The VOrtex Ring Transit EXperiment (VORTEX) GAS Project

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ABSTRACT

Get Away Special (GAS) payload G-093, also called VORTEX (VOrtex Ring Transit EXperiment), is an investigation of the propagation of a vortex ring through a liquid-gas interface in microgravity. This process results in the formation of one or more liquid droplets similar to earth based liquid atomization systems. In the absence of gravity, surface tension effects dominate the drop formation process. The Shuttle's microgravity environment allows the study of the same fluid atomization processes as using a larger drop size than is possible on Earth. This enables detailed experimental studies of the complex flow processes encountered in liquid atomization systems. With VORTEX, deformations in both the vortex ring and the fluid surface will be measured closely for the first time in a parameters range that accurately resembles liquid atomization. The experimental apparatus will record images of the interactions for analysis after the payload has been returned to earth. The current design of the VORTEX payload consists of a fluid test cell with a vortex ring generator, digital imaging system, laser illumination system, computer based controller, batteries for payload power, and an array of housekeeping and payload monitoring sensors. It is a self-contained experiment and will be flown on board the Space Shuttle in a 5 cubic feet GAS canister. The VORTEX Project is entirely run by students at the University of Michigan but is overseen by a faculty advisor acting as the payload customer and the contact person with NASA. This paper summarizes both the technical and programmatic aspects of the VORTEX Project.

INTRODUCTION

A group of students at the University of Michigan have begun the design and development of a Get Away Special (GAS) payload experiment called VORTEX (VOrtex Ring Transit EXperiment). The experiment will study the propagation of a vortex ring through a liquid-gas interface in microgravity. This process results in the formation of one or more liquid droplets similar to earth based liquid atomization systems. The limit of interest is when surface tension effects dominate the interaction and drop formation processes. The microgravity environment allows the study of these processes for a parameter range relevant to atomization systems but using a larger droplet size than is possible on Earth. This allows detailed experimental studies of the complex flow processes encountered in liquid atomization systems. Deformations in both the vortex ring and the fluid surface will be measured closely for the first time in a parameters range that accurately resembles liquid atomization. The experimental apparatus will record images of the interactions for analysis after the payload has been returned to earth.

The physics of liquid break-up and drop formation by a vortex ring flow in microgravity is a fundamental problem with application to manufacturing and systems development in space. It is also important in many Earth-based engineering systems. For example, fuel atomization—the break-up of a liquid stream into small droplets—is an important aspect of the design and operation of internal combustion engines. Another example is inert gas atomization used in powder metallurgy to produce metal powders of desired characteristics. Medical and biological applications are in the manufacture of encapsulated drops of complex structure for drug delivery.

VORTEX is a student-run project organized by the University of Michigan Students for the Exploration and Development of Space (UMSEDS). UMSEDS is a student engineering organization which brings together U of M students who have an interest in space and space exploration and helps them in exploring those interests by 1) providing its members with information and opportunities helpful to careers in space-related fields; 2) being a forum for the discussion and exchange of ideas in space-related areas of interest; and 3) educating students and the general public about the benefits of space exploration and development. By designing, building, and flying a GAS payload experiment, UMSEDS members are able to apply their interest in space exploration to a real-world engineering problem which will advance scientific knowledge.

