Academy. A critically relevant and real problem was selected to illustrate how such a template could be used to connect students and faculty directly to very real problems facing NASA, DOD, industry, etc. In addition, it also demonstrates how the federal government and industry can tap directly into and take advantage of a highly motivated and creativity-rich environment—academia—as a resource for fresh, innovative ideas and solutions.

The format of the course coincides with a philosophy whereby instruction of basic principles follows with an illustrated example: for this class we used the conceptualization, design, analysis, testing, development, implementation, and operation of an on-orbit technique for repairing the wing leading edges of Space Shuttle damaged by debris (similar to that which caused the *Columbia* break up on re-entry[1]). This very real and recent project is used to highlight most of the basic principles and themes presented in the body of the course and to serve as an example of the philosophy of innovative design that the students are taught. The students are then totally immersed in the actual course problem/challenge: in this case the development of a solution for the contingency land landing of the *Orion* space capsule, which results in the safe landing of all crewmembers without injury. Key experts familiar with the technical problem—in this case landing dynamics, impact attenuation, and biomechanics—present all the relevant information that describes the problem statement, requirements, and constraints. Students are taught the necessary tools to help articulate, functionally decompose, and restate the problem from their own perspective/discipline; develop simple analysis methods to represent the problem; sketch ideas; convert sketches to computer-aided designs for rigorous numerical models (e.g., finite element, finite difference, etc.); prototype concepts; evaluate ideas; and experimentally verify promising candidate concepts. An active learning methodology is utilized to practice skills taught in the classroom and to directly apply those skills to solve the problem at hand.

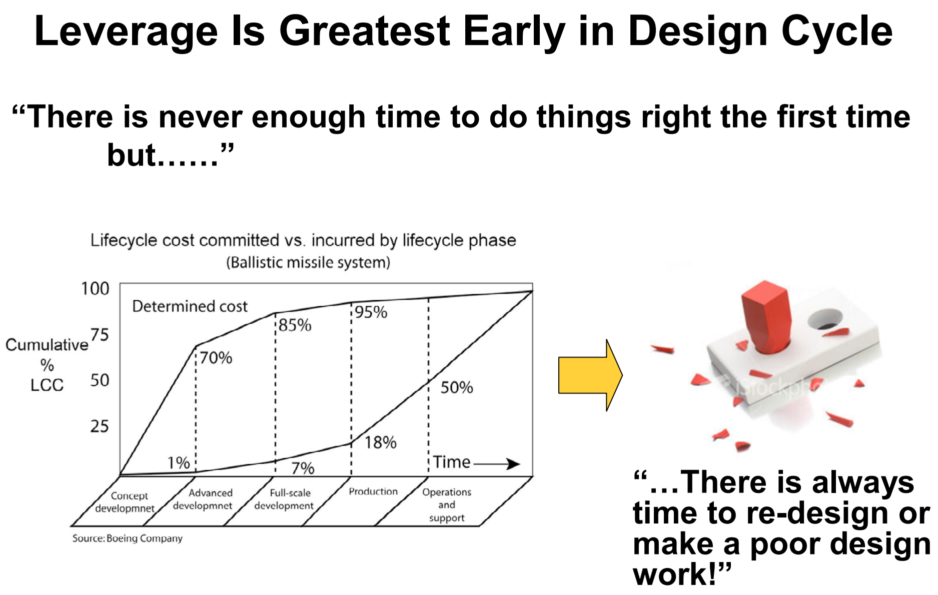
The Penn Stater Hotel and Conference Center, the Bernard M. Gordon Learning Factory (http://www.lf.psu.edu/), and Penn State classrooms and computer facilities were chosen as the site for this short course because they provided the necessary isolation; aesthetically pleasing and serene surroundings and amenities; and rapid prototyping, test, and manufacturing facilities. The very creative staff of CIBER, Inc. was chosen to develop the learning and training material; audio and video documentation; and student evaluation instruments. The academic faculty members were chosen because of their experience in industry, the classroom, product development, research, creativity/innovation, optimization, and entrepreneurial and design skills. The group of students were selected based on their diverse experience and skills (we were looking for a mix of students from all NASA Centers) with varying discipline expertise, computer and leadership skills, etc.; their experience (we were looking for younger engineers/managers with 1–5 years experience); and their project/program experience.

Results from the course were overwhelmingly positive based on the feedback from the students and faculty; the number and diversity of creative ideas/solutions; the connection of the students to real problems facing NASA; and the opportunity to attract funding for research grants back to universities such as Penn State and MIT.

Why a Course on Innovative Engineering Design?

The problems NASA is struggling with today are similar to those facing many large companies and industries in various sectors across the country. The recent economic crisis and bailouts of several of those sectors, for example the financial and automotive sectors, may be traced, in some respects, to a decided lapse in research, creativity, innovation, and entrepreneurship. According to Ko and Butler[2], during times of economic downturn, "governments see high-technology firms as a buffer to economic downturns, as well as critical to future economic growth, they have uniformly been very supportive of this sector." Ideas for regaining and/or maintaining leadership have focused on enhancing creativity, innovation, and entrepreneurship. This can be seen in an explosion of reports on innovation and creativity within the last five years as leading articles in key business journals such as the Harvard Business Review headline innovation (see for example, Ref. 3) in their top stories. Albert and Runco[4] state that the percentage of articles dealing with creativity in the psychological abstracts grew from 0.002% in the 1920s to approximately 0.01% in the 1980s. In addition, from the late 1960s until 1991, almost 9,000 creativity references were added to the literature.

The initial or conceptual design phase of a project is most critical and is the best time to positively affect the outcome and success of a project. As shown in Fig. 1, during the early part of the design cycle of most programs, the total life cycle cost (LCC) committed during the conceptual design phase is often insignificant (~1%) and yet the total LCC incurred is about 70%. In simple terms, down-selection to a design too early in the product development cycle, with insufficient or inappropriate analysis, test, and evaluation commits one to a sub-optimal concept, which can cause significant penalties downstream and may even result in an infeasible or intractable design. For example, improper assessment of the debris threat to fragile thermal protection system (TPS) on the Space Shuttle and the need for tedious TPS waterproofing operations after each flight resulted in significant post-flight TPS inspections, repair and replacements (R&R), and tremendous operational expenses that were not foreseen during the initial evaluation of competing concepts during down-select and the initial concept development stage of the Shuttle program. This was just one of many design oversights that prevented the Space Shuttle from achieving its goal of affordable and routine (50–100 flights per year!) access to space.



Leverage Is Greatest Early in Design Cycle

“There is never enough time to do things right the first time but……”

“…There is always time to re-design or make a poor design work!”

Image reprinted with permission of Prof. Olivier de Weck, MIT

Figure 1. The relationship of life cycle cost (LCC) to typical product design cycle phase.

One of the guiding premises of this course assumes that combining the art and science of engineering will enhance the generation of simple, elegant solutions to complex engineering problems resulting in simple yet robust alternatives. Techniques are taught that can accelerate the rapid accumulation of relevant technical information from both intelligent testing, and analyses that can address critical failure mechanisms early in the design cycle before considerable investment is made and decisions force limiting alternative design options.

Finally, the creative process is one of the most rewarding activities individuals and/or teams can experience. Csíkszentmihályi[5] said it best: “Creativity is a central source of meaning in our lives…most of the things that are interesting, important, and human are the results of creativity…[and] when we are involved in it, we feel that we are living more fully than during the rest of our lives.” We have experienced this firsthand in witnessing unmotivated employees’ careers completely changed by their experiences working on interesting projects as members of highly creative teams. Bennis and Ward–Biederman[6] make similar observations of seven highly-successful teams ranging from Disney and the Lockheed Martin Skunk Works to the Manhattan Project. Most important, by allowing students and young engineers the opportunity to exercise the right/creative side of their brain they can experience the joy of discovery and design and develop the passion for engineering and the sciences which will sustain them through their education and life.

