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Design and Flight Qualification of the Rigidizable Inflatable Get-Away-Special Experiment

Richard G. Cobb,* Jonathan T. Black,† and Eric D. Swenson‡
Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio 45433

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The Air Force Institute of Technology developed the Rigidizable Inflatable Get-Away-Special Experiment to demonstrate the feasibility of using rigidizable inflatable technology for space structures. The experiment autonomously deployed and captured the structural characteristics of three rigidizable inflatable tubes while in the space environment. The three identical tubes were made from carbon fibers in a thermoplastic resin. The experiment was designed to fly in the Canister for All Payload Ejections container within the Space Shuttle Orbiter's payload bay. It successfully completed its mission on 26 March 2008 after being in orbit for 16 days. The Rigidizable Inflatable Get-Away-Special Experiment represents the first successful deployment and rigidization of inflatable rigidizable structures in space. It also validates the unique heating, inflation, and rigidization process and hardware and shows the potential of this technology to enable substantially larger space structures.

Nomenclature

A	=	area of the surface, m^2
C_p	=	specific heat, $J/(kg\,K)$
F	=	a time dependant the view factor between elements
k	=	proportionality constant
q	=	heat transfer, J
T_g	=	glass transition temperature, °C
$T_{i,j}$	=	element temperature at the i and j spatial coordinates, K
V	=	volume, m^3
ε	=	emissivity of the surface
ξ	=	a dummy variable representing the x, y, or z coordinate
ρ	=	density, kg/m^3
σ	=	Stefan–Bolzmann constant, $5.6704e^{-8}\ kg/(s^3\,K^4)$

I. Introduction

NUMEROUS future space mission concepts involve the use of large space structures for solar power collectors, solar sails, large aperture antennas, and sunshields. Unfortunately, tight launch constraints on payload mass and volume preclude many of these concepts from becoming a reality. Mechanically deployed systems typically are used to tightly package and stow payloads for launch, however, they often result in undesirably complex mechanisms. Alternatively, employing inflatable rigidizable structures can reduce payload mass and volume and provide necessary packing flexibility without overcomplicating the system [1–4].

The term inflatable structure indicates that a condensed configuration will be launched into space and then deployed by pressurization to its full intended form. Pneumatic pressure must remain within the structure in order to keep it in a rigid, structurally stiff, state. As used herein, rigidization is the process of using mechanical stiffness rather than pneumatic pressure to maintain structural stiffness after inflation. The advantage of rigidized structures is that they do not require backup inflation gas to overcome small leaks due to material imperfections and micrometeorite impacts [4]. Here, a *rigidizable inflatable structure* is defined as a structure that before inflation is highly flexible to enable efficient packing and reliable deployment, and upon inflation is rigidized, obtaining a high degree of structural stiffness and strength. Over the last several decades, inflatable structure concepts have been developed and tested, producing enough ground data to show their potential to provide a low cost, low mass alternative to conventional space hardware with high mechanical packing efficiency and deployment reliability [2]. To date, only limited data from on-orbit testing of inflatable technology exists (summarized below) and even less for rigidizable inflatable structures. This paper describes the design of an experiment that successfully deployed, rigidized, and tested these unique structures *in space*.

The limited history of space inflatables begins with the NASA ECHO balloons. On 12 August 1960 NASA launched the first of many ECHO balloons from its Wallops Island test facility. The balloons were stowed in a 26-in.-diam container and launched on a Delta rocket into low Earth orbit. Upon achieving orbital altitude, the balloons were inflated to a diameter of 100 ft, at which point an ejection system separated the balloon from the launch vehicle. The balloons were coated with a thin layer of aluminum, which yielded slightly upon inflation. The yielding caused the aluminum to work-harden and rigidize, holding the spherical shape of the balloon without the need to maintain pressure. The resulting passive spheres, used for ground radar calibration, orbited for several months and were the first successful large-size high-precision inflatable space structure on orbit. The test program continued throughout the 1960s [1,5,6].

L'Garde Incorporated tested inflatable exoatmospheric objects (IEOs) in the late 1960s as decoys of the Mark 12 nuclear warhead reentry vehicle. The IEOs were 1–2 m in length, downloaded temperature, pressure, acceleration, and flight telemetry data to the ground in real-time, simulated the pitch and roll characteristics, and radar and infrared signatures of actual reentry vehicles, and inflated in several milliseconds. The decoys had a carbon fabric outer skin and integrated a "water blanket" directly beneath the outer skin for temperature control. The test program concentrated on investigating miniaturized inflation systems, fully instrumented membrane systems, and used the first shaped inflatable structures [5,6].

On 29 May 1996, the Space Shuttle *Endeavour* on mission STS-77 launched the Inflatable Antenna Experiment (IAE) as a joint L'Garde, NASA, and Jet Propulsion Laboratory (JPL) effort. IAE consisted of a 14-m-diam inflatable canopy reflector and three 28-m-long inflatable struts. The antenna was released from the shuttle,

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*Assistant Professor, Department of Aeronautics and Astronautics, 2950 Hobson Way. Associate Fellow AIAA.

†Assistant Professor, Department of Aeronautics and Astronautics, 2950 Hobson Way. Senior Member AIAA.

‡Assistant Professor, Department of Aeronautics and Astronautics, 2950 Hobson Way. Member AIAA.

which then filmed the deployment. Residual air inside the stowed volume caused a much more rapid and violent deployment than desired, but the resulting deployed shape was qualitatively as designed. The unanticipated violence of the deployment demonstrated the resilience and strength of the gossamer materials from which the IAE was manufactured. The experiment demonstrated a capability to deploy high-precision inflatable structures in space as well as the benefit of the low cost and ease of manufacturing of gossamer structures in general. Namely, should unanticipated events cause failures on actual missions, replacements or redundant spacecraft are inexpensive to manufacture and launch [5–9].

In the late 1990s, ILC Dover, in cooperation with the U.S. Air Force and JPL, began testing a large solar array structure, also called the Teledesic Blanket Array. The array was 3×10 meters in size and was composed of three inflatable rigidizable carbon-fiber and thermoplastic beams supporting a rigid solar cell substrate. It was intended to produce 9–12 kW of power at a power-to-mass ratio of 100 W/kg versus the then-standard 45 W/kg. It was expected that the maximum potential of the technology was a power-to-mass ratio of 300 W/kg. The array structure was a technology demonstrator originally intended for flight on STS-107, the final *Columbia* mission in January 2003. The design was then to be employed on the Deep Space 4 Champollion mission to land a spacecraft on and study the nucleus of a comet, but the program was cancelled in 1999 due to budget constraints [5,6,8,10,11].