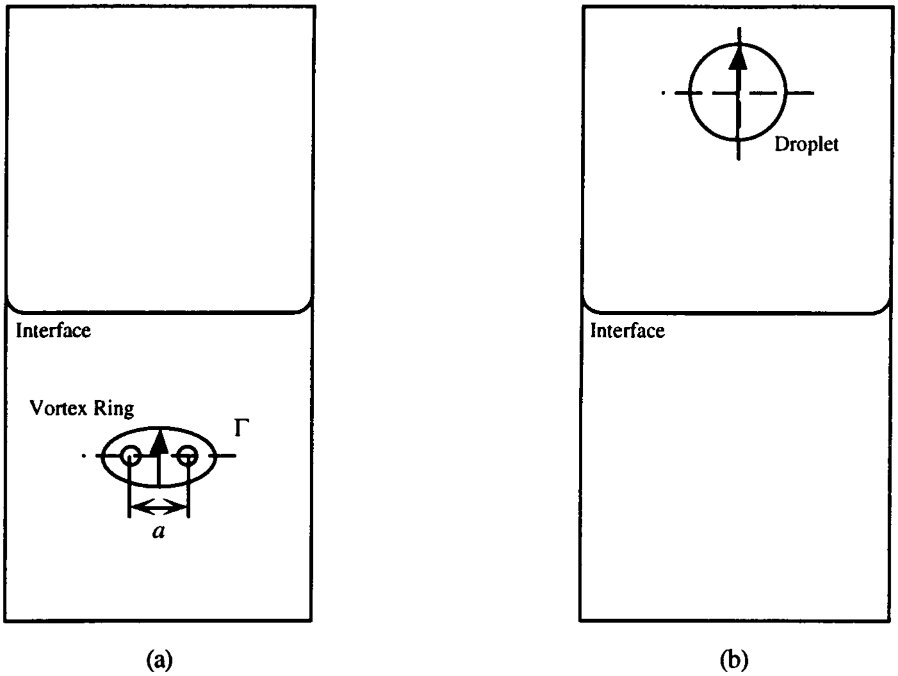
This paper summarizes both the technical and programmatic aspects of the VORTEX project. An overview of the scientific objectives and theoretical considerations is presented first. This is followed by a description of the experimental apparatus and how the experiment will be implemented. Following the technical aspects, a description of the VORTEX organization and educational aspects is presented.

SCIENTIFIC OBJECTIVES AND THEORETICAL CONSIDERATIONS

Scientific Objectives

The microgravity environment represents an opportunity to study surface tension dominated phenomena relevant to many earth-based engineering systems. This is particularly true for fluid interfaces with a large density change across the interface. On earth, the shape and dynamic evolution of the interface is dominated by the gravitational force. In the microgravity conditions of space, the shape and evolution of fluid interfaces is dominated by surface tension effects, and not gravitational effects.

The flow configuration is shown schematically in Figure 1. It consists of a vortex ring formed in the liquid below the interface propagating towards the interface (Figure 1a). If the vortex ring has sufficient impulse, then the collision of the vortex ring with the interface results in the formation of a droplet (Figure 1b). The volume of liquid moving with the vortex ring determines the size of the droplet. The vorticity distribution in the vortex ring determines the motion of the liquid inside the droplet. This relatively simple flow captures many important dynamical processes relevant to the evolution of fluid interfaces in microgravity and in other flow systems.



(a) (b)

Figure 1 Schematic diagram of the interaction of a vortex ring with a liquid-gas interface: (a) idealized diagram before the interaction; (b) idealized diagram after the interaction.

Figure 2 is a sequence of photographs of the interaction of a vortex ring with a fluid interface in simulated microgravity conditions [1]. These photographs illustrate the main features of the interaction. Simulated microgravity conditions were obtained by using liquids of similar densities. Initially the slightly heavier liquid is below the interface. A vortex ring is formed in the heavier liquid which then propagates towards the interface (Figure 2a). When the vortex ring penetrates the interface it forms an elongated column of liquid from the lower layer into the upper layer. The interface breaks at the bottom of the column in Figure 2c forming a droplet. The droplet is highly elongated after breakup but subsequently evolves into a more spherical shape. The droplet motion is upwards initially but due to the larger density of the fluid inside it eventually moves downward toward the interface due to gravitational pull.

