The Evolution of the WPI Advanced Space Design Program—An Evolving Program of Technical and Social Analysis Using the NASA Space Shuttle for Engineering Education

Fred J. Looft *Senior Member, IEEE,* Robert C. Labonté, and William D. Durgin

Abstract—**In December of 1982, Worcester Polytechnic Institute, with the cooperation and support of the MITRE Corporation, initiated a primarily undergraduate educational program to develop experiments to be flown onboard a NASA Space Shuttle. Christened the MITRE WPI Space Shuttle Program, it sponsored the development of five educationally meritorious experiments over a period of four years. Although the experiments were ready to fly in early 1986, the Challenger disaster delayed their flight until the Spring of 1991. The delay notwithstanding, the benefits of the first program were sufficient to justify the development of a second set of experiments. More comprehensive in scope, this new venture, named the Advanced Space Design Program, addresses both technical and social areas of interested related to space flight. This paper presents a general historical overview and self-assessment of WPI's space design programs. Although some of the material presented has been published elsewhere, most of the material presented is new in that it represents an analysis of the problems and pitfalls we have encountered over the past nine years.**

I. Introduction

THE small self-contained payloads program of the National Aeronautics and Space Administration—known best as the "Get-Away-Special Cannister" (GASCAN) program—has provided unparalleled opportunities for educational institutions to participate in our nation's space program [6]. The GAS program has also proven to be an excellent mechanism for engineering colleges and private corporations to join together in programs oriented toward the development of space-flight hardware [8], thus furthering institutional and industrial relationships [9]. A companion program known as the Advanced Space Design Program, sponsored jointly by the University Space Research Association and NASA, provides opportunities for universities to focus on design issues associated with the exploration of space.

WPI undergraduates have been developing experiments for NASA's GASCAN program since 1982. Although these experiments were ready to fly in early 1986, the Challenger disaster delayed the flight of the experiments until the Spring of 1991. Even with the delayed launch, the benefits of the first program were such that the development of a second set of experiments was started. The second program, known originally as GASCAN II and later renamed as the Advanced Space Design Program, is more comprehensive in that both technological and sociological areas of interest related to space flight are addressed.

What we seek to accomplish in this paper is to present a general historical overview and self-assessment of WPI's space design programs. Some of this assessment will be a review of comments previously published, but updated to reflect a renewed commitment by the WPI faculty to their most recent undertaking, our own Advanced Space Design Program. Much of this material, however, is relatively new in that it represents an analysis of the problems and pitfalls that we have encountered, as well as our accomplishements, over the past nine years. We will start with a brief description the WPI educational environment and our decision to initiate the development of an organization for creating GASCAN experiments, and end with a general discussion of what we anticipate for the future.

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F. J. Looft is with the Department of Electrical Engineering, Worcester Polytechnic Institute, Worcester, MA 01609.

R. C. LaBonté is with the MITRE Corporation, Bedford, MA.

W. D. Durgin is with the Department of Mechanical Engineering, Worcester Polytechnic Institute, Worcester, MA 01609.

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II. The WPI Educational Environment

Worcester Polytechnic Institute (WPI) is a private college of engineering, science, and management with approximately 2500 undergraduate students [1]. Although the two largest undergraduate departments are those of mechanical and electrical engineering, a significant portion of our students elect to major in other areas. The school year is divided into four seven-week terms and, unlike many other colleges, students take three courses a term, each course meeting four or five days a week.

Student Projects

One of the unique educational aspects of the WPI degree program has been the college's long term commitment to student projects as a mechanism for cementing the relationships between theory and practice. In particular, there are two projects required of each student. At the senior level, each student must complete an intensive, year-long technical project [1]. This project, known as the major qualifying project (MQP), is designed to reinforce skills that students would typically learn as part of their major area courses taken during the junior and senior year. Ideally, a typical MQP is a blend between synthesis, analysis, and design and represents a capstone academic experience.

At the junior level, each student is required to complete a project relating technology to society. Known as the interactive

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qualifying project (IQP), this project is designed to help students understand the interrelationships between technology and society. Thus, for example, while a bioengineering MQP student might be involved in the design and analysis of a complex medical device, an IQP student might try to assess the risks and benefits of, and propose guidelines for, the use of a life-sustaining device.