II. Overview

The Air Force Institute of Technology (AFIT) developed the Rigidizable Inflatable Get-Away-Special Experiment (RIGEX) to advance development of rigidizable inflatable space structures. This small autonomous experiment was designed to fly in the Space Shuttle Orbiter payload bay inside the Canister for All Payload Ejections (CAPE) and was designed to test the deployment and structural characteristics of three 20-in.-long rigidizable inflatable tubes. Each tube is composed of a three-ply carbon-fiber material in a proprietary polyurethane resin designated as L5. The L5 material is designed to remain rigid while below a specified glass transition temperature T_g, and once heated above T_g, the material softens. For RIGEX, the T_g value was set at 125°C. To demonstrate this technology on orbit, ovens successively heated each tube above T_g. The tubes were then inflated, cooled (rigidized), vented, and excited using piezoelectric patches. The patch, along with a triaxial accelerometer mounted at the free end of the cantilevered tube, provided on-orbit modal characterization data. Digital cameras provided photographic documentation of the deployment process. This paper documents the overall design and flight qualification tests of RIGEX before launch. Another paper documents on-orbit performance and postflight data analysis [12].

Rigidizable inflatable structures are very intriguing for a variety of space applications. These structures, most with relatively high strength and stiffness, can provide "enhancements in the performance characteristics of many space deployable systems such as large antennas, solar arrays, and sunshields," due to small volume and mass as compared to conventional constructions [1]. While this innovative technology sounds very practical, the actual value of rigidizable inflatable structures must be substantiated by research and successful on-orbit testing before use on operational satellites. Spaceflight heritage of a proposed technology is a significant risk mitigation method to prove its functional capability and reliability on orbit. RIGEX was designed to address the development of rigidizable inflatable structure technology by advancing four main technology issues: heating system, inflation system, deployment verification, and robustness [2].

For AFIT, the RIGEX program had both scientific and educational objectives. The science objective was to perform an experiment to validate the process of heating, deploying, and rigidizing *in space* inflatable rigidizable space structures and collect data on the space-rigidized structures for comparison with ground tests. As part of this experiment, deployed accuracy and modal properties of the inflated tubes were measured on orbit, and then the inflated/rigidized structures were returned to the laboratory for additional testing and analysis. In addition, RIGEX had educational objectives to provide students a complete hands-on experience in the design/build/test of a space experiment. Over the course of the project, 14 M.S. students worked on the project [13–26]. The AFIT students were fully accountable for all aspects of the experiment, including component selection, prototyping, fabrication, build, test, and scheduling.

III. RIGEX Experiment Description

The Rigidizable Inflatable Get-Away-Special Experiment is a preliminary proof-of-concept step in employing large-scale inflatable rigidizable structures in space applications. RIGEX was a Space Shuttle Orbiter payload-bay container experiment designed to mount inside the U.S. Department of Defense Space Test Program's CAPE container, as shown in Fig. 1. CAPE makes use of the previous Get-Away-Special (GAS) beam-mounting plate to attach the whole payload assembly onto the orbiter bay sidewall. The CAPE ejection capability was not exploited for RIGEX.

Simply stated, the goal of RIGEX is to take three 20-in.-long inflatable rigidizable tubes through their full deployment and rigidization process and then test their modal characteristics on orbit. For each tube, there is a five-step sequence of events during the execution of RIGEX. First, a tube is heated to over 125°C within its oven. Then the latch over the oven door is released and the tube is pressurized with nitrogen gas, causing inflation. After inflation, the tube remains pressurized until its material temperature drops below the T_g and the tube rigidizes. The nitrogen inflation gas is then vented out of the tube. Finally, the tube is excited by two macrofiber composite (MFC) piezoelectric patches, while a triaxial accelerometer mounted at the free end collects data to be used for modal characterization.

The whole deployment process is then repeated (heating, inflation, cooling, venting, and excitation) for the next tube, until all three tubes have been deployed. As each tube is deployed, the RIGEX flight computer, based on a PC-104 architecture, collects pressurization and temperature data as well as a series of digital photographs for postflight analysis. Comparison of the on-orbit versus ground-test data will aid in determining the accuracy of laboratory deployment simulations and structural performance and reliability of the sub-T_g tubes. The three flight tubes and a similar deployed tube are shown in Fig. 2. Each stowed configuration tube is mounted to the RIGEX main structure inside a small oven. The ovens, shown in Fig. 3, are heated using resistive heaters attached internally to the oven sidewalls. A digital camera is mounted above each oven to document the deployment process.

The complete design history of RIGEX has been fully documented in the 14 student theses completed over the life of the experiment, an eight-year process [13–26]. Each year, as few as one and as many as three students were involved with the project. As the name implies, RIGEX was originally designed as a Get-Away-Special Experiment, but later modified to be compatible with the CAPE after the GAS program was cancelled. As presented in what follows, only select highlights of the design process and the final experiment

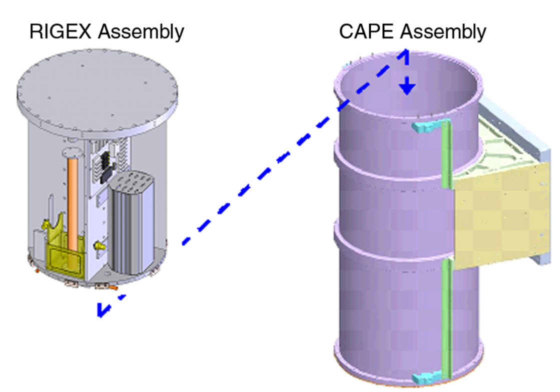

Fig. 1 CAPE/RIGEX configuration [4].

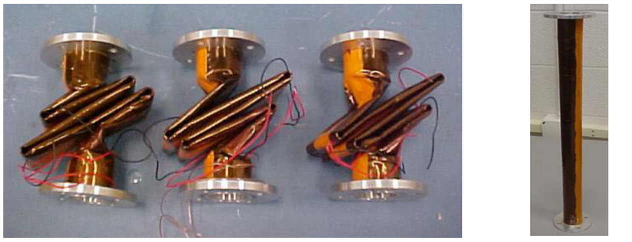

Fig. 2 Inflatable rigidizable tubes.

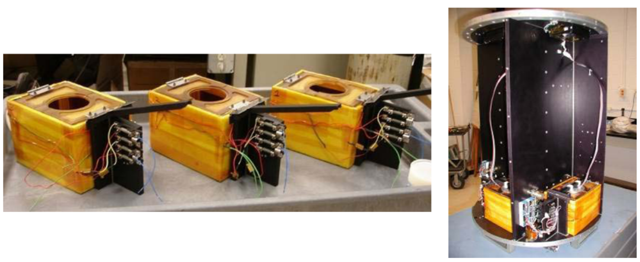

Fig. 3 RIGEX oven assemblies and full experiment showing oven locations.

configuration will be discussed. Functionally, the experiment is composed of: 1) the inflatable structures (tubes), 2) the supporting structure, 3) the heating and inflation subsystem, 4) the command and control subsystem, and 5) the actuator/sensing subsystem. Each subsystem is briefly discussed below, followed by a discussion of ground verification testing and flight qualification in the next section.