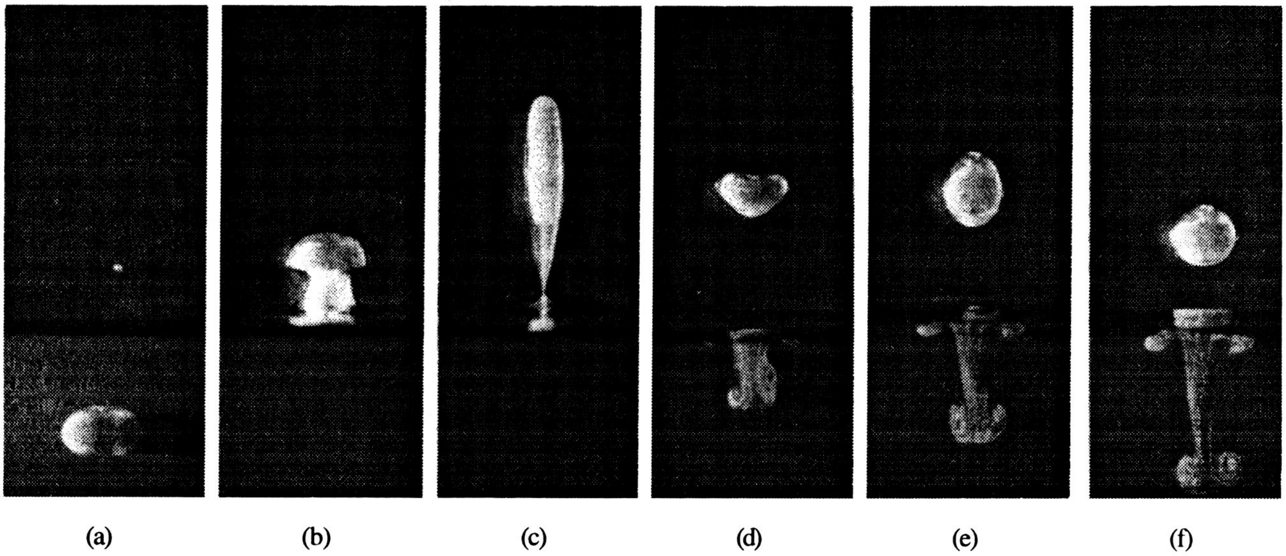

(a) (b) (c) (d) (e) (f)

Figure 2 Interaction of a vortex ring with a liquid interface in simulated microgravity conditions, $\Gamma\, t/a^2$ (a) 0; (b) 14; (c) 29; (d) 43; (e) 57; (f) 72.

The major differences between VORTEX and the experiment described above and shown in Figure 2 is that VORTEX will examine the case of large density change across a liquid-gas interface, not a small change across a liquid-liquid interface. In addition, VORTEX will be dominated by surface tension effects and not gravitational effects. The flow evolution will be documented by visualization using a high speed camera. Typical images would be similar to the photographs shown in Figure 2. Several flow conditions will be studied each corresponding to a different strength of the vortex ring flow. The flow visualization data will be analyzed to determine the number and size of the drops formed, and the relation of these parameters to the vortex ring diameter and strength.

Theoretical Considerations

To determine the relevant flow parameters for the experiment we follow the analysis of *Bernal et al.* [1]. The initial state before the interaction is characterized by the vortex ring diameter, a, and the circulation, Γ. The interface is characterized by the densities ρ_1 and ρ_2, the viscosities μ_1 and μ_2, and the surface tension σ. The ring moves toward the interface with speed V and collides with it. Generally, the collision and the subsequent evolution of the droplet depend on fluid inertia, viscosity and surface tension. Therefore, three nondimensional numbers define the problem: the Weber number, the Bond number, and the Reynolds number which are defined as

$$\mathrm{We} = \frac{V}{\sqrt{\dfrac{\sigma}{\rho_1 a}}},\quad \mathrm{Bo} = a\sqrt{g\,\frac{\rho_1 - \rho_2}{\sigma}},\ \text{and}\ \mathrm{Re} = \frac{\rho\, V\, a}{\mu_1} \qquad (1)$$

respectively. In addition, the density ratio $r = \rho_2/\rho_1$ and the viscosity ratio $\lambda = \mu_2/\mu_1$ must be specified. Here, subscript 1 denotes the liquid below the interface and inside the droplet and subscript 2 denotes the gas or liquid above the interface. The Bond number characterizes the relative magnitude of surface tension and gravitational acceleration in the dynamics of the interface. It is important to recognize that for a fixed liquid-gas interface the Bond number depends only on $a\sqrt{g}$, thus atomization phenomena in 1 g with droplet size of the order of a few microns can be examined in microgravity (10^{-5} g) at a much larger scale.