Creativity, Creative Individuals, and Creative Teams

According to Csíkszentmihályi[5] “Creative individuals are remarkable in their ability to adapt to almost any situation and to make do with whatever is at hand to reach their goals…. They contain contradictory extremes—instead of being an “individual,” each of them is a “multitude.” According to Csikszentmihalyi, creative/complex individuals tend to exhibit ten antithetical/paradoxical traits such as: being smart yet naïve; energetic yet often quiet and at rest; a combination of playfulness and discipline; passionate yet extremely objective; etc. Redfield Jamison[7] even posits a link between creativity and bipolar disease. We all can relate to some of these paradoxical traits to varying degrees. The success of highly creative teams, however, must also include leadership that understands the big picture and has a broad knowledge, which is necessary to properly recruit the very best members that are the best "experts" in all the key disciplines/fields[6]. A good leader of highly creative teams is also an excellent people person and leader who can summon the very best of each individual on his or her team and rewards them accordingly. Leaders and their behavior command a very powerful influence over the creative/innovative performance of teams[8]. Creative teams usually have a flat organizational structure, where people are assigned tasks based on ability and not position and the importance of the mission transcends ego. The behavioral, social, organizational, communication, and leadership skills necessary to build, lead, and work effectively on such highly creative teams is a valued commodity that is highly sought after in industry.

Impediments to Creativity

In order for us to understand what inspires a culture where creativity can flourish, we first start by recognizing some of the very detrimental elements that can stifle creativity. The greatest impediment is arrogance. Some may argue this point by noting some world class artists and "creatives" who are, or appear to be, very arrogant; this could be countered with a long list of very creative and highly successful people who are very humble and selfless. It could also be argued that the creatives who are arrogant could have been so much more effective and creative if they were less arrogant! Arrogance is an immature emotion that prevents the deep understanding and careful listening to other ideas and positions and also prevents one from recognizing and correctly assessing the deficiencies in one's own ideas/concepts.

People who follow rote procedures and processes with a blind allegiance and without using their brain to critically think and understand what they are doing, lose the benefit of applying their own creative ability to search for a better, more elegant solution. The very idea of blindly following a standard "process" negates the possibility of a new solution. Surprisingly, many of the engineers at NASA Johnson Space Center followed standard procedures and processes to analyze what was then believed to be an "operational" space vehicle, the Space Shuttle. In fact, the very act of blindly following such procedures without allowing critical thinking and analysis was found to be a contributing cause of the Shuttle *Columbia* tragedy.[9]

Many leaders of teams who do not fully understand the entire scope of the problem will often limit the discipline participation of teams early in the concept development stage, only to find critical faults later in the design process (e.g., preliminary design and/or final design stages) where total redesign may then be the only course of action. In addition, arrogance may be the cause of limiting the early team membership. For example, if machinists, welders, or other artisans are excluded in early meetings, it may result in a design that is impossible to manufacture. In addition, many of the skilled artisans are very adept at visualizing the final design in three dimensions and often are very creative in developing innovative solutions to problems, which are very elegant and most times very efficient and less expensive.

The more disciplines and diversity involved in the beginning phases of the concept development, the more likely the chances for a creative solution to the problem, because more often than not, the innovative answers lie on the boundaries between disciplines. Limitations in flexibility of the team and or a stifling environment that limits psychological safety and member trust will also greatly limit the success of the team. Hence, an important element of this course is the development of a psychologically safe environment where trust abounds.

Lastly, the team should be aware of cultural, organizational, and/or cognitive biases that could arise from natural human tendencies and that limit objectivity and lead to poor decisions. There are several good books and papers discussing these areas, some of which are noted in Starbuck and Farjoun.[10]

Stimuli for Creativity

Provided below is a list of some of the stimuli that can help enhance the creative output of a team:

1. **Diversity** – of culture, gender, race, ethnicity, experience, etc., creates a multiplicity of views or perspectives with which to define, frame, and solve a problem. We tried very hard to select teams to maximize diversity and distribute critical skills.
2. **Environment** – we selected a setting—Penn State, the Penn Stater Hotel and Conference Center, and the Learning Factory—which was aesthetically pleasing with serene surroundings and amenities; excellent classroom and design studios; and rapid prototyping, test, and manufacturing facilities. We created a psychologically safe environment where failures were expected and communication was free and open. We included plenty of stimuli for each of the senses, which were both relevant and non-relevant to the problem being studied (e.g., launch vehicle models; energy absorption materials and systems for aircraft; biomimetic systems; etc.)
3. **Deep Analogies** – we included faculty who could discuss ideas from biologically inspired design and biomimetics so students could draw possible analogous solutions from nature.
4. **Creativity Enhancing Activities** – we exposed students to various techniques like TRIZ[11] the theory of inventive problem solving, intelligent fast failure,[12] SCAMPER, Block Busting,[13] Brainstorming,[14] etc.
5. **Experimentation** –several lectures were presented on rapid prototyping, modeling, and experimentation using design-of-experiments (DOE) methods. Dr. Jaroslaw Sobieski also presented more rigorous methods of mathematical optimization. The students utilized the Learning Factory to fabricate models of their concepts and conduct tests to verify performance.
6. **Simulation** – methods to simulate the observed behavior and environment offer additional tools to stimulate the flow of creative ideas.
7. **Subconscious** – it is often necessary to create an environment where informal activities, play, and relaxation are included because very often ideas need time to incubate or gel. Idea journals were passed out at the beginning of the course for students to jot down ideas throughout the course, sketch, and take notes.

8. **Creative ideas at the boundaries** – students were instructed to pay close attention to ideas that were formed by the intersection of several disciplines, using methods of combining ideas and/or extending ideas from one discipline to another**.**
9. **Extend yourself** – including activities that are foreign to many students and allowing each member to grow and explore areas/disciplines that are not familiar will increase the creative potential of each individual.

Problem Selection

We selected a problem on which NASA was currently working for which they had no solution: A contingency land landing of the *Orion* vehicle for the Constellation Program (CxP) (Fig. 2). The reason for selecting this problem was twofold: an ongoing real problem provides a direct tie of the students and faculty to a real problem the U.S. space program was wrestling with and the fact that there was no current solution provided motivation, a sense of urgency, and at the same time some relief in knowing that many very sharp engineers throughout NASA and its contractor base had also not been able to develop any workable solutions. As shown below, these requirements added to the dynamic of the course and helped to capture the passion and intensity of the students as the five days of lectures and experiments progressed.