A. Inflatable Structures

The major physical characteristics of the rigidizable inflatable tubes are as follows: The thermoplastic composite inflatable tubes are constructed from carbon-fiber three-ply weave with a polyurethane-based resin with a 125°C glass transition temperature. The tubes are rigid below T_g and pliable above. The tube caps are made of machined T-6061 aluminum, with the 74.02 g base cap, the 74.6 g tip flange, and a 94 g tube. Each tube is lined with Kapton inside and out. Affixed to the base of each tube is a pair of MFC piezoelectric patches (refer to Fig. 4 below). These patches were epoxied directly to each tube just above the aluminum flange, and were installed before each tube was *z*-folded for flight (Fig. 2). For folding, each tube was heated well above the T_g temperature to approximately 300°C, which was also above the heat rating for the MFCs. A series of laboratory tests were conducted that showed there were no adverse effects from installation and heating of the MFCs. The leads from the installed MFCs can be seen in Fig. 2. In all, 10 tubes were purchased and only five had the MFCs installed. Three pristine tubes were used for flight, so ground testing relied on the ability to refold the tubes when conducting deployment tests.

Fig. 4 Inflated tubes and *z*-folded tube and MFC patch.

B. Support Structure

Since conception, RIGEX was designed for the GAS payload project and was redesigned as a self-contained experiment for the CAPE (see Fig. 5). The CAPE platform was originally developed to fill the role vacated when the shuttle program deactivated the GAS program after the *Columbia* incident of 2003.

The original RIGEX structural concept was developed as a GAS experiment and was later modified to fix the pressure system obstruction of the tubes that was observed during deployment testing. CAPE makes use of the previous GAS beam-mounting plate to attach the whole payload assembly onto the orbiter bay sidewall. The CAPE platform was an easily adaptable option for RIGEX following the cancellation of GAS due to the envelope and placement similarities, even though the CAPE ejection capability was not exploited. The most influential change between these two containers was access to space shuttle power.

RIGEX originally used an internal power subsystem when designed for the GAS canister; however, CAPE allows its payloads to obtain power through a direct space shuttle connection. This external power eliminated the need for the large alkaline batteries of the RIGEX power subsystem and freed up the interior bay to expand and improve the inflation subsystem.

Other modifications to the initial structural design were undertaken as a result of finite element model analyses. The original ribs and fasteners were found to be undersized for the anticipated loading during launch, and were redesigned into the long internal walls of the flight experiment. This design was verified when a bolt analysis resulted in the final placement of the structural fasteners and determined that the main structure would support the payload through launch [27]. The evolution of the design and the final structure are shown in Fig. 6.

C. Heating and Inflation

The heating system consisted of resistive elements in an oven used to warm the tubes past their T_g of 125°C. One of the challenges with the initial GAS design was the necessity to heat the tubes using only the power available from the D-cell batteries. A series of analytical and experimental tests were conducted to provide a suitable design. For simulation purposes, a transient heat model was created to model the time-temperature characteristics of the experiment. The dynamic model was based on modeling the folded tube as a series of elements, where each element is represented by a differential energy balance equation consisting of a radiation and conduction term. The number of elements used were based on the physical geometry of the folded tube. Since the inflatable tube is flattened and then folded in a *z*-shaped, or accordionlike, fashion (Fig. 2 and 4), each fold consists of two layers, with a total of five folds, or 10 layers. The top and bottom folds are half the length of the rest of the folds. Each layer of the tube was discretized into three principle kinds of elements: corner, side, and interior. All elements were square and of the same dimension to facilitate rapid model construction. For the full-size

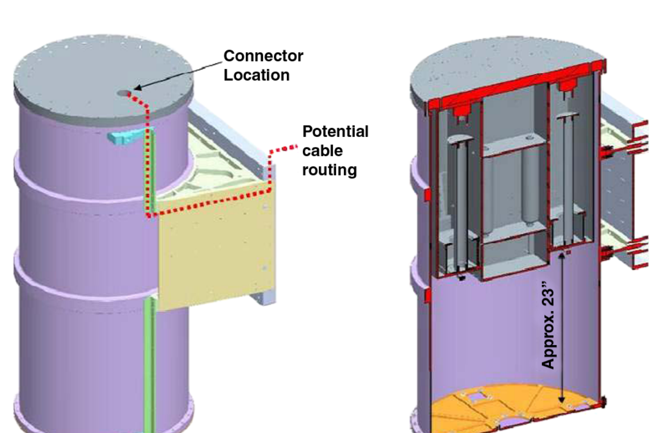

Fig. 5 RIGEX inside the CAPE canister, showing the difference between CAPE and GAS.

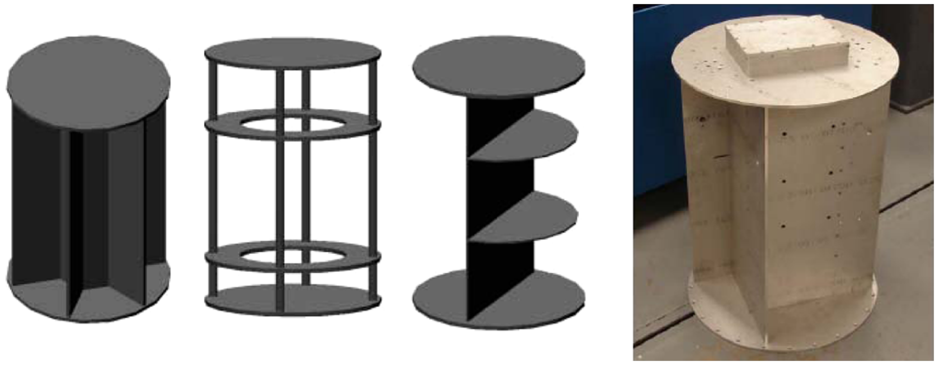

Fig. 6 Various RIGEX structural designs and the final support structure.

layers, the model contained three elements across the width and seven across the length. Only three general differential equations need to be derived, one for each type of element: corner elements, side elements, and interior elements. These equations are given in Eqs. (1–3), respectively:

$$\frac{\partial T}{\partial t} = \frac{1}{\rho V C_P}\left(k\Delta x(T_{x+1,y} + T_{x,y+1} - 2T_{x,y}) + \sum q\right) \tag{1}$$

$$\frac{\partial T}{\partial t} = \frac{1}{\rho V C_p}\left(k\Delta x(T_{x+1,y} + T_{x,y+1} + T_{x-1,y} - 3T_{x,y}) + \sum q\right) \tag{2}$$

$$\frac{\partial T}{\partial t} = \frac{1}{\rho V C_p}\left(k\Delta x(T_{x+1,y} + T_{x,y+1} - 2T_{x,y}) + \sum q\right) \tag{3}$$

Using the assumption of radiation heat transfer between gray bodies, the radiation heat transfer between any two elements is governed by the following equation:

$$q_{\text{rad}1,2} = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1-\varepsilon_1}{A_1\varepsilon_1} + \frac{1}{A_1 F_{1\to 2}} + \frac{1-\varepsilon_2}{A_2\varepsilon_2}} \tag{4}$$

The conduction term in the energy balance is governed by Fourier's law:

$$q_{\text{cond}} = kA\frac{\partial T}{\partial \xi} \tag{5}$$

Element size was chosen based on the fact that conduction should take place rapidly enough through the material in the innermost layers that the temperature profile should remain linear. Fourier number was also checked and satisfied for each of the element. The basic element was coded for a single element and for a full layer. Finally, each layer was combined into a complete model of the tube.