To illustrate the implications of this Bond number scaling, consider the case of a vortex ring in water with a diameter of 1 cm propagating through the water-air interface, which are typical of VORTEX. The density ratio is $r = 10^{-3}$ and the Bond number is 0.01 at a microgravity level of 10^{-5} g. This value of the Bond number corresponds to a droplet size of 30 μm in a 1 g experiment. Clearly this droplet diameter is in the range found in typical fluid atomization systems [see for example ref. 2]. VORTEX will examine, for the first time, the details of interface breakup and droplet formation by a vortex ring at a range of parameters relevant to fluid atomization processes with a resolution that can not be obtained in ground based experiments.

EXPERIMENTAL APPARATUS DESCRIPTION

The final design of the VORTEX payload has not yet been completed; however, the current payload design consists of a fluid test cell with a vortex ring generator, digital imaging system, laser illumination system, computer based controller, an array of housekeeping and payload monitoring sensors, and batteries for payload power. All equipment is mounted on an equipment support structure. VORTEX will be a self-contained experiment and will be flown onboard the Space Shuttle in a 5 cubic feet GAS canister.

Experiment Instrumentation

The following is a brief description of the experimental instrumentation. A schematic of the instrumentation and the flow of information between subsystems can be seen in Figure 3.

The fluid test cell is a rectangular container 60.0 cm x 12.5 cm x 12.5 cm with transparent walls. In the initial state, before orbital insertion, a silicon liquid occupies the lower part of the container closed by an interface cover system. Once the experiment begins, the interface cover opens leaving a flat fluid interface. The experiments will then take place beginning with the higher velocity tests. The vortex rings are produced by a vortex ring generator at the bottom of the container. The upper part of the test container will be filled with a liquid absorbing foam material to collect the drops after each test. It is expected that after several tests, fluid droplets may accumulate in the middle of the test area hindering the flow visualization experiments. To avoid this the interface cover system will be closed after a number of experiments to force the free standing drops back into the original lower half of the tank.

The vortex ring generator is located at the bottom of the container and consists of a rapidly moving piston that is driven via a gear assembly by a stepper motor. Fluorescent dye is added above the piston by a positive displacement pump for the purpose of flow visualization of the vortex ring by laser induced fluorescence. The vortex ring generator and dye injection

