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Characterization and Ground Test of an Inflatable Rigidizable Space Experiment

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CHARACTERIZATION AND GROUND TEST OF AN INFLATABLE RIGIDIZABLE SPACE EXPERIMENT

THESIS

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Table of Contents

Page

Acknowledgments v

Table of Contents vi

List of Figures ix

List of Tables xi

Abstract 2

I. Introduction 3

Background 3

Problem Statement 4

Previous RIGEX Research 5

Research Objectives 9

Assumptions/Constraints 11

Methodology 15

II. Literature Review 18

Chapter Overview 18

Inflatable Structures 18

History of Inflatables 20

Current Efforts 23

Analytical Efforts 27

Utility of Inflatable Structures 28

Space Experiment Review Board (SERB) Process / Space Test Program 31

Summary 33

III. Methodology 35

Chapter Overview....35
Experiment Assembly....35
Heating Tests....36
Inflation Tests....38
Inflation Test Setup and Procedures....45
Summary....47
IV. Analysis and Results....48
Chapter Overview....48
Heating Tests....48
Inflation Tests....56
Summary....66
V. Conclusions and Recommendations....68
Chapter Overview....68
Conclusions of Research....68
Significance of Research....69
Recommendations for Future Research....69
Summary....71
Appendix A. System Weight Tabulations....73
Appendix B. Heating Test Results....73
Appendix C. Inflation Test Results....77
Appendix D. Success Criteria....79
Appendix E. DoD SERB Briefing Slides....80
Appendix F. System Architecture....86
Appendix G. Updated NASA Payload Accommodations Requirements....91

Appendix H. Inflation System Calculations 103
Bibliography 108
Vita 111

List of Figures

Page

Figure 1. RIGEX Preliminary Design Concept (14) ... 6

Figure 2. Initial RIGEX Tube Design (25) ... 7

Figure 3. Interim RIGEX Heater Boxes ... 8

Figure 4. Final RIGEX Heater Box Design ... 8

Figure 5. RIGEX Graphical Operational Concept ... 11

Figure 6. GAS Canister Concept (12) ... 12

Figure 7. RIGEX Tube in Folded Configuration ... 13

Figure 8. RIGEX Structural Design (14) ... 14

Figure 9. Effect of End Cap Weight on Deployment ... 15

Figure 10. Single Bay Experiment Setup ... 16

Figure 11. NASA Echo 1 (8) ... 21

Figure 12. Inflatable Antenna Experiment (28) ... 22

Figure 13. ARISE Design Concept (27) ... 24

Figure 14. SSP Truss Test Article (3) ... 25

Figure 15. Deployed Structures Experiment (29) ... 26

Figure 16 Inflatable Space Antenna Representation (19) ... 28

Figure 17. Aperture Versus Resolution ... 30

Figure 18. Pressure Retention Test Setup Schematic ... 41

Figure 19. Pressure Sealed Section of Inflation System ... 43

Figure 20. Heating Test Setup (21) ... 49

Figure 21. Locations of Thermocouples for Heating Tests 51

Figure 22. Ambient Air Heating Test Results 52

Figure 23. Repetitive Temperature Curves From Separate Heating Tests 53

Figure 24. Vacuum vs. Ambient Heating Comparison.. 55

Figure 25. Initial Inflation System Layout (21).. 57

Figure 26. RIGEX Inflation System Schematic.. 58

Figure 27. Single Bay Inflation Test Setup.. 59

Figure 28. Time Phased Inflation.. 60

Figure 29. Inflation System Tubing Routing 61

Figure 30. Pressure Retention Test Hardware 62

Figure 31. Pressure Sensor.. 62

Figure 32. Pressure Loss Due to Observation... 63

Figure 33. Inflation Pressure Observed Decrease... 65

Figure 34. RIGEX Functional Hierarchy.. 87

Figure 35. Basic IDEF0 Syntax 88

Figure 36. RIGEX A-0 Diagram.. 89

Figure 37. RIGEX A-2 Diagram.. 89

Figure 38. RIGEX A-3 Diagram.. 90

Figure 39. RIGEX A-4 Diagram.. 90

Figure 40. Model of Pressurized Tube Under Stress (5) 104

Figure 41. Hoop Stress Differential Element (5).. 105

Figure 42. Longitudinal Stress Differential Element (5) 105

List of Tables

Page

Table1. RIGEX Concept of Operations 10

Table 2. Shuttle GAS System Constraints 12

Table 3. Inflatable Tube Derived Constraints 13

Table 4. Battery of tests to ensure RIGEX experiment is ready for space flight 36

Table 5. Testing Overview 40

Table 6. Other derived testing 40

Table 7. Test Procedures: Inflation, Flight Configured Inflation System, Ambient 45

Table 8. Test Procedures: Heating In ¼ Section Mock-Up, External Power 46

Table 9. Test Procedures: Heat Tolerance Test For PZT Patch Bonding 46

Table 10. Test Procedures: Heating ¼ Section Mock-Up, External Power, Vacuum 46

Table 11. Long Term Pressure Retention Data 64

Table 12. System Weights 73

Abstract

As greater capability is demanded of space based assets, their size and complexity are growing. Inflatable rigidizable structures offer significant improvements in the areas of weight, size and complexity over traditional mechanically deployed systems. These structures are not well understood and little testing of them has been done in the space environment. Widespread acceptance of these technologies will not be achieved without significant reduction in the risk of using inflatable rigidizable structures in space. The goal of this experiment is to verify and validate ground testing of small tubular truss structures for use in space. This experiment builds on previous research done in this area to reduce the risks involved in testing inflatable rigidizable structures in space.

The Rigidizable Inflatable Get-Away-Special Experiment (RIGEX) is designed to launch as a self contained experiment on the Space Shuttle. It will inflate and rigidize three redundant experiments in the open space environment. Once these structures are deployed and rigidized, the experiment will vibrationally excite the deployed structures and record vibrational response in the space environment.

This thesis presents the final design and testing results of the RIGEX experiment. The RIGEX structure, command and control, and power subsystems are being developed in concurrent but separate thesis work.

CHARACTERIZATION AND GROUND TEST OF AN INFLATABLE RIGIDIZABLE SPACE EXPERIMENT

I. Introduction

Background

The use of space has become nearly invaluable in the conduct of commercial, military and even personal affairs. Global communications rely heavily on traffic through space based systems. Positioning systems can provide accurate position, velocity and timing data across the globe.

While some satellite functions are shrinking to the picosat size (14), satellites in general have been growing larger since their introduction. Sputnik I, launched in 1957, weighed 83.6 kg and consisted of a 58 cm diameter aluminum sphere (15). Current launch capabilities exceed 29,000 lbs in the Boeing Delta IV evolved expendable launch vehicle and all of that capability is used to launch current communication and reconnaissance satellites (1). This increase in payload weight does not come cheap. The average cost to lift a single pound of payload into a geosynchronous transfer orbit is approximately $10,000 (24).

Inflatable and inflatable rigidizable structures have been shown to decrease volume and weight over mechanically deployable systems by 50-90% (13). This translates to a large decrease in launch costs over their mechanical counterparts. Due to the preformed nature of most inflatable structures, deployment to the expected final state is also less risky than mechanical systems.

While inflatable space structures have distinct advantages over mechanical and other structures in space, they are not without their problems. While the final deployed configuration is almost guaranteed, the dynamics of deployment is poorly understood and has been described as "chaotic" in particular instances (28). RIGEX attempts to advance the understanding of the deployment and deployed characteristics of inflatable rigidizable truss structures through comparison of ground and space tests.

Problem Statement

The overall goal of the Rigidizable Inflatable Get-Away-Special Experiment, RIGEX, is to correlate ground test and flight test characteristics in order to reduce risk and increase the use of inflatable, rigidizable technology in space applications. Specific characteristics of interest are the deployment dynamics, deployment accuracy, and vibration modal response in space as compared to ground test results.

A Get-Away-Special or GAS experiment is a specific type of experiment mounted in an enclosed cylinder inside of the Space Shuttle cargo bay. These cylinders provide a near zero-gravity environment for experiments inside the canister without allowing them free-flight outside of the shuttle. In this way, experiments can take advantage of the space environment without the complications of separate launch, guidance, or propulsion systems. This drastically reduces the cost and complexity compared to launching a mission that requires access to the space environment, but has no specific orbital or pointing requirements.

Once in the space environment, the RIGEX experiment will deploy and test three inflatable, rigidizable tubes. The data from these tests will be recorded on board and returned to earth with the Space Shuttle and recovered for further data reduction and interpretation.

The goal of this thesis is to complete production of flight suitable hardware for the RIGEX vehicle for installation in a GAS canister and integration with the Space Shuttle. Additional goals are to improve on previous RIGEX research by gaining more in-depth knowledge of the critical flight processes: heating and inflation. By gaining a thorough understanding of these processes, a major source of risk can be mitigated that otherwise could lead to failure of the experiment.

Previous RIGEX Research

RIGEX is an ongoing project at the Air Force Institute of Technology. It was initially requested by the Defense Advanced Research Project Agency and is now sponsored through the National Reconnaissance Office as well.

Previous work began with an initial operational concept and conceptual design for the RIGEX experiment. This effort, conducted by Capt John DiSebastian (12), worked to design a system that would fit into a Space Shuttle Get-Away-Special canister and meet the overall objectives of deploying an inflatable, rigidizable structure and collecting data on the deployed experiment. The initial design, which has remained much the same throughout the RIGEX design process, is shown below.

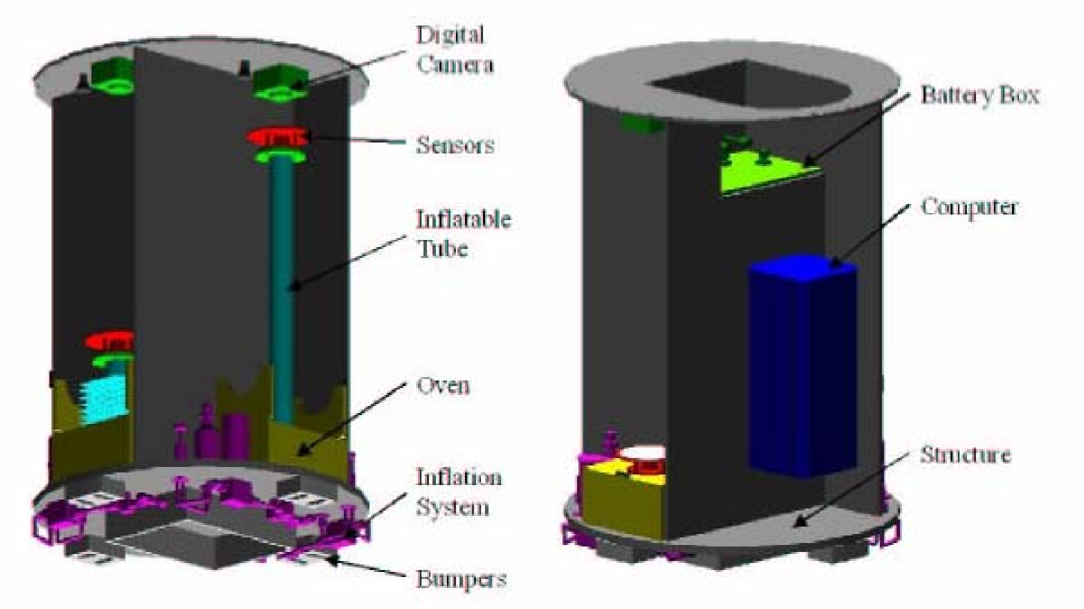


Figure 1. RIGEX Preliminary Design Concept (14)

Once the preliminary design work was completed, Capt Thomas Single conducted follow-on research into the vibrational response characteristics of the inflatable tubes themselves (14). This research formed the basis by which the current efforts attempt to correlate ground test and space test results.

The centerpiece of the entire RIGEX experiment is the rigidizable inflatable material. This type of material is structurally stiff below a certain transition temperature and becomes flexible above that transition temperature. Conversely, the material becomes structurally stiff again once the temperature drops below the transition temperature. The rigidizable material used in RIGEX has a transition temperature of 125 C.

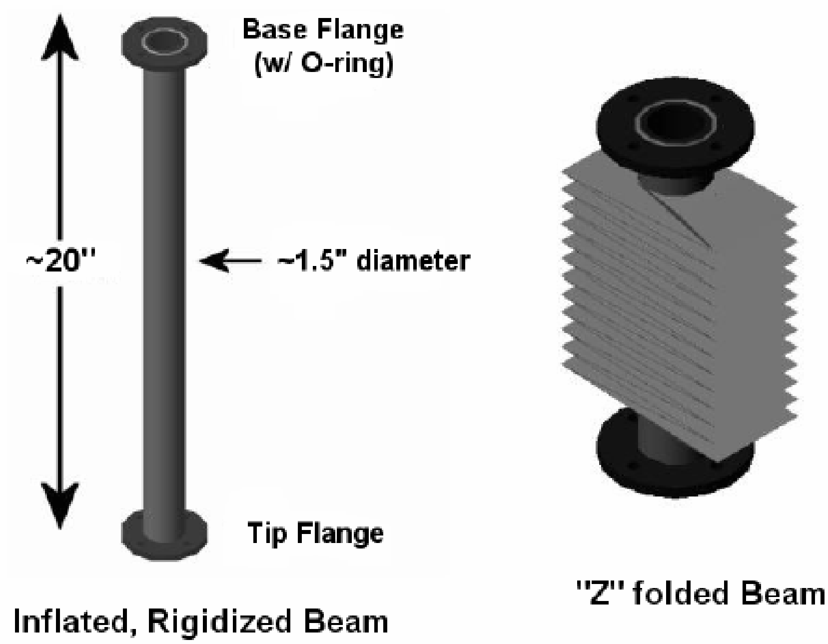


Figure 2. Initial RIGEX Tube Design (25)

Further research was conducted into the heating of the rigidizable tubes. This was manifested ultimately in the optimized design of the heater box used to warm the tubes past their transition temperature of 125 C. This research looked at several configurations of the heater box with several different types of insulation techniques to find an acceptably efficient heater with minimal loss (34). The efficiency of the heater box ties directly to the amount of power required to transition the tubes before inflation. The amount of power ties directly to the weight of the power subsystem and is therefore very important for space launch applications. The heater boxes went though several iterations in design before determining the final configuration. Interim, as well as final, design of the heater box is shown in the following figures.