If a student is not ready for an MQP or IQP, a preliminary qualifying project (PQP) can be undertaken. A PQP can be quite broad, but has two main objectives. First, a student can undertake a PQP if there is a specific need or desire to develop a background in an area. In this case, the PQP is essentially the same as an independent study course. Within the context of our space design programs, however, the second primary objective—that of preparing for or planning for project work—has been most important.

The IQP, MQP, and PQP are the central mechanisms by which the MITRE/WPI Space Shuttle Program, and now our Advanced Space Design Program, have been implemented. Although the project names are unique to the WPI educational program [1], it is now not uncommon to find that many engineering colleges have some form of project design requirement in their curriculum. Thus, while the organizational structures for the programs we describe below have been developed based on the project structure at WPI, they can be viewed more generally as educational objectives or options.

III. GASCAN I

Background

In December of 1982, early in the evolution of NASA's GAS program, the MITRE Corporation (Bedford, MA) and Worcester Polytechnic Institute entered into a cooperative agreement of joint sponsorship for the design and implementation of a Get Away Special payload. For MITRE, the cooperative arrangement presented an opportunity to obtain first-hand knowledge and experience with NASA space operations and procedures. For WPI, the cooperative arrangement with MITRE presented an excellent opportunity for the college to combine its project-oriented educational philosophy with real-world problem solving [2].

Upon initiation of the MITRE/WPI Gas program, a technical steering Committee (TSC), composed of WPI faculty and a MITRE engineer/manager, was appointed. The charter of this committee was to develop and implement the MITRE/WPI Space Shuttle Program (described in more detail in [8]).

To initiate the program, ideas for experiments were solicited from interested faculty members. From these ideas, twelve were chosen for preliminary development. At the same time, the preliminary experiment descriptions were used to attract students to the program to satisfy their MQP requirements.

As shown in Fig. 1, the multilayer program that evolved was based on a five-term commitment by students and a multilayer commitment by faculty and industry advisors. For the students, an experiment project started with a PQP during their last term as a junior. The rookie team members were expected to work with the veteran team members to learn the details of an experiment. Furthermore, the rookies were responsible for writing a project proposal detailing what they expected to accomplish during their senior year. With the start of the senior year, the project students continued to work on the development of the experiment, dividing the work into tasks appropriate to the level and background of each of the team members. The process repeated in a similar manner for the students in the following years, and, indeed, is essentially the same structure used today.

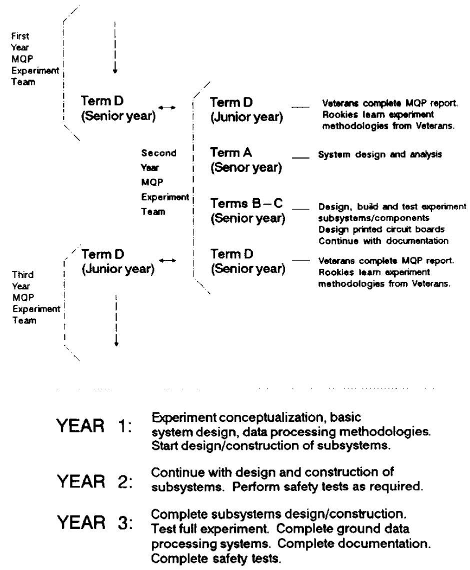


Fig. 1. Top: experiment project teams work on the development of an experiment for five terms. The first term (D) occurs during their junior year. The remaining four are completed during their senior year. The overlap between project teams during the junior–senior D term provides a mechanism for the veteran project team members (seniors) to pass what they have learned on to the rookie (junior) team members. Bottom: typically, once work has begun, it takes three years for an experiment to be completed.

Experiments

Between 1982 and 1986, five experiments were selected, developed, and tested in sufficient detail to be flight ready. In addition to these five flight experiments, there were a number of other support projects conducted by other project teams. These included the development of flight recorders for data collection, a frame for mounting the experiments internal to the GASCAN, and a technical communications project. Each is briefly summarized below.

1) Zeolite Crystal Growth Experiment: This experiment, portrayed in Fig. 2, was designed to determine if a low acceleration environment would promote the growth of large zeolite crystals. The need for a small, heated reactor vessel and its temperature controller presented a challenging design problem.