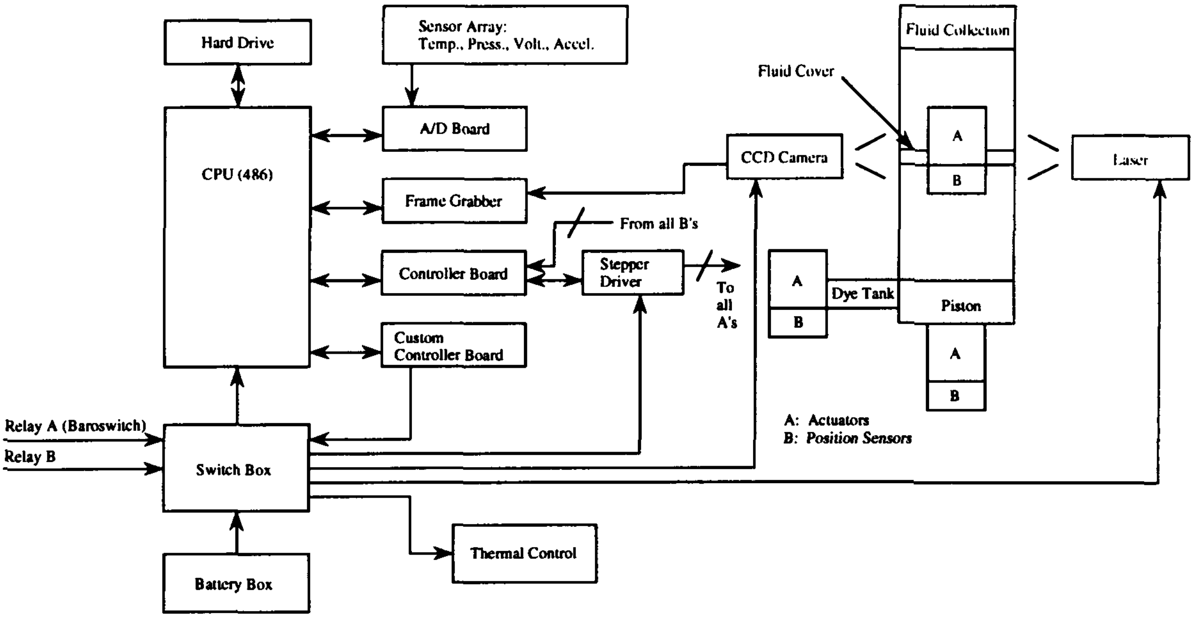


Figure 3 VORTEX instrumentation schematic and information flow diagram

system are under computer control. The experiments will be captured by a charged coupled device (CCD) digital camera with 128 x 512 pixel resolution that is capable of filming 100 frame bursts at speeds up to 300 frames per second. The laser illumination system will consist of a solid state visible green laser with output power of about 5-10 mW. An optical system will be used to generate a plane of laser light from the pencil beam output. This light plane will be used to illuminate a single plane in the fluid tank perpendicular to the camera plane. The laser will only be operated during camera data acquisition.

The computer system serves to control the entire experiment event sequence. The hardware consists of a 486 architecture microprocessor, a motherboard with eight expansion slots, a frame grabber to store photographic data, a 1 GB hard drive, and multiple controller cards for the sensor and stepper motors. The computer will collect and store sensor data such as acceleration, piston speed, temperature, pressure, and camera images, and will monitor failure modes for all subsystems.

Several sensors will also be included. The output of these sensors will be conditioned if necessary and then sampled via an A/D board attached to the computer. Data rate will depend on the temporal resolution required from the sensor. Temperature sensors will be placed on the battery box, computer, electronics boxes, laser, camera, and along the walls of the fluid container. Pressure sensors will be used to measure ambient pressure in the GAS canister as well as in the fluid test cell and on the motorized interface door. The accelerometer will measure the level of microgravity. The fluid level will be measured with a capacitive proximity sensor mounted on the fluid tank wall. The piston position will be measured with a linear encoder on the piston. The battery current and voltage will be monitored to determine power consumption.

Payload Power System

The payload power system (PPS) is responsible for safely delivering the power to run all payload components for a total of eight hours. The design of the PPS has been broken down into smaller tasks which include battery selection, fusing, circuit design, and construction. Currently, payload power requirement estimates indicate that power will be supplied by nineteen Silver-Zinc cells with a capacity of 50-60 A-hr and a total output voltage of 28 V. From these batteries, power will be conditioned and transformed to fit the needs of the payload's various electrical components.

VORTEX will consume approximately 1 kW-hr during its estimated eight hours of operation. The estimated total battery capacity under worst case scenario is 1500 W, thereby leaving a 50% margin of error between the expected energy consumption and the energy available. Under nominal operating conditions the extra energy will be used to power the experiment beyond its intended minimum lifetime and to heat the payload before experiment activation.

Equipment Support Structure

The components of the VORTEX payload will be supported by an equipment support structure (ESS), consisting of two complete shelves and one half shelf. The complete shelves are circular plates with a radius of 247.7 mm and a thickness of 9.525 mm. The half shelf has the same dimensions, but is a semicircle. The plates will be separated by six "I"-shaped support beams, which are 124.9 mm wide at the ends, 74.1 mm wide in the center, and 12.7 mm thick. These beams will be spaced equally around the perimeter of each plate as is illustrated in Figure 4. The beams will be bolted to the plate for easy removal and access to the components. The plates and beams are made of 6061T6 aluminum, and the entire shelving unit weighs approximately 23 kg.