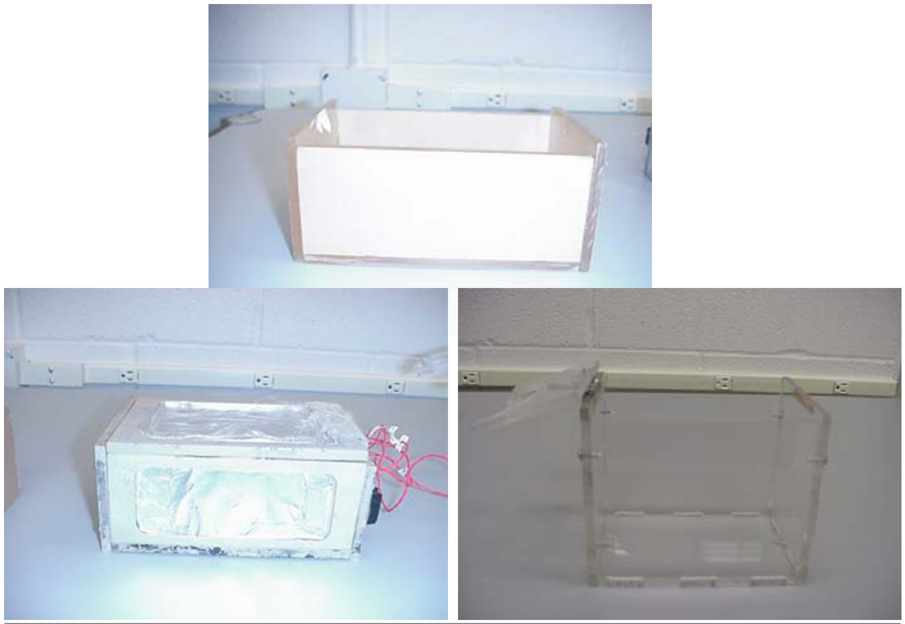


Figure 3. Interim RIGEX Heater Boxes

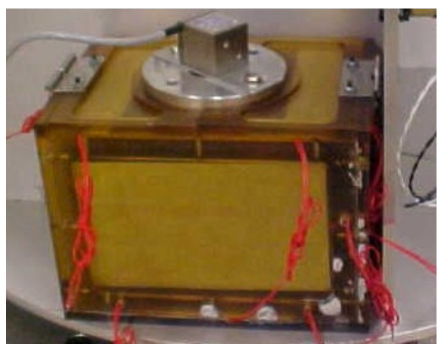


Figure 4. Final RIGEX Heater Box Design

The most recent efforts accomplished on RIGEX were focused on verifying the original design concepts by building a test article to represent one of the 4 system bays of the full experiment. This included a full scale model of the system, but only encompassed one of the 4 bays that would ultimately be required in the flight hardware. This representative mock-up tested the overall concept of heating and inflating the rigidizable tubes. This testing was done inside a vacuum chamber in order to most accurately simulate the operational environment. This test used external systems for power, heating, and gas pressure. Also, since the gravity free environment could not be created, the entire experiment was mounted and conducted inverted inside the vacuum chamber (21).

Much of the design and structure from previous research was used as a basis for current work.

Research Objectives

This thesis effort as well as previous related research efforts have centered on a stated generic mission statement for the overall RIGEX project. The following is the RIGEX mission statement (12):

To verify and validate ground testing of inflation and rigidization methods for inflatable space structures against a zero-gravity space environment

Keeping the accomplishments of previous research in mind and working toward the overall mission statement, the research that is the topic of this current thesis has the following objectives:

Primary Objective: Produce functional hardware suitable for flight that can be used to accomplish the items in the RIGEX Concept of Operations shown in Table 1.

Secondary Objectives:

- Reduce risk through testing by gaining sufficient understanding of the tube heating process to avoid mission failure
- Reduce risk through testing by gaining sufficient understanding of the tube inflation process to avoid mission failure

The basic RIGEX concept of operations is shown in Table 1 below.

Table1. RIGEX Concept of Operations

EVENT	DESCRIPTION
Launch	Shuttle Takeoff
Activate Environmental Heaters	50K ft altitude
Computer on	Boot-up & diagnostic
Activate Environmental Sensors	After specified wait period
1st failsafe point	(in case of inadvertent restart)
Inflation process	Heat and inflate all tubes
Venting process	Vent all tubes to ensure structural stiffness
Excitation process	Vibrate tubes and observe modal response
2nd failsafe point	(in case of inadvertent restart)
Shutdown flight computer	Prepare for mission end
Turn off power to environmental Heaters	Shuttle crew preparing for reentry
Land and recovery	Collect experiment

The RIGEX experiment is divided into four main subfunctions. These subfunctions are power, command and control, the conduct of the experiment itself, and the structure supporting RIGEX and providing the interface with the Space Shuttle. These systems are shown together below in a graphical representation of the RIGEX operational concept.

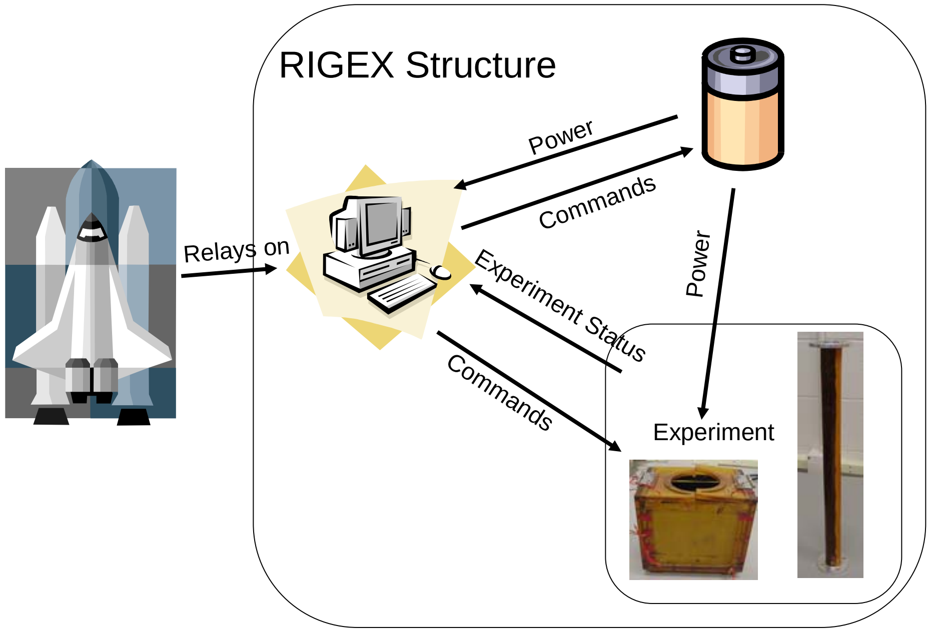


Figure 5. RIGEX Graphical Operational Concept

A more detailed breakdown of the RIGEX component functions is included in a system architecture format in Appendix F. This architecture devolves the main functions of RIGEX and shows the interfaces, dependencies and communication links between functions.

Assumptions/Constraints

The main constraints placed on the design of the RIGEX experiment stem from the choice of launch option. Since RIGEX is designed to be launched in a shuttle Get-Away-Special (GAS) canister, it will need to conform to the GAS parameters and limitations. Figure 6 below graphically shows the layout of the GAS system and how experiments are incorporated into the system.

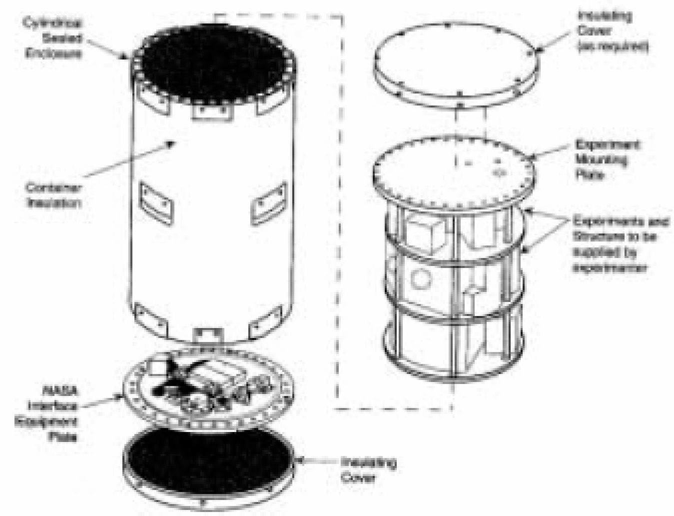


Figure 6. GAS Canister Concept (12)

The RIGEX experiment will mount to the NASA interface plate and be completely enveloped by the GAS cylindrical sealed enclosure.

Table 2 below shows the main physical constraints placed on RIGEX by choosing to launch in a shuttle GAS system (12). These are the limitations that allow the experiment to fit within the GAS container.

Table 2. Shuttle GAS System Constraints

Item	Constraint
Weight	200 lb
Size	19.75 in (diameter) 28.25 in (height)

These are significant limitations given the functionality desired from the RIGEX system. Other constraints are also derived from design choices that have already been made. At this point, much of the design of the system has been completed and much is expected to remain virtually unchanged through completion. Major design choices that constrain future options include the inflatable tubes themselves, the internal structural design of the GAS bus, and the design of the individual heater boxes. Other elements of the design are still undefined and their ultimate configuration is still considered flexible.

The design of the inflatable tubes, manufactured and supplied by L'Garde, Inc., will not be changed for the rest of the RIGEX experiment. The critical characteristics of these tubes are the physical dimensions and the designed transition temperature.

Table 3. Inflatable Tube Derived Constraints

Item	Constraint
Transition Temp	125 C
Size	1.375 in (diameter)
	22 in (height)

Figure 7 below depicts the current tube design in its stowed configuration.

Figure 7. RIGEX Tube in Folded Configuration

Another design feature that has already been designed and will not change is the experiment main structure inside the GAS canister. Except for a minor change in the design of the internal battery box, the main structural dimensions and materials remain the same. In order to produce three complete inflation experiments, the structure was designed to have three bays set aside for experiments, one bay for command and control systems, and a central bay for power. The structure design is shown below in Figure 8.

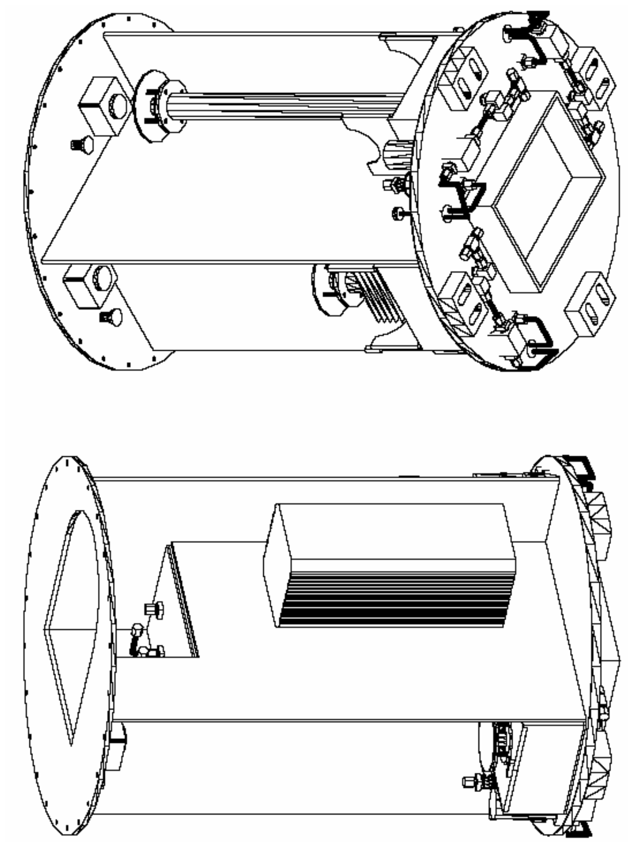


Figure 8. RIGEX Structural Design (14)

The final main constraint on the RIGEX testing is the environment in which testing must be completed. While vacuum can be emulated in the laboratory, zero-gravity cannot be simulated. This is the most significant constraint on ground testing and is the main reason for launching the RIGEX experiment on the shuttle. If the zero-gravity environment could be reasonably simulated in the laboratory for sufficient time, the RIGEX experiment would not need to be tested in space in order to meet its overall objectives.

The primary concern with testing on earth is the effect of gravity. Many inflatable structures are physically large and even the low weight of inflatable material can be significant when applied in conjunction with a long moment arm. In the case of the RIGEX tubes, the end caps are much heavier than any other part of the tube. This fact coupled with their location at the end of the tubes leads to a large difference in predicted deployment dynamics in comparison with deployment in a zero gravity environment. In other words, the weight of the end caps creates a significant moment in a gravitational environment compared to zero-gravity. Figure 9 shows the effect of the added weight of the end cap on earth while Figure 10 shows the expected deployed state of an inflatable tube.

Figure 9. Effect of End Cap Weight on Deployment

Methodology

In order to satisfy the RIGEX mission statement and correlate ground testing results with actual space experiment results, the ground testing must simulate actual experiment conditions as closely as possible. To this end, previous research efforts have designed and built a flight representative heater box and a single experiment produced to the dimensions of a single flight experiment bay.

Figure 10. Single Bay Experiment Setup

Also, in order to partially simulate the space environment, a vacuum chamber was originally used in testing (21). This gave a more realistic representation of the heating profile of the tubes inside the heater box. The lack of air in the vacuum chamber eliminated convection as a source of heat transfer and left only conduction and radiation as means of transferring heat from the heater box to the tubes themselves. This enabled a true determination of how the system would heat in the vacuum of space and how much time and therefore power would be required to reach the transition temperature.

Simulating the zero-gravity environment is a much more difficult proposition. There are many methods for simulating zero gravity and near zero gravity on earth, but none sufficient for testing RIGEX deployment, as discussed below.

NASA operates the Zero Gravity Research Facility in order to conduct preliminary tests on certain items that will fly on the Space Shuttle. They simulate the zero gravity environment by dropping items from a 140m tower in a vacuum. The items are left in a state of free-fall, giving them a micro gravity time of about 5 seconds (22). Parabolic trajectories inside cargo aircraft can produce the same effect for periods of time on the order of 30 seconds (6). Neither of these types of actual free-fall provides enough time to conduct the RIGEX experiment. Also, compared to the relatively low cost of a GAS experiment, these simulation methods are either complicated, costly or both.

Other methods of simulating zero gravity include gravity off load. This method involves lifting the test subject at specified locations just enough to counter the effects of gravity. This method can be useful for static or predictable dynamic situations, but is not suitable for use during the deployment of an inflatable tube where dynamics are not well understood and can be chaotic.

Previous research also examined the heating characteristics of the tubes inside the heater box. This initial data showed a range of temperatures at different points on the tubes themselves. This area required further study and is addressed in this thesis.

II. Literature Review

Chapter Overview

The purpose of this chapter is to detail past work done in the area of inflatable space structures including rigidizable and non-rigidizable structures. Past work extends back to the beginning of the US space program and continues through current efforts underway today.

The DoD Space Experiment Review Board (SERB) process and its implications are also addressed in this section.

Inflatable Structures

Overview

Inflatable structures can be defined as any structure that uses internal gas pressure to attain its final deployed shape. Some structures, purely inflatable structures, rely on this inflation gas to maintain their structural integrity throughout the structure's life. Other structures, inflatable rigidizable structures, use the inflation gas to achieve a deployed configuration then gain structural strength from the structure skin itself without further reliance on internal gas pressure.

The use of inflatable structures in space dates back to the beginnings of the space program when large structures were required and large launch envelopes were not yet available (7). This early need highlights the largest advantage of inflatable structures over their mechanical counterparts: they are light-weight and easily packaged in comparatively small volumes.

Initial efforts focused on merely achieving large surface area structures that would be best described as balloons. These initial efforts were followed by a period of little activity in the realm of inflatables. The space race was on and work on the unfamiliar inflatable structures gave way to the more traditional mechanically deployable systems. While mechanical systems were heavier and more difficult to package, engineers had much more experience and familiarity dealing with them.

The use of mechanical systems raised the need for larger and more powerful launch platforms. In turn, the larger launch platforms allowed the use of large mechanically deployed systems to continue.

Cost, schedule and performance have always been the three competing factors in any major technical project. From the beginning of the space race through the 1980s, the emphasis for large programs was on performance over both cost and schedule. This allowed the trend toward larger launch vehicles to continue even though the cost was immense (26).

As dollars became scarcer in the 1990s, focus began to shift to cost as the driving factor in large programs. This change has reinvigorated research into cutting edge inflatable materials and concepts. Ideas for the use of inflatables have expanded drastically from the original balloons. Current ideas focus on creating very large structures compared to their launch envelope. These large structures lead to large apertures for antennas and radars. They also lead to large solar sails and power collection devices. Configurations of inflatables have progressed from the original spherical shape to tubular components of large truss structures and parabolic lenses. The following section details specific examples in the history of inflatables.

