NASA-CR-202061

Final Report

Dynamics and Control of Orbiting Space Structures

NASA Advanced Design Program (ADP)

Grant NAGW-4252

NASA Headquarters

Washington, DC

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Report 96-08-02

20 August 1996

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1. Summary

The report summarizes the advanced design program in the mechanical engineering department at Vanderbilt University for the academic years 1994-1995 and 1995-1996. The course structure consists of two semesters taken during the students' senior year and is a required course. Approximately 100 students participated in the two years of the subject grant funding.

The NASA-oriented design projects that were selected included lightweight hydrogen propellant tank for the reusable launch vehicle, a thermal barrier coating test facility, a piezoelectric motor for space antenna control, and a lightweight satellite for automated materials processing.

The NASA supported advanced design program (ADP) has been a success and a number of graduates are working in aerospace and are doing design.

2. Overview of the Advanced Design Program at Vanderbilt

2.1 Design course goals and organization

The following paragraphs reproduce the course handout for the two semester design sequence in the Mechanical Engineering Department at Vanderbilt University. The course reflects to professional experience and attitudes of its author who feels strongly that current ME students do not have enough experience with real equipment and real engineering practice. The lack of adequate numbers of summer internships and other technical working opportunities results in the fact that a very high percentage of our students have no idea what real engineering problems are and what their work experience is going to be like once they graduate. As a result, many decide to choose other career paths even before they get the BS degree.

The two elements that I seek to convey to the students in the design sequence then are experiences with real (but simple) mechanical devices and professional expectations regarding the conduct of the course. The approach is based on my 18 years of working in industry including 11 years in the aerospace industry. The mechanical devices are often in the form of simple consumer products such as toilet valve systems, hand operated pumps, sprinkling systems, etc. The following comments set the tone for the rest of the course.

Textbook: **The Mechanical Design Process**
David G. Ullman
McGraw-Hill, Inc. (1992)

Background: The design course is a two semester course taken by all graduating Mechanical Engineering students. The first semester of the course is *ME 242 Design Synthesis*, and the second semester is *ME 243 Engineering Design Projects*. The two courses are integrated in such a way you are introduced to modern design issues through hands-on participation in all elements of design.

This course may be contrasted with most other courses that you have had, especially in engineering. In those courses you were taught fairly narrowly defined, in-depth knowledge that you were expected to be able to demonstrate through homework and exams. Design deals with the much less structured reality of how engineers generate ideas to solve development challenges. The challenges may themselves be narrowly defined, such as redesigning a flange fillet to solve a cracking problem, or they may be broadly defined, such as designing a propulsion system for a supersonic transport. Each of these problems shares the fact that the answer is non-unique and requires more than just narrow technical knowledge. *Design is the art (some say technology) of developing solution strategies to open-ended problems.*

Goals: The goals that I have set for this course include giving you a working knowledge of the elements and tools of good design and exposing you to some of the realities of engineering as a profession. You will deal with the fun (some say frustration) of solving problems without a well-defined solution, while recognizing the realities of constraints - time, money, and performance (the product's, not yours!). Additionally, you will experience the significant challenges and opportunities of working as a team to solve design problems, especially in ME243.

Elements of the Course: The course is broken into two parts. The first semester will focus on tools of the trade, while the second semester will focus on team design problems. The first semester will emphasize discussion, exercises, and a focused design task. The work during the first semester will be primarily based on individual effort. There will be several major design projects during the second semester effort. The work during the second semester will be performed by teams of students working on a common design objective.

Some of the items of concern in design are mundane, but critical. These involve cost and time. All design problems are subject to schedule and dollar limitations. The analogy for you in this course is that you have a finite budget of time in which to deliver an acceptable result. When you are a practicing engineer you will find that the cost of engineering time is one of industry's greatest problems. The problem usually comes in the guise of "productivity improvement". Your ability to deliver quality work in a fixed budget of time is a key part of what you might learn in this course. Hopefully you will learn how to pace work and how to integrate a project through the work of several people.

We will also be concerned with idea generation and idea refinement. Good designs evolve, they rarely come in the flash of an idea, although the flashes are important. How to generate a lot of possible solutions, and then how to narrow and refine these ideas is a key part of successful design.

No idea or design or problem solution is worth a plug nickel, if you can't document and communicate the solution. No matter how trite it seems, the ability to effectively communicate your ideas will affect your personal success in the work place more than any other element of your training - and its the area in which you get the least training! I place a premium on communication in this course. I'll give advice, but you are ultimately responsible for pulling it off.

Lastly, there is the much-used idea that you will get out of this and any course only what you put into it. In the case of this course that means that you will have to read, think, record your ideas, discuss those ideas, prepare solutions, defend those solutions, and carry those solutions forward to the point of a meaningful end result. You will be given a lot of freedom to develop your design work, but this will be at the cost of learning to live with the frustration inherent in trying to define your own activities, tasks, goals, and to be able to evaluate your own work achievements.