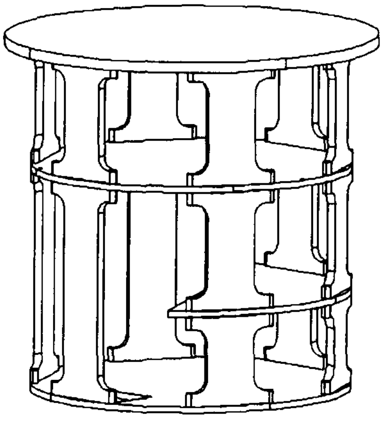


Figure 4 Schematic of the VORTEX equipment support structure.

The major components will be arranged on the support plates as illustrated in Figure 5. Some of the components on the top level will be attached to the experiment mounting plate (EMP), instead of the support plate, in order to reduce the amount of weight, and consequently stress, on the shelving unit. There will also be ventilation and wiring holes in each of the plates (not shown in Figure 5).

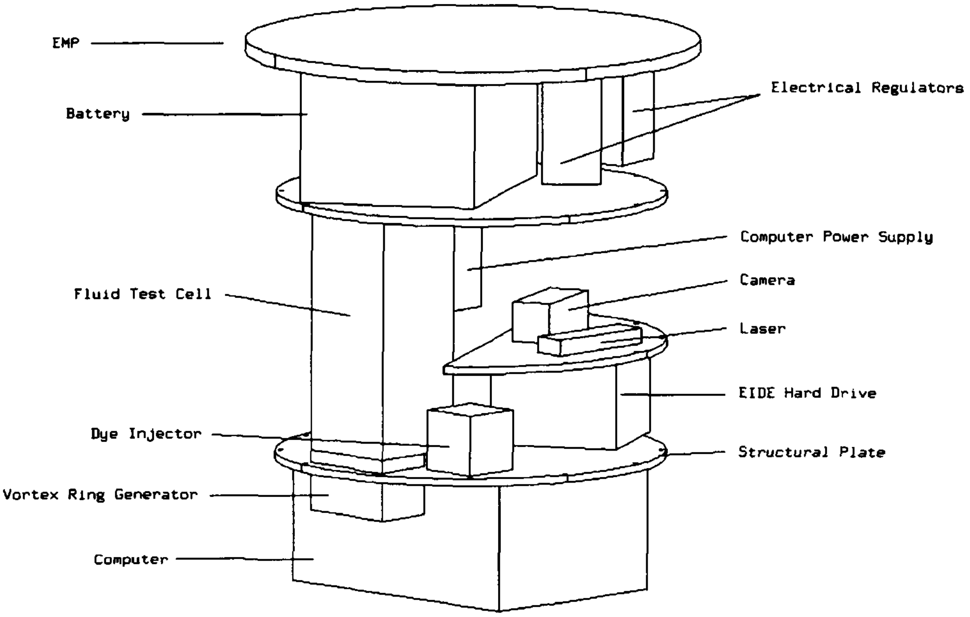


Figure 5 *Payload component placement on the equipment support structure.*

Systems Integration

Because it is essential that each subsystem understands what another subsystem may require of them, a systems engineer was designated to ensure communication and teamwork between the subsystems. A performance requirements document (PRD) was developed to facilitate this. In the PRD, each subsystem lists each piece of hardware and the requirements it imposes on another subsystem. In this manner the systems engineer becomes aware of all needs and requirements of the experiment. Subsystems designers must then work together to meet these requirements.

A VORTEX database system was also developed to aide in integrating the systems. This database encompasses all documents received and sent out by the VORTEX project members. Having all of these documents cataloged on-line and as hard copies further facilitates communication between subsystems. This is due to the fact that all project information is then available to all team members virtually anywhere on campus since almost all computers are networked. The on-line information system expedites any search for data and eliminates the chance that the data is already in use or unavailable. It is hoped that careful planning will allow all systems to be integrated successfully and with minimum hassle.