History of Inflatables

Echo 1

This series of satellites, Echo 1 and Echo 2, were designed as passive communication platforms. They were very large (30.5m diameter) spheres designed with a metallic surface that would reflect communication signals for over the horizon communication between ground stations. Inflatable technology was relatively immature at this stage, but NASA found it necessary to use it since no other available technology existed to fulfill mission requirements while still fitting within existing launch envelopes (27). The 30.5m satellites had a mass of roughly 76kg (8). One problem that the Echo series ran into was that of micrometeoroid impact. The solution to this problem for the Echo program was to fill the satellite with a low density aqueous material that would fill in any small holes left by penetrating micro meteors.

The RIGEX system gets around this problem by being rigidizable. Once the structure is rigidized, internal pressure is no longer needed to maintain structural strength and micrometeoroid impact will have little effect.

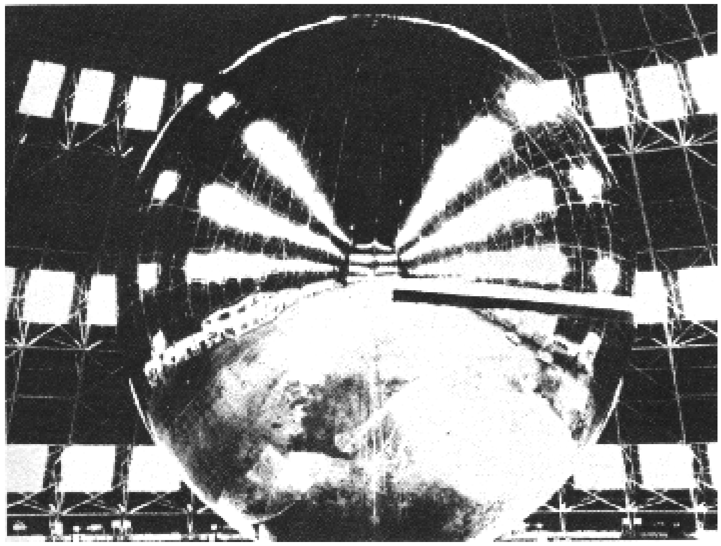


Figure 11. NASA Echo 1 (8)

Echo I, even with its massive deployed size, was contained and launched in a 26 inch diameter sphere. This demonstrates that, even in the early days of inflatables, the major benefits of inflatable structures could be realized.

Inflatable Antenna Experiment

This experiment had five main objectives: 1) Verify that large inflatable antennas can be built inexpensively, 2) demonstrate high volume packaging efficiency, 3) demonstrate deployment reliability, 4) verify that large aperture reflectors can be manufactured with high surface precision, and 5) measure surface precision in the space environment (28).

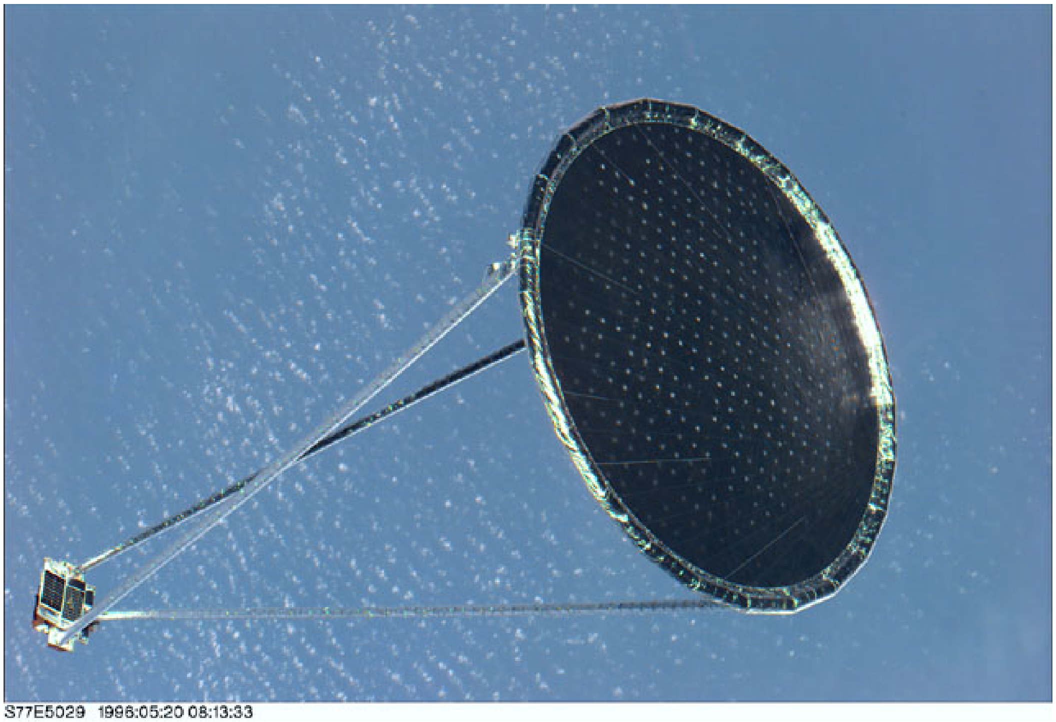


Figure 12. Inflatable Antenna Experiment (28)

The experiment consisted of a 14m parabolic aperture antenna that was deployed and maintained its structural integrity through internal gas pressure. Because of the vacuum of space, the IAE was designed to use 3x10E-4 psi of inflation pressure to stress the structure to 1200 psi (28). This small amount of internal pressure would not be enough for the IAE to support its own weight on earth. This example illustrates the importance of testing in a zero-g environment.

This experiment launched on STS-77 on 29 May, 1996 and was deployed on a Spartan spacecraft. The deployment exhibited unexpected characteristics and the antenna dynamics were apparently chaotic. While the antenna did achieve the general desired parabolic shape, the design internal pressures were not achieved. The lack of sufficient pressure caused the surface accuracy, designed to be 1mm rms, to be less than planned and immeasurable with the onboard systems (28).

The IAE was not robustly instrumented on non-flight critical systems. Because of this, it was difficult to isolate where the failure occurred. The exact cause of inadequate inflation is not known.

Even though the inflation was chaotic and inadequate for the overall mission objectives, IAE was considered a partial success. It did deploy from a comparatively small package into a generic 14m parabolic antenna shape. Although the deployment dynamics were chaotic, the ultimate deployed structure conformed to the designed and manufactured shape.

Current Efforts

Several efforts are currently underway in the arena of inflatables. These efforts are far ranging and have potential to impact many aspects of science and our daily lives. This section addresses some of the work being accomplished in the field of inflatable structures for space.

ARISE

The Advanced Radio Interferometry between Space and Earth (ARISE) is an inflatable system designed to have an 82 ft diameter aperture and be capable of resolution 3,000 times better than the current Hubble Space Telescope. The launch canister that will contain the ARISE satellite is designed to be 1.3 ft tall with a diameter of less than 6 ft. This represents over a 92% decrease in diameter from the deployed state to the packaged state (27).

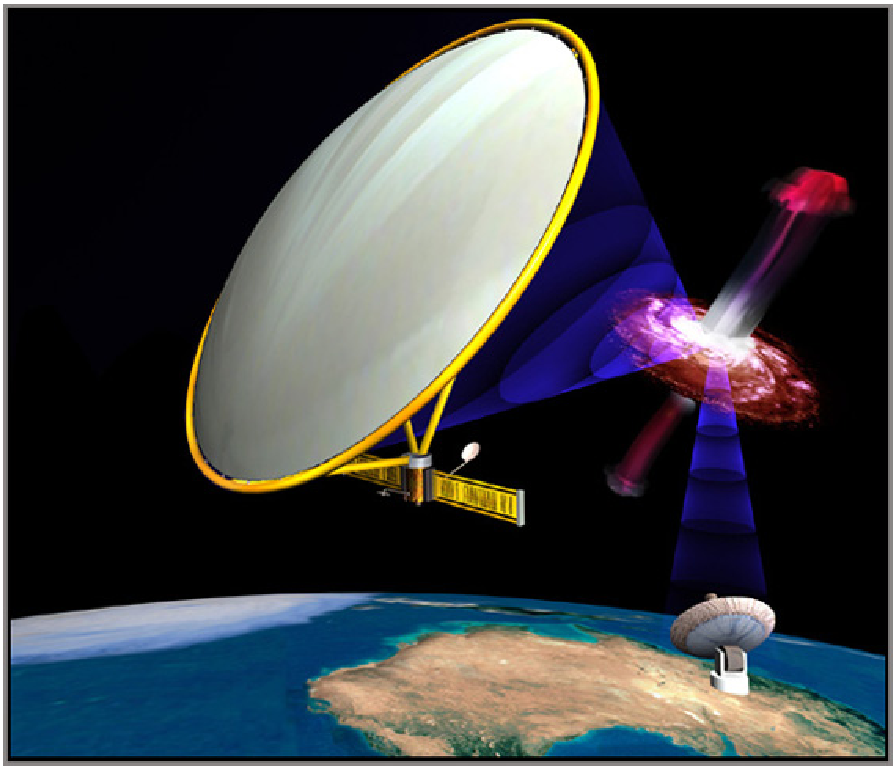


Figure 13. ARISE Design Concept (27)

The ARISE program highlights the large scale of structures that can be compacted into existing launch envelopes. The RIGEX experiment plans to take advantage of this aspect of inflatable technology on a much smaller scale.

Space Solar Power Truss

The SSP Truss is designed to take advantage of inflatable rigidizable technology in order to produce a large surface area on which to collect solar energy. This truss has been developed through initial ground test article.

Figure 14. SSP Truss Test Article (3)

This test article has been successful in producing a truss that is 8 meters in length, weighs only 9 lbs and has stiffness and vibrational characteristics suitable for mounting flexible solar panels (3).

The tubular structures that form the individual components of the SSP truss are very similar to the tubes being tested in the RIGEX experiment. Observing and understanding the deployment characteristics of the RIGEX tubes will help to understand and predict the space deployment of structures such as the SSP truss before they commit to a costly launch.

DSX

The Deployed Structures Experiment is an experiment with wide ranging goals. It is designed to use inflatable technology to achieve extremely lightweight, high power arrays that are survivable in high radiation environments. The combination of effects they expect to get from this very large inflatable structure are intended to overcome hurdles in the way of realizing giant inflatable structures. The large size aspect of this mission is encompassed in their l6m trusses and 50m booms. These are intended to observe and counteract the effects on large structures imposed by the micro gravity environment and the gravitational variations imposed on a satellite in MEO orbit.

High power is gained through massive surface area on the DSX roll-out solar array. Flexible thin-film photovoltaic cells covering this large area are expected to produce power on the order of 20kW (29).

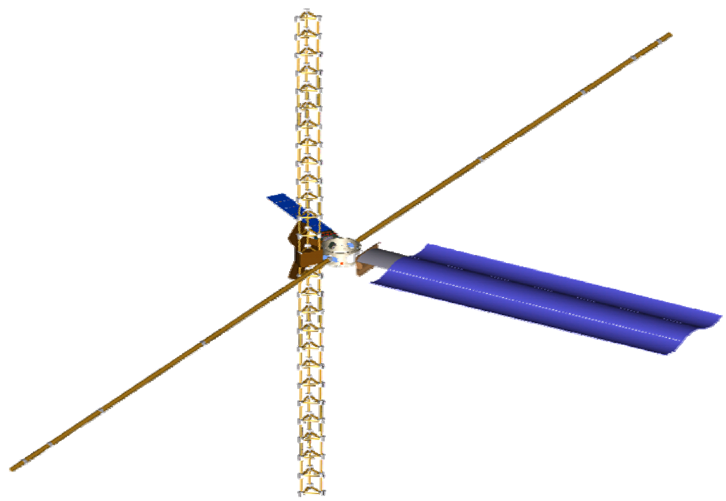


Figure 15. Deployed Structures Experiment (29)

The scale of this experiment makes it vastly different from RIGEX even though it uses inflatable rigidizable technology to attain its large size. Perhaps the most telling aspect of this program is that, even with its impressive size, it is intended to be packaged as a secondary payload on existing expendable launch vehicles. This demonstrates the compact size of this experiment before deployment.

DSX is currently in the early stages of development and the configuration described and depicted herein will undoubtedly change as it nears execution.

Analytical Efforts

With the high expense of launching and testing in space, many researchers and scientists are attempting to model the behavior of inflatables inside their computers rather than in space. Gravity can cause drastic differences in how inflatable structures deploy on earth from how they deploy in space's zero gravity environment.

As mentioned earlier, the cost of space launch can be prohibitive, especially for testing purposes or non-revenue generating purposes. If analytical models could be developed that would adequately describe the behavior of inflatable structures, they would drastically decrease the cost of testing as well as increase the overall use of inflatables in meeting future requirements. Several types of these models are currently being tested or are under development.

Palisoc and Huang in their 1997 AIAA paper *Design Tool for Inflatable Space Structures* (19) present a design tool that attempts to simulate the characteristics of an inflatable aperture antenna. This code is a combination of separately developed finite element code for the inflatable antenna with commercially available pre and post processing software.

This design tool was able to simulate the on-orbit static and modal behavior of an inflatable antenna as shown in Figure 16 below.

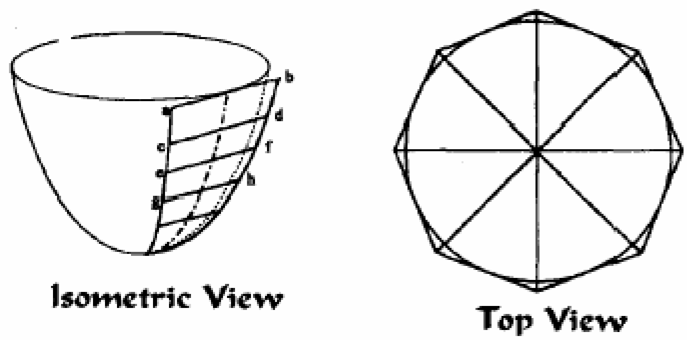


Figure 16. Inflatable Space Antenna Representation (19)

This simulation compared well to other types of analytical solutions. Although this tool was designed for post deployment behavior of inflatable structures, it is a step toward understanding the overall behavior characteristics of inflatables in space.

A main problem with all of these models is validation. In order to validate the results of the software packages, they must be compared with the actual results they are attempting to simulate. RIGEX would be a useful tool to validate some of these models.

Inflatable Tube Model

Even more specific to RIGEX than the previous example, Miyazaki and Uchiki have developed a numerical model that predicts the deployment dynamics of deployable membrane structures. The specific example presented in their AIAA paper studied an inflatable tube similar to those used in RIGEX, but with only a single bend.

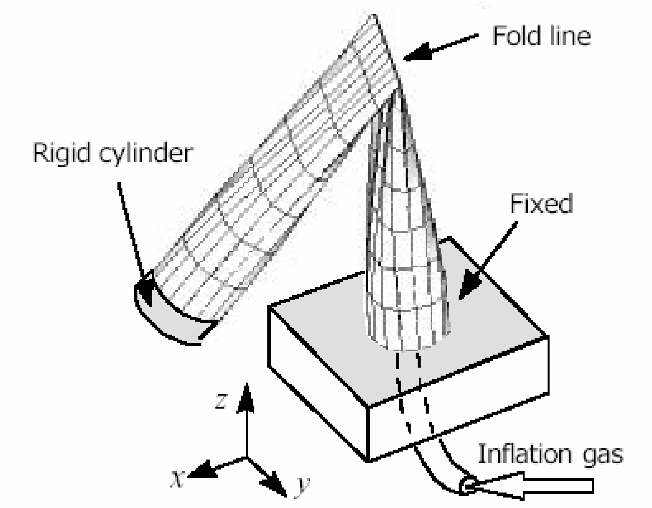


Figure 17. Inflatable Tube Model (18)

The time-phased deployment characteristics compared well with experimental results gained as part of the same study. Some aspects of the inflation, such as the time-phased pressure profile, were not modeled accurately (18). Minor differences between the analytical model and the experiment would be amplified if complexities such as more folds or longer structure were introduced. Also, comparison with testing in the space environment is required to make this model more useful in space applications.

