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TOWARDS A BETTER MIRROR

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ABSTRACT

Telesat's Getaway Special competition was designed to promote interest in space among high school students in Canada. The winning entry proposed the manufacture of mirrors in microgravity and to compare the optical properties of these mirrors with similar ones made on earth. Telesat engineers designed and built the experiment which flew on the Atlantis shuttle on November 27,1985. This paper outlines the design evolution, its implementation, the manufacture and test of the GAS and the results of the experiment.

INTRODUCTION

Telesat, the owner and operator of Canada's domestic communications satellites, announced its Getaway Special competition in October, 1983. The contest challenged all secondary school students in Canada to come up with an idea for a space experiment. Telesat ran the competition to promote "space consciousness" and interest young Canadians in the space industry.

The closing date for the entries was December 15, 1983. Telesat received 72 entries from 290 high school students. Telesat set up a panel of judges including scientists from Canadian universities, research establishments and a NASA astronaut.

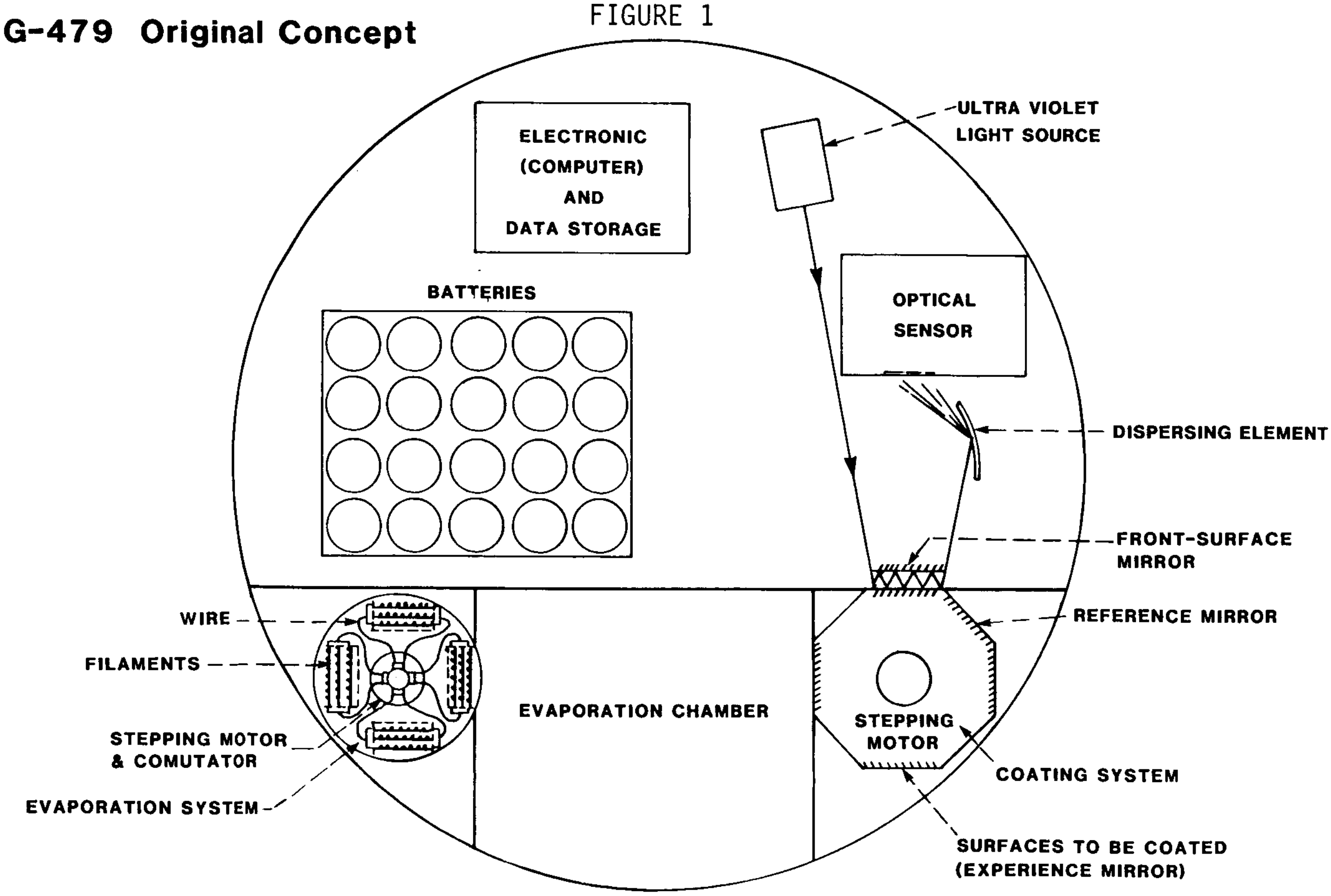
In mid January, 1984 the winner was chosen. The winning selection was submitted by two students from Ottawa who proposed the fabrication of mirrors in microgravity to compare their optical properties with similar ground-made mirrors. The students stressed the need for high-quality mirrors for such applications as lasers and telescopes which operate in the lower UV spectrum. They went on to suggest producing mirrors in the contamination-free environment of space for subsequent use in space-based telescopes. The judges were impressed by the students' presentation and were interested not only in the information to be gained in optics, but were also intrigued by what might be gathered from a metallurgical viewpoint as a by-product of the mirror making experiment.