EXPERIMENT IMPLEMENTATION

Sequence of Events

The experiment sequence of events is outlined here. During ascent, the baroswitch will turn on the GAS payload power via relay A for thermal control within the canister. Relay B will be controlled by the astronauts. Once relay B is activated, the computer turns on and takes over the thermal control. The experiment operational procedure is then as follows:

- Baroswitch turns on Relay A, experiment thermal control begins, payload power is on;
- GCD Relay B enables experiment;
- Computer initializes;
- Computer performs diagnostics on all systems;
- Experiment sequence begins;

  - Open interface door within fluid test cell;
  - Wait for fluid stabilization;
  - Inject fluorescent dye;
  - Pull down piston;
  - Turn on laser;
  - Fire vortex ring, record piston position;
  - Start image capture;
  - Turn off laser;
  - Transfer images to disk;
- After five experiments have been run, reset fluid interface by closing fluid test cell door and return to computer diagnostics of systems;
- Run experiments for up to eight hours.

Implementation Issues

Although there are several issues regarding the payload implementation which must still be addressed, two are particularly important. The first has to do with ensuring that the microgravity experiments are truly run under microgravity conditions. Since astronaut movement and orbiter maneuvering system (OMS) firing will greatly affect the microgravity environment, VORTEX is requesting that the experiment be activated prior to a low g period lasting from 5-8 hours, such as a crew rest period, and that no OMS burns occur during experiment operation. In addition to this request, the VORTEX payload will use its accelerometer to monitor the level of microgravity during the experiments.

Another implementation issue yet to be resolved is how to maintain the fluid-gas interface in microgravity. It is anticipated that the cover mechanism will be sufficient to periodically re-establish the interface; however, there is no way to fully test the device before flight.

VORTEX ORGANIZATION

The VORTEX project is entirely student run but is overseen by a faculty advisor acting as the payload customer and the contact person with NASA. The project has adopted a management structure that allows for the free flow of information between all levels. Day to day operations are run by a project and deputy project manager. Other groups, each with its leader, are responsible for a specific section of the payload. These groups are safety, systems engineering, sensors and controllers, fluid systems, electrical and power, computer, structures, ground support equipment, and science and theory. The VORTEX organizational structure is shown in Figure 6.

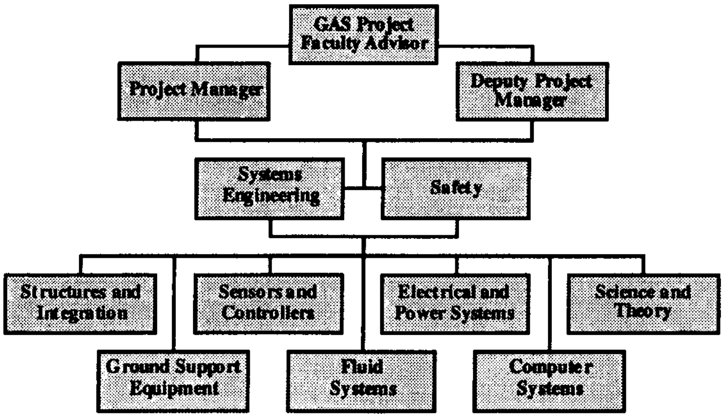


Figure 6 UMSEDS VORTEX organizational structure

Project management is responsible for the oversight of the GAS project. The management will consist of a faculty advisor and a project and deputy project manager. The faculty advisor acts as the GAS experiment customer; provides engineering support and guidance; and acts as the liaison between the students, NASA, and the University of Michigan administration. Before starting the VORTEX Project, UMSEDS felt that it was extremely important that the faculty advisor acts as a customer, since he is keenly interested in seeing the project fly. The project teams are responsible for helping to define mission goals with the project management as well as specification of system requirements and components. Two of the project teams, systems engineering and safety, work together and with NASA to ensure that the project meets safety requirements. The remaining seven project teams are responsible for building and testing the GAS hardware. First-year students to Ph.D. candidates in majors ranging from engineering to business are involved with the project.