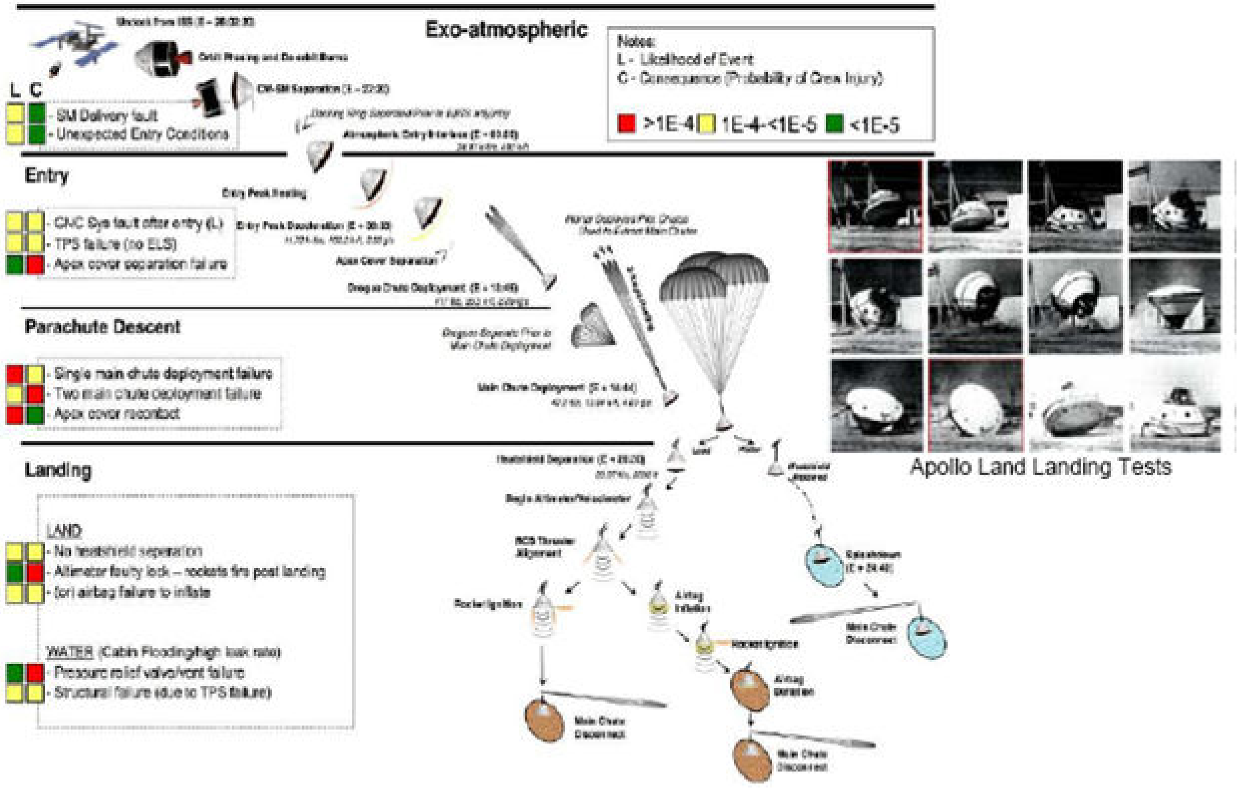


Figure 2. *Orion* landing scenario.

Faculty Selection

The faculty selected were chosen because of their expertise in several critical areas: 1) first and foremost, several of the faculty were expert in critical technical areas of the problem: impact dynamics; impact load attenuation; human physiology and biomechanics; structures; and materials science; 2) design, optimization, and product development; 3) creativity, innovation, cognitive science, and rapid prototyping techniques; and 4) biomimetics.

Student Selection

The course was specifically designed as a training experience for young NASA engineers (~1–5 years of service), researchers, and technical managers. We attempted to draw from all NASA Centers and were successful in attracting engineers from seven of the ten NASA Centers. Hence, there was diversity related to the emphasis of each particular center, e.g., research, spaceflight, operations, ground support, etc. In addition, the specific major discipline focus of each of the students was varied (e.g., structures, heat transfer, acoustics, computer-aided design, etc.). As explained above, diversity is a very important to help enhance the creative output of the team. In addition, other student skills and interests were also used to help form diverse teams of students to tackle the course problem/challenge.

Course Location/Environment

Penn State was chosen to host the NESC Academy Innovative Engineering Design course for several reasons: the location provided an aesthetically beautiful and isolated setting so students could focus on the problem; the Penn Stater Hotel and Conference Center provided nicely equipped conference facilities complete with large breakout spaces/rooms for teams to interact; the university provided computer design classrooms for CAD instruction and search techniques; and the resources of the Learning Factory (Fig. 3) provided a work environment where students could rapidly prototype, manufacture and test ideas/concepts. There were numerous areas where students could socialize and relax during breaks and in the evenings. All meals and snacks were included in the package so students could spend maximum time mingling with teammates, faculty and other students both formally in class and informally, at meals and later in more relaxed settings.

Figure 3. Penn State Learning Factory with participants design and prototyping.

Course Outline and Agenda

The course was designed to be a very intensive week of learning, fun activities, guest lectures, design experiences and problem solving (in fact, some of the students remarked it had the flavor of an "Innovation Boot Camp"). Standard pedagogical methods of instruction were used but were interspersed with hands-on-learning activities to build on lessons taught by more traditional lectures. Guest lectures, laboratory experiments and fun exercises were also included to help stimulate creativity and build team esprit de corps. A pre-class questionnaire was created and administered to ascertain the self-perceived creativity quotient of the students and to also determine the various levels of experience and discipline expertise. This was used to pre-determine teams and, thus, ensure diversity as well as to equally distribute key skills necessary to address the course problem/challenge. The faculty team decided on an "ice breaker" that was related to the actual problem. The students were introduced to each other during Sunday's afternoon registration introductory social, were assigned to their teams, and introduced to their first fun team activity. The ice breaker was the classic egg drop competition described below.

Monday, the class was introduced to the faculty and the training staff, and was given the overall agenda and logistics of the week. The first lecture introduced the students to the major themes they would hear regarding innovative engineering, the typical types of design cycles, and the course focus on the very early conceptual portion of the design cycle. The students then began their immersion into the *Orion* contingency land landing problem from key faculty who are considered to be experts in the field of impact and landing attenuation, physiology, human tolerance, and structural dynamics. The students learned about past experiences and research in all critical fields of impact, landing load attenuation, and human tolerance. They were exposed to all the necessary facts and data related to aircraft, helicopter, spacecraft (both robotic and human rated) impact dynamics and attenuation of craft from the U.S. and Russia. The first day ended with a review of the egg-drop high-speed camera results and an insightful commentary of results by the impact experts. The students were then allowed time for individual teams to ponder re-design of their earlier egg-drop impact attenuation system and to make changes based on what was learned.

Every morning before each class, a series of exercises got the class "loose" and were absolutely necessary to help create an atmosphere where looking silly was okay, in fact, it was expected. In addition, this helped to bring about a sense of camaraderie and trust, which is crucial to create "great groups".[6] The first half of day-2 began with a lecture on "stupid ideas" and was followed by several lectures on various methods for inspiring creativity and innovation: TRIZ, biomimetics, functional abstraction, etc. Techniques for efficient background searching were taught, a lecture on what was expected of each team for their final project and the outcome of the course, and a lecture on methods for visualizing concepts using sketching and isometric projection was give.

The Ice Breaker

It was decided during our first pre-course faculty/staff meeting that an ice-breaker would be a good idea to help set the right mood for the course and to help students to get acquainted with each other, the faculty, and teammates. The problem selected was the classic egg drop competition, where teams would be give a set time and set of materials to develop an impact resistant system that would protect two eggs (“crew stimulants”), inside a given plastic container (“capsule”) from cracking/breaking (“injury”). The highest successful drop without breakage would be considered the winner. A drop tower was devised (Fig. 4, lower right-hand corner) that was erected easily and allowed rapid cycling of each team’s designs. Each team was allowed one attempt at redesign after a failed drop test. Teams were allowed multiple drops (three total).


The Intensity

The Teamwork

The Test

Figure 4. Egg drop “Ice Breaker” class project.

A high-speed digital camera filmed all of the students drop test attempts (Fig. 5). The video then was edited quickly and instant feedback was provided during class after the students learned the physics of impact dynamics. This was very informative and enabled the principles learned from lectures to provide real-time “test experience” correlation for each of the students. It also turned a very simple ice breaker into a real experiment.

Figure 5. Matt Melis of NASA Glenn research Center (GRC) utilized a high-speed camera to help transform a fun exercise into a real experiment and learning opportunity for the students.

The Seven Themes

A short list of key ideas or themes that are critical to innovative design were developed and captured as easily recognizable icons that the faculty and lecturers could refer to and help integrate throughout the lectures and sessions to positively reinforce and provide relevant examples of how these themes were/are used in real projects (Fig. 6).

The human mind – use it

Arrogance is the enemy of creativity

Understand the mechanisms of failure

Failure is not an option…it's a requirement

Pan out and zoom in during the design process

Allow ideas time to incubate

Everyone is creative

Figure 6. – Innovative Engineering Design thematic icons.

The first theme was borrowed from a colleague and well respected expert in structural dynamics, Dr. Robert Ryan, and changed slightly: "The human mind – use it" speaks to a habit of young inexperienced engineers who may tend to dive into the numerical analysis of a problem without first understanding the physics. Very simple models should be tried first to establish this preliminary understanding and to assess the important or key parameters to ensure the physical understanding, simple model, and observed behavior all agree. The mind's ability to use experience and judgment to correctly formulate the problem together with realistic assumptions and boundary conditions is critical and will serve to better understand more rigorous and complex representations and to determine if errors exist.