The topics treated in the first semester include the design process, with emphasis on the procedural tools needed to do design. Planning is one key tool and includes design problem definition and task schedule development. Product safety, liability and human factor issues are incorporated in early design exercises. Design documentation is critical; the first semester will introduce and emphasize the proper use of design journals, along with the elements of written documentation. Other technical elements during the semester include design idea synthesis and brainstorming, design refinement, analysis and evaluation.

During the first semester, each of you will work a sequence of design problems involving mechanical systems of a suitable degree of simplicity to demonstrate design principles. You will be then be given a common, ill-defined hardware design problem to solve. Each of the individual designs will culminate in detailed technical documentation of your effort, including the design journal, schematic drawings, and a written report. The second semester focuses on team design of a mechanical system to meet a design specification given to each of the design groups.

The effective communication of your design effort will be continued through both semesters. Major written reports and design journals will be supplemented by oral presentations of progress and final reports. All modes of communication appropriate to design will be exercised. Lessons learned will be discussed and retained at each major breaking point in the design curriculum. There will be a poster session display of the results of your ME242 individual designs in lieu of a final exam.

Course Requirements: While design has a critical emphasis on creativity, design also relies on clear and effective communication of results, as well as accurate and thorough design evaluation procedures. Standards will be defined regarding these elements of the design effort; work submitted that does not meet minimal standards will be returned with no credit. Individual design process exercises will be assigned during the first semester. Failure to submit the exercises when they are due, or to obtain prior approval for late submittal, will result in no-credit for that exercise. Each design exercise is critical to understanding the design process; each one relies on the earlier exercise(s). Failure to receive credit on ***any** single design exercise* will result in loss of one grade level for the course.

As will be discussed in some detail, the use of the **Design Journal** is the key element in documenting one's design work for protection of intellectual property relative to patent rights, documentation of critical design information and decisions, as well as for protection of you and your company in the event of litigation stemming from the use of a product you design. The Journal is to be your sole repository of notes and work done each semester. It is your responsibility to maintain your Journal in an up-to-date and complete condition. You will use the Laboratory Research Notebook (Item 43-649 in the bookstore), or an approved equivalent. The carbon pages will be removed on a weekly basis and deposited with the TA for grading and evaluation comments.

Design Journal Requirements: You will date the work on each Journal page and sign your name on each page. You may add figures, tables, computer output sheets, etc. to the Journal, and carbon copy page, with scotch tape - remembering to date and sign each page. You will use all consecutive pages of the Journal. In-class product design discussion notes, product sketches, design thought-process comments, design change rationales, engineering analyses of your product, multiple design concepts, evaluation of alternative design concepts, and many more items are to be found in your Journal. Examples of previous-student Design Journals and exercises may be seen in Olin Hall 336B, next to my office.

Design Course Requirements: You are to complete all reports and analyses on tools available on the Engineering School ICL's or on comparable tools on your own PC.

- All reports will be word-processed and computer printed using laser or Inkjet technology according to criteria that will be defined on the weekly exercise sheets.
- All project planning tasks will use the Microsoft Project software system or an approved alternative project planning tool.

- All analysis tasks will be documented including schematics, assumptions, and equations. Any software model will be a part of the documentation.
- All CAD tasks will use CADKEY , CADKEY for Windows, or an equivalent product capable of producing three dimensional renderings.

All reports ***not stapled*** or ***not meeting basic standards of neatness and readability*** will be returned with no credit. A stapler is available in the ME office! Grading of each project will be on an absolute scale of 1-10 (A = 10; A- = 9, B+ = 8, B = 7, etc.).

Class Grading: All design work the first semester is individual work. Failure to develop your design in an individual manner will be considered an honor code violation, unless group work is a specific part of the assigned exercise. Discussion with other students is to be limited to the design process elements, and is not to include the elements of your own design effort.

The class grading includes the following items and weights:

- 20% Design Journal
- 50% Design project exercises
- 20% Final design and documentation
- 10% Participation in discussions

2.2 Design problem statement philosophy

Each design problem is posed in a simple manner. The intent is to define the principal requirements for the "product" as given by the customer. In all cases, we restrict the definition of the customer to the end user of our "product" rather than to include such other customers as manufacturing, product support, etc. The time is too short and our resources too limited to take on the full concurrent design teams of industry. However, we do talk about this greater sense of the customer. The following is an invitation which has been used in the past to solicit basic design problem statements.