Telesat's Getaway Special was intended to fly on October 14, 1984 on the same flight as Anik D2, Telesat's eighth telecommunications satellite. This anticipated flight date gave Telesat six months to design, build, and test the GAS experiment before delivering it to NASA for flight. The evolution of the design was completed by April with the cooperation of the students and Telesat's technical advisors. The construction of the flight model, its environmental and system tests were completed by July. Due to delays in the Getaway Special program, the Telesat GAS did not fly until November 27, 1985 aboard flight 61-B.

DESIGN EVOLUTION

The design of the winning entry was rather complex (see figure 1). It employed many mechanisms, a microprocessor for control, data acquisition and storage as well as scientific instrumentation to measure reflective properties of the mirrors and to determine their degradation with time. Although experimentally a sound proposal, due to the lack of time to develop and prove such critical items as the mechanisms, optical measuring systems and data acquisition and storage systems, Telesat engineers, the students and other advisors cooperated to redefine the experiment within, cost, schedule and STS imposed constraints.

FIGURE 1

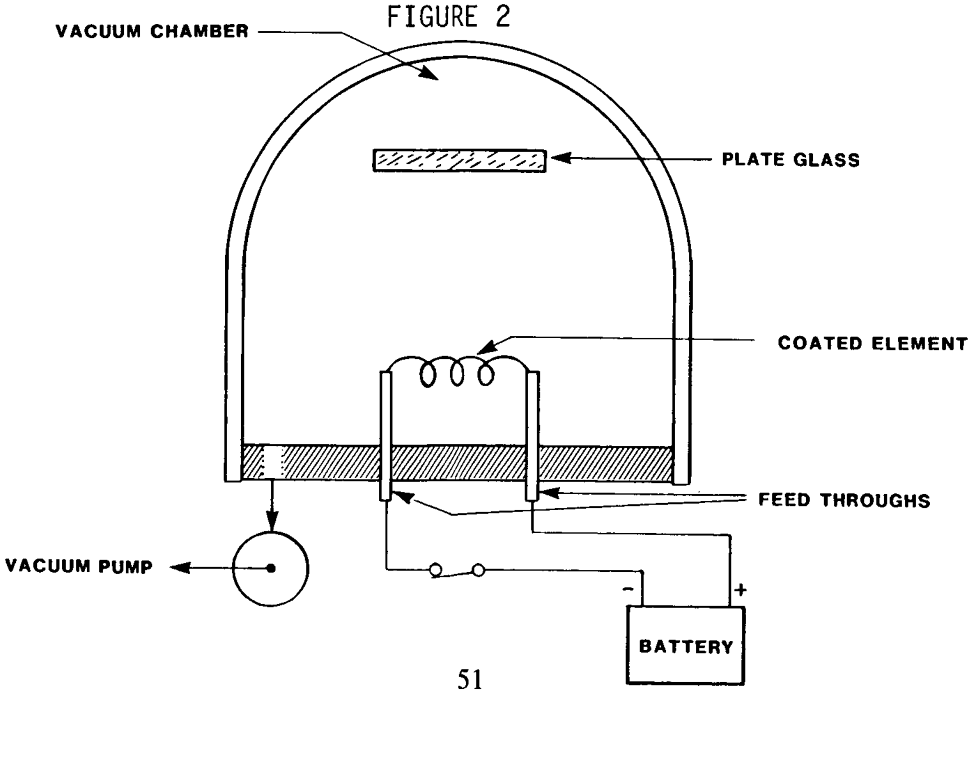


The initial phase in the development process eliminated many complex aspects of the experiment. The technique of manufacturing mirrors suggested by the high school students is widely used in the optics industry. A tungsten filament with an element, such as gold or silver, wetted to it, is placed in an evacuated chamber and powered. The current heats the filament just as a toaster filament is heated. The element vaporizes, radiating in all directions while coating everything in its path, including the required substrate, with a thin film. Quartz glass lenses were used as the substrates. Figure 2 illustrates this process.

In formulating the design of the experiment, two aspects of the shuttle environment that were kept in mind were the vacuum of its parking orbit which is in the order of two to five millitorr, and the effect of the earth's gravitational force which is in the one to two milli-G range at this altitude. A vacuum in the order of one to six microtorr is generally required to produce high-quality mirrors on earth. For most of the experiment it was decided to use the conditions readily available to see what could be done in the environment afforded in the shuttle parking orbit.

Initially there were many unknowns including the elements to be used to form the mirror reflective coatings, the temperature of vaporization of the elements, the power needed by the filament, the mass of the element to be vaporized, the size of the quartz substrate and the thickness of the coating required. To better specify the design, the unknown parameters had to be determined. The first step in this experimentation stage was to make a mirror. A 12 volt power supply was selected for simplicity. A piece of silver was wetted to a tungsten filament and was then inserted into a glass bottle. The bottle was placed in a vacuum chamber and, once evacuated, power was applied across the terminals of the filament. The amount of current consumed was recorded and used as a measure to design a power subsystem. A series of similar tests followed to optimize the filament selection and the weight of the element.