2) Fluid Behavior Experiment: As shown in Fig. 3, several methods for measuring the properties of a liquid in a zero-G environment were evaluated. Development difficulties with this experiment included the design of an ultrasonic, fluid film thickness measuring instrument accurate to 0.01 mm, and a microprocessor control system that could provide for data collection even in the event of motor and/or valve failures [3], [13].

3) Microgravity Accelerations: We developed an accelerometer system that, as part of the fluid behavior experiment, could detect and record low level (10^{-6}G) accelerations.

4) Environmental Data Acquisition System: A completely automated data acquisition system was developed to monitor the canister environment. The parameters measured were sound pressure level, triaxial accelerations, temperatures, and battery voltages.

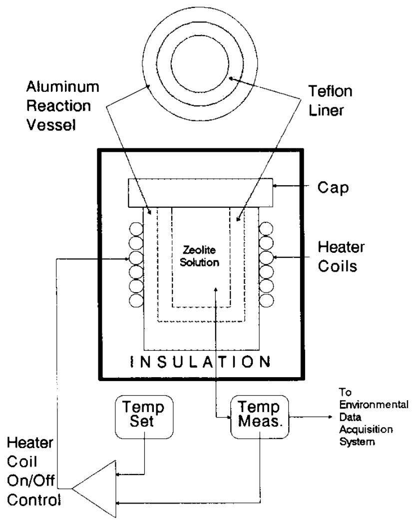


Fig. 2. Zeolite crystal growth experiment. Crystals are grown inside a teflon lined reactor vessel. The temperature of the vessel is maintained through the use of heater coils wrapped around the outside of the aluminum vessel. A temperature controller monitors the solution temperature and powers the heater coils as required.

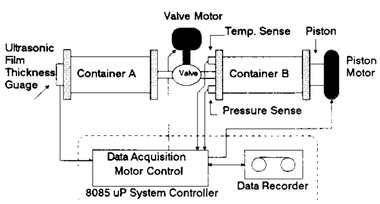


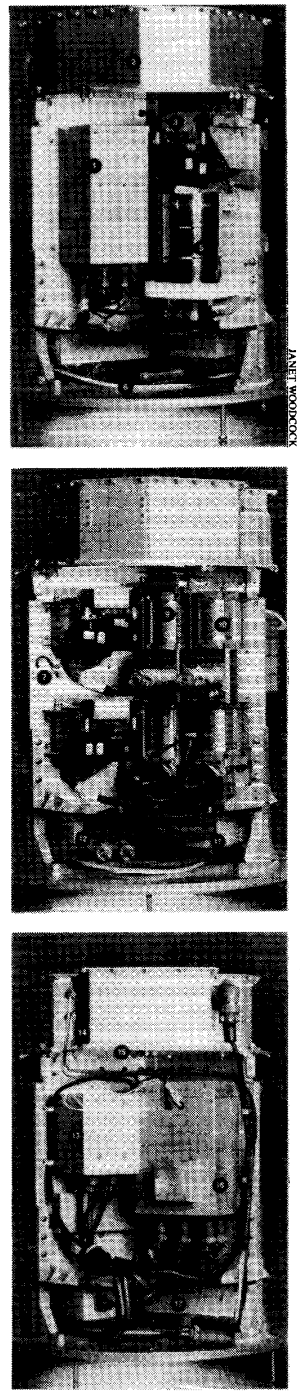
Fig. 3. The fluid properties experiments has two, double container vessels. One set of vessels contains a wetting fluid, the other is a nonwetting fluid. Prior to flight, one of each of the dual vessels is filled with the appropriate fluid, the other is kept empty. During flight, the valve between a set of vessels is opened, allowing fluid migration between the vessels. Subsequently, volume measurements are made to determine the amount of fluid migration.

5) Space Radiation Detector: This experiment was designed to quantify the level of film fogging that occurs as a result of exposure to space radiation. A junior-high school student worked with one of the program directors (Looft) to develop this experiment.

6) Experiment Support Structure (ESS): Although not an actual experiment, a triwall frame mechanical structure was developed for holding the batteries and experiments inside the GASCAN. The design of this structure was difficult because of the requirements for light weight, strength, and a high fundamental resonant frequency. Furthermore, because of NASA requirements, the structure had to be either tested at its design limits, or analyzed using finite element analysis techniques. The ESS design work was performed by undergraduate mechanical engineering students. The structure was built by MITRE technical support professionals. Full details of the structure, including the location of the experiments, are shown in Fig. 4.