Utility of Inflatable Structures

The major benefit of inflatable structures is that their deployed configuration can be several times larger than their launch configuration. This translates into increased capability in several areas.

Increased surface area provides more area on which to place photovoltaic cells, thus allowing increased solar power available to the system. Thin film photovoltaic cells have been developed that are flexible and can be packaged on large inflatable systems (29).

Large aperture is a key to increasing viewing resolution. Theoretical achievable resolution is limited by the diameter of the first minimum of the diffraction image for any given light frequency. Diffraction limited ground resolution thus depends on three factors: distance from the sensor to the viewing area, wavelength of light being observed, and diameter of the sensor aperture (30).

$$\text{Ground Resolution} = \frac{2.44h\lambda}{D} \tag{1}$$

Where

h = slant range to the target
λ = light wavelength of interest
D = aperture diameter

Since h and λ are fixed for any orbit and application, increasing aperture diameter can significantly improve ground resolution as shown in Figure 18.

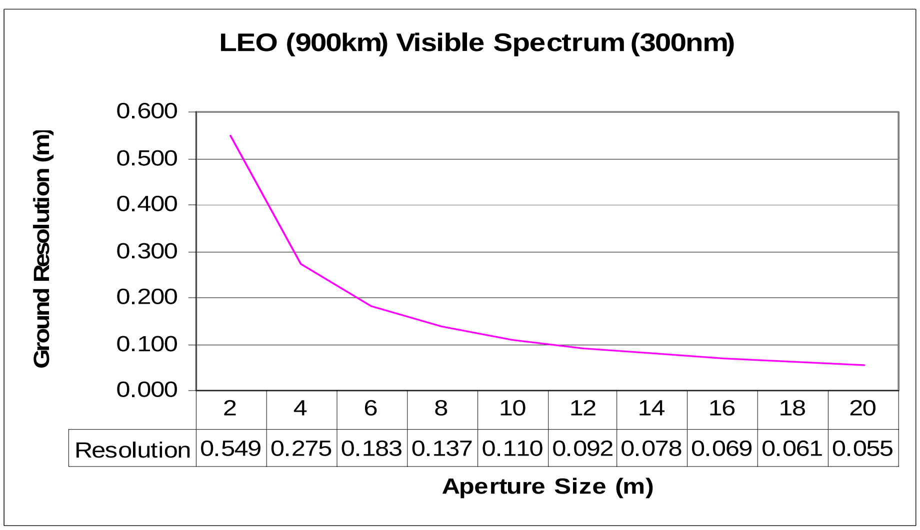


Figure 18. Aperture Versus Resolution

Figure 17 shows that increasing aperture size can drastically improve diffraction limited ground resolution. This implies that resolutions that are currently achievable only from low earth orbit could be achieved from geo-stationary altitudes with larger aperture diameters. It also implies that current resolutions at lower orbits could be improved several times over existing systems.

Space Experiment Review Board (SERB) Process / Space Test Program

Overview

This section summarizes the processes by which RIGEX will be manifested on the Space Shuttle. These include dealing with the NASA Small Payloads office as well as completing the Department of Defense Space Experiment Review Board (SERB) process.

In order for an experiment to launch on the Space Shuttle in a GAS container, it must first satisfy the range safety requirements placed on payloads that are determined and supplied by NASA. In short, all GAS payloads must clear requirements set out by NASA's Small Payload project office. Previous research on RIGEX addresses this issue fully (12).

In order to begin the process of working with NASA, a project must first either provide funding directly to NASA or must be specifically ranked as an experiment on the DoD SERB yearly ranking. Once this has occurred, NASA engineers are free to work with the project and make initial preparations for mission safety, mission integration and launch.

Space Experiment Review Board

The SERB is designed in a hierarchy. The formal process begins with the meeting of either an Air Force or Navy SERB in order to review proposed projects and determine their relative scientific importance and relevance to the military. Once projects have passed this stage and have been approved to move forward they will undergo a similar process at the DoD level.

The DoD SERB convenes after both the Air Force and Navy SERBs have completed their selection and ranking process. Those forwarded from the Service SERBs are considered at the DoD SERB and appropriately ranked based on their military relevance, level of maturity and scientific importance.

The DoD SERB itself consists of senior members of AF, NAVY and DoD agencies that share a stake in gains through experimentation in space.

Once the SERB has identified experimental missions that meet their baseline requirements, these selected experiments are ranked. This ranked list is forwarded to the Space Test Program, centered at Detachment-12 of the Space and Missile Systems Center at Kirtland Air Force Base, New Mexico.

Space Test Program

The Space Test Program (STP) has its focus divided between three main types of launch: free flying missions, secondary payloads on already manifested missions, and shuttle payloads. Missions are matched up with one of these three areas depending on their mission requirements.

STP is designated a certain amount of money it is allowed to spend each year with the objective of using it most efficiently to launch experimental missions from the DoD SERB ranked list. The higher ranking missions receive more consideration than the lower ranking missions on the list, but the higher ranked missions are often much more costly as well. There is not enough funding for every mission to launch and funding generally only covers the top few missions on any given year.

Of the three mission areas, dedicated free flyer missions are normally the most costly (on the order of 10s of millions of dollars). Secondary payloads and shuttle missions are generally less expensive but costs can vary widely within these categories. Secondary payloads are on the order of $1 million while shuttle mission can be much less or much more costly. In the case of RIGEX, the overall mission cost is estimated by STP to be between $150k and $200k. This fact makes RIGEX attractive as a launch option regardless of ranking from the SERB.

In the current SERB rankings, RIGEX was ranked as 31st out of 41 ranked missions. Since requirements for RIGEX lead it to the shuttle launch mission area, it will compete for funding with other experiments in this area separate from the other two mission areas. Since most of the other payloads require either dedicated launch or inclusion as a secondary payload on an expendable launch vehicle, RIGEX is expected to be funded by STP for launch on the Space Shuttle.

The briefing that was presented to the DoD SERB in order for the experiment to be ranked is included in this document as Appendix E.

Summary

Inflatable structures have been present since the beginnings of the space program but have not been studied to their full extent because of the design community's relative familiarity in developing mechanical systems as well as the availability of large payload envelopes.

With the increasing importance placed on cost and the desire to make structures much larger than current launch vehicles can carry, focus is returning to inflatables as a way to gain deployed size without requiring large volumes for packaging.

Modern uses for inflatable structures vary widely. From gaining otherwise unachievable observation resolutions to providing large surface areas to collect solar energy, inflatable structures are providing an opportunity where mechanically deployed systems seem to have achieved their maximum benefit.

RIGEX is a step toward making inflatable structures more appealing by providing some understanding of how they will behave in space without having to actually test each one in space. This risk reduction will make inflatable structures more appealing in general.

RIGEX must be tested in the space environment in order to compare its zero-g behavior with behavior on the ground. The way to achieve this zero-g environment is though launch on the Space Shuttle in a Get-Away-Special canister. Access to this launch platform is achieved through ranking on the DoD SERB experiments listing.

III. Methodology

Chapter Overview

The purpose of this chapter is to detail the testing methodology used to prepare RIGEX for flight. This includes descriptions of planned tests and test objectives as well as details of the individual experiment set-up for the tests that were accomplished. The planned tests are divided into two categories: those tests that were determined prior to the beginning of testing and those that were derived as a result of issues from past testing. Both types of testing are further broken down to show how the tests were conducted and the procedures that were used.

Since much work was completed in past research, testing objectives for this phase of RIGEX development were clear: to resolve issues identified in previous work and finally to produce hardware suitable for flight on the Space Shuttle. This meant that problems in previous testing had to be worked out and the testing itself must then be taken from the ¼ scale model to the full scale flight article to prove functionality.

Experiment Assembly

Planned Battery of Tests

The initial battery of tests was determined prior to attempting any testing. These tests were designed to ensure correct function of the completed system as a flight article. During the accomplishment of the planned battery of tests, some of the future tests were determined to be unnecessary. These are noted in Table 4 below.

Table 4. Battery of tests to ensure RIGEX experiment is ready for space flight

Test	Description
1	Heating test in ¼ section mock-up, external power, ambient pressure
2	Heating tests in ¼ section mock-up, external power, vacuum
3	Inflation test with flight configured inflation system, ambient
4	Inflation test in ¼ section mock-up, flight power and computer, ambient
5	Inflation test in ¼ section mock-up, flight power and computer, vacuum (not required due to results from test 2)
6	Inflation test in flight configuration (Full Structure), ambient
7	Inflation test in flight configuration (Full Structure), vacuum (not required due to results from test 2)
8	Inflation System Pressure Retention Test

Heating Tests

Heating is the first critical function of the RIGEX experiment. Aside from proper functioning of the heating system and the heater boxes themselves, the amount of time to heat the inflatable tubes is very important. Insufficient time heating the tubes will cause failure to bring the entire tube to transition temperature and ultimately lead to improper deployment of the tubes. Excessive time heating the tubes could increase temperature in the ovens past the operating temperature of adhesives and internal bonding temperatures of the piezoelectric actuators. Because of this, it is imperative to understand the differential heating across the tube.

A series of tests was developed to characterize the heating process within the tube using as close to flight conditions as possible. The first set of tests involved heating the tubes with flight representative power source while the second included a vacuum environment to make the testing more flight representative. The following are the tests designed to characterize the heating of the tubes.

Heating test in ¼ section mock-up, external power, ambient pressure.

This test will be used to ensure that all systems are working well with external power in an environment where problems can be identified and changes can be made more easily than in the vacuum chamber. Heating data from this set of experiments will be used to correlate with heating data from the vacuum to see if ambient testing can be used in the future as a reasonable substitute for vacuum testing of heating characteristics. The primary purpose of the heating tests is to determine how different parts of the RIGEX tubes heat up at different rates. It is also to determine the correct location to place thermocouples to ensure that the entire tube has crossed its transition temperature and is ready for inflation. Improper understanding of this factor could result in an in-flight failure of the entire experiment. Success of this experiment will be achieved if temperature data that is obtained shows a reasonable and repeatable profile for heating of the RIGEX tubes.

Heating tests in ¼ section mock-up, external power, vacuum.

This test will be a copy of the initial test, except the heating experiment will be conducted in the vacuum chamber. The vacuum chamber will all but eliminate the heating effects from convection in the experiment oven. These results will be compared with the results from the ambient tests to ensure that vacuum testing of heating characteristics is required in future tests. This test may eliminate the need for future vacuum testing. Success of this test will be achieved if the temperature data obtained shows a reasonable and repeatable profile for heating of the RIGEX tubes.

Inflation Tests

Inflation of the tubes also needs to be well understood. Improper inflation could result in insufficient deployment or structural failure of the tubes. Proper deployment also depends on unfolding and extension of the tubes without interference from components in the experiment bays. Because of the criticality of the inflation system, it is tested to ensure appropriate pressures are met, deployment characteristics are observed and sufficient inflation pressure is maintained throughout expected pre-flight operations.

. The following sections address the specific tests used to verify the inflation system reliability. Inflation pressure maintenance is discussed in the section entitled "other derived testing". Appendix H discusses how internal pressure affects tube inflation

Inflation test with flight configured inflation system, ambient.

This test is designed to test the layout and integrity of the flight configuration inflation system. Previous thesis work identified a nominal layout for the inflation system, but this must be tested and modified as needed on actual hardware. Previous thesis testing showed successful inflation of a tube, but was accomplished using an externally mounted pressurization/inflation system. The vacuum environment should have little effect on the operation of the inflation test, so it will be conducted in the ambient pressure environment. Success will be determined by complete inflation of the tube using the inflation system configured within the expected flight envelope.

Inflation test in ¼ section mock-up, flight power and computer, ambient.

This test will simulate the heating and inflation of the RIGEX experiment in the ¼ scale mockup in the ambient environment. This will test the inflation system as well as the power and command and control algorithms of the C&DH system. For the ¼ scale mock-up, this is designed to be our closest test to the actual flight article environment. Success of this test will be determined by complete inflation and re-rigidization of the test tube. Secondary test objectives will be correct and timely accomplishment of all pre-programmed command actions.

Inflation test in ¼ section mock-up, flight power and computer, vacuum.

This test is the same as test #4, except that it will be powered and controlled by the flight computer and batteries. This test will have no external power or control, but the results will be monitored through external data collection and distribution systems. The necessity of this test will be dependent on the results of test #2, the initial vacuum heating test. If test #2 shows no appreciable difference in heating and heating rate for the tubes in vacuum vs. ambient, then further vacuum tests will become unnecessary. Success of this test will be achieved in the same manner as test #4.

Inflation test in flight configuration (Full Structure), ambient.

This test is intended to show the systems capability to accomplish a simulated full mission. This will serve as an operational test of the flight article. As such, it should be as representative as possible of the planned flight configuration. Success of this test will be determined by successful completion of all steps in the RIGEX concept of operations.

Inflation test in flight configuration (Full Structure), vacuum.

This test is the same as test # 6, except that it will be conducted in the vacuum environment. The necessity of this test will be dependent on the results of test #2, the initial vacuum heating test. If test #2 shows no appreciable difference in heating and heating rate for the tubes in vacuum vs. ambient, then further vacuum tests will become unnecessary. Success of this test will be achieved in the same manner as test #6.

A summary of these tests, objectives and conditions is shown below in Table 5.

Table 5. Testing Overview

Test	Objective	Condition	Scale	Success Criteria
1. Heating	Determine heating profile	Ambient	¼	Reasonable and repeatable heating profile
2. Heating	Determine heating profile	Vacuum	¼	Reasonable and repeatable heating profile
3. Inflation	Test inflation system	Ambient	¼	Complete inflation
4. Inflation	Test C&DH	Ambient	¼	Execution of all programmed command actions
5. Inflation	Test C&DH	Vacuum	¼	Execution of all programmed command actions
6. Inflation	Test C&DH	Ambient	Full	Completion of all steps in RIGEX CONOPS
7. Inflation	Test C&DH	Vacuum	Full	Completion of all steps in RIGEX CONOPS

Other Derived Testing.

Other events that occurred or were brought to our attention during the testing sequence made other tests necessary to achieve the objective of a final flight article. These are listed and described as other derived tests in Table 6 below.

Table 6. Other derived testing

Test	Description
1	Heat tolerance test for PZT patch bonding material and adhesive
2	Inflation system long-term pressure maintenance test

Heat tolerance test for PZT patch bonding material and adhesive.

This test was designed because the PZT operating temperature ceiling is lower than temperatures seen in the patch installation process. Also, the bonding material that holds the individual elements of the PZT patch is not rated to the temperatures experienced in the heating oven. This test stresses the functionality of a PZT patch installed on a single tube before and after extreme heat is applied. The installed patch was tested before applying heat by activating the PZT through an experiment representative vibration profile. The ultimate objective of this test is to compare the functional use of the bonded PZT patch before and after the heating process. Success of this test will be determined by similarity in vibration test results before and after the heating process.

Inflation system long-term pressure maintenance test

This test is necessary to ensure that the RIGEX system will be able to maintain sufficient pressure in the inflation system during Shuttle ground operations, launch and pre-experiment mission operations. Success of this test will be determined by sufficient retention of compressed air volume and pressure. Sufficiency of these elements is determined by ability to maintain at least 47psia in the system pressure vessel from last charge through experiment start.

The pressure retention test will be accomplished on a subset of the actual flight hardware. This subset, depicted in the schematic below, incorporates all components of the inflation system upstream of the solenoid valve. This allowed a check of the integrity of the systems affected during ground operations and pre-experiment flight operations without requiring the full system to be in place.