FIGURE 2



The experiment needed a means of holding the quartz substrates while taking advantage of the vacuum of space. To do this, two quartz lenses were placed at either end of a steel tube with a filament inserted between them. Holes were drilled in the tube. These holes allowed air to evacuate from the tube when the shuttle left the earth's atmosphere (the GAS cannister was open to the shuttle bay).

For elements such as sodium, that require a vacuum in the one to six microtorr range to sublimate, a sealed hourglass tube was designed. The neck of the hourglass contained the element to be vaporized, and each end of the hourglass served as the flat substrate forming the desired mirror surface. The glass tube was evacuated on earth and a filament was wrapped around the neck.

DESIGN IMPLEMENTATION

With the initial experimentation completed, the final design began in earnest. Many of the design rules used by Telesat's team of engineers are standard in the spacecraft industry: such as redundancy, safety factors and the use of conservative estimates. These rules were applied to maximize the probability of success and to avoid a single point failure. For redundancy, it was decided that two separate experiments would fly. Two power and control subsystems, two separate wire harnesses and two sets of experimental hardware made up the experiment.

The design of the steel tube to hold the quartz substrates had to be optimized. The quartz lens size was determined by what was readily available (two inch diameter) and the size of steel tube was chosen from standard stock. The steel tubes had to be baked to drive off any impurities in the steel. The tubes' lengths were maximized to fit in the GAS container vertically. The drawback of this tube system was the fact that air re-entered the tubes when the shuttle returned to earth. The mirrors started to oxidize as soon as they came in contact with air and some contamination followed. This contamination prevented the definitive study of degradation which was one of the students concerns.

The packaging for the hourglass tube was designed to absorb the vibration of launch and contain the chemically reactive sodium if the glass were to break. The size of the hourglass tube was modeled after the steel tubes. Two drawbacks to this hourglass tube were the fragility of the glass and the fact that helium permeated the glass walls degrading the vacuum over time. This made it imperative that the flight tube be manufactured and installed as late as possible in the experiments integration into the shuttle.