The next theme, "arrogance is the enemy of creativity" was touched upon earlier and one of the most serious impediments to creativity and should be recognized and avoided at all costs. Highly competent teams should avoid crossing the line and becoming arrogant because this will limit acceptance of new ideas, learning, and prevent objective criticism/review of one's own ideas and those of the team! This is directly related to the next theme: "understand the mechanisms of failure." Petroski[15] links good design as one that "obviates failure" by adequately addressing potential failure mechanisms early in the design process. If you understand and can visualize potential failure mechanisms early enough in the design it will open up avenues of new ideas to simply and elegantly address and eliminate these modes of failure from ever occurring. Studying the histories of past failures of similar or analogous systems provides a starting point for this critical analysis.

The next theme is “failure is not an option…it is a requirement.” In contrast to the popularized Mission Operations Directorate (MOD) of the movie “Apollo 13”, while failure cannot be tolerated for operational vehicles, failure is a necessity for research and development. Discovery and innovation go hand-in-hand with failure and failure to permit failure impedes exploration, discovery, and innovation. We learn so much more from our failures and, in fact, success may actually increase the chances for failure. Starnes often stressed the importance of understanding all failure modes and of testing to failure to corroborate and verify analysis. An environment must be ensured that allows engineers and scientists to experiment/tinker, fail, and learn. Matson calls this “intelligent fast failure”.[12]

During the course of the design cycle teams had to pan out and view the problem in its entirety and at the same time be able to zoom in and rigorously look at critical details to understand key local as well as global failure modes. This ensures that a true “systems” approach is always taken. When working on one detail or component of the whole system, the designer has to step back and assess how the detail changes affect the whole system. It is crucial that a good systems engineer can recognize when highly rigorous, detailed analyses, and experimentation is necessary to ensure the true representation of a complex behavior!

When pondering the problem, it is often necessary to allow time for ideas to incubate, gel, and morph and allow non-linear patterns and cross pollination. The teams were given idea journals to use throughout the course to jot down and sketch any thoughts or ideas.

The final theme is that everyone is creative and has the ability to enhance their creative potential. In addition, the creative quotient of a team can be enhanced. Good groups/teams can become “great groups”.[6]

Problem Immersion

The first step in innovative problem solving is to totally immerse all team members into the problem. The team must understand the problem from the “one-hundred thousand foot level” (pan out) so that they can see the importance of all the critical disciplines and where all the pieces fit together and also grasp the intricate details of the physics of the problem. Osborn,[14] the father of “brainstorming”, however, believes that too much “digging” of data and past ideas may flood the team with past experiences, drown otherwise useful initial concepts, and possibly result with a pre-disposed bias to these prior concepts. Hence, facilitators of creative teams must be constantly aware of such cognitive biases, instruct the basic principles and physics of the problem at hand, and yet also continually introduce methods to spark the “stupid ideas” and develop strategies for “flipping” stupid ideas into real solutions.[12]

The students then began their immersion into the *Orion* contingency land landing problem from key faculty who are considered experts in the field of impact and landing attenuation, physiology, human tolerance, and structural dynamics. Dr. Edwin Fasanella of NASA LaRC has over 35 years of experience of crash dynamics and landing attenuation of helicopters, aircraft, and spacecraft. He has developed and uses complex numerical methods for analysis and also is responsible for creative methods of testing to correlate analysis and test results. Mr. Joseph Pellicciotti is the NESC Technical Fellow for dynamics, is responsible for leading the NESC Contingency Land Landing Project, and leads a network of dynamics experts from across the country in industry, academia and government agencies. Medical doctor and astronaut Lee Morin is also an engineer and scientist who has studied the effects of impact on humans and who developed a simple computer program which the students used to rapidly assess the viability of initial concepts for impact attenuation.

The students learned about past experiences and research in all critical fields of impact, landing attenuation, and human tolerance. They were exposed to all the necessary facts and data related to aircraft, helicopter, spacecraft (both robotic and human rated) and impact attenuation of craft from the U.S. and Russia. The students were instructed on the limitations of the human physiology to accelerations in various orthogonal directions, as shown in Fig. 7.

Another important aspect during the conceptual design phase is to simplify the complex problem using a reduced model that the students can use repeatedly, vary key parameters to get a feel for the design space, and gain an understanding of the physics of the problem and which parameters are important. This gives the designers an intuitive idea of which changes will cause movement in the direction of improvement, etc. (measures of goodness/"betterness"). Toward that end, the students were instructed on a computer code, developed by Morin, that determined the survivability of a crewmember given an acceleration/deceleration loading profile and a given stopping distance. Again, it must be stressed that these are very simplistic relationships at this point and, at most, very crude approximations of actual behavior. However, they are very useful for students to develop a "feel" for how parameter variations can affect performance and design.

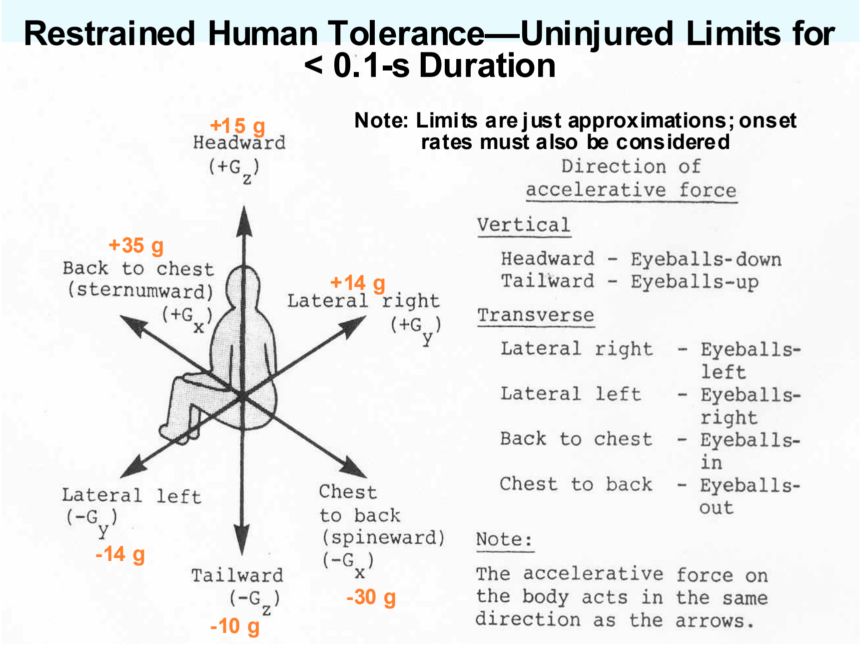
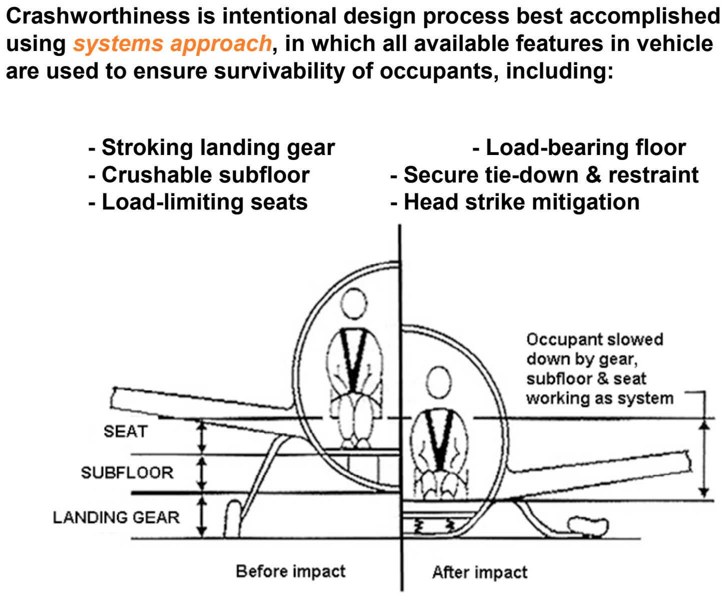


Figure 7. Physiological human tolerance acceleration limits.