Experimental Selection and Development

We have found that it is important to choose experiments that are not only educational interesting, but also scientifically meaningful. Futhermore, it has been our experience that senior engineering students, with the proper support of their faculty advisors and a few dedicated graduate students, have the necessary skills to develop such sophisticated systems. It is important to stress, however, that the students must be supported with the proper engineering design tools, whether it be a finite-ele-



The photographs on this page depict the interior of WPI's GASCAN I, a set of experiments and associated hardware that will fly on a space shuttle. The structure is three feet high and 18 inches in diameter and weighs about 170 pounds. Shown in this photo are the: (1) Environmental Data Acquisition System (EDAS), (2) battery compartment, (3) data recorder for EDAS, (4) side supports for mating with outer canister, (5) zeolite crystal growth experiment, (6) pressure relief valves for battery compartment.

Seen in this second view are the: (7) temperature sensor for EDAS (other sensors located in the GASCAN feed information about pressure, sound and light to EDAS), (8) data recorders for the fluid behavior experiment, (9) fluid behavior experiment: wetting fluid cylinder, (10) fluid behavior experiment: nonwetting cylinder, (11) power distribution control hardware, (12) temperature controller for the zeolite crystal growth experiment.

In this third view are seen the: (13) power converter for the fluid behavior experiment, (14) over-pressure vent lines for the battery compartment, (15) film fogging experiment (other film holders are located in other spots and in other orientations in the GASCAN), (16) controller for the fluid behavior experiment, (17) triaxial precision accelerometer. The GASCAN structure seen here will be delivered to NASA shortly before launch to be inserted into an external aluminum canister.

Fig. 4. GASCAN I experiment support structure with experiment placement noted.

ment analysis program for ME students or a control systems, time-series, modeling program for EE students. Furthermore, the project advisors must insist that the work be done in a professional precise manner. The students must be encouraged to perform all required analysis prior to constructing hardware or writing software. Student team members should be able to prove, on paper, that an experiment will work prior to starting hardware development. Probably more than any other facet of the program, this attention to design detail and analytical assessement, a fundamental precept of engineering science, will not only ensure the success of an experiment, but will also provide the students experience with sound engineering practices essential to their professional lives in the future.

Paper Work and Design Aids

It should come as no surprise to anyone who has ever been associated with a spaceflight program that the amount of paperwork required to document equipment is ponderous indeed. The GAS program documentation requirements, while streamlined to accommodate the typical development program normally encountered in an educational institution, is still a formidable obstacle. The primary problem is that students have no experience in providing the type of documentation required to support a thorough safety and operational analysis of an experiments. Thus, whatever program structure is envisioned by an institution, it should include a well-developed component for ensuring that students adequately document the systems they develop.

Our primary suggestion here is that whatever method is used to ensure documentation preparation, that it be based on the use of standard CAE tools and that document preparation and format follow established guidelines. Thus, if a document needs to be accessed or changed, one can at least be assured that it will be found in a standard form. Proper design aids should include a campus-standard word processor, a standard schematic capture and printed circuit design package, standard mechanical structures analysis systems, and so forth. The use of standard CAE systems will simplify both system and safety documentation preparation.

Engineering Reviews

One of the key elements of both our GASCAN I program and our Advanced Space Design GASCAN II program (below) is a series of periodic technical reviews [7]. These reviews are conducted throughout the duration of a project and fall into two primary categories; those that take place four times a year and those that occur only once a year.

The quarterly reviews take the form of formal briefings. The reviews are held alternately on WPI's campus and at MITRE's Bedford (MA) facility. Students are required to prepare high-quality visuals for projection and a professional atmosphere is maintained throughout, giving students full benefit of this snapshot of the engineering work environment in which they will find themselves after graduation.

Following a standard format, each project student group presents its objectives, a discussion of the details of the system design, design alternatives, including technical choices and justifications, laboratory development and testing, theoretical analyses conducted to justify conclusions, and a short discussion of future activities. Each presentation is followed by a question and answer period wherein MITRE and WPI staff professionals seek to uncover flaws in the students' reasoning and design approach. If a shortcoming is observed, the problem is discussed, along with suggested corrective action. Subsequently, in their final project report, teams are expected to address the comments made by audience members.