The placement of the filaments and the weights of the elements on them were selected by the students to achieve the desired variety of film thicknesses coating the quartz lenses. To cover the lower UV spectrum, gold, silver and aluminum were selected as elements to put on the filaments in the steel tubes. In addition to these elements, sodium was selected as it was an interesting element to study. The sodium was placed in an evacuated hourglass tube. In all, six tubes were flown: five steel tubes and one hourglass tube.

After the GAS experiment was built and tested, the students suggested a minor modification that would greatly increase the amount of scientific data that could be gathered. Following some research, inserts holding smaller samples were placed in the steel tubes along with the original quartz lenses. These samples were later examined for their metallurgical properties by performing transmission electron microscopy (TEM) tests.

The power requirements were determined by fabricating mirrors with the flight hardware and calculating the power needed by the control subsystem. One problem that the tungsten filament presented was that its resistance was very low when the filament was cold, thus drawing a lot of current. By placing a low-value, high-power resistor in series with the filament this surge of current was minimized.

For three reasons Gates lead acid "J" cells were chosen to power the experiment: 1). they met the power requirements even after derating for cold temperature and losing up to 35% capacity due to self discharge. This discharge occurs from the time the experiment is integrated at KSC until liftoff (the payload is not accessible during this time); 2). the "J" cells were selected because they were approved by NASA and had flown on previous missions; 3). they were available and affordable. Extensive tests on the cells were performed in Telesat's battery lab. The cells were subjected to many charge and discharge cycles to characterize them. These tests verified the ability of the experiment to perform under worse case conditions, such as temperature and starting with 35% depth of discharge.

The control subsystem was designed around the power and thermal constraints as well as the timing requirements determined from the initial glass bottle mirror experiment. The optimized timeline required that the mirrors be made sequentially rather than simultaneously, with a one minute gap between each mirror production. The gap between mirror fabrications allowed the electrolyte to redistribute itself in the batteries and let the structure equalize thermally. With this in mind the circuit was designed using readily available military specification parts. A separate board was made to control each experiment.

The wiring harness consisted of teflon wire and non-outgassing wire connectors. The wire was derated for use in vacuum. The fuses chosen were also selected using a vacuum derating policy. This created some concern with NASA safety experts so tests were run with the fuses in a thermal vacuum chamber to verify the safety of the wiring harness. The grounding techniques used for the harness prevented ground loops.

CONSTRUCTION TECHNIQUES

The construction techniques were along the conservative lines set out in the design phase. Where possible, the materials and parts were selected from Goddard's preferred parts list (PPL-17). Standard processes and procedures common to the spacecraft industry were adhered to. Clean room techniques were used in the handling of flight hardware.

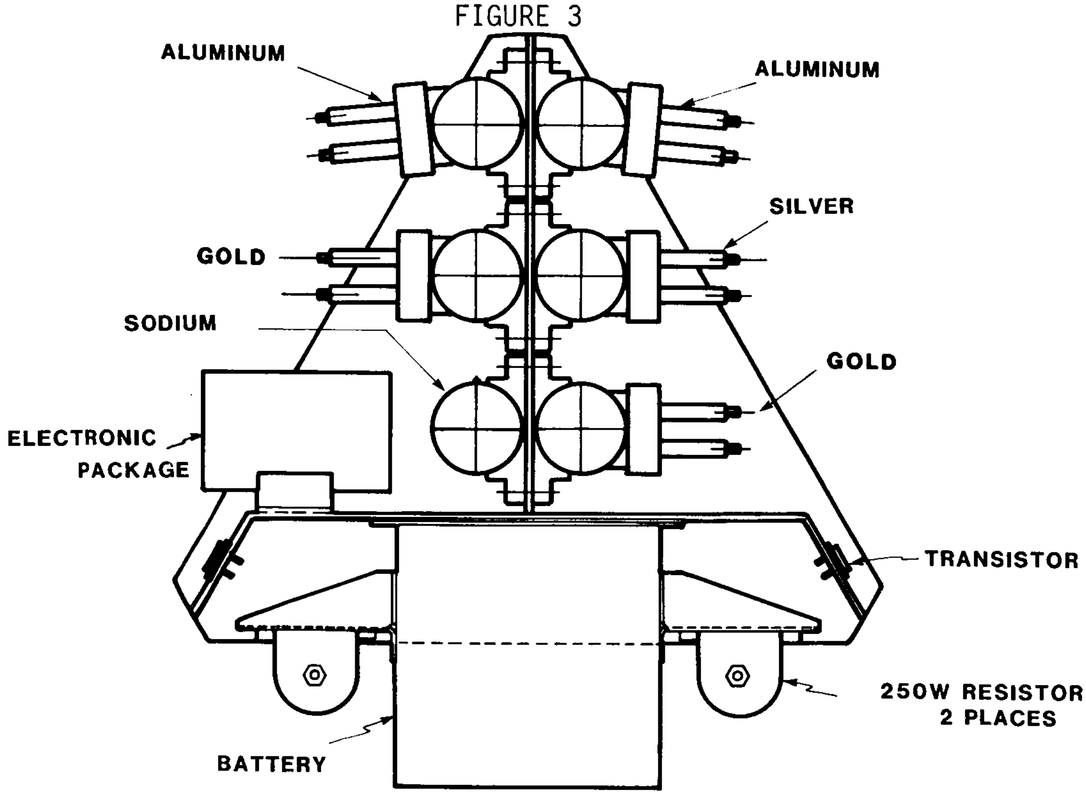
The structure (see figure 3) was made of 6061-T6 aluminum and was welded to reduce its weight and to simplify its fabrication. The structure was anodized black to equalize thermal gradients. All components such as the steel tubes and battery box were bolted to the structure using steel bolts. To ensure mechanical strength through the vibration of launch, all fasteners were secured with lockwashers and Loctite was applied.