Memorandum

To: Interested Developers of ME Design Projects

CC: ME 242 Design File

From: Thomas A. Cruse

Date: August 20, 1996

Subject: Design Project Opportunities

You are getting this memo as you have expressed some interest in defining a design project for the Senior Design Course. The course is two semesters long, starting in the Fall each year. The approximate enrollment is 50 students. The following elements are contained in the Fall term (ME242):

1. A series of reverse-engineering exercises which allow the students to perform a comprehensive functional decomposition of a defined product, to develop an understanding of the design sub-problem solutions embedded in the product, to assess its human interface and safety design features, and to perform an analytical modeling exercise associated with the product design. The products, typically, are consumer products.
2. A general design problem exercise for individual application of the elements of structured design sometimes including group exercises. An example from the 1995-96 academic year is attached. The elements of the structured design approach include defining the customer(s) and customer requirements, developing an engineering understanding of the customer requirements leading to a form of design specification, performing a functional decomposition of the design problem, seeking solutions to the design (sub-)problems, synthesizing design options, performing feasibility and design trade studies, and creating a schematic design of the product.
3. The students prepare written reports and memos, keep detailed design journals, prepare CAD-type renderings of their designs, and perform extensive product research to generate their design ideas. The final effort consists of a formal written report and a poster displaying their product design and basic bill-of-materials.

During the Spring term, the students work in design teams to carry the product design forward to the level of working prototypes on some critical sub-system or total product function. The teams often are created in a manner that requires system-level integration of their assigned portions of the total design. Often, the teams are placed in two competing groups with performance criteria providing the basis for the competitive assessment. The students give weekly progress reports on their work. The Semester projects end with a formal written report by each design team and a formal oral presentation of the design projects.

The design problem statement is intended to provide clear guidance of what the customer wants in terms of product performance, without giving or implying guidance as to how the design is to be developed. The attached sample from the current year is given as a statement of the overall problem, a list of the mandatory design requirements, and a list of the desirable features. The mandatory requirements, ideally, are those that have binary answers - the design either meets the requirement or not (grounds for rejection or modification). However, sometimes this is not really accomplished, as in the first requirement stated. The other features are then weighted in consultation with the customer. This single sheet constitutes the assignment as given to the students about in the sixth week of the term.

If you have one or more design problems for us to consider, either for schematic design in the Spring '96 term or for a full-year design effort in '96-'97, I invite you to create such a single sheet definition of the problem. There will then need to be interactions with you or your designee at the appropriate time. If prototype development is desired, the direct costs of the prototype would have to be reimbursed.

At the end of the design, you will receive a full written report documenting the research, the design process and product design specification, and the resulting design renderings. If a prototype is involved, we will supply the detailed designs of that prototype as well as records of the performance of the prototype. Of course, we invite a higher level of participation and oversight of the student work, including engineering reviews of the design during the term.

Thank you for considering this opportunity.

2.3 Representative design problem statements

2.3.1 Solar powered materials processing satellite design

Background: The future of NASA-launched satellites centers on the design and use of new micro-satellites, each of which is special purpose, inexpensive, and can be launched using a variety of platforms, including the Pegasus or Taurus air-launched vehicles. Each micro-satellite will achieve a well-defined and meaningful science goal. The focus on small size and low expense is crucial in trying to get the satellite funded and launched.

The SPMP satellite is one such possible concept. The satellite is to produce PbI_2 single crystals for use in X-ray and Γ-ray detectors. The purpose in using a satellite is the achieve very low levels of crystalline structure defects through the micro-gravity environment of earth orbit. A successful design in this project can materially affect possible acceptance of such a satellite as a future NASA project.

Your goal is to develop a design of a suitable micro-satellite for this scientific purpose. The design is to include specific selections of the physical means of crystal growth, satellite configuration, weight and inertial properties, and subsystems selection. You are not responsible for defining the recovery method for the crystals or replenishment of the satellite. You will produce a detailed graphical solid body rendering of the design and video animations showing the operation of the satellite suitable for presentation to NASA.

Mandatory Requirements:

1. Satellite must be of a stowed size and weight permitting Pegasus or Taurus launch capability
2. Satellite must be capable of withstanding the launch loads and orbital operations involving the thermal cycling heat loads and thermal gradients for its orbital operations
3. Satellite must be capable of producing high quality single crystals of PbI_2
4. Satellite must be solar powered and meet all electrical and heating requirements
5. Satellite must make maximum use of off-the-shelf hardware
6. Satellite materials and subsystems must be capable of long life operations in space and microgravity
7. Minimum of five specimens must be prepared under different conditions
8. Specimens have to be a minimum of 0.5" in diameter
9. Specimen solidification rate must be ground-controllable and monitorable; thermal control of temperature level and gradients is to be sufficient for the scientific purposes