To gain additional data on the heating differential across the tube, experimental tests were performed in which six locations at which to attach thermocouples to the z-folded tube were chosen as representative of likely spots where heating would be the slowest. Most of these locations were chosen because they were on the inside of each bend in the folded tubes. These locations were the most protected from direct transmission of heat through radiation and must be heated through conduction from other parts of the tube that had faces incident to the radiant heaters. Added to these was a thermocouple located on the inside of the tube to test the heating gradient between the inner and outer surfaces of the tube material. Convection from air and conduction through air were also a concern, but were shown in subsequent vacuum tests to have had little effect on the heating process.

Several configurations of the oven were analyzed with several different types of insulation techniques using the thermocouple-insulated tubes to find an acceptably efficient heater with minimal loss. The efficiency of the oven ties directly to the amount of power required to transition the tubes before inflation. The amount of power is directly proportional to the weight of the power subsystem and is therefore very important for space launch applications. The oven went though several iterations in design before determining the final configuration. The final design of the ovens is shown in Fig. 7.

Electrical resistive heaters were mounted inside the ovens. The combinations of heaters were connected in three different circuits around the oven, yielding load impedances of 9.5, 13.65, and 22.6 Ω. These heaters were then powered using a 24 Vdc battery supply. The calculated current draw for the three heater circuits was 2.53, 1.76, and 1.06 A, respectively, for a total current draw of 5.35 A. These heaters combine Kapton insulation and polyimide adhesive to create a flexible heater that can be attached to any surface. They were also space-flight-rated and capable of surviving temperatures of 260°C.

The use of resistive heaters to warm the tubes above T_g originally necessitated the use of eight stacks of 40 D-cell batteries to run the experiment (Fig. 8), because relying on shuttle power lessened the odds of getting a ride; shuttle-powered slots were rare in the GAS configuration.

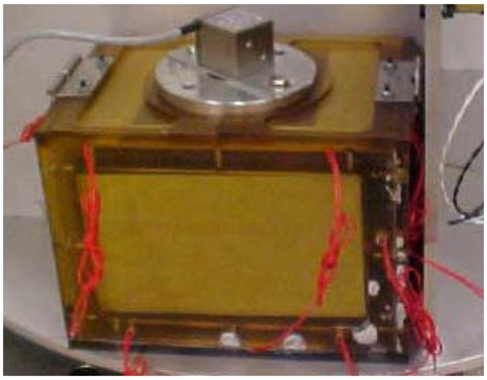

Fig. 7 Final oven design.

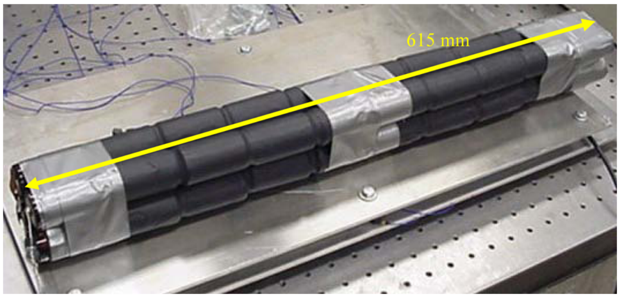

Fig. 8 One of eight battery packs originally used to power RIGEX.

The decision was made to use the shuttle power option, due to the many advantages it offered over RIGEX's internal battery supply. Shuttle power would increase probability of success, due to the lack of experiment dependency on the limited life of the batteries. The possibility of a 90-day delay between experiment integration into the shuttle and launch could potentially cause enough battery charge loss to cause mission failure. This loss combined with the decrease in power at cold extremes and the increased need for tube heating at these extremes became major constraints in the RIGEX design. Using shuttle power also mitigated any safety concerns and regulations for using batteries. Without the batteries, the weight of RIGEX dropped approximately 21 kg and a large volume ($21.6\times 15.9\times 71.1$ cm) of usable space in the center of the main structure was freed up. The change to shuttle power therefore increased the chances of mission success, dramatically reduced experiment mass, and greatly simplified the inflation system.

Once the tubes were heated above T_g, the inflation system inflated the tubes from their stowed z-folded configuration (Fig. 2 and 4). The original design of the system was quite complicated, due to space limitations imposed by battery storage, and was required to store inflation gas to 347 psia. The gas cylinder was then connected to a pressure regulator. The regulator maintained an outlet pressure of 0 to 10 psig to ensure controlled tube inflation. The solenoid valve remained closed until commanded open by the computer to inflate the warmed tube. From the solenoid valve, the flow of gas had two paths. The first connected to the base of the heater box to provide the inflation gas to the tube. The second path connected to a pressure-relief valve that prevented overpressurization of the tube.

The original inflation system design was modified primarily due to the relatively high pressure of the system. The original system also contained several components increasing the complexity and decreasing the reliability of the entire pressurization subsystem to deal with a pressure of 400 psia. The high pressure was needed because the pressure vessels had to be small (50 cm^3) due to both a lack of area on the surface of the main structure and the maximum weight allowable in the GAS system. The problem with so many components was that each one added two to three more possible leak points where the system could have lost pressure.

One method of avoiding the complexity of the inflation system caused by the use of high-pressure gas was to increase the volume in the pressure vessel that feeds the inflation system. With a large-enough bottle, the system could function successfully even if the pressurized portion of the system equalized with atmospheric pressure before mission launch. With this single improvement, two of the components could be eliminated. The regulator would no longer be needed to slow down flow to the solenoid, considering the entire pressurized system during tube deployment would be 8.4 psia maximum. The fill valve could also be eliminated. Simply removing the pressure transducer on the ground for a few moments and then reinstalling it would be enough to pressurize the system to ambient 14.7 psia. This improvement also negated the possibility of the system losing pressure on the pad while waiting for launch, which could be up to 90 days. Should there be a small leak, the system would equalize with the atmosphere and therefore did not need monitoring.