The next idea that the conceptual designer has to understand is the relationship of the component to the "larger" system and how each of the components can be utilized to enable a beneficial cumulative effect. For example, when designing an airline seat attenuation system, you must look at the entire system and the contribution of each component in the energy absorption process (e.g., tires, landing gear, seat structure, seat cushion, etc., see Fig. 8). Hence, even though our design team may have been asked "by the program" to consider only load alleviation possibilities within the *Orion* crew capsule, it is important to question "why" these restrictions on requirements exist and if indeed they truly are essential. Are there innovative ways to expand the design space of your "system" to include, for example, the extension of the *Orion* heat shield to help accommodate a larger distance with which to absorb the impact and consequently reduce g-loads to the crewmembers?



Crashworthiness is intentional design process best accomplished using *systems approach*, in which all available features in vehicle are used to ensure survivability of occupants, including:

- **Stroking landing gear**
- **Crushable subfloor**
- **Load-limiting seats**
- **Load-bearing floor**
- **Secure tie-down & restraint**
- **Head strike mitigation**

Figure 8. – Systems approach to engineering design requires "panning out" to see all the mechanisms involved with the problem and how they interact to provide an overall effect.

Design Philosophy

As explained earlier, the course philosophy deliberately focused on the conceptual portion of the design cycle because it is during this very early portion of the design cycle that the most gains can be realized. However, to enable the students to understand several differing design cycles, both the Waterfall and Spiral design cycles and the pros and cons of each were discussed. A real-time example was provided of a design-of-experiments (DOE) application to a paper airplane design, which the 30 students participated in the design, testing, and analysis of results.

Techniques to Enhance Creativity and Generate a Multitude of Original Ideas

The class was introduced to many different types of creativity tools and exercises such as: brainstorming, SCAMPER, Fishbone Diagrams, 6–3–5 Method, and TRIZ (the theory of inventive problem solving.[11–14,17]

Brainstorming: A general creativity tool best applied in small groups when idea generation is important rather than technical problem solving. It produces results quickly, inexpensively, and in-house, which maintains secrecy. It is the most widely employed technique.

Hence, it was viewed as critical to expose the students to other creativity techniques, many of which can be found at http://www.mycoted.com. One technique that we went into more depth for the students was TRIZ. The key point that was made to the students was that TRIZ allows a designer to access solutions outside of their sphere of knowledge (Fig. 9). Particularly for less experienced designers, this is important as they have yet to build up significant experience.

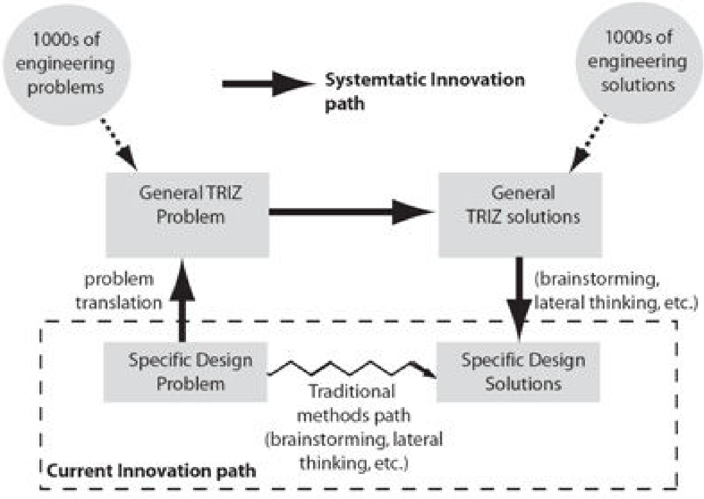


Figure 9. TRIZ solution strategy.

Biomimetics and Biologically Inspired Design

The students were instructed in biologically inspired design (BID), which uses inspiration from the biological or natural sciences to identify analogical methods for functional elements of a given problem in order to understand the problem from a unique perspective and, thus, propose innovative solutions.[18,19] Although there are some limitations to the biological process of evolution as a design methodology, there is much that can be learned by studying biological solutions to analogous problems in nature and understanding its underlying principles.

Some of the advantages of looking at biological systems include: the numerous opportunities that nature affords us that have evolved many different solutions to the same problem; the fact that nature typically uses robust principles in design; nature often uses the principle of multifunctionality in striving to optimize a solution in order to conserve energy; and nature learns through failure by rejecting all but the successful designs, albeit evolution is an extremely slow process! Some aspects of the evolutionary design process require that individuals using biologically inspired design be cognizant of potential limitations. These are: evolution is a random process; selection is directional, constrained by evolutionary lineage; nature tends to solve for many parameters simultaneously thus satisficing; and there may not exist a biological analogue for a specific problem. However, these limitations often may be overcome by searching broadly across evolutionary space (to minimize the effects of random, slow change and evolutionary constraints) as well as combining solutions derived from more than one biological system.

The methodology used in this course for incorporating BID into the solution and design process follows the following process: 1) problem decomposition, 2) search, 3) source understanding, 4) principle extraction, 5) principle application, and 6) design, analysis, and test of principle. One capability that we can incorporate that nature cannot is the ability to combine ideas from different "species" by extracting the "principles" used in each.

One example of a "Champion Adapter" by handling very large accelerations successfully is the woodpecker (Fig. 10), whose tongue wraps entirely around its tiny brain to support it during pecking where it can achieve accelerations as large 1900 g's. In addition, its neck structure and cartilage also absorbs some of the shock of this impact and helps attenuate negative physiological effects. Cartilage is a complex biological system that can actively vary its properties to sustain impact loads. The cartilage and bone structure of the woodpecker is ideally suited to cushion the tiny brain from excessive, damaging impacts. Understanding the mechanics and biological functions results in principles that can be used to modify and/or improve existing mechanical systems and to help develop advanced methods to accomplish a similar energy absorbing function for the *Orion* land landing problem under consideration.

Figure 10. Biomimetic analogies for impact attenuation – mechanics of woodpecker. The wood pecker's neck muscles are thick and strong allowing it to absorb energy; its long tongue wraps around the skull; and a membrane blinks over the eye to keep out wood chips (after *National Geographic*, Oct. 2007)

Rapid Concept Development Strategies

One of the keys to successful conceptual design is to rapidly generate as many dissimilar ideas/concepts as possible and to actively develop and mature these ideas and simultaneously evaluate each of the concepts for as long as possible throughout the project and for as little cost as possible. Hence, during early prototyping stages, it may be necessary to substitute materials, components, mechanisms, etc., which may not be similar but which only serve to mimic a proposed function. Utilizing a building block approach that addresses "key failure mechanisms" of each concept early and combining this with an "Intelligent Fast Failure" strategy[12] results in a Rapid Concept Development strategy that enables rapid learning, alternate solutions, and rapid maturation and evaluation of ideas. The rapid concept development of an on-orbit repair system for the Space Shuttle Orbiter was chosen to provide an example of this process. Figure 11 illustrates all of the components that comprise a rapid development strategy for a Reinforced Carbon Carbon (RCC) repair of the Shuttle wing leading edge.

The idea for repairing damage to a Shuttle wing leading edge was inspired by an idea proposed and rejected very early by the government team. At one of the first brainstorming sessions, it was proposed that an EVA astronaut go out and drill and tap a hole in the wing leading edge where the damage was and then fill that hole with a C-C fastener. Many of the original NASA team thought this was an improbable and risky solution and thought the idea of drilling a hole in the wing would not only be very difficult/impossible but that it would unnecessarily cause more damage. However, a handful of researchers were able to develop a means for drilling and tapping a hole through the SiC oxidation protection coating and the RCC substrate using a specialized step-tap drill bit shown in the upper left-hand portion of Fig. 11. This drill bit was patented and certified for flight in less than one-and-a-half years and was carried aboard the first flight post *Columbia* (STS–114) and has been flown every Shuttle flight since. This small team was able to develop many of the necessary components needed to repair a small hole/damage to the RCC leading edge because they were able to build a small network of knowledgeable experts and technicians who operated out of a small laboratory garage and were allowed to fail fast and furiously and were undaunted by what they were told to be impossible tasks!