10. Satellite must be capable of remote ground monitoring on an at-least intermittent basis

11. Specimens have to be retrievable from the fabrication process

12. Satellite has to be self-deployable once it is placed in orbit

Desirable Features:

1. The weight and size are to be minimized

2. Weight is to be less than 100 kg

3. Orbit to be sun synchronous or low earth orbit

4. Optics can be focusing or non-focusing

5. Attitude can be controlled by N_2 gas or satellite spin

6. Specimen lengths are to be maximized

7. Minimal use of solar electrical energy

8. Satellite is to be controlled by ground command for specimen processing

2.3.2 Wind generating turbine design

Background:

Since the early 1970's, the use of wind energy for the production of electricity in the USA has increased dramatically. Several areas of the country are particularly valuable as "wind energy farms." In particular, the central portion of the country has high wind speeds which may eventually be utilized. Already, portions of California have been developed to produce electrical energy from the wind. (Efforts are being made to use electrical energy for transportation, and recent announcements from GM have indicated that a small electrical automobile is soon to be available in that area.) Obviously, wind energy is intermittent, and considerable effort has been made by companies to consider how this power might be integrated into the grid. In any event, as our reserves of fossil fuels diminish, there will be increased emphasis on other forms of energy.

It is desirable that Mechanical Engineering students have available a working model of a windmill to illustrate some of the more fundamental aspects of this form of power. Such a model should emphasize the importance of modeling of prototypes and the testing hardware required as well as the collection and analysis of data produced by a model. Your responsibility is to produce a design, a working model of the apparatus, and an experimental protocol.

The experiment is also to address the integration of computers and design into science courses. The design effort will include full specification of the experimental hardware, vendors, and costs. The final report will include a video based on CFD simulations of the experiment and CAD renderings of the facility.

Mandatory Requirements:

1. Fits into the wind tunnel in the energetics lab, located in Jacobs Hall.
2. Has high operating reliability.
3. Easily installed/removed from the tunnel.
4. No significant wind tunnel changes are permitted.
5. Experiment must provide for a wide range of tests.
6. Flow variables must be measurable.
7. Model to produce properly scaled performance conditions
8. Data acquisition of windmill performance variables to be included.
9. Windmill design should provide a high quality laboratory experience for ME undergraduates.
10. Must be safe!

Desirable Features:

1. Design should be appealing (This must be a professional job.)
2. Provide for some variation in testing, e.g. by changing blading
3. Construction of your design is to be done in-house
4. Minimize cost. Target is under $2000 plus data acquisition
5. PC to be used for control, data acquisition, and analysis
6. Experiment to be integrated into classroom using the network and available interfaces
7. Experiment to have a CFD flow visualization counterpart incorporating all of the scaling for each blade configuration

2.3.3 Flexible Space Structures Piezoelectric Stepper Motor Design

Background:

The problem is to design linear and rotary motors which rely on piezoelectric materials for the conversion of electric potential to mechanical work. The primary focus of the effort should be on the **innovative** design of a linear motor with secondary consideration given for the design of a rotary motor. The motors to be designed are intended for space based applications, so the materials and components must be selected for the space environment. The motors are to be designed for precision position control. Accurate positioning should be accomplished quickly and regardless of load.

Precision position control includes both a large macroscopic range of travel and a fine positioning micro-resolution. The linear motor should have a range of travel 30 cm or more and a resolution of 50 nm. the positioning must be accomplished with a reasonable time response. As such, the minimum speed performances is specified as 20 mm/sec. The load capability of the motor must be greater than 10 N. The holding force of the motor must be greater than the driving force, so that the motor is not "back drivable."

The design process should begin with the extensive literature that is available, supplied and to be researched. However, the emphasis in this project is on innovation of configuration to achieve the stated performance goals. Material can be supplied to build a suitable prototype for demonstrating a key performance characteristic. The product design has real applications. The effort will also involve engineering simulation using finite elements for stress and dynamic analysis. ANSYS contains piezoelectric materials. Detailed schematic design and simulation is required.

Mandatory Requirements:

1. The linear action motor design must be the first design; a rotary design concept can then be developed.

2. The motor is to use piezoelectric materials for conversion of electrical to mechanical energy.

3. The materials used in the design must be capable of indefinite operation in the space environment.

4. The linear motor must meet or exceed the following performance specifications:

   Speed: 20 mm/sec   Range: 30 mm   Load: 10 N

   Resolution: 50 nm

5. The motor is to be less than 2 cm^2 in cross sectional area and 5 cm long.

6. The motor is to have high reliability, possible using redundancy. Reliability is to be documented.

7. Motor is not to be "back drivable."

Optional extension to rotary motor — desirable design task

8. The rotary motor is to meet or exceed the following performance specifications:

   Speed: 100 rpm   Torque: 100 N-cm

   Resolution: 50 μ rad   Range: continuous rotation

9. The size of the rotary motor is to be least than 4 cm^2 in cross sectional area and 3 cm long.

Desirable Features:

1. Weight is to be minimized (mass).

2. Power efficiency is to be high

2.3.4 Single-stage to Orbit Tank Design

Technical Background:

The single-stage to orbit (SSTO) vehicle is under active consideration by NASA as the replacement to the current Orbiter vehicle and the associated shuttle launch system with the disposable external tank and the reusable solid rocket motors. The vehicle is a vertical launch, horizontal recovery vehicle similar to the current Orbiter vehicle. The new design is to achieve higher payload capacity, reduced launch and operating expenses (largely by being fully reusable), and higher levels of overall vehicle and subsystem reliability.

The current system is seen to be a bi-propellant launch system using cryogenic oxygen and hydrogen. This is the same basic engine and propellant system as the current space shuttle main engine (SSME) system, although the performance and thrust levels would be much higher than the current SSME.

The empty weight of space vehicles is always a critical design issue. The more dead weight of the vehicle, the lower the overall system capacity to launch payloads to space. The structural component that is to be designed for the SSTO system is the liquid hydrogen tank. This tank is selected for detailed study because it is the largest and thus the heaviest tank in the vehicle.

The fuel tank (LH2) is designed such that it contains the LH2, provides the thermal and pressure environment for the LH2, provides the structural backbone for the SSTO during launch and recovery, and must properly integrate with the vehicle and main engines. The tank serves both structural and thermal functions for the vehicle.

The fuel tank currently uses aluminum-lithium as the bill-of-material, based on a skin-stiffener construction. This form of construction is common to aircraft and the current external tank design. The tank is designed to meet specified loads. The tank is insulated to meet the thermal environment and heat condition requirements of the vehicle design. The material and the construction are considered to be within the current state-of-the-art and do not pose significant risks in terms of their technology readiness.

Problem Statement:

Each of the two design teams is charged with designing a unique, low weight LH2 tank and system interface for the SSTO based on today's baseline for the vehicle design. The tank is to fully contain the LH2, provide the thermal protection necessary for the design requirements, provide equivalent structural support as the current aluminum-lithium design, and to be fabricable using reasonable levels of technical risk. The design emphasis is to be on innovations in materials selection and fabrication such that vehicle weight is minimized, but such that the materials and processes are sufficiently feasible to be considered for the design.

The design team is to propose the most critical issues that must be resolved to show the feasibility of the selected material and fabrication system given the LH2 fuel and its operating environment. A low-cost test plan is to be designed which is to be performed subsequent to the current semester. The testing is to provide critical data for the feasibility assessment. The testing should be as simple as possible and use existing test facilities and methods.

The design will document the flight environment in terms of loads and thermal environment, meet the physical design requirements for the tank, and provide sound means for interfacing to the SSTO engine systems. The detailed design requirements that will be defined and met by the design are in the following areas:

1. Physical constraints such as tank volume and shape
2. Mechanical loads and loading conditions
3. Thermal protection and insulation
4. NASA safety factors and design life margins
5. Other NASA design requirements for materials and systems
6. Mechanical interface requirements for LH2 plumbing
7. Material properties appropriate to the design conditions

Multiple means for satisfying the desired structural and thermal requirements are to be considered in the selection of the proposed system. Design trades are to be made on the basis of weight performance and cost. The competitive trade factor model will be developed by the course TA/NASA and by the two design groups; it will be used as the basis for judging the winner of the competition.

Research and Study Items:

Each team is to assemble and read source literature sufficient to successfully complete the designs. The areas of research include background reading on vehicle design, rocket performance, materials for cryogenic applications, current tank design concepts and system interfaces, NASA design requirements and standards, vehicle launch and flight profile data necessary to support and interpret the design, and material fabrication processes for very large tanks.

It is suggested that each team develop individual or small group research tasks with each researcher charged with being the "expert" for a given technology(s). Each individual is to collect their research material in file and/or notebook collections which will be locked in Olin 336B and are part of the final deliverables at the end of the term. It is suggested that each researcher keep detailed notes on the data and their readings in their lab notebook. Finally, it is the responsibility of each researcher to brief the rest of the team on their findings on a regular basis such as weekly group meetings.

The first two weeks of the design course is devoted to study of the design problem with extensive discussions and interactions with the course TA, NASA, Dr. Cruse, and other relevant faculty in the department. Summaries of the research work are to be given at the two design class meetings during the research period.

Major Milestones and Project Planning:

Each design team is to develop a design task schedule for the entire semester. The schedule is to recognize each of the elements of the design process from developing the design specification (PUF) to the design final report and presentation. The schedule is to allow for parallel activities to the maximum extent possible in order to make best use of each team member during the entire semester.