As discussed previously, the use of shuttle power allowed RIGEX to be relieved of its battery-powered requirement. This change left the RIGEX main structure with a large usable volume ($21.6\times 15.9\times 71.1$ cm) where the batteries were originally mounted. Larger pressure vessels could therefore be used. To increase reliability and reduce risk, an analysis was performed to determine what size pressure vessel could be used to maintain atmospheric pressure and still contain enough gas to fully inflate the tubes in the vacuum of space. The analysis revealed that a 500 cm^3 pressure vessel would allow full inflation within the 4 to 10 psia constraints and be maintained at atmospheric pressure 14.7 psia (0 psig). The size comparison to the original 50 cm^3 vessel and the design of the final, much simplified, system are shown in Fig. 9.

D. Command and Control

The autonomous nature of RIGEX required a controlling computer to be embedded in the experiment. This computer had to be capable of being initiated by an external signal, activating the experiment, collecting all data, and then shutting down automatically. The computer also had to mark fail-safe points within its routine. These fail-safe points were used for experiment shutdown by the shuttle crew in the event of an emergency. These points also allowed for restart of the experiment at the shutdown point.

The PC/104 computer system was chosen to implement the RIGEX control system. It was chosen because of its compact size. The computer consisted primarily of a small motherboard with an embedded Intel x86 series processor. It had a data bus that allowed other circuit boards to be stacked with the processor board.

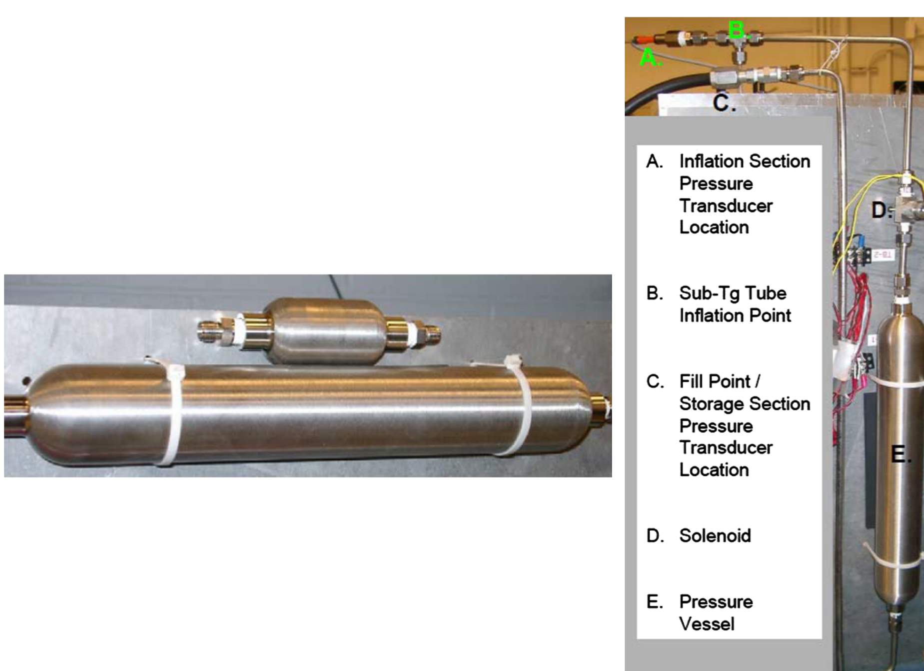

Fig. 9 Comparison of original 50 cm^3 and final 500 cm^3 pressure vessels (left) and final inflation system (right).

The PC/104 architecture has design flexibility and is an industry standard. Job-specific modules can be built and stacked together to create a fully capable embedded system.

The PC/104 computer was a small modular circuit board that contained all the necessary equipment to function as a computer. The selected processor was a full computer on a single chip. It required only external clocks, dynamic random access memory (DRAM), and basic input–output system read-only memory (ROM)/flash memory. The processor's specifications were as follows: 32-bit processor, 8 KB of layer-1 cache, four 256 MB external memory bus capability, 12 KB fail-safe boot ROM, watchdog timer for timing events and processes, and pulse-width-modulator for controlling servos and motors. The PC/104 computer board could run Linux, DOS, Windows 9*x*, and Windows NT. The original prototype setup used Windows 98 as its operating system. This general operating system configuration can allow for any high-level programming language such as C, BASIC, or JAVA to be used.

The processor has several built-in interfaces, including universal serial bus (USB); extended integrated drive electronics interface for connecting to hard drives and CD-ROMs; standard computer interfaces for keyboard, PS2 mouse, and floppy drive; full PCI bus; full ISA bus; one parallel port for such uses as printing; two serial ports for RS-232-based communication with speeds up to 115.2 kbaud; and Ethernet 10/100BaseT. Accessing these connections with standard cables required a utility board to be stacked on the primary computer board with the appropriate cable connections between the two.

The PC/104 architecture used synchronous DRAM for its volatile memory. It had an onboard dual-inline-memory-module socket capable of handling up to 64 MB of DRAM. For nonvolatile memory requirements, the board had a 32-pin socket to house a flash-memory module that was capable of holding from 8 MB to 1 GB of memory. Flash memory is solid-state memory that can be read, written to, and erased when needed, and because it does not include moving parts, is well suited to space applications.

The PC/104 has a robust architecture allowing for many application-specific cards to be added to the computer, including analog-to-digital (A/D) converter boards, counter/timer boards, digital camera interface boards, relay boards, Global Positioning System boards, and power supply boards. The RIGEX computer used several of these boards.

The original command and control configuration used two computers to run the experiment based on function. The first (primary) computer conducted the flow of the experiment and collected all the analog data signals. The second computer performed the imaging of the tubes. The data acquisition computer was the primary computer for the experiment. It was responsible for controlling the flow of the experiment, performing all analog data collection and notifying the imaging computer when to take pictures. Each of the above functions was controlled by using a specific application board. A relay board controlled the experiment's mechanical systems. The first relay turned on the heaters in the tube oven by switching a voltage to activate a high-current solid-state relay. The second relay applied voltage to the pin-puller to open the oven. The third relay opened the solenoid, allowing the inflation gas to enter the tube. Upon closing this relay after inflation, the gas was vented from the tubes. Other relays turned on the light-emitting diodes (LEDs) in the tube inflation bays to provide light for the cameras and shut the computer off by shorting the two pins to the power supply board.

An A/D board performed the majority of the data collection. It provided for 16-bit analog-to-digital conversion. For a 0–5 V range signal, the board provided a 1-bit resolution of 76 μV. It had 32 channels of A/D conversion and four 12-bit D/A channels. On its 32 A/D channels, all vibration and pressure measurements were collected. The channels for the tubes were grouped into sets of four. Each set of four contained the channel for measuring pressure and three channels for measuring the three axes of vibration from the triaxial accelerometer. During inflation and excitation of the tubes, the channels associated with that tube were recorded. Three additional channels were used to take measurements of the pressure in the inflation gas storage containers. These measurements were used to determine if any inflation gas leaked between the final integration into the shuttle and the on-orbit experiment.