The annual design review constitutes a comprehensive, independent, and in-depth evaluation of student design work. Since this review is considered a critical element of the experiment development process, an entire week is scheduled for MITRE engineers to review design details of those experiment that comprise a flight canister. Typically, a MITRE review team, composed of at least four engineers and representing several engineering specialities, meets with a project team for a full morning or afternoon.

The main purpose of this review is to ensure that an evolving design is capable of meeting its functional requirements. Consequently, while the review team may criticize a student's facility with a particular design element or approach, the group concludes its review by indicating design alterations or adjustments that are believed to be essential to the success of an experiment. We note that this approach is unusual with undergraduates who are ordinarily expected to take whatever action is required to achieve specific academic goals on their own. We believe that giving direction toward a goal rather than simply assessing progress is essential to achieving the practical aspects of the program; an experiment package that not only achieves its technical objectives but is also capable of surviving launch and operating safely and successfully once in space.

Advising

Because of the interdisciplinary nature of most experiments we try to have at least one mechanical engineering professor and one electrical engineering professor advising each project. Furthermore, when an experiment has a significant component related to another area of science or engineering, advisors are drawn from the appropriate disciplines. At first glance, this may seem like an extraordinary effort on the part of the faculty for a few students. In fact, while we do not deny that it is, we also recognize that often these same experiments, being developed primarily by undergraduate students, have a research component that is central to the research interests of the advisors, e.g. [10]–[12]. Thus, project advising is, ideally, a natural extension of the research and educational activities of an advisor.

Graduate students, traditionally associated with faculty research programs as research assistants (RA) or with educational activities as teaching assistants (TA), provide valuable assistance in project advising. In particular, they have two important roles in our program. First, we encourage our program TA's to be actively involved in the day-to-day activities of our project team students. Thus, for example, they are encouraged to monitor student progress to help students find and evaluate components and to work with student teams in our laboratories as they test system designs. Their second role is significantly more important. We often use our program TA's to monitor safety tests both to ensure compliance with applicable testing requirements and to ensure the accuracy of the tests. In short, they often act as our expert witnesses.

IV. GASCAN II

Background

The second WPI GASCAN program was initiated with the start of the 1986 academic year. Although our first GASCAN had been completed and was awaiting a flight opportunity, there

was a general belief that the projects that had evolved from the first set of experiments had, by their very nature, been excellent MQP's and had emphasized the critical importance of a strong background in the basic sciences—particularly at a time when such an emphasis was sorely lacking both locally and nationally. Furthermore, MITRE was interested in continuing its relationship with WPI (as well as WPI with MITRE). To demonstrate its commitment, MITRE donated a second GASCAN to the college, this time reserving 20% of the internal payload space and weight for their own experiments.

Experiment Selection

In contrast to the first program, specific faculty members with an interest in space flight as a mechanism for furthering their own research areas were contacted and a set of experiments selected for development. The criteria for experiment selection were the educational value, the scientific merit, the potential for cooperative undergraduate and graduate research, and the potential for future funding. From these criteria, one would correctly surmise that we had changed our program focus from primarily an MQP based undergraduate experience to that of a broad, interdisciplinary project program with a potential for long term support by outside agencies.

Experiments

Currently, we have six project teams developing four experiments. Because of the two-year delay between the Challenger accident and the Shuttle's return to space in October of 1988, full development of these experiments was halted during the 1988–1989 academic year. However, with the 1989–1990 academic year, project teams were once again working on the experiments with the goal of having them ready for testing and integration by the summer of 1990. These experiments and our support projects are summarized below.

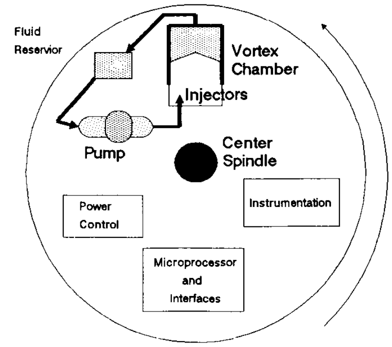
1) Experiment Support Structure: Undergraduate mechanical engineering students are developing a new support structure. The unique aspect of this structure is its accommodation of a rotating artificial gravity table.