Some of the elements of the design that are new this term, in regards to the amount of emphasis given, are the research tasks (which are emphasized early in the semester but which will go on through the first 2/3 of the semester), and the analysis tasks. You should also plan for extensive use of the phone in order to obtain hardware and pricing information for your product design.

There are three critical milestones that are not negotiable. These are the preliminary design review (PDR) presentation, the final oral presentation, and the final written report. The PDRs are all scheduled for the seventh week of the semester. The final written report is due on the class day of week 15 for the semester. An oral final presentation is due on a date to be scheduled during finals week.

Areas of Technical Activities and Responsibilities:

The design project and thus the design team will find that it is best to break up the overall design into its technical elements. The design team leader(s) is responsible for seeing that the entire design process is being adequately addressed, while participating in the technical activities. The team members are responsible for the detailed work that must be done.

The following areas of investigation and design are suggested. These are not to be taken as fixed or complete, but as suggestions to begin your planning process.

1. Engine cycle and combustion analysis and modeling
2. Material behavior and mechanical properties development including the effects of the cryogenic environment
3. Heat transfer problem definition and modeling analysis
4. Structural design requirements for rocket propellant tanks
5. Basic mechanics of composite materials
6. Material and system test methods
7. Fabrication processes for large tanks and innovative materials
8. Project scheduling
9. CAD/CAE support

The tools that are available for the course include the ANSYS finite element code for heat transfer and stress analysis, specialized composite materials modeling code, the IDEAS package for CAD and design animation, SuperProject and Microsoft Project planning tools, and the possible use of NASA simulation codes. Of course, the usual ICL software is available and is to be used as needed.

Reporting Requirements:

Each student is to maintain for inspection at any time his or her design journal. The journal is to be the primary repository of each individual's work for the entire semester. Your design journal is to be turned in for final grading on the same day as the final report, the fifteenth class of the semester.

Each design team is to turn in a single design report for their project. The design report is a formal engineering summary of your design task and will fully document your design including engineering analyses, design drawings, design assessment, etc. A detailed specification of the report format and content will be issued several weeks before the last class.

Each design team is to present a formal transparency progress report each week. The speaker(s) each week will be rotated among the team, although the design team leader may choose to act as the presentation coordinator each week. The format of the viewgraphs and the presentation style will be discussed in the first class period. The transparency material and the class charge account number for the oral presentation material will be given in class. The weekly progress report will include the following items in a format and agenda to be established by each team:

1. Cover sheet naming the project, the date, the design team name, and the day's speaker(s)
2. Overview of the day's presentation (the roadmap chart)
3. Summary of the major accomplishments for the week
4. Technical content (will change each week and may be broken into sub-presentations)
5. Technical issues or problems to be addressed in working meeting that day or any matter needing discussion and attention; less formal, working charts may be used that are reproductions of work in progress
6. Updated project Gantt chart showing %-completion for each task (this can be a hand-update for each bar on the Gantt chart)
7. Summary of the presentation

Each design team will provide two hardcopies of the full set of the presentation charts prior to the start of the presentation. Each of the day's presenters is to wear "interview dress" although this may be waived for the team leader if that individual is presenting the overview each week. All students are expected to use the oral presentations as a means to develop and/or improve their skills in presenting high quality engineering briefings.

2.3.5 Thermal Barrier Coating Test Facility Design

Technical Background:

The operating temperatures of the structural components of various heat engines is the limiting factor in overall engine efficiencies. Industry and government research has focused on the development of many new materials and processes in the past in order to increase the efficiencies of heat engines or to extend the lifetimes of the engine components.

A material class that has received much attention is that of ceramic materials. Ceramics are among the oldest materials used by mankind. Ceramic materials offer high temperature capability, low thermal conductivity, and oxidation/corrosion resistance.

The use of ceramics as structural materials, however, is limited by the lack of tensile strength of ceramics, which is often an order of magnitude lower than the compressive strength of the material. Recent attempts to develop monolithic ceramic materials for heat engines has not proven to be successful for this reason along with the defect sensitivity of ceramic materials.

A highly successful use of ceramics in heat engines is to spray certain ceramic material droplets onto metal components. The purpose of a ceramic coating is to protect the base metal from the thermal loads of the combustion processes. As a result of the low thermal conductivity of the ceramic material, the heat conduction to the base metal component can be greatly reduced.

The initial use of ceramic coatings in heat engines employed thin coatings on the order of a few mils in thickness. More recently, attention has been focused on the use of thick ceramic coatings with thickness approaching 100 mils. The coatings are applied by melting a carefully prepared batch of ceramic powder in what is called a plasma spray gun facility. The powders are dropped into a plasma spray (very hot gases!) which then melts and transports the melted drops to the work surface. Contact with the work surface causes rapid solidification of the melted drops of ceramic material. Multiple passes with the plasma spray gun results in a build-up of ceramic coating.