A specific thermocouple A/D board was used to monitor each of the thermocouples used in the RIGEX experiment. Each tube had two thermocouples located on it and the structure had a thermocouple located on the base plate. The data acquisition computer prototype is shown in Fig. 10.

Over the course of the multiyear RIGEX program, technology inevitably advanced. The flight version of the experiment only contained one computer instead of two. That computer was identical to the original data acquisition computer shown in Fig. 10. The imaging computer was able to be eliminated through the use of standalone cameras that contained their own LEDs for illumination and solid-state flash memory. When the data acquisition computer was controlling the deployment of each tube, it activated the camera in each bay that autonomously collected and stored images and preprogrammed intervals, then shut down when the tube deployment and testing were complete. This change greatly simplified the RIGEX command and control system.

E. Actuation/Sensing

RIGEX was designed to gather pressure and acceleration data during tube deployment and structural data on the deployed tubes following rigidization and venting. This data collection used pressure sensors, accelerometers, and temperature and voltage sensors.

Pressure sensors had two purposes. The first was to monitor the ambient environment. The environment is supposed to be a vacuum, and any pressure buildup in the CAPE canister is vented through a relief valve. Only a single pressure sensor was required to monitor the ambient environmental pressure. For this experiment, the required sensitivity was 0.001 atm. The sensor location on the structure was nonspecific, due to its general use.

The second pressure sensing requirement was inside the inflation system. It was important to monitor the inflation gas pressure within the tubes. This data provides information on how well the inflation process performed and how well the gas was vented after inflation and rigidization. These sensors also required a sensitivity of 0.001 atm. In the final configuration, pressure was monitored inside the pressure vessels and the tubes.

To test the structural properties of the rigidized tubes, a modal analysis was performed on the tubes. The modal analysis was performed by exciting the tubes using the attached MFC piezoelectric actuators. These devices transferred frequency energy into the tube. The tube's response was then measured at the free end with a triaxial accelerometer. The sensitivity for the accelerometers is 10 mV/g. The second requirement was for an accelerometer to be placed on the structure to measure the vibrations of the space shuttle. This data was needed to decouple the measured tube data with that of the shuttle. The required sensitivity was 20 mV/g.

The inflation and rigidization processes of the tubes are based solely on temperature. To allow the tubes to inflate, they must have been heated to at least 125°C. For the tubes to rigidize, they then had to cool below T_g. Since the success of both processes is highly dependent on temperature, appropriate temperature sensors were employed. There were three specific uses for these sensors: monitoring the tubes, monitoring the environment, and monitoring such temperature-sensitive devices as the computer and cameras. One thermocouple was attached to the base of the tube to measure the external heating of the tube and another was located within the first fold of the uninflated tube to measure the part of the tube most insulated from the heaters requiring the greatest amount of time to heat. Additional thermocouples were located on the experiment structure and on the computer board.

A camera system was used to image the inflation and measure the static deployed position of the inflated tube. The use of a camera is a cost-effective alternative to using laser displacement sensors. The camera was placed at the top of the structure directly above the inflated tube. This placement gives the best view of inflation as well as accuracy for measuring straightness. Since there are three

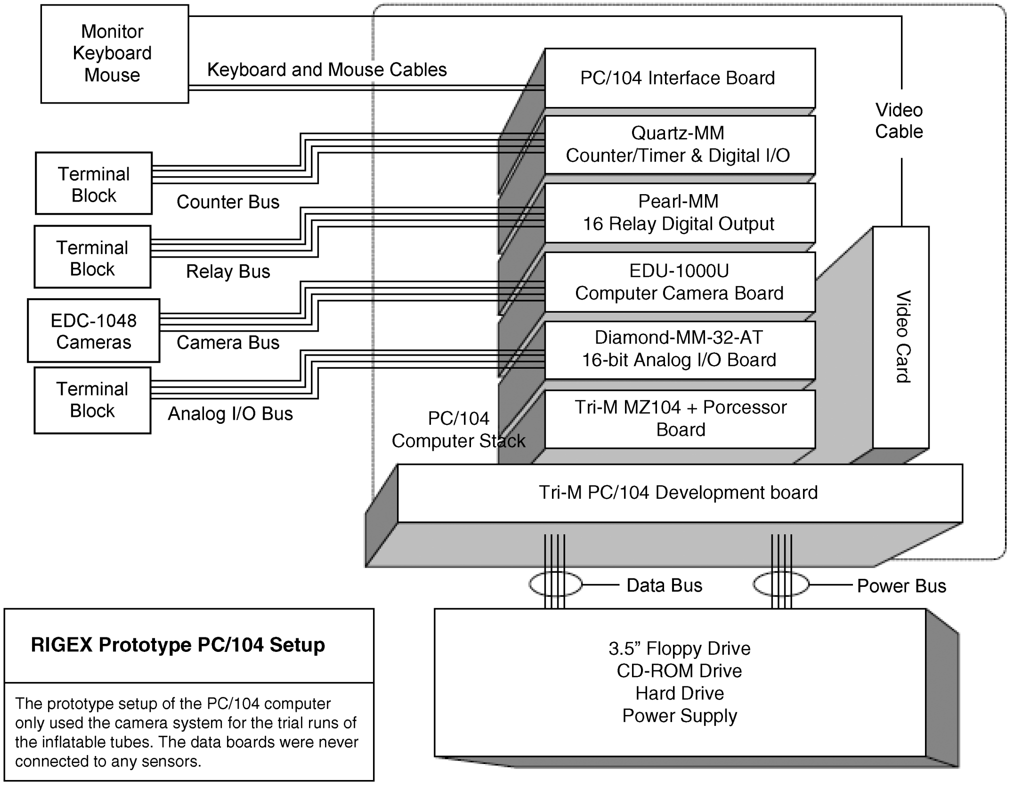

Fig. 10 RIGEX data acquisition computer.

experimental tubes, three cameras are required to support the experiment.

The camera images were used to measure the inflation during various stages of the process. Comparing before and after tube-deployment images determines the height and inflation angle measurements. The images also allowed for a qualitative analysis of the tubes.

To make the camera images worthwhile sealed in the GAS canister, light needed to be available for the camera. Originally, two 24 V incandescent lights per tube were mounted to the inside of the structure. These lights provided sufficient illumination for the cameras.

The required resolution for the images was originally set to be 1000×1000 pixels. This resolution yields distance measurements accurate to 0.01 in. It was determined that at least 60 images need to be taken over a 1 min interval with an exposure time of 25 ms, yielding a frame rate of one frame per second.