The circuit board for the control subsystem was assembled on an anti-static mat. Heat sinks were used where necessary. The boards were conformally coated to ensure good mechanical strength, and protection from static, moisture and debris which could cause shorting of components. The circuit boards were mounted in a box which was bolted to the structure. Edge connectors carried the power and signals to the rest of the circuitry. These connectors made assembly, test and board exchange a simple task.

To avoid damage during the vibration of launch, the wiring was well secured. Tie points were spaced no more than three inches apart and tie wraps were used to secure the wires to the structure. All exposed terminals were coated with Hemoseal, an epoxy-like insulating material.

The aluminum battery box was lined with teflon to contain the corrosive battery acid in the event of a battery rupture. Gaps between the cells were packed with fibreglass insulation to absorb any possible electrolyte spillage. A gasket was used to seal the battery box to ensure that it kept its one atmosphere pressure (a NASA requirement).

FIGURE 3



VIEW LOOKING INTO CANISTER

TEST METHODOLOGY

Testing was the most important phase of the mirror experiment. As mentioned earlier, tests helped to shape the design by narrowing down parameters such as, what current was required, how the batteries would perform and how derated fuses would work. Without these preliminary tests the design would have been poorly specified. Later on, the system tests acted to qualify the experiment for flight worthiness.

The test philosophy was the same as applied by Telesat to normal space flight hardware. Everything was tested as it would be used in flight with a safety margin added. Mathematical analyses were performed on the thermal, electrical, and mechanical subsystems. The analyses were backed up with tests using more extreme than anticipated levels (temperature, voltage, vibration). The experiment's operation was verified in a thermal vacuum chamber and all tests were performed using the flight hardware.

There were several phases to the test program. The electrical subsystem was tested first. The electrical subsystem test powered the experiment as if it were in flight. Instead of making mirrors, however, electrical loads received the power in place of the flight filaments. This test verified the timing and control subsystem as well as the power subsystem. Upon completion of this sequencing test, the flight filaments were hooked up, visually inspected for flaws and then checked with an ohmmeter for continuity. Next, during the mechanical subsystem test, the experiment was vibrated to levels 1.2 times higher than those suggested by NASA in their experimenter handbook, as an added safety factor. An electrical subsystem test was again performed to ensure the correct operation of the experiment. The following stage of the test program most closely resembled the flight conditions. The experiment was activated in a thermal vacuum chamber at the worst case temperature conditions, and mirrors were fabricated. This was the last test performed prior to putting the experiment in storage to await an opening in NASA's queue.

When a flight opportunity was announced the experiment was taken out of storage and another electrical subsystem test was performed. The experiment was shipped to KSC, unpacked and inspected by Telesat engineers and the NASA project manager. As the experiment had been in storage for over a year, a new sodium tube was installed as the original tube's vacuum had probably diminished. The experiment was reassembled, then underwent an electrical subsystem test. The batteries were recharged and the Telesat GAS was then handed over to NASA, ready for flight.