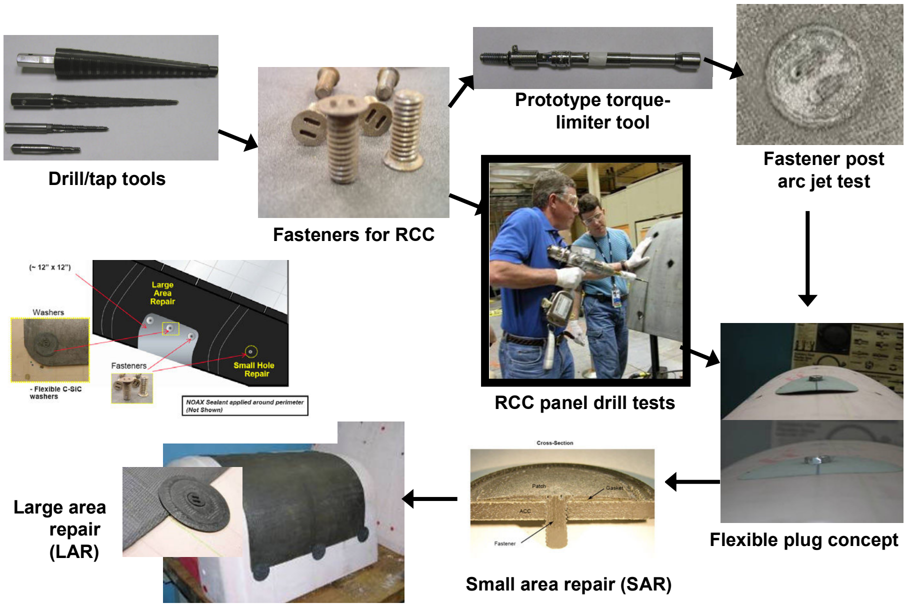


Figure 11. Rapid Concept Development: components of reinforced carbon-carbon (RCC) repair methodology for repairing very small to very large damage in a Shuttle wing leading edge.

In addition to the drill bit shown in Fig. 11, the small research team considered many alternate ideas for developing small to large repairs (called plugs, patches, and overlays according to increasing size) by rapidly prototyping ideas for flexible doubly-curved ceramic patches that would easily flex to conform to varying curvatures of the wing leading edge easily and, thus, reduce the total number of required patches from 1800 to 18[1]!

One of the key for successful rapid development is the parallel maturation of numerous ideas and the obviation of potential failures of any one concept by consideration of ideas for solutions to potential problems *before they become problems during the testing phase.* For example, as shown in Fig 12, the team considered many ideas for doubly-curved patches ranging from different materials (e.g., refractory composites, high-temperature metals and super alloys, liquid metal-filled screens, etc.), gaskets (to prevent flow beneath the patch and to add redundancy in patch bonding), and fasteners. In addition, the team was able to test ideas rapidly in the laboratory by acetylene torch and utilizing a small arcjet facility. This allowed rapid maturation because there was no interference with other larger facilities which were overbooked by the project office. This independence allowed the environment which enabled the progress.

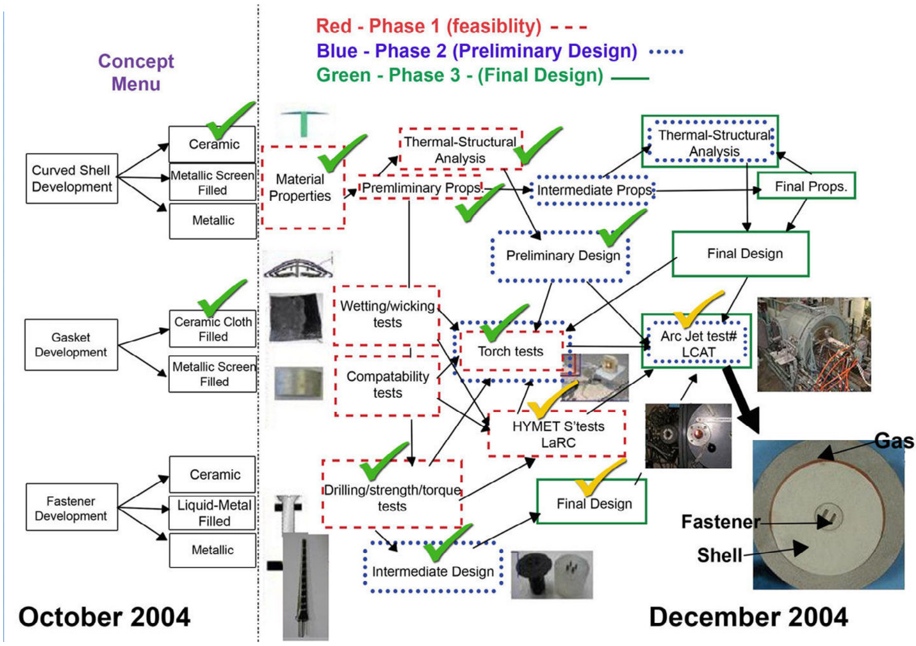
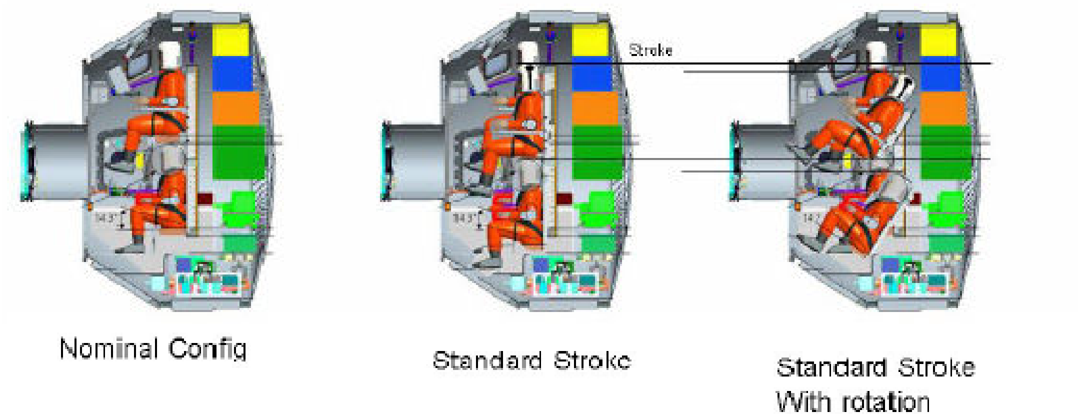


Figure 12. Building-block approach used to rapidly develop and mature the RCC repair concept.

Student-Generated Solutions

There were many ideas/concepts that were conceived during the five-day short course. The six teams of five students selected several of their promising ideas to analyze, prototype, and, in some cases, actually test. Several of the ideas presented were new to the CxP and were very interesting.

The concept shown in Fig. 13 is a very simple method for increasing the length of seat stroke by rotating the crew seats prior to landing. There was a very strict requirement for seat/crew eye-point location to allow astronauts proper views from windows. However, part of the lessons taught during the course was to push back on requirements to determine if there was any possible flexibility. As it turned out, by separating this particular requirement in space and time (a TRIZ principle), it was possible to vary the eye-point during the landing phase when astronaut window views were not necessary!