While the original actuation and sensing requirements did not change over the life of the RIGEX development, the hardware did. Originally, four expensive space-rated triaxial accelerometers were purchased. Two of these were damaged in the first several months of experiment assembly and testing. Therefore, the large space-rated accelerometers were replaced with smaller, lighter, more cost-effective ones that performed adequately. These are shown in Fig. 11.

The final RIGEX configuration to fly used self-contained cameras with single zoom and focus settings, an onboard LED for illumination, and removable flash-memory chips for image storage. The use of these cameras met all of the original requirements while also enabling the elimination of the separate camera control computer, greatly simplifying the experiment.

IV. RIGEX Documentation

RIGEX was designed to fly on the Space Transportation System (STS), or shuttle. The requirements and documentation process for launch on the space shuttle is complex and lengthy, yet necessary. This process is vital because, except for research and development of the RIGEX science objectives, a large majority of the work for a successful launch concerns meeting requirements for flight readiness. Spaceflight requirements are stringent for all launch vehicles to ensure the safety and success of an expensive volatile launch vehicle and related facilities.

Furthermore, an experiment hazard on the space shuttle could put the astronaut crew in danger in addition to endangering the launch vehicle or ground facilities. Therefore, all shuttle payloads are required to abide by the instructions detailed in NSTS 1700.7B [28]. A wide variety of requirements documents, technical standard documents, technical memoranda, and safety guidelines stem from this root publication.

Fig. 11 Accelerometers: space-rated (left), interim (middle), and flight (right).

RIGEX was the second scheduled flight of the CAPE hardware. While CAPE is a relatively new program, the container was designed as a reusable housing to carry small experiments into space. Therefore, a series of documents delineating its integration and testing procedures had already been developed. The Canister for All Payload Ejections/Internal Cargo Unit (ICU) Structural Verification Plan is one such document. This text, referred to as CAPE-SVP-0001 [29], provides guidance for structural analysis and verification of any CAPE/ICU payload. This guidance is designed to ensure that all payload structures are verified to be compatible with the space shuttle and that any CAPE payload can meet all mission objectives when subjected to anticipated load conditions [28]. A summary of the structural verification approach using analysis paired with physical testing is included in Table 1. This table shows the minimum expected effort for structural validation. Specific load levels used for testing must be compliant with the design conditions stated in NSTS 21000-IDD-SML [30], the Space Shuttle Orbiter/Small Payload Accommodation Interfaces document. CAPE-SVP-0001 [29] contains all necessary information from NSTS 21000 IDD-SML [30] compiled into a concise CAPE-specific document. All of the qualification issues from Table 1 are addressed in this CAPE document.

V. RIGEX Test Activities

Numerous component level, subsystem-level, prototype, and full-system-level tests were conducted for RIGEX. A list of specific system-level tests conducted on RIGEX is shown in Table 2. During each phase of system-level testing it was desired that a quick assessment could be made that all components were functioning without having to process all the data stored on the flight computer. As previously mentioned, the experiment had only an on/off switch, with a simple status light indicator. To quickly verify that all components were functioning, the current profile was closely monitored, and each experiment event was correlated with its corresponding nominal current draw. A sample current draw recorded during a functional test is shown in Fig. 12, along with a sample full mission profile shown in Fig. 13. As labeled, the current spikes indicate when the resistive heaters in each oven are active, when the cameras are active, and so on. From the current profile, it is then possible to determine in which phase the experiment is operating. A sample of the photographs captured by the experiment's onboard digital camera is shown in Fig. 14. These tests qualified RIGEX for space flight.

Table 1 Structural verification tests for RIGEX

Qualification issue	Analysis	Test
Structural strength (static limit, ultimate)	X	——
Structural stiffness	X	——
Random vibration	X	X
Mechanical shock	NA	NA
Mass properties	X	X
Thermal	X	X
Fracture	X	——
Pressurization/depressurization	X	——

Table 2 System-level testing

Test	Name	Quick purpose
4.A	System pressurization test	Leak test and overpressurization test for flight safety.
4.B	System deployment test	Verify payload operation and current consumption at 28 and 32 Vdc.
4.C	Electromagnetic inference test	Verify electromagnetic inference radiative and conductive levels are within allowable tolerance.
4.D	Vibration test	Verify system structural integrity.
4.E	Weight and balance test	Determine weight and c.g.
4F	Thermal vacuum test	Verify system survivability and operability and structures ability to handle thermal loading. Collect modal characteristics of test tubes.

VI. RIGEX Flight

RIGEX was launched on the Space Shuttle *Endeavour* (STS-123) in March 2008 and was activated during quiescent operations on flight day 14 (24 March 2008). Figure 15 shows RIGEX preflight, with all three tubes stowed in the ovens. Upon activation, the experiment autonomously sequentially activated each oven to heat the tubes above their T_g, inflated them, held pressure while they cooled and rigidized, then vented to ambient. As stated previously, overall objective of RIGEX was to validate deployment and rigidization techniques for three 50.8-cm-long (20-in.-long) carbon-fiber tubes in a microgravity environment. As Fig. 15 shows, RIGEX completed its experimental objectives by successfully inflating and rigidizing carbon-fiber composite booms in space. It was a successful

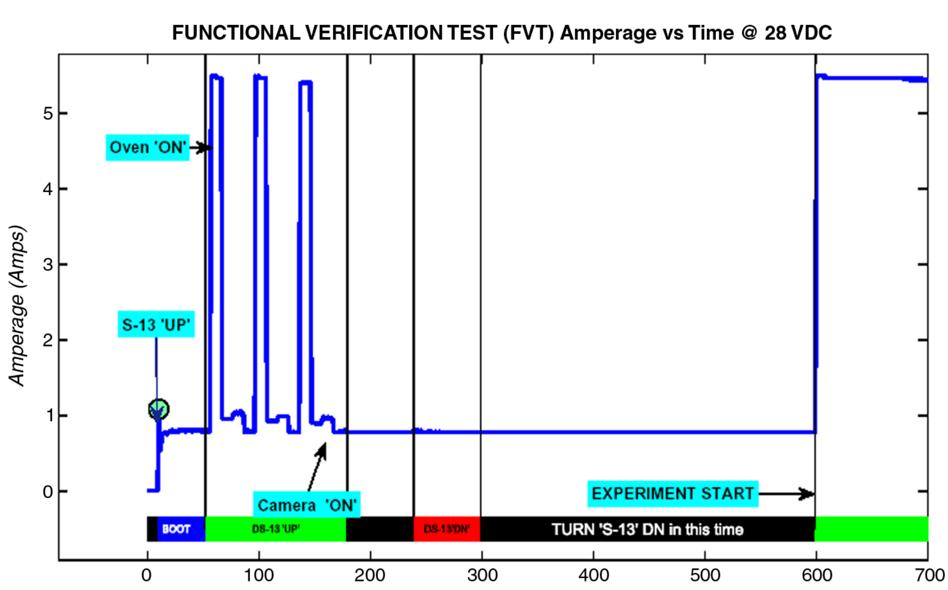

Fig. 12 RIGEX functional verification test current profile detail.