The resulting material system is called a thick thermal barrier coating (TTBC). Extensive test work has been done to develop material processes and design criteria for this class of materials.

Testing of TTBC materials is generally characterized by compromise. If the coated component is tested in the heat engine, the amount and quality of test data in terms of heat flux, temperatures, and pressures is quite limited or is not obtained in a direct manner. Laboratory testing of TTBC specimens uses simulated heat engine loading conditions such as in a burner rig. However, the heat fluxes that are generated in such environments are not uniform and are generally lower than would be encountered in the actual engine. The reason for this is the reduced pressures in the testing which reduces the heat transfer rate to the TTBC.

Problem Statement:

Each of the two design teams is charged with designing a unique, low-cost test facility that will produce high quality data on TTBC specimens at a range of high heat flux loads that exceeds the levels encountered in today's heat engine (diesel and gas turbine). The design goal is to achieve a 2X increase in heat loads from today's engine technologies at a facility cost under $25,000 plus the cost of instrumentation.

The test facility is to provide the means for automated test control and data recovery in real time. The test data to be obtained include a full characterization of the specimen temperatures, heat fluxes, and related environmental conditions specific to the test method being designed. The actual test specimen geometry is open except that it must be reasonably easy to coat with the TTBC and must provide a hot area of TTBC that is at least 4 square inches in size.

Multiple means for achieving the desired heat loads are to be considered in the selection of the proposed system. Design trades are to be made on the basis of performance and cost. The trade factor model will be developed by the two design groups and used as the basis for judging the winner of the competition.

Research and Study Items:

Each team is to assemble and read source literature sufficient to successfully complete the designs. The areas of research include background reading on the selected test material (an 8%

yttria, partially stabilized zirconia) and fabrication processes, combustion conditions in large diesel and gas turbine engines, current test methods, heat flux sensors and associated thermal instrumentation, and product cost data. Each design team is to identify a resource list of individuals at Vanderbilt, in industry, or at NASA who will serve as contacts for their design projects.

It is suggested that each team develop individual or small group research tasks with each researcher charged with being the "expert" for a given technology(s). Each individual is to collect their research material in file and/or notebook collections which will be locked in Olin 336B and are part of the final deliverables at the end of the term. It is suggested that each researcher keep detailed notes on the data and their readings in their lab notebook. Finally, it is the responsibility of each researcher to brief the rest of the team on their findings on a regular basis such as weekly group meetings.

The first two weeks of the design course is devoted to study of the design problem with extensive discussions and interactions with Dr. Cruse and other relevant faculty in the department. Summaries of the research work are to be given at the two design class meetings during the research period.

Major Milestones and Project Planning:

Each design team is to develop a design task schedule for the entire semester. The schedule is to recognize each of the elements of the design process from developing the design specification (PUF) to the design final report and presentation. The schedule is to allow for parallel activities to the maximum extent possible in order to make best use of each team member during the entire semester.

Some of the elements of the design that are new this term, in regards to the amount of emphasis given, are the research tasks (which are emphasized early in the semester but which will go on through the first 2/3 of the semester), and the analysis tasks. You should also plan for extensive use of the phone in order to obtain hardware and pricing information for your product design.

There are three critical milestones that are not negotiable. These are the preliminary design review (PDR) presentation, the final oral presentation, and the final written report. The PDR's are all scheduled for the seventh week of the semester. The final written report is due on the class day of week 15 for the semester. An oral final presentation is due on a date to be scheduled during finals week.

Areas of Technical Activities and Responsibilities:

The design project and thus the design team will find that it is best to break up the overall design into its technical elements. The design team leader(s) is responsible for seeing that the entire design process is being adequately addressed, while participating in the technical activities. the team members are responsible for the detailed work that must be done.

The following areas of investigation and design are suggested. These are not to be taken as fixed or complete, but as suggestions to begin your planning process.

1. Engine cycle and combustion analysis and modeling
2. Material behavior and mechanical properties

3. Evaluation analysis of current and needed test conditions
4. Heat transfer problem definition and modeling analysis
5. Test instrumentation requirements and acquisition
6. Test facility design and data automation
7. Project scheduling
8. CAD/CAE support

The tools that are available for the course include the ANSYS finite element code for heat transfer and stress analysis, the IDEAS package for CAD and design animation, SuperProject and Microsoft Project planning tools, and the NASA turbine engine simulation code. Of course, the usual ICL software is available and is to be used as needed.