Figure 19. Pressure Retention Test Setup Schematic

The actual test will be a series of pressure readings taken from the pressure sensor shown in Figure 19 above. These pressure readings will be taken at approximately 4-24 hour time periods and extrapolated to determine the characteristics of pressure loss within the system.

During integration of the RIGEX experiment into the Space Shuttle bay, there may be long periods of time where the experiment will be inaccessible for maintenance or upkeep procedures. According to conversations with the Space Test Program, access to the inside of the GAS canister system will be discontinued after the experiment is loaded into the shuttle bay. This scenario would leave RIGEX inaccessible for approximately three months prior to launch. Under these conditions, it is unlikely that the RIGEX inflation system will maintain sufficient pressure.

Access is available to the shuttle interface plate until less than 1 week prior to scheduled launch (20). Because of the low priority of RIGEX on the Space Shuttle, the schedule for this access is determined by the requirements of the primary mission. According to the Space Test Program Small Payloads Office, the Space Shuttle flight that RIGEX will be manifested on is almost certain to be a mission to the International Space Station, ISS. Pre-flight procedures for these missions are well established. This gives RIGEX an estimated timeframe for access to the shuttle bay of up to one week before scheduled launch. This scenario allows a much more reasonable time to maintain sufficient pressure in the inflation system.

Success of this test depends upon the system's ability to maintain enough air volume and pressure to fully inflate a tube in the space environment after a long duration from final charge of the pressure cylinder. This measure of success coincides with the mission success criteria spelled out for the inflation system in Appendix D.

Operations of the Space Shuttle allow for up to 90 days delay before the vehicle must be removed from the launch pad and RIGEX can be re-pressurized. This leads to a possible delay of 97 days between the final charge of the inflation pressurization system and shuttle launch. Because of this, the following section of this document looks at the feasibility of successful inflation in the event that the inflation system cannot maintain pressure through RIGEX mission start.

In order to do this, the following calculations show the amount of air and air pressure required to inflate an inflatable tube in a zero gravity environment.

If the system leaks and loses pressure during a long prelude to launch, it may still retain enough pressure to successfully complete the RIGEX mission. This is because the system will not lose pressure beyond the atmospheric pressure at the launch site. The following calculations address this question.

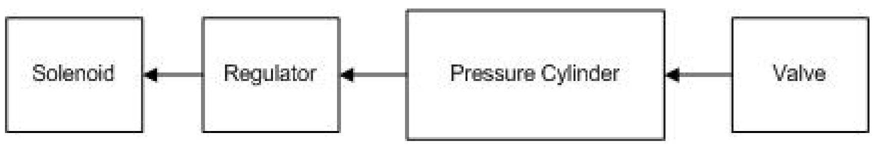


Figure 20. Pressure Sealed Section of Inflation System

The upper section of the inflation system is the section that maintains pressure during the time leading up to mission execution. If it is assumed that pressure in this section has leaked over time and equalized with the external pressure, there will still be a significant volume of air in this section. During the relatively short period between launch and RIGEX mission execution, the inflation system will retain this pressure as the outside pressure decreases to near zero. Since the launch facility is at sea level, the internal minimum internal pressure will be 14.7psi.

The question at hand is whether the amount of air remaining in the system is sufficient to inflate the tube to 4psi internal pressure. The two basic steps involved in determining the answer to this question are:

1. Determine the mass of air available in the pressurized section

2. Determine the mass of air required to inflate the tubes to the desired pressure

Determine the mass of air available in the pressurized section

The number of moles of air within this section can be calculated by the perfect gas law:

$$PV = nRT \tag{2}$$

or

$$n = \frac{PV}{RT} \tag{3}$$

where conditions are assumed to be standard temperature and pressure, STP, and R is the gas constant.

Using the values

V= 0.0655 liter,

P= 760 torr,

$R = 62.36\frac{Ltorr}{molk}$,

T= 300K,

We find that 0.0020 moles of air are available within the pressurized section of the inflation system. Given that the average molecular weight, M, of air is 29 g/mol (31), there is

$n * M$ or 0.059 grams of air resident in that section.

Determine the mass of air required to inflate the tubes

Using the same equations, the mass of air required to inflate the tube with a volume of 0.54 liter to the desired pressure of 4psi is 0.13 grams. This is much more than would be available if all pressure were to leak from the inflation system. This particular scenario would only provide 1.25psi of gage pressure inside the tube. With this low pressure, the tube will still inflate, but may not inflate fully enough to overcome residual stresses in the folds of the tubes. In this case, the tube will not deploy to a full, upright and straight configuration.

The amount of pressure required to be retained within the inflation system prior to experiment start is 47psi. This is retention of 8.5% of the original pressure in the inflation system.

The following tables address the procedures used to conduct the remaining inflation and heating tests.

Inflation Test Setup and Procedures

Table 7. Test Procedures: Inflation, Flight Configured Inflation System, Ambient

#	Step	Condition
1	Open main valve on pressure vessel	
2	Adjust main regulator to 400 psi	
3	Open regulator valve	
4	Readjust main regulator to 400 psi	
5	Open experiment pressure valve	
6	Adjust overcurrent	5.5 Amps
7	Adjust Voltage	30 Volts
8	Start heating timer	
9	Turn on power to pin puller	Temp >/= 127.5 C
10	Turn on power to solenoid	Temp >/= 127.5 C
11	Use high speed video to record deployment	
12	Turn off power supply	
13	Turn off power to solenoid (vent air)	60 sec after deployment
14	Turn off power to pin puller	

Table 8. Test Procedures: Heating In ¼ Section Mock-Up, External Power

#	Step	Condition
1	Open LabView program	
2	Select output file for data	
3	Turn on power supply	
4	Set current limit	5.5 Amps
5	Set voltage level	30 Volts
6	Run LabView routine	
7	Record power source current	300, 600, 900, 1200 sec after routine start
8	Record ending current	Lowest temp reading reached 125 C
9	Turn off power supply	
10	Stop LabView run mode	
11	Transfer data to excel for analysis	

Table 9. Test Procedures: Heat Tolerance Test For PZT Patch Bonding

#	Step	Condition
1	Photograph PZT and bond for pre/post comparison	
2	Collect vibration data on bonded PZTs before test	
3	Attach tube to top rack of oven (ensure minimal deformation above transition temperature)	
4	Set oven temp control to 320 F	
5	Record tube temperature at 3 minute intervals	3, 6, 9, 12, 15 min
6	Increase oven temp control to 400 F (to increase heating rate of oven air)	15 min
7	Turn off oven	Internal temp reaches 320 F
8	Open oven door to increase cooling	

Table 10. Test Procedures: Heating ¼ Section Mock-Up, External Power, Vacuum

#	Step	Condition
1	Open LabView program	
2	Select output file for data	
3	Turn on power supply	
4	Set current limit	5.5 Amps
5	Set voltage level	30 Volts
6	Run LabView routine	
7	Record power source current	300, 600, 900, 1200 sec after routine start
8	Record ending current	Lowest temp reading reached 125 C
9	Turn off power supply	
10	Stop LabView run mode	
11	Transfer data to excel for analysis	

Summary

The purpose of this chapter was to detail a testing plan and methodology that would reduce overall system risk and prepare the RIGEX system for flight. In order to do this, two main risk areas pertaining to the conduct of the RIGEX experiment itself were addressed. These were the heating and inflation processes. Proper heating is vital to the success of the RIGEX mission since transition of the inflatable tubes from a stiffened to a flexible state is entirely dependent on targeted and thorough heating.

Inflation is the other centerpiece of the RIGEX experiment. To accomplish the overall objective of verifying and validating zero gravity inflation of the system as compared to ground testing procedures, the inflation system must work properly in a remote environment. The testing laid out in this chapter assesses the inflation system's ability to meet that goal.

The testing planned in this chapter does not stand alone, but builds on previous research accomplished in this area. It further refines results found previously and prepares the RIGEX system for launch.

IV. Analysis and Results

Chapter Overview

This chapter will discuss the conduct and results of the various tests that were performed in pursuit of the objectives of this thesis. Beyond that, this chapter will analyze the data gained from each test and state how it applies to the overall accomplishment of the objectives of this thesis.

Heating Tests

Heating is a critical factor in the success or failure of the RIGEX mission. Reaching the correct transition temperature is essential to full inflation and proper deployment of the inflatable tubes. As was noted in past RIGEX thesis work, there is a substantial difference in heating rates between different locations on the tubes themselves. These differences have the potential to lead to serious problems. If the inflation were to initiate based on the temperature of a fast heating section of tube, other parts of the tube may not have reached transition and therefore will not inflate and deploy properly. This would result in failure of one of the key mission success criteria (Appendix D). Because of this, the heating characteristics of the tubes inside the heater boxes must be well known.

The heating tests for which the results are described in this section are designed to determine the location on the tubes that will reach transition temperature at the latest time. Since it is the last to heat to transition, this point will be the location that is monitored during flight to determine when the entire tube is ready to be inflated.

Understanding the heating profile is important for another reason as well. Much of the power required for this mission is used in the heating process. The length of this process, and thus the power required to conduct it, is determined by the heating rate of the tubes in realistic conditions.

In order to achieve the two main objectives, those of identifying the slowest heating point and estimating the time it takes to heat each tube, a test was designed to gain this data.

The test setup is shown here in Figure 21 and uses the single bay mock-up of the RIGEX GAS configuration as its base structure.

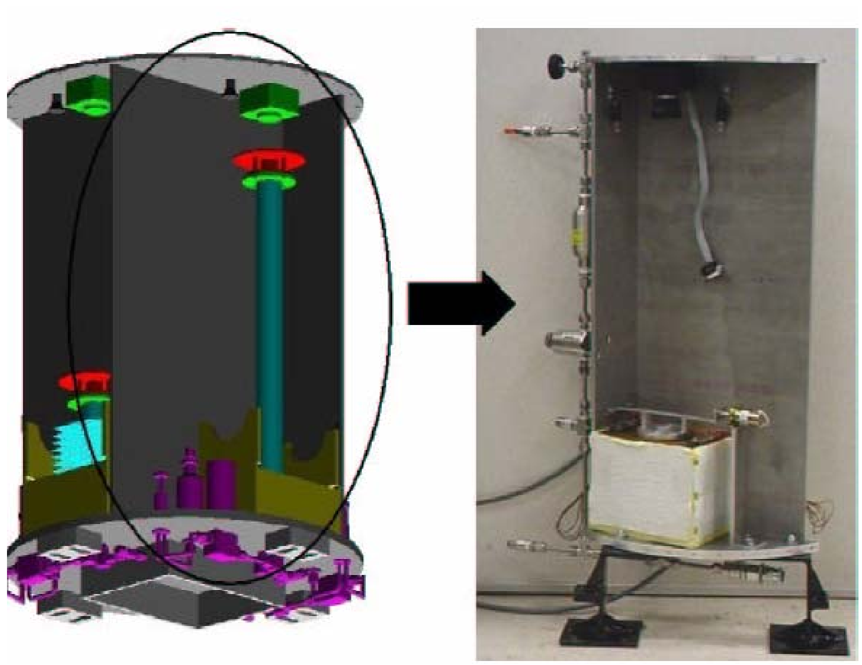


Figure 21. Heating Test Setup (21)

Previous thesis work recorded some data on the heating characteristics of the heater box and the tubes themselves (21). This information was enough to identify that there was a significant difference in heating rates, but did not identify specific areas and how they would behave. There were several reasons why the information gained in this early experiment was insufficient for current purposes. The two main reasons are addressed below.

First, temperature data was taken on the heater surfaces, on the tube end caps, and on the tubes themselves. These measurements did not include exact placement of thermocouples nor did they include multiple thermocouples on the tubes themselves.

Second, the power source used to drive the heater box was not representative of the flight power source. This power supply only provided a maximum voltage of 24V whereas the flight power supply would be 30V. This caused uncertainty in how long the actual heating process would take.

The current experiment addressed these areas in order to gain insight into the differential heating process across the tube as well as an expected timeframe for the tube to reach transition temperature.

In order to gain data on the heating differential across the tube, six thermocouple locations were chosen as representative of likely spots where heating would be the slowest. Most of these locations, depicted below in Figure 22, were chosen because they were on the inside of each bend in the folded tubes.

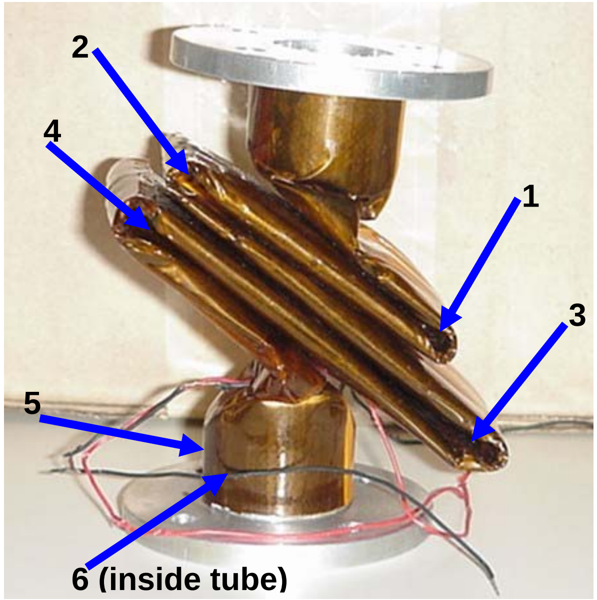


Figure 22. Locations of Thermocouples for Heating Tests

These locations are the most protected from direct transmission of heat through radiation and must be heated through conduction from other parts of the tube that have faces incident to the radiant heaters. Added to these is a thermocouple located on the inside of the tube, labeled #6 in Figure 22, to test the heating gradient between the inner and outer surfaces of the tube material. Figure 22 shows that fold #2 is partially protected from side heaters by fold #4 and is partially protected from direct heat from the top heaters by the top end cap. This protection from direct heating is the reason that fold #2 heats at a slower rate than other areas of the tube.

Convection from air and conduction through air were also a concern, but will be shown in subsequent vacuum tests to have had little effect on the heating process.

The test was conducted using the procedures in Table 8 and the results were recorded using LabView. They were then imported to and analyzed with a spreadsheet program. Figure 23, shows the results of the first test in the ambient air condition.