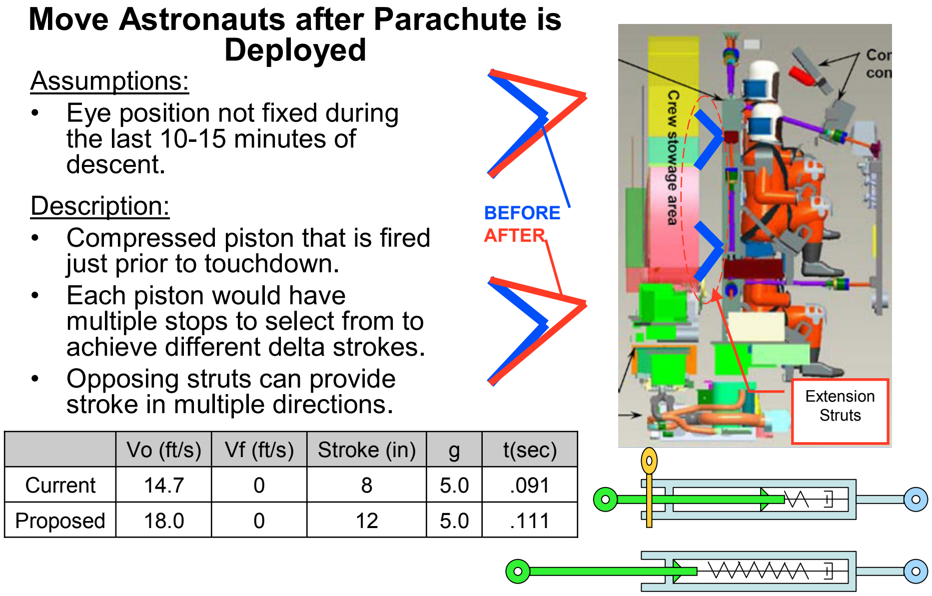
Nominal Config

Standard Stroke

Standard Stroke With rotation

Figure 13. Method for enabling crew seat rotation to increase the length of seat stroke to reduce acceleration forces.

Another method for gaining seat stroke to accommodate a greater distance to slow the astronaut and absorb landing loads is shown in Fig. 14. This particular concept actually fires just prior to entry and takes advantage of the reduction in relative velocity of the crewmember prior to impact and by changing the astronaut's eye-point and thus increasing the stroke just prior to impact. This particular idea was actually prototyped and tested by a very simple demonstration during the final day of class.



Move Astronauts after Parachute is Deployed

Assumptions:

- Eye position not fixed during the last 10-15 minutes of descent.

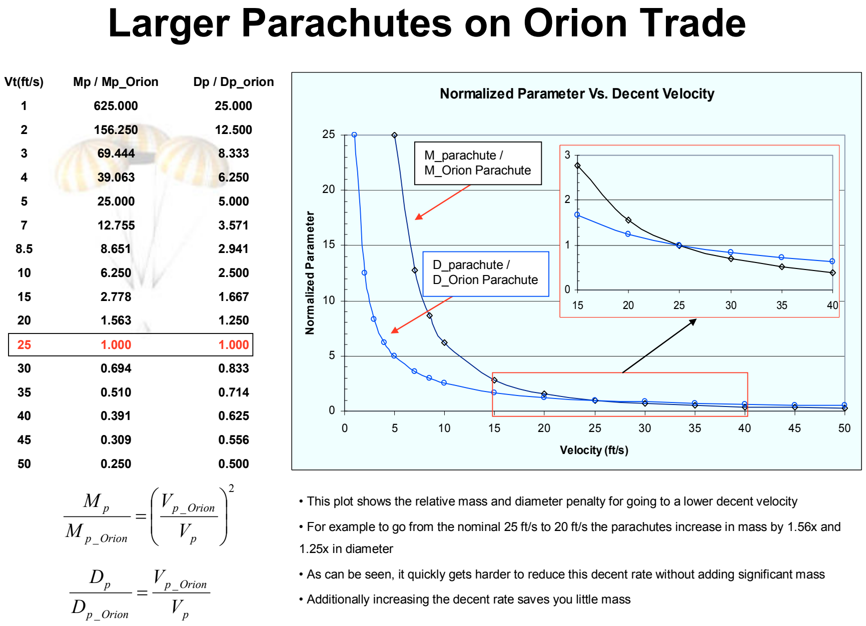
Description:

- Compressed piston that is fired just prior to touchdown.
- Each piston would have multiple stops to select from to achieve different delta strokes.
- Opposing struts can provide stroke in multiple directions.

	Vo (ft/s)	Vf (ft/s)	Stroke (in)	g	t(sec)
Current	14.7	0	8	5.0	.091
Proposed	18.0	0	12	5.0	.111

Figure 14. Concept that increases seat stroke to minimize impact loads. In addition, the seat imparts a negative velocity to the crewmember just prior to impact to reduce relative velocity at impact.

One team investigated the use of larger parachutes (Fig. 15) and conducted the preliminary analyses necessary, which determined that the size of parachute necessary to reduce impact velocity sufficiently would result is an excessive increase in mass. Hence, while this idea was not feasible, it taught the students the importance of conducting the preliminary, simplistic physical modeling necessary to determine feasibility of individual ideas/concepts.



Larger Parachutes on Orion Trade

Vt(ft/s)	Mp / Mp_Orion	Dp / Dp_orion
1	625.000	25.000
2	156.250	12.500
3	69.444	8.333
4	39.063	6.250
5	25.000	5.000
7	12.755	3.571
8.5	8.651	2.941
10	6.250	2.500
15	2.778	1.667
20	1.563	1.250
25	1.000	1.000
30	0.694	0.833
35	0.510	0.714
40	0.391	0.625
45	0.309	0.556
50	0.250	0.500

$$\frac{M_p}{M_{p\_Orion}} = \left(\frac{V_{p\_Orion}}{V_p}\right)^2$$

$$\frac{D_p}{D_{p\_Orion}} = \frac{V_{p\_Orion}}{V_p}$$

Normalized Parameter Vs. Decent Velocity

- This plot shows the relative mass and diameter penalty for going to a lower decent velocity
- For example to go from the nominal 25 ft/s to 20 ft/s the parachutes increase in mass by 1.56x and 1.25x in diameter
- As can be seen, it quickly gets harder to reduce this decent rate without adding significant mass
- Additionally increasing the decent rate saves you little mass

Figure 15. Investigation of increasing parachute size to reduce impact velocity.

A deployable heat-shield concept, Fig. 16, which uses shock absorber pistons to help absorb impact forces was also investigated analytically and demonstrated by a drop test with a high-speed camera video.

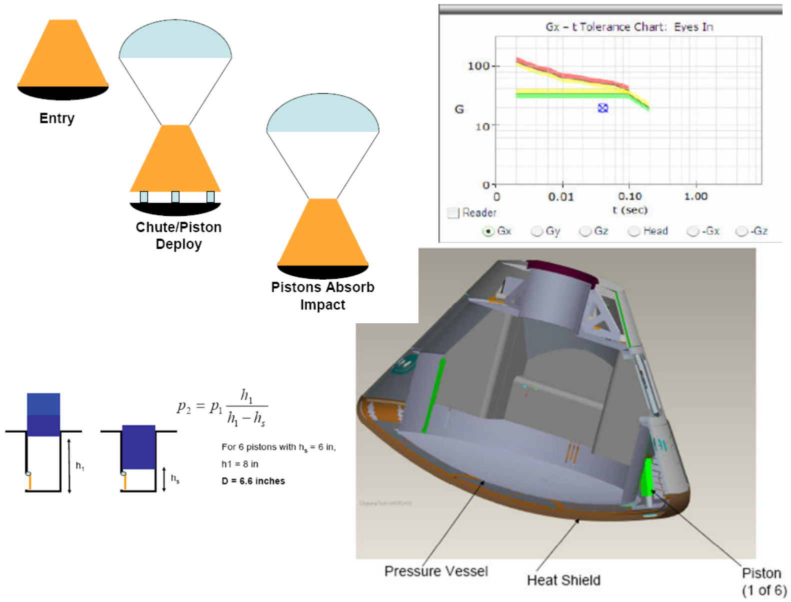


Figure 16. Deployable heat shield concept with pistons to help absorb impact force.

One team investigated using a combination of two-layer foam with an outer layer of non-Newtonian material, which conforms to the crewmembers shape and which stiffens during the deceleration loads on impact and distributes the force to a second foam layer (Fig. 17). This idea would be useful as a seat-liner that could be compatible for crewmembers of different sizes and eliminate the need for individually-designed seat liners as are currently used on the Russian *Soyuz* vehicle. The inspiration for this idea came from a YouTube video of students who filled a swimming pool with cornstarch and water and demonstrated how it was possible to run across the pool on the surface of this non-Newtonian fluid!