Reporting Requirements:

Each student is to maintain for inspection at any time his or her design journal. The journal is to be the primary repository of each individual's work for the entire semester. Your design journal is to be turned in for final grading on the same day as the final report, the fifteenth class of the semester.

Each design team is to turn in a single design report for their project. The design report is a formal engineering summary of your design task and will fully document your design including engineering analyses, design drawings, design assessment, etc. A detailed specification of the report format and content will be issued several weeks before the last class.

Each design team is to present a formal transparency progress report each week. The speaker(s) each week will be rotated among the team, although the design team leader may choose to act as the presentation coordinator each week. The format of the viewgraphs and the presentation style will be discussed in the first class period. The transparency material and the class charge account number for the oral presentation material will be given in class. The weekly progress report will include the following items in a format and agenda to be established by each team:

1. Cover sheet naming the project, the date, the design team name, and the day's speaker(s)
2. Overview of the day's presentation (the roadmap chart)
3. Summary of the major accomplishments for the week
4. Technical content (will change each week and may be broken into sub-presentations)
5. Technical issues or problems to be addressed in working meeting that day or any matter needing discussion and attention; less formal, working charts may be used that are reproductions of work in progress
6. Updated project Gantt chart showing %-completion for each task (this can be a hand-update for each bar on the Gantt chart)
7. Summary of the presentation

Each design team will provide two hardcopies of the full set of the presentation charts prior to the start of the presentation. Each of the day's presenters is to wear "interview dress" although this may be waived for the team leader if that individual is presenting the overview each week. All students are expected to use the oral presentations as a means to develop and/or improve their skills in presenting high quality engineering briefings.

3. Summary and Statistics of the NASA Grant funded ADP

3.1 Students and Teaching Assistant

There were 48 students enrolled in each of the two years of the grant. The design teams for each project were 6-8 students. Each design team selected its group coordinator in the first year. The group coordinator was selected by Dr. Cruse and the course teaching assistant (TA), Mr. Vince Sidwell. All but one student completed the course successfully the first year; the remaining student successfully completed the course in the second year.

Mr. Vince Sidwell was an undergraduate in the design course when it was part of the USRA ADP effort. He enrolled in the M.S. program in mechanical engineering in the fall term of 1994 and was the course TA for two years. During the first summer prior to the start of the current grant, Vince worked under the USRA auspices at the Marshall Space Flight Center in the preliminary design group of Mr. Frank Swalley. Vince worked on the lightweight tank design for the reusable launch vehicle. Vince is now employed by Pratt & Whitney commercial aircraft engine group in Middletown Connecticut. He is working on integrated turbine disk design and manufacturing.

None of the students were employed by NASA. However, several students have gone to aerospace industries including one at Lockheed and six at Pratt & Whitney government engines in Florida. One senior is doing design for a General Motors subsidiary and he has supplied the major design task for 1996-1997.

3.2 Money utilization

The budget was spent according to the approved budget as modified during the first year. The principal expenditure during the first year was TA support for Mr. Sidwell. Additional categories included supplies, travel, and copying. The support provided by NASA assured the ability of the ADP to operate with a degree of financial freedom that is important to project design efforts.

The budget was extended in a no-cost manner to the second year since we did not have to make a major trip to the summer meeting. Rather, the project presentations were made at the MSFC's invitation at a motel in Huntsville Alabama. The course TA was paid for by the department in the second year.

3.3 Project coordination

The technical effort on the space related design projects was coordinated with members of Mr. Frank Swalley's division at the NASA MSFC. The principal individuals were Reginald Alexander, Bart Campbell, and Melody Herrmann.

4. Design Projects

4.1 AY 94-95

There were two projects on the reusable launch vehicle (RLV) liquid hydrogen tank design. Each project consisted of competing design teams of 12-13 students each, and each team was broken into smaller design sub-task teams. The design goal was a cost-weighted performance index driven by tank weight. NASA performed the cost analysis of the two tank designs. Both tanks made use of composite tank materials and used the aluminum-lithium tank design done by the MSFC as the baseline design.

There was a third and smaller design effort on a test facility for thermal barrier coatings used in turbine engine applications. The design goals were coordinated with the NASA Lewis Research Center. The team consisted of 7 students. The design that was selected was based on quartz lamp heating of the thermal barrier coating specimens.

4.2 AY 95-96

There were six design teams and three of them worked on NASA design goals. Two of these were for a piezoelectric motor to be used in space antenna controls. The third design was for a small satellite to be used as a material processing facility for lead iodide.

Three other design projects were selected for this academic year. Two teams competed on the design of a bag retrieval system to be used in an automated municipal waste handling plant. The project was defined by a local small business. The last design project was a wind tunnel test facility for wind power generators.

4.3 Design Reports

Design reports were issued by each design team. The design reports are individually available through Dr. Cruse at Vanderbilt University.