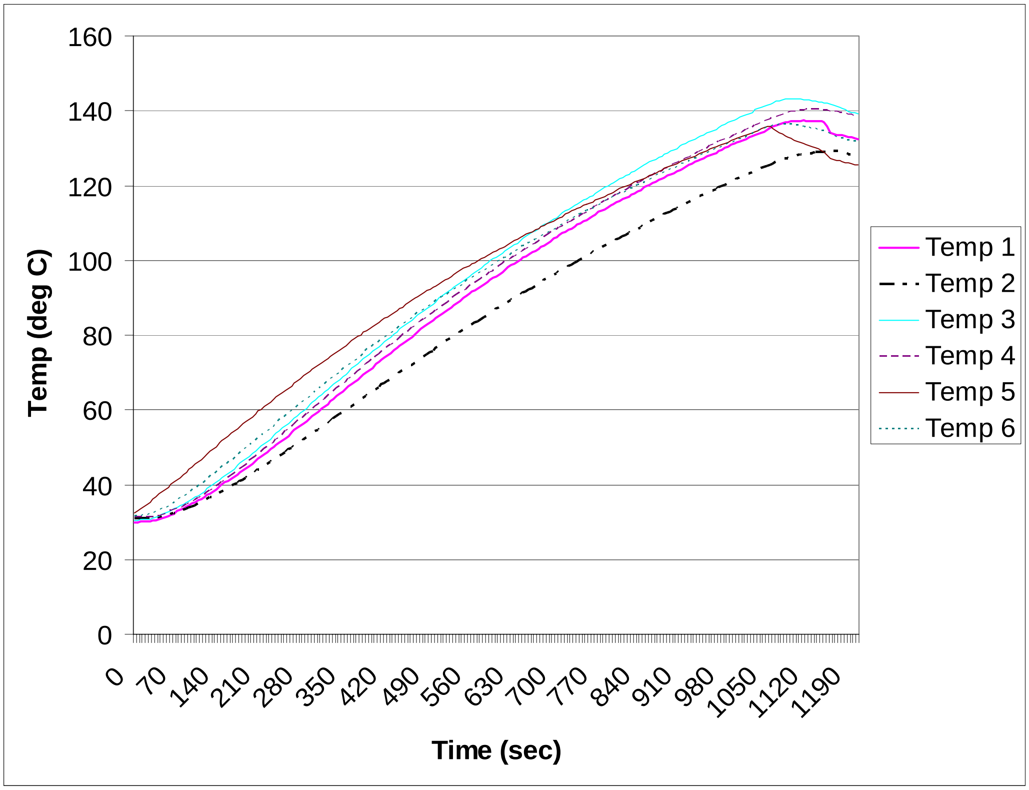


Figure 23. Ambient Air Heating Test Results

These results seem to indicate temperature #2, the temperature in the second fold of the tube, to be the slowest to heat. Subsequent testing confirmed this assumption and identified this location as the location of interest and the location at which tube temperature should be monitored during the actual flight experiment.

It makes sense that this location would be the slowest to heat. Due to the location of the radiant heaters in the heater box, the location of thermocouple #2 is the most protected from a heat source. This protection is both in distance from the heat sources as well as incident heat being blocked by other parts of the tube.

Subsequent testing showed very strong correlation to these test data and served to verify the validity of this first test. A second test, conducted from the same starting ambient air temperature, reached the transition temperature at thermocouple #2 within five seconds of the same event from the first test. The isolated results from thermocouple #2 can be seen in Figure 24 below.

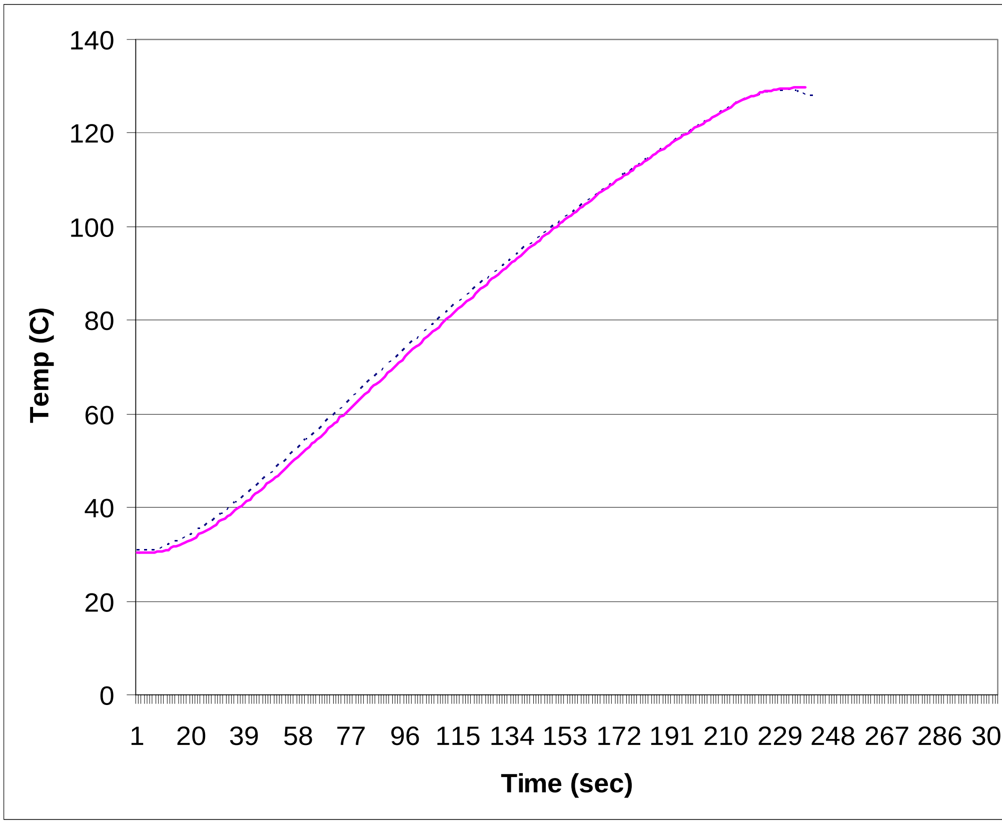


Figure 24. Repetitive Temperature Curves From Separate Heating Tests

As starting temperatures changed, the time it took to achieve transition temperature also changed, but the results were consistent in indicating location #2 as the slowest heating location on the tube.

This test may have been lacking in direct correlation to actual flight since it was conducted in an ambient condition and not in vacuum as the final experiment will be conducted. To verify our lessons from this test, the next step was to conduct similar tests inside a vacuum chamber.

The set up for this test was much the same as the previous heating test. The structural housing, power supply, and thermocouple monitors were the same. The main difference was that the test structure was mounted inverted inside a vacuum chamber.

This test was conducted using the procedures from Table 10. The results from this series showed some difference from the ambient tests, but still identified location #2 as the slowest heating location on the tubes. Overall temperature readings for location #2 varied as much as 13% across the entire heating profile, but reached transition temperature within 30 seconds of the ambient testing time. Given the overall time of approximately 850 seconds, the change represented only a 3.5% increase in time to heat in a vacuum. A comparison of location #2 for ambient and vacuum heating can be seen in Figure 25 below.

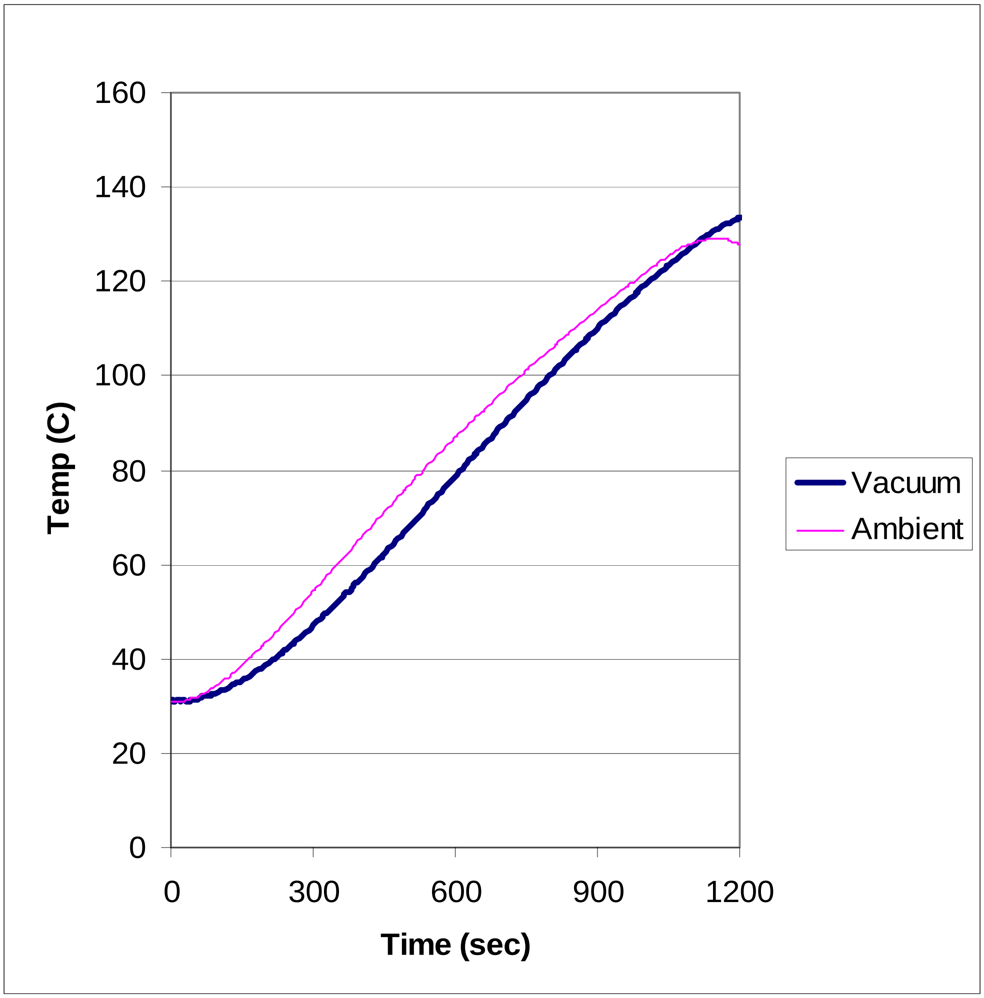
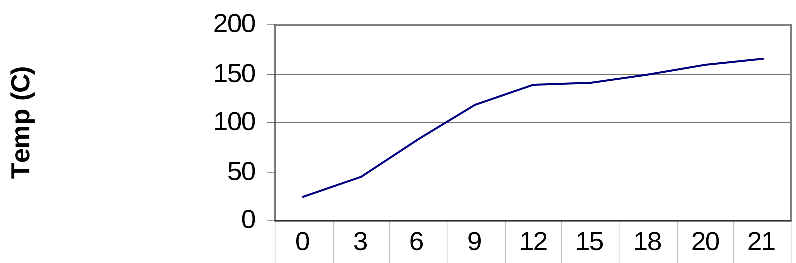


Figure 25. Vacuum vs. Ambient Heating Comparison

Because of the small difference in heating time, and the agreement under vacuum that location #2 heated slowest, further vacuum testing was considered to be of limited use. This conclusion is welcome since testing on the final flight article would require a much larger vacuum chamber than is currently available.

Heat Tolerance Test for PZT Patch Bonding Material and Adhesive

This test showed that the PZT bonding agent still functions properly after exceeding its design heating limit. In order to show this, a tube with PZT patches installed went through a three step process. First, the tube was vibrated to determine the functionality of the PZT patches and the response of the tube itself. Second, the tube was heated to a point representative of the tube manufacture process. The heating profile that was applied is shown in Figure 26.



Time (min)	0	3	6	9	12	15	18	20	21
Temp (deg C)	24	46	84	118	138	140	150	160	164

Figure 26. PZT Heating Profile

Third, the tube was vibrated once again for comparison with the initial test. Results of this test showed no degradation in the performance of the PZT patches due to the application of excessive heat. This test was considered a success and no changes were made to the PZT installation process.

Inflation Tests

Inflation of the tubes is the second critical function of the RIGEX experiment. Inflation includes storing pressurized gas prior to and during the mission. It also includes the actual functioning of the inflation system and deployment of the tubes. Failure of the inflation system to work properly could result in mission failure. The originally tested inflation system is shown in the Figure below. Where the labels on the picture represent the following:

A) Valve

B) Pressure Cylinder

C) Pressure Regulator

D) Solenoid Valve

E) Pressure Relief Valve

F) Pressure Sensor

G) Pressure Sensor

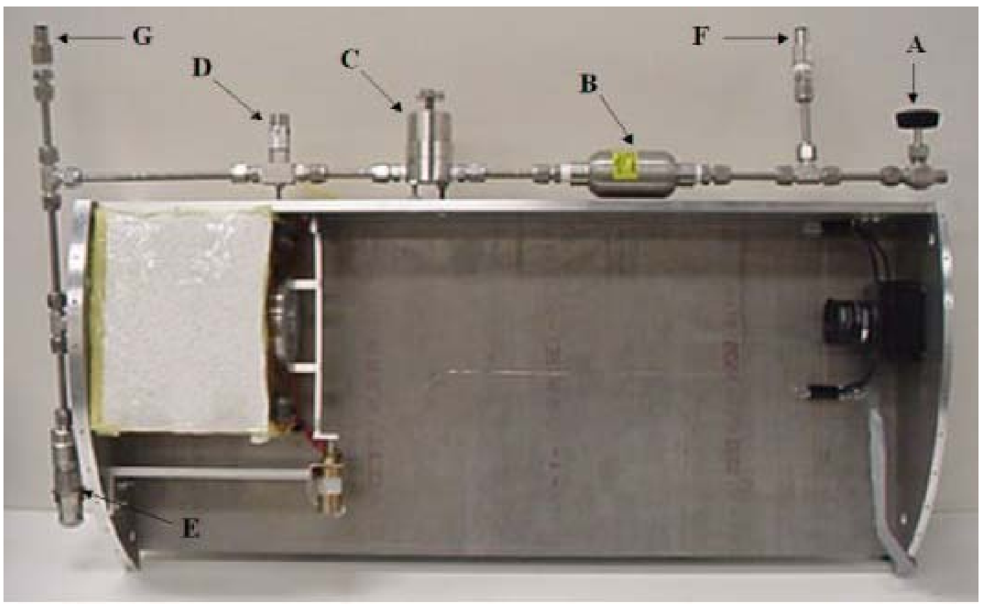


Figure 27. Initial Inflation System Layout (21)

This arrangement worked well for the ¼ test model but would not fit into the actual flight article. In the flight article, the entire inflation system must be contained within and underneath the three experiment bays and the computer bay. Because of this the inflation system was modified to fit internally either in the computer bay or in the bay with the experiment and pass through the base plate. The schematic for the inflation system is shown below in Figure 28. This reflects some changes from the old system other than the placement of the items. The solenoid now in use is a 2-way valve that will allow pressure to vent backward once it is turned off. This eliminates the need for the pressure relief valve.

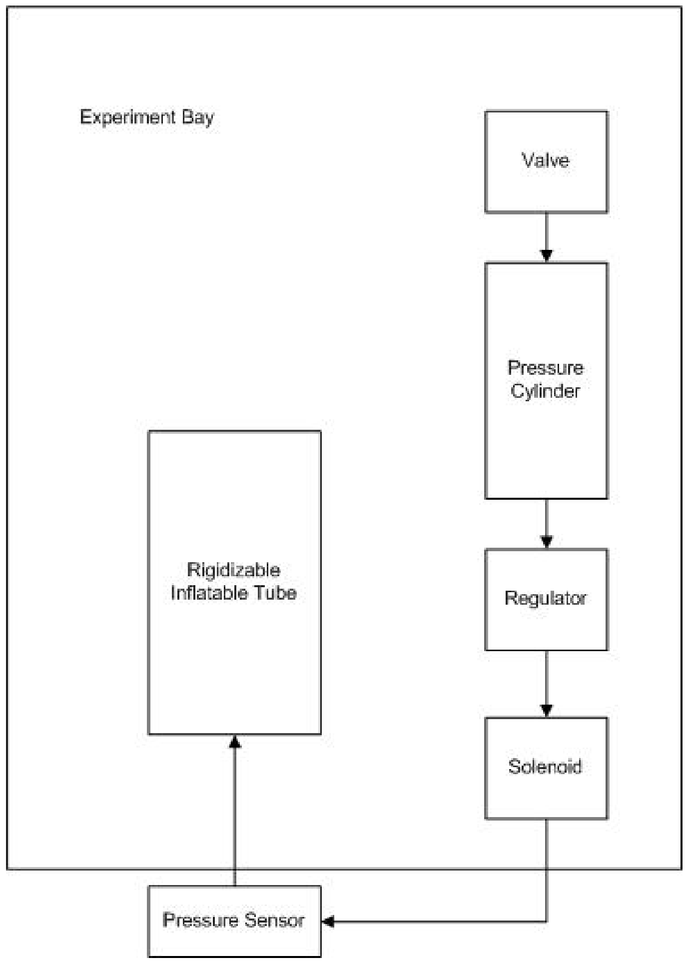


Figure 28. RIGEX Inflation System Schematic

Figure 29 below depicts the single bay inflation test setup. Power was provided by a non-flight external power supply. Temperature at the key fold in the tube was monitored during inflation in order to judge when transition temperature had been achieved across the entire tube. Pressure was monitored via a pressure sensor attached to an external, non-flight monitor. The conduct of this inflation test was recorded using digital video media.