VORTEX PROJECT EDUCATIONAL ASPECTS

As a project run by university students, the educational aspects of a project such as VORTEX are of utmost importance. There is considerable interest among engineering students in obtaining hands-on experience with "real-world" projects. To be challenging to the students, the projects must go beyond "cookie-cutter" laboratory experiments. Building and flying an experiment on the Space Shuttle is just such a "real-world" engineering project, and as such can motivate learning in engineering and science fields, as well as in other fields such as business. Space experimentation provides a medium where faculty and students can work together with industry and government toward a common goal. The knowledge and experience gained by participating in developing and flying GAS payloads can be significant and extremely beneficial to future careers [3, 4].

The VORTEX Project specifically provides students with essential experiences necessary for successful scientists, engineers, and businesspersons. Each student has the opportunity to be involved in the design, fabrication, integration, and testing of the GAS project. Therefore, each student is able to experience the design and development of an engineering project from its beginning through its completion. For the VORTEX Project, this involves such activities as writing progress reports emphasizing technical writing, preliminary design via computer aided design (CAD), structural analysis via finite element methods (FEM), systems integration, and the establishment of industry investors.

Although the nature of payload design is not like traditional laboratory classes, several opportunities for academic credit are available. For example, several students have taken directed studies for the design of a certain subsystem. Other students have taken the opportunity of using their design efforts for final projects in design classes. Still other students are satisfied with the engineering experience gained through their involvement in the project. In all cases, students are learning what it takes to design real engineering and science systems under external deadlines. They are also learning how to interact with industry, academia, and government.

One of the most vibrant and important activities UMSEDS engages in is educational outreach to K-12 schools near the U of M campus. UMSEDS has set up semester long programs in several schools to talk to K-12 students about space and related topics. In future semesters, UMSEDS will be talking to middle and high school students about what engineers do and how they develop space-flight hardware using VORTEX as an example.

Upon successful completion of the first GAS payload, UMSEDS plans to continue with future payloads. Much of the effort of this first project will involve setting up the infrastructure which can be immediately applied to subsequent projects. In this way, students can continue to learn through GAS experiment development.

CONCLUSION

The technical and programmatic aspects of the VORTEX project have been summarized in this paper. VORTEX is an investigation of the propagation of a vortex ring through a liquid-gas interface in microgravity. The current design of the VORTEX payload consists of a fluid test cell with a vortex ring generator, digital imaging system, laser illumination system, computer based controller, batteries for payload power, and an array of housekeeping and payload monitoring sensors. It is a self-contained experiment and will be flown on board the Space Shuttle in a 5 cubic feet GAS canister. The VORTEX Project is entirely run by students at the University of Michigan but is overseen by a faculty advisor acting as the payload customer and the contact person with NASA.

It is felt that some of the experiences of the VORTEX Project, as outlined here, may prove beneficial to other GAS projects, especially student run projects at universities. With the wide-spread availability of the Internet and the World Wide Web (WWW), UMSEDS and VORTEX maintain a WWW homepage (http://www.engin.umich.edu/societies/seds), where information of a public and general nature about the project can be obtained.

REFERENCES

1. Bernal, L.P., P. Maksimovic, F. Tounsi, and G. Tryggvason, "An experimental and numerical investigation of drop formation by vortical flows in microgravity," AIAA paper 94-0244, AIAA 32nd Aerospace Sciences Meeting, Reno, Nev., Jan. 10-13, 1994.

2. Wu, P.-K., and Faeth, G. M, "Aerodynamic effects on primary breakup of turbulent fluids," *Atomization and Sprays*, vol. 3, 265-289, 1993.

3. Gerondakis, G. G., "Get Away Special (GAS) educational applications of space flight," *IEEE Transactions on Education*, vol. 34, no. 1, 5-10, 1991.

4. Sacco, A., Jr., "The NASA GAS program: A stepping stone to education," *IEEE Transactions on Education*, vol. 34, no. 1, 27-30, 1991.