As explained, the test program was quite extensive. Testing was performed at every phase of the program to ensure the correct operation of the experiment. Though not required by NASA, tests such as vibration and thermal vacuum tests, were performed to give confidence in the integrity of the experiment hardware.

TECHNICAL RESULTS ACHIEVED

The experiment was a success; mirrors were made. Of the six sets of mirrors to be manufactured, five worked. The sixth set was the hourglass type containing sodium. The neck of the glass cracked, apparently due to the vibration of launch. As discussed earlier, the vacuum achieved in the shuttle's parking orbit is not sufficient to allow the sodium to sublimate, thus sodium mirrors were not made. After the experiment was returned to the lab, a set of ground sample mirrors were made using the flight hardware in a thermal vacuum chamber as comparisons for test purposes.

A series of tests are being performed on the mirror samples. The tests are being conducted at research labs of the National Research Council of Canada, the University of Toronto, and by Litton Systems in Toronto. The testers are comparing the space-made samples with the ground-made ones. Some of the measurements being made include: reflectance measurements, polarization measurements, backscatter measurements, diffraction tests, transmission electron microscopy, scanning electron microscopy and spectroscopic analysis. The evaluation process is not yet complete. The technical reports should be available in the near future.

CONCLUSIONS

Planning and flexibility of design are the keys to a successful GAS experiment. To reduce costs and avoid bottlenecks in the program, long lead-time items were ordered at the outset. Spare parts of hard-to-get items were also purchased. The material costs were a small fraction of the budget so a few critical spare parts were purchased in order to alleviate possible problems further on in the development program.

Near the end of the construction phase it was determined that a minor modification of the steel tubes could yield much more valuable data. This modification referred to earlier, was the addition of the TEM inserts. In addition to this change, another experimental package was added to our structure taking up unused space and excess battery capacity. The extra hardware designed, built and tested by a separate research establishment, melted cadmium and allowed it to resolidify. This resolidification experiment fitted well with our mirror experiment. This flexibility late in the program extended the scope of the experiment.

To take advantage of an unexpected flight opportunity, experimenters should be ready to fly at a moment's notice. To facilitate the integration of the experiment, final preparations at KSC should be minimized.

As mentioned earlier, everything should be tested thoroughly prior to flight and done in a flight configuration. If a test results in a failure, the failure's cause should be determined, corrective action should be taken and the test should be repeated. Two problems were experienced in the Telesat GAS that illustrate these rules. First of all, the hourglass tube cracked due to the vibration of launch. This problem also occured during the vibration test. As a result of the original failure, the packaging was redesigned and an analysis was done on the vibration environment. A retest, however, was not performed due to time constraints. A price was paid for cutting corners.

The next problem occured with the experimental package added to the GAS after the mirror package was complete. As the resolidification experiment was previously tested, the system tests on the main experiment were not changed to cover the extra package. When performing the final system test at KSC a dead short was discovered in the resolidification experiment. This problem was corrected prior to flight.

We have a few suggestions for NASA to help future experimenters. It would be of great benefit to receive accurate temperature and vibration data from NASA. Telesat has launched several satellites on the shuttle, so were able to access data from these past flights. Other experimenters are generally not so fortunate. An explanation of techniques and materials for use in evacuated GAS cannisters would be useful as well. Our major complaint was NASA's inability to forecast a realistic launch schedule. It would be of great benefit to the experimenter to know, within a fixed time-frame , for example three months, when their payload would fly. This would allow the experimenter to budget his development time accordingly. On the whole, the NASA interface worked very well both at GSFC and at KSC.

The original intention of the GAS competition for Telesat was to generate interest in space studies among high school students in Canada. Right from the beginning this exercise proved successful, as was evidenced from the number of responses to the competition in the short time from its announcement to its closing date. The interest continued throughout the development of the experiment which received a considerable amount of media coverage across Canada. The Getaway Special proved to be a relatively inexpensive and effective tool to arouse the "space consciousness" of Canadians and it helped the high school students, who worked on the program, better understand the scientific method and see how a project comes together.