2) Ionospheric Properties and Propagation Experiment (IPPE): The IPPE experiment is designed to test for the occurrence of radio frequency ducting in the ionosphere. The three primary components of this experiment are a WWV receiver at 15 MHz for carrier strength measurements, an ion density detector with a probe external to the GASCAN, and a microprocessor controller for data processing.

3) Artificial Gravity Platform: This rotational table is designed for experiments requiring an artificial gravity. As such, the table is designed to rotate at precisely controlled angular velocities to generate accelerations in the range of 0.2–2.0 G.

4) Vortex Experiment: The management fluids in a low acceleration environment will be of critical importance for long duration space flight. To provide data to help the design of such management systems, the experiment is designed to evaluate the conditions under which vorticies are generated. As shown in Fig. 5, this experiment will be mounted on the rotational table so that vortex formation can be studied as the effective gravity is reduced towards zero [5].

5) Combustion Ignition Experiment: Another concern for long duration space flight is fire safety. This experiment is designed to study the effect low acceleration environments have on the ignition of materials by studying ignition energy requirements for nonpiloted ignition.



ROTATING PLATFORM FOR
VORTEX GENERATION EXPERIMENT

Fig. 5. GASCAN II will support a rotating platform. A vortex generation experiment will be mounted on the platform and, during flight, acceleration levels between 0.2 and 2.0 G will be created. The formation and characteristics of vortices will then be studied at the different acceleration levels. As shown, the experiment will be completely self contained—all of the experiment instrumentation and pumping equipment being located on the platform. We expect to only provide power, through heavy duty slip rings, to the experiment.

6) Environment Data Acquisition Experiment: Similar to the data system flown on our first GASCAN, this fully solid-state system has been designed to catalog the internal environment parameters of the GASCAN.

Program Changes

Although we are still in the midst of developing these experiments, we can comment on the changes that have been implemented to enhance the overall program. In particular, the engineering reviews conducted by MITRE have been refined to include an analysis of the documentation provided by the students, with a perspective of what NASA will require for hazard analysis and overall testing. Furthermore, we have also reaffirmed our commitment and emphasis on good engineering practices, not only providing the students with new and updated CAE tools, but also expecting a detailed analysis of the operation of systems and circuits prior to hardware development.

Most recently, we have found that in the experiment development process, it is important to have the early project development groups identify what they believe to be the most crucial, or most difficult part of an experiment, and to undertake the development of that element first. Generally, for each experiment there are only one or two subsystems of sufficient complexity that if not designed correctly will inhibit development of an experiment. Indeed, although full GASCAN II experiment development was halted during 1988–1989 academic year, we sponsored two project teams to work on experiment subsystems that we believed were critical to the correct operation of those experiments. In short, project teams were able to apply additional time to those elements that appeared to be the most difficult to develop.

V. The Advanced Space Design Program

Background

WPI joined the NASA/USRA Advanced Space Design Program in 1986. Since then, this program has become an umbrella for all WPI space related projects, both technical and sociological. Thus, in addition to MQP's in areas such as GASCAN

experiment development, satellite design, refueling, and orbital mechanics, several IQP's are also being sponsored. These IQP's have spawned projects with titles such as "Implications of long duration space missions," "Analysis of the potential impact of international space treaty negotiations and space law proposals," and a more comprehensive technical communications publication entitled *The Advanced Space Design Journal.*

As implied in the previous paragraph, the first reaction to joining with NASA/USRA was to form an Advanced Space Design Program that consolidated all of our space related project work, both MQP and IQP, into a single program. This was a logical organizational change since project work at WPI encourages small interdisciplinary groups working and learning in an environment that encourages synergistic behavior. From WPI's perspective, the Advanced Space Design Program perfectly matched the educational mode already in place and enabled significant expansion of our space related design activities into a coherent overall program.