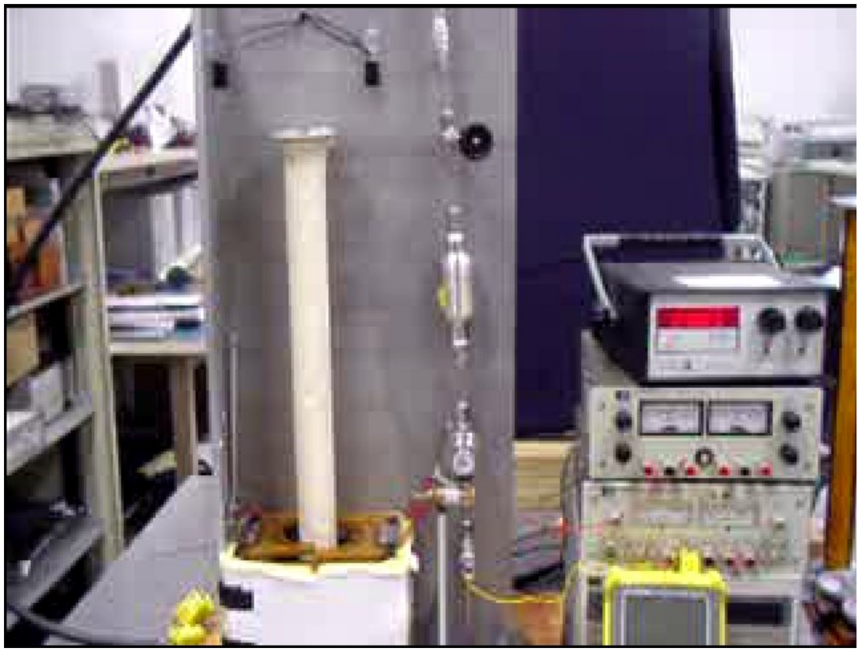


Figure 29. Single Bay Inflation Test Setup

Inflation tests were conducted using actual rigidizable inflatable tubes in some cases, but due to the limited availability and relatively high cost of these tubes, variations of the inflation were conducted with a flexible cloth tube in order to study deployment dynamics. Results of one of the dynamics tests are depicted in Figure 30 in the time phased photographs of a tube deployment.

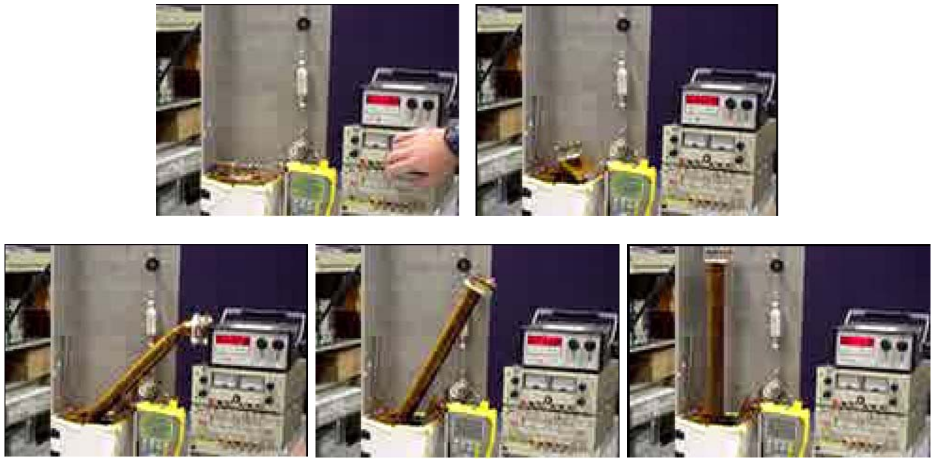


Figure 30. Time Phased Inflation

These tests identified basic behaviors of inflating tubes, plus identified key areas of interference where tubes could be caught during inflation and not allowed to fully deploy. Having the inflation system plumbing in the same bay as the inflating tube presents many opportunities for interference with proper inflation. Tube end caps often caught on plumbing hardware and were unable to fully inflate afterward. This interference is shown in frame 4 of Figure 30. For this reason, inflation system tubing and hardware has been moved out of the experiment bays and into the computer bay with only necessary tubing leading from that bay to the base of the tubes. The routing of the tubes in the inflation system is shown in Figure 29 below.

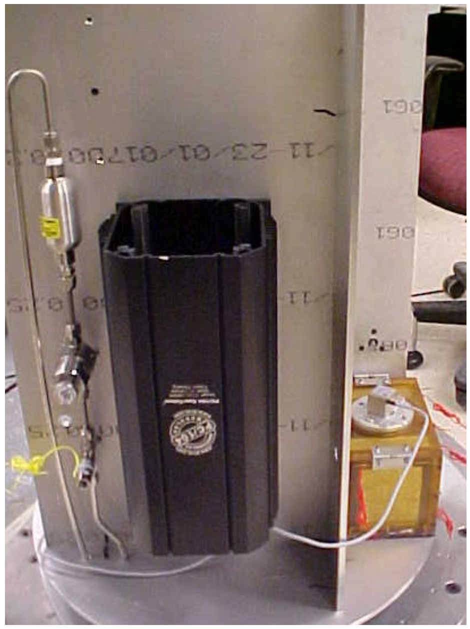


Figure 31. Inflation System Tubing Routing

Inflation Pressure Retention Test

Inflation pressure retention is a key factor in the success of the RIGEX mission. It is imperative to maintain sufficient pressure for at least 7 days in order to successfully inflate the rigidizable tubes. The test hardware used to verify retention is shown below in Figure 32. Pressure readings were taken at 4-24 hour intervals and recoded to a database. The data were then curve fit using an exponential distribution curve and plotted to show the expected pressure loss over time.

Figure 32. Pressure Retention Test Hardware

A major difficulty in testing the pressure retention of the inflation system is the interference of the test itself. In order to test the pressure, we must introduce a pressure sensor into the system. This is shown below in Figure 33.

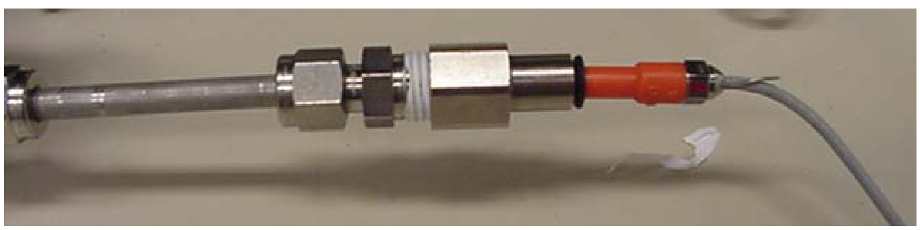


Figure 33. Pressure Sensor

Each time pressure is tested, this section of the inflation system must fill with air in order to be recorded. This means that every time the system is checked for pressure maintenance, air is allowed to leak out into the testing section. This makes an accurate characterization of the inflation system difficult.

To account for the pressure lost during testing, this pressure loss was characterized as well. Pressure was measured in a fully charged system and then the system was resealed. Pressure was then immediately measured again. Any pressure loss between these measurements can be attributed to losses due to observation and not losses due to normal leakage. This sequence was repeated until most of the pressure in the system was lost in order to develop a profile of how much pressure is lost during observation. The results of this testing are shown below in Figure 34.

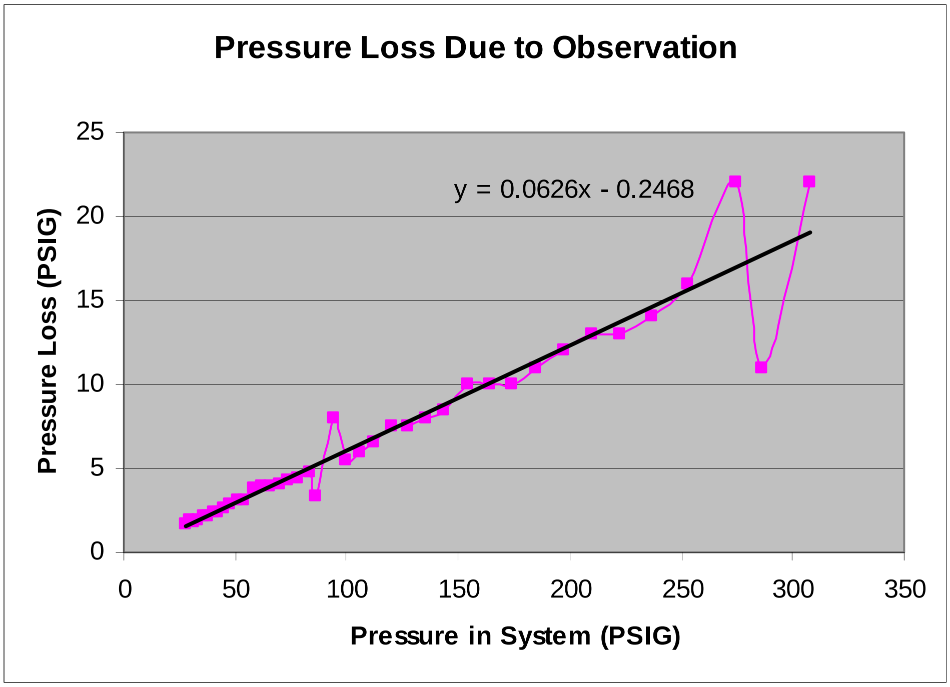


Figure 34. Pressure Loss Due to Observation

As expected, pressure loss due to testing decreased as total pressure in the system decreased. This was expected since higher pressure in the testing section would allow a larger mass of air to enter the testing section. After the test, that section is vented and the air inside is lost. Higher pressures directly relate to higher masses of air lost. The large variations in the high pressure portion of this curve are due to the high pressure in the system, the relatively high leak rate of the testing setup itself, and the amount of time the pressure sensor takes to level of at actual pressure.

The observations recorded were tabulated and graphed in the figure above. These data were then trended with a straight line approximation,

$$y = 0.0636x - 0.2468 \tag{4}$$

This approximation had an R^2 value of

$$R^2 = 0.916$$

signifying good agreement between the actual data and the trendline.

This equation was then applied in the actual measurements of the system to adjust for test losses and determine losses due solely to system leakage. Measurements were taken at various times between 4 and 24 hours for up to 5 days. These raw measurements are shown in the table below.

Table 11. Long Term Pressure Retention Data

Time (days)	Pressure (PSIG)
0	350
0.69	235
0.88	217
1.93	202
3.28	188
3.39	177
4.18	166

These data were adjusted using expected losses due to observation to show us a profile of pressure losses due solely to leakage. This information is shown in the figure below. The corrected data was then used to predict future leak behavior of the system over several days.

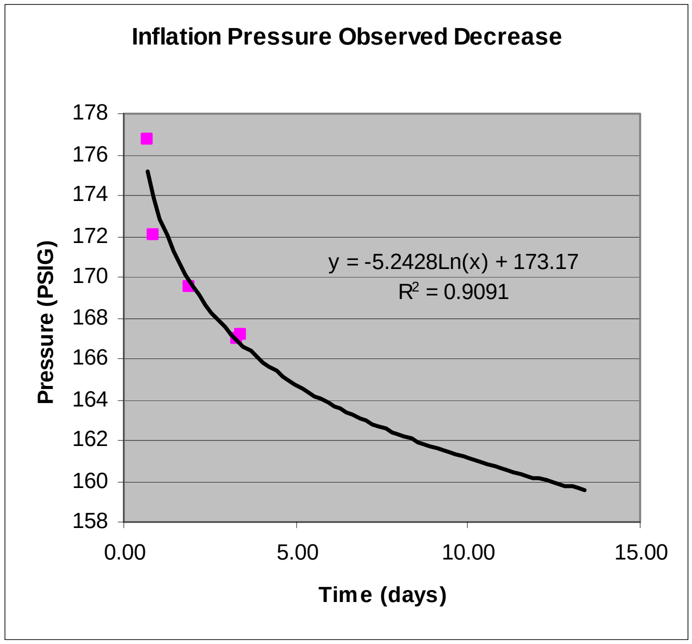


Figure 35. Inflation Pressure Observed Decrease

This data was curve fitted using a logarithmic distribution. This curve fit the data with an R^2 value of

$$R^2 = 0.9091$$

showing very good agreement with data. This exponential equation,

$$y = -5.24Ln(x) + 173.17 \tag{5}$$

was then used to estimate pressure at distinct points in time.

Since the overall objective of the inflation system is to maintain sufficient pressure to inflate the rigidizable tubes in space after 7 days, the expected pressure value was calculated at 7 days to be 163psig. This exceeds the required pressure of 32.3psig by 500%. The estimated leak rate for this system is

$$y = -5.24Ln(x) \tag{6}$$

This shows a slow leak rate once the pressure decreases to <200psig. At this predicted rate, sufficient pressure to achieve mission success would remain in the system for well over even the 90 days that may be required between system charge and launch.

This estimated retained value exceeds the minimum required by a significant amount. These results demonstrate that a pressure system similar to that designed for RIGEX is capable of retaining the requisite amount of pressure for sufficient time. Suggestions for further improving the pressure retention of the RIGEX pressure system are proposed in Chapter V.

Summary

This chapter detailed the tests used to characterize the main risk areas of the RIGEX experiment: heating and inflation. These tests were successful in gaining and understanding of these critical areas of the RIGEX mission.

Heating was determined to be variable across the area of the tubes themselves, but consistent at specific locations. These results allow RIGEX to monitor heating at only one location in order to determine when the entire tube has exceeded transition temperature. This finding significantly simplifies the tube thermal sensing by requiring only one sensor.

Heating results in vacuum were only slightly different than results in the ambient air environment. These results rendered further testing in vacuum unnecessary. This was a welcome conclusion due to the difficult nature and lack of easy accessibility when working inside a vacuum chamber.

A sequence of inflation tests improved our understanding of inflation dynamics and the working of the entire self-contained inflation system. These tests identified several points of possible physical interference during inflation and prompted a change in the design of the inflation tubing layout.

Due to the nature of launch on the Space Shuttle, long periods of time may be required for the inflation system to delay without recharge. Inflation pressure retention testing shows the capabilities and limitations of the inflation pressurization subsystem design. Required capability is estimated to be achievable using the pressure retention systems as designed.

While the testing performed was very successful in meeting its objectives, the complete system, including all three tubes, on-board power and on-board computer has not yet been tested in an end-to-end fashion. Recommendations for future work on RIGEX are discussed in Chapter V.

V. Conclusions and Recommendations

Chapter Overview

This chapter will address the overall conclusions of the current RIGEX research and its implications. This chapter will also provide recommendations to continue research on the RIGEX system and RIGEX concept.

Conclusions of Research

The primary objective of this thesis was to produce functional hardware suitable for flight that can be used to accomplish the items in the RIGEX Concept of Operations. A set of hardware for a single experiment bay, including the pressurization system has been produced. This hardware is fully flight ready and is expected to be used as actual flight hardware in the future.

Secondary objectives were to reduce mission risk by gaining sufficient understanding of the heating, pressurization and inflation systems of the RIGEX experiment in order to avoid mission failure. Research into characterizing the heating system has successfully accomplished this goal by recording and describing the heating profile over the surface of the inflatable tubes. Characterization of the inflation system has been successful in identifying possible interference problems, exercising the inflation subsystems and characterizing inflation pressure loss profiles.