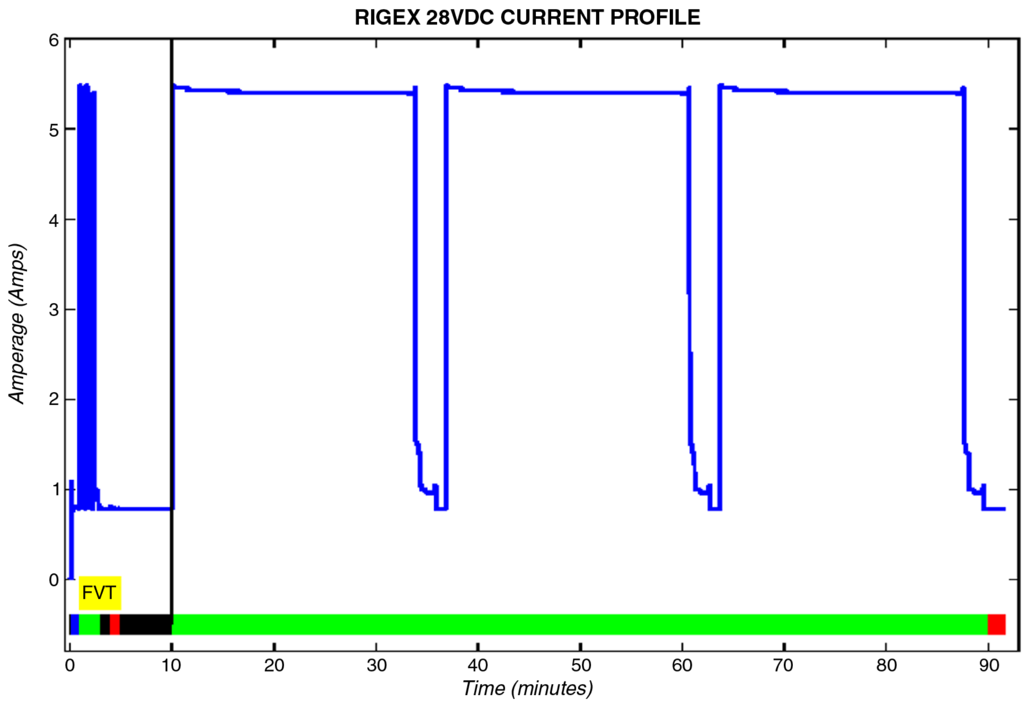

Fig. 13 RIGEX mission current profile.

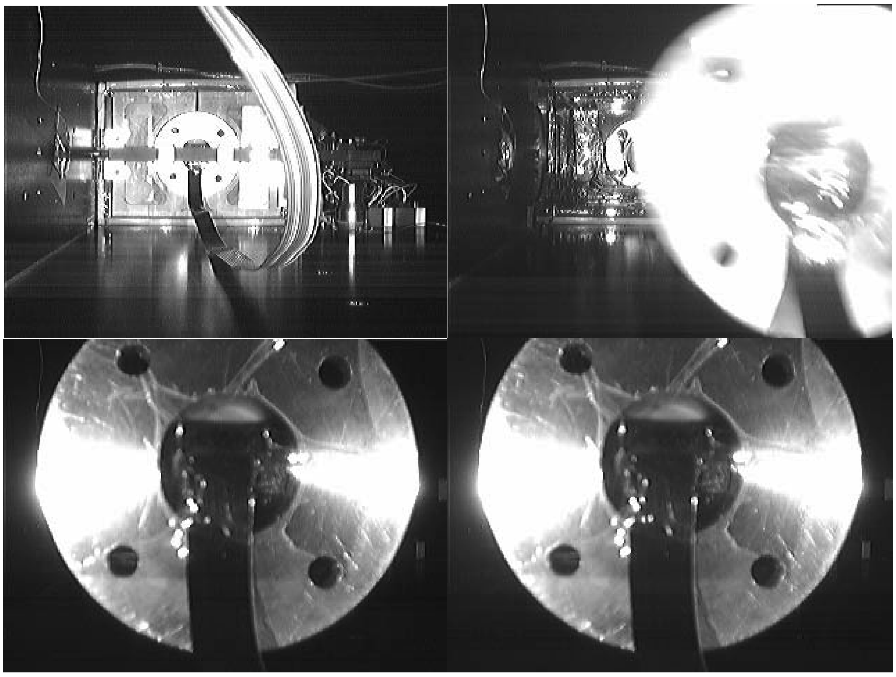

Fig. 14 RIGEX bay 3 photographs of the tube deployment taken during thermal vacuum testing.

proof-of-concept demonstration, and results in a Technology Readiness Level (TRL) increase of inflatable/rigidizable technology for space applications.

VII. Conclusions

The RIGEX experiment was successfully flown aboard the Space Shuttle *Endeavour* in March 2008 and was subsequently returned to AFIT. The experiment functioned as planned, successfully heating, deploying, rigidizing, and testing all three inflatable rigidizable tubes. The space test was a successful proof-of-concept demonstration and will result in a TRL increase for the future use of inflatable/rigidizable technology to help alleviate payload mass and volume limitations.

All of the modifications to the original experiment discussed here proved to be successful. These modifications generally reduced the complexity and risk of the experiment while causing no degradation in the ability of the experiment to complete its objectives. The three deployed and rigidized tubes that returned from space succeeded in completing the four main objectives of the experiment. The heating, inflating, rigidizing, and venting of three separate tubes for the first time in space validates this unique process and serves as an important

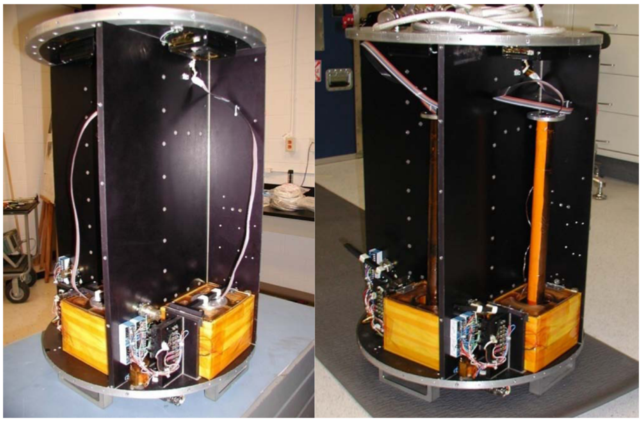

Fig. 15 RIGEX before shuttle integration (left) and following shuttle return (right).

step in advancing and proving the viability of inflatable rigidizable technology in space applications.

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J. Martin
Associate Editor