- **First layer a non-newtonian fluid which conforms to astronauts shape, hardens on impact and distributes forces uniformly to a second energy-absorbing foam layer. The pressure distribution of the body is more efficient hence will support greater accelerations.**
- **The astronauts when returning from space could suffer up to a 3 inches of spinal growth. With two-layer foam, the seat will reshape to accommodate these type of biological changes before re-entry.**

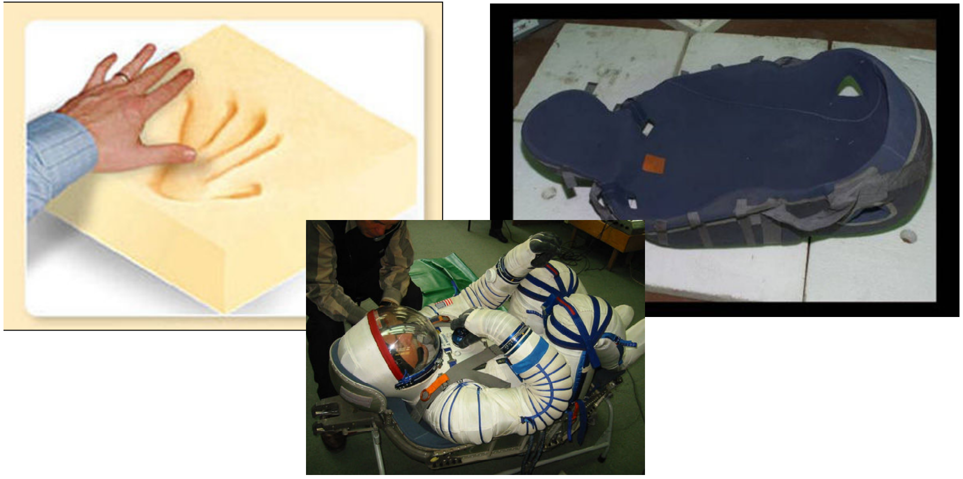


Figure 17. Two-layer foam seat-liner design composed of an outer non-Newtonian fluid and an inner layer of memory foam.

The idea of "personalized" air bags, Figure 18, was proposed as a means of incorporating an "air-bag" system into the crewmembers seats in order to allow additional distance between structure and adjacent crewmembers to absorb impact energy during landing. This idea was selected by NASA project managers for further research and resulted in the collaboration of student and faculty teams from MIT and Penn State.[20]

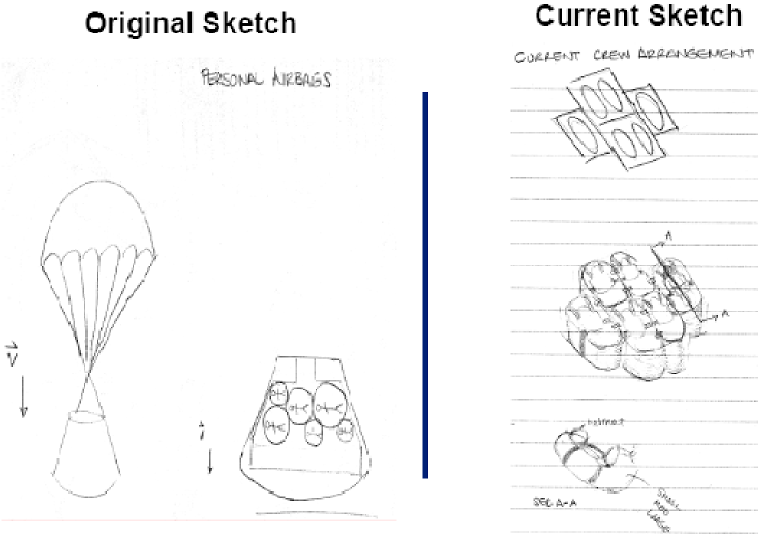


Figure 19. Personal air-bag conceptual sketches.

Figure 20 is a photograph of a personalized airbag test at MIT. The instrumented test dummy was supplied by NASA Langley Research Center, the funding support was from a grant from the

NESC, and the collaborative research resulted in research for several graduate students from Penn State and MIT.

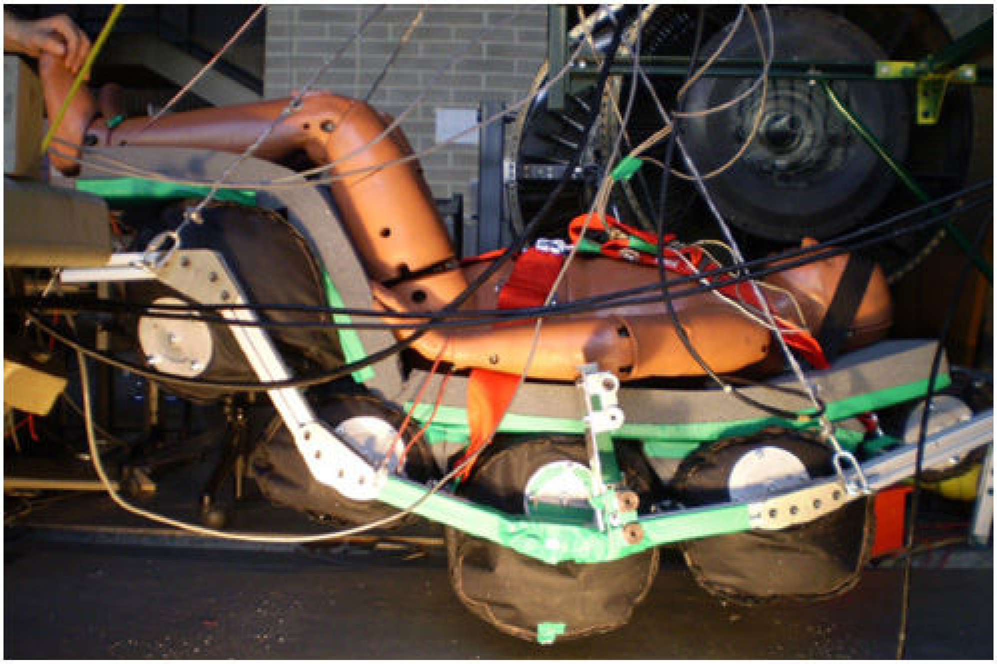


Figure 20. Preliminary design and test of a personal air-bag system resulting from a collaborative study by students from Penn State and MIT on a grant from NASA.

Conclusions

A template for teaching innovative conceptual engineering design has been presented. The template follows a phased approach for approaching and solving complex, multidisciplinary engineering design problems beginning with problem definition and background research and proceeding rapidly through the concept ideation, rapid prototyping, analysis, and test phases. The methodology employs methods for convergent and divergent thinking and uses analogical means to introduce alternate ideas.

The methodology was demonstrated using a class of young NASA engineers who were given a complex problem that NASA was currently struggling with: the alternate land landing of the *Orion* capsule. The current Constellation Program baseline crewed capsule, *Orion*, is constrained to a water landing due to excessive impact loads of a land landing. However, in the event of an abort, the capsule may encounter situations that can result in a land landing and eventual injury to the crew. In one week, the NASA student teams were immersed in this problem and coached on methods to help enhance their creativity and critical problem solving skills. In one short week, ideas were conceived, analyzed, prototyped, and, in some cases, tested. Several of the ideas proposed were evaluated by NASA project leaders as worthy of merit and considered for future funding. A collaborative team of students and faculty from Penn State and MIT were selected for research funding. Resulting designs were developed and tested.

This exercise demonstrated the capability of large corporations and government agencies to tap into the creativity-rich resources of academia to develop innovative solutions to real problems. This same methodology could inspire undergraduate engineering students[21] as well as high-school students to pursue science and engineering by illustrating the joy of discovery and creative problem solving which allows them to exercise their natural creative abilities. These techniques are currently being employed at The Polytechnic Institute of NYU to instruct undergraduate, graduate and high-school students.

Acknowledgments

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