Success of these secondary objectives has been achieved and is made explicit in the conclusions from Chapters III and IV of this document.

Significance of Research

The research contained in this thesis is a significant continuation of work done in previous RIGEX theses. Specifically, this thesis has characterized the heating, pressurization and inflation systems to the point where they can be used in a flight vehicle with little risk of failure. Prior to this thesis, none of these subsystems were well enough understood, designed or tested to provide confidence during operational use.

Overall success of RIGEX could lead to dramatic increases in the relative value of space launches. A 50% reduction in weight alone would lead to $145 million on a single launch of a heavy EELV at $10,000 per pound. Aside from the dramatic cost savings, more widespread use of inflatable rigidizable technology in space could drastically increase space based capabilities well beyond that currently attainable with mechanically deployable systems.

Recommendations for Future Research

This section details areas for further study and areas for improvement in the RIGEX system. These recommendations focus on the experiment subsystem of RIGEX and exclude recommendations for improvement or further study of the command and control, power, or structural subsystems as they are being addressed in separate thesis work.

End-to-End Testing for All Three Experiments

Further ground testing is needed for confidence in the overall functionality of the RIGEX experiment. While testing was conducted on a full scale model, some aspects of the testing were not representative of the flight vehicle. While an acceptable power supply was used for the end-to-end test, flight conditions would be better simulated using actual flight hardware batteries installed in the RIGEX structure. Also, during the end-to-end testing, only one tube was inflated. This was reasonable given the constraints on number of tubes available for testing, but the full sequence of inflations should be attempted prior to experiment launch.

Increase Pressure Retention Efficiency

While the pressure of the inflation system has been tested for a 1 week period, there is a possibility of up to a 90 day delay on the pad before mission launch. Further study should be conducted into the pressurization system to ensure sufficient pressure can be maintained during a long delay. Insufficient pressure in the inflation system could lead to RIGEX mission failure.

One possible way to reduce pressure loss in the system would be to decrease the number of possible leak points. The current system allows for 18 possible points for air to escape the pressurized system. This number could be greatly reduced through two steps.

1. Incorporate a solenoid that is rated to deal with the 400psi directly from the pressure vessel without first going through the regulator. This would allow the regulator to move from the pressurized section of the system into the non-pressurized section. This would eliminate 5 possible points of leakage.
2. Connect components directly together when possible in lieu of using tubing to connect them. This would eliminate the swaged ends of the tubing connections and again reduce possible leakage points by 4-8.

These two improvements alone could drastically increase the amount of time the system is able to maintain pressure.

A final improvement for the inflation system would be 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. A pressurized volume of $9.77in^3$ is required in order to fully inflate a single tube while providing 4psi of internal pressure. In this case, or in the case of a larger pressure vessel, charging of the system prior to launch may not be necessary. RIGEX is an important step toward making these uses of inflatable rigidizable technology into viable missions.

Summary

As requirements drive up the size of space assets, inflatable technology will become more and more in demand. There are several past and current applications for inflatable and inflatable rigidizable structures. Some of these applications have become operational and many are still being designed and built. The data gained from RIGEX has applications in improving the understanding of how inflatable rigidizable structures behave in space. This will allow some future testing to be done prior to mission launch and ultimately will result in higher confidence in inflatable missions and wider use of inflatable technology in space applications.

In conclusion, RIGEX is an excellent opportunity for AFIT and the entire inflatable space structures community. It will provide valuable data on the differences and similarities between ground and space behaviors of inflatable tube structures. These data can be used to validate current and future analytical models or could be used to develop ground testing that would be more representative of the space environment. The DoD Space Experiment Review Board community has agreed with the importance of RIGEX enough to consider it worthwhile. The knowledge gained from a RIGEX mission will prove useful to both the government and commercial space industry.

Appendix A. System Weight Tabulations

The weights for system components were estimated as part of the original thesis work on RIGEX (12). This appendix updates those values to reflect actual hardware when possible. Changes in the final structure have eliminated the need for battery boxes.

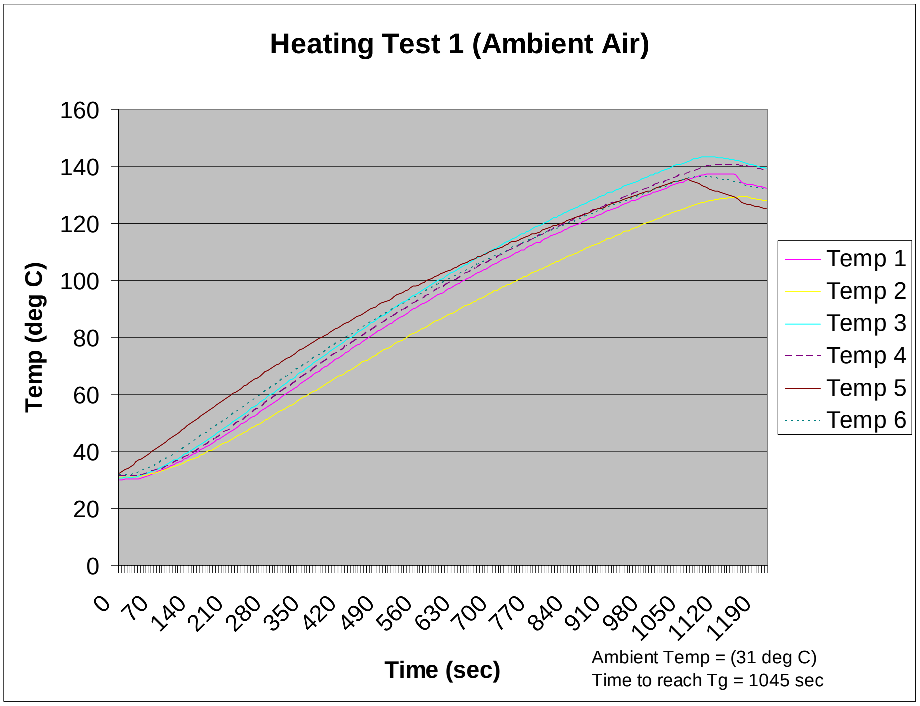
Table 12. System Weights

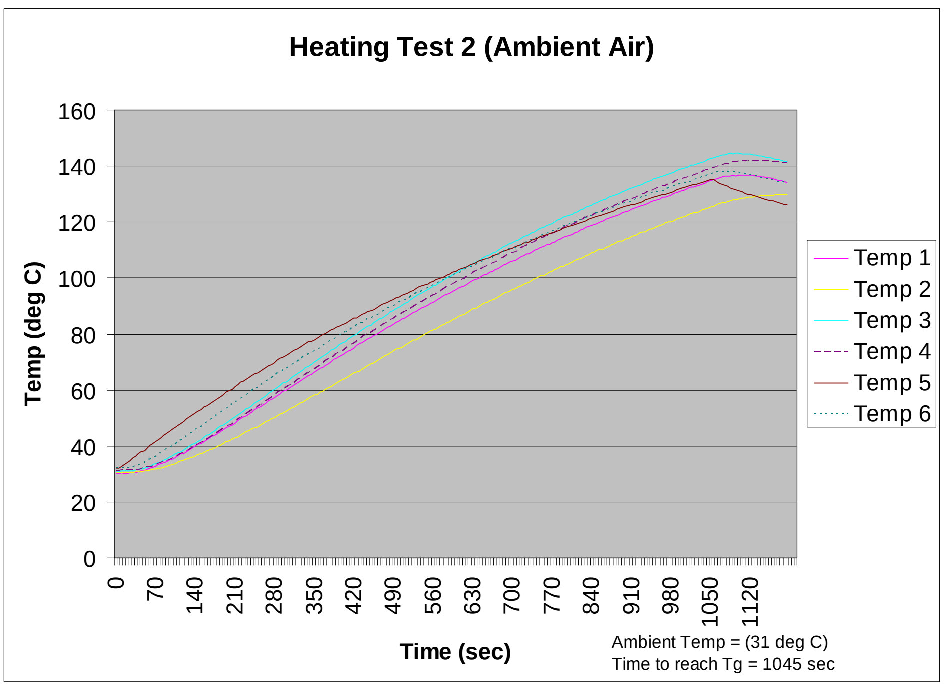
Item	Weight (lbs)	Quantity	Total
Structure	45.00	1.00	45.00
Battery Cell	13.67	4.00	54.68
Battery Box	n/a	1.00	n/a
Computer	1.28	2.00	2.55
Sensors	**2.48**	-	**2.48**
Heaters	**1.00**	-	**1.00**
Oven	**4.25**	3.00	**12.75**
Tubes	0.53	3.00	1.58
Inflation System	1.98	3.00	5.95
Video	**0.75**	3.00	**2.25**
Wiring	**10.00**	-	**10.00**
	Grand Total		138.25

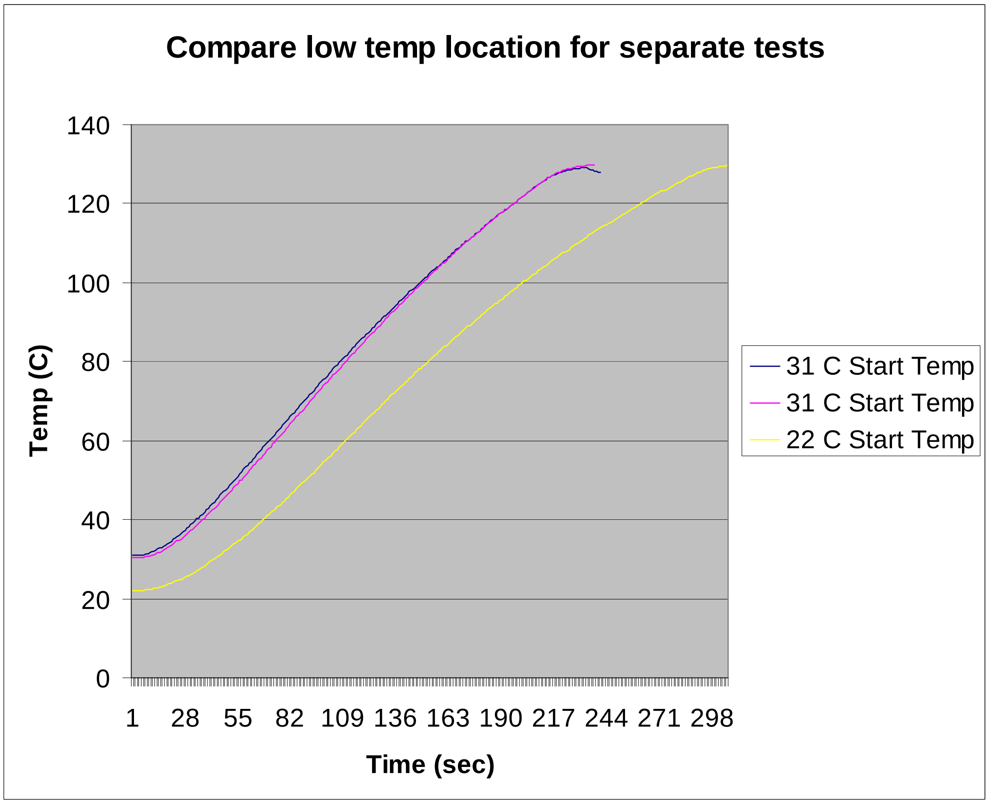
Items listed in bold are estimates.

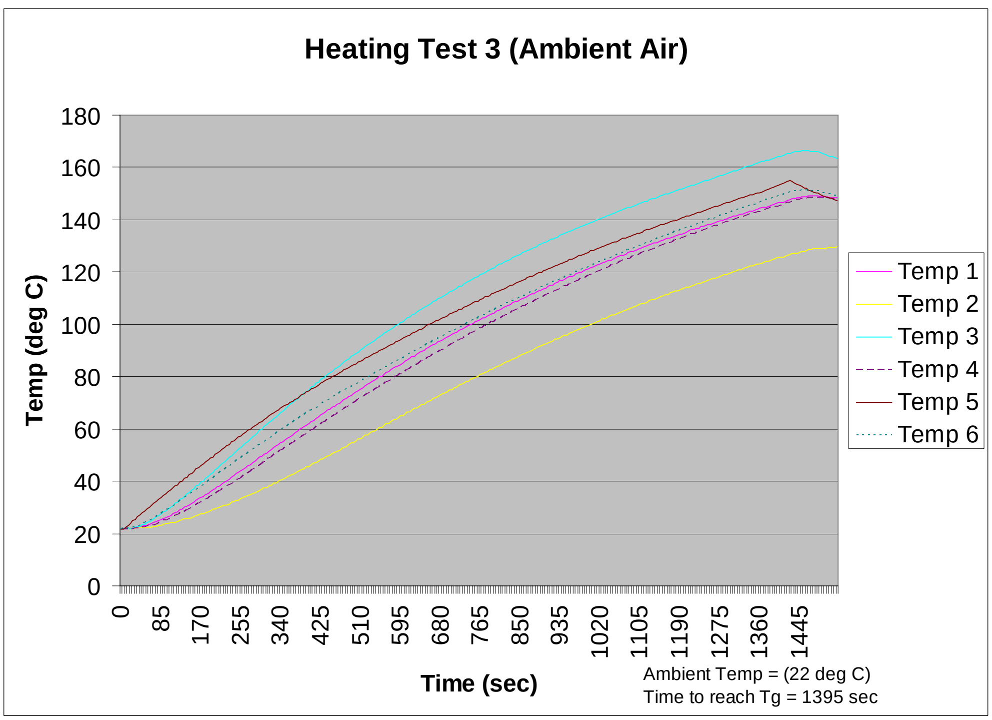
Appendix B. Heating Test Results

C.1 Ambient Air Heating Test Results

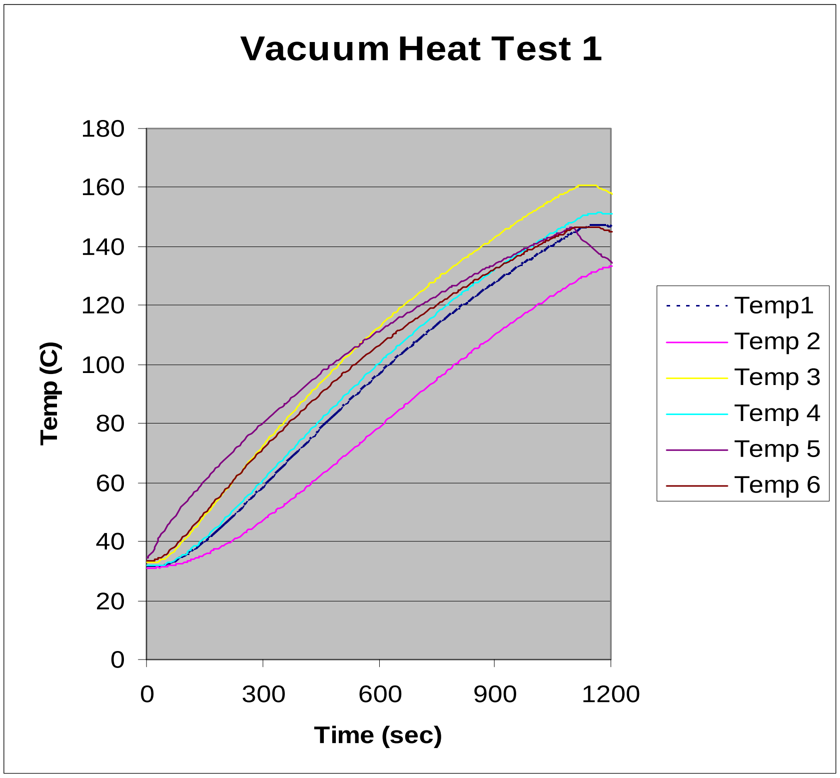