This consolidation was all the more reasonable when one considers that by late 1986, when WPI joined the NASA/USRA program, the GASCAN I program was nearly completed. Furthermore, WPI had successfully completed a design program within the context of the NASA/ASEE Spacesuit Glove Design competition [4]. As a result, WPI was eager to

- continue and expand its commitment to integrating space-environment engineering design into the undergraduate curriculum;
- refocus WPI space design activities from detailed experiments identified by faculty to those that would include, as well, more universal design issues that have been identified as important by NASA and the space industry;
- expand and strengthen faculty contacts with NASA and space industry professionals to assist in identifying research efforts to complement our current teaching efforts; and
- extend our current space design efforts into WPI's growing graduate program.

The Advanced Space Design Program clearly provided the opportunity to move toward all four objectives.

Sociotechnological Projects

One unique and evolving aspect of our Advanced Space Design Program is its emphasis on sociotechnological issues. Projects that have been completed include: "ultrasonic sources and space instrumentation," "firesafety design considerations for advanced space flight," and "propellant resupply of orbital spacecraft." Topics currently being explored by project groups include: "advanced space design journal," "fire projection and risk analysis associated with space missions," "problems associated with long duration missions," and "study of economic feasibility of lunar concrete production for structural applications." In addition to being intriguing projects of substantial merit, the (junior-level) students who have worked on these projects are typically highly motivated and eager to rejoin the program as seniors, working on technical problems the second time around.

Assessment

Probably one of the most exciting aspects of the new program is that it has successfully generated spinoff opportunities for students and focused faculty interests on space experimentation and exploration. Some of these spinoff projects include

- zeolite crystal growth experiments being prepared for the United States Microgravity Laboratory-1 (USML1) flight through the Center for the Commercial Development of Space,
- regular offerings of WPI's Space Forum through a grant from the WPI Educational Development Council.
- spacecraft firesafety studies being conducted in association with NASA/Lewis Research Center, and
- Extraction of oxygen from lunar ilmenite, sponsored by NASA/Johnson.

During the summer of 1989, both a graduate assistant and an undergraduate MQP team were in residence at the Johnson Space Flight Center (JSC), conducting their respective research/program projects. This was significant for WPI and NASA because, while WPI has many IQP off-campus centers, the JSC project was WPI's first off-campus MQP center. As a result, we are currently assessing the benefits of these off-campus MQP/Graduate projects and exploring possibilities for placing project teams every year at NASA centers to conduct technical and sociotechnical studies of interest to NASA, while simultaneously satisfying student degree requirements.

VI. Discussion

There are many facets of the space experiment design programs that, through time, have arisen at critical junctures in the program evolution process. For example, early in the organization of our first GASCAN program, we initiated a student-generated journal to keep the WPI GAS experimentor's community informed of the program's progress. The project of an IQP, the journal, known originally as the *Get Away Special Journal* and now as the *Advanced Space Design Journal*, has been extremely well received by the extended community of students, supporters, and interested observers. The benefits to WPI have included a mechanism for disseminating up-to-date program information and keeping our supporters informed of experiments' progress through in depth experiment descriptions.

Continued participation in the Advanced Space Design Program will be very beneficial to the engineering design education process at WPI. The NASA/USRA Advanced Space Design Program is a beacon which helps us attract outstanding students into primarily the mechanical (aerospace) and electrical enginering programs. The NASA affiliation gives the program a status that it would not otherwise enjoy. By participation in the program, our students have the opportunity to present their own ideas to a much wider audience and, in turn, are exposed to the ideas of many other people.

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Fred J. Looft, for a photograph and biography, see this issue, p. 4.

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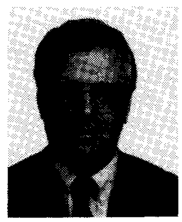

William D. Durgin was born in 1942 in Framingham, MA. He received the Sc.B. degree from Brown University, Providence, RI, in 1964, the M.S. degree from the University of Rhode Island, Kingston, in 1966, and the Ph.D. degree from Brown University in 1970.

In 1970 and 1971 he was a member of the Engineering Science and Mechanics Faculty at the University of Florida. In 1972 he joined the Alden Research Laboratory and the Mechanical Engineering Department of Worcester Polytechnic Institute. He is presently the head of the Mechanical Engineering Department.

Dr. Durgin's research interests include low gravity fluid mechanics. He maintains a laboratory and supports graduate students in this field. Dr. Durgin has overseen the establishment of WPI's Advanced Space Design Program which provides undergraduate students with design opportunities through their senior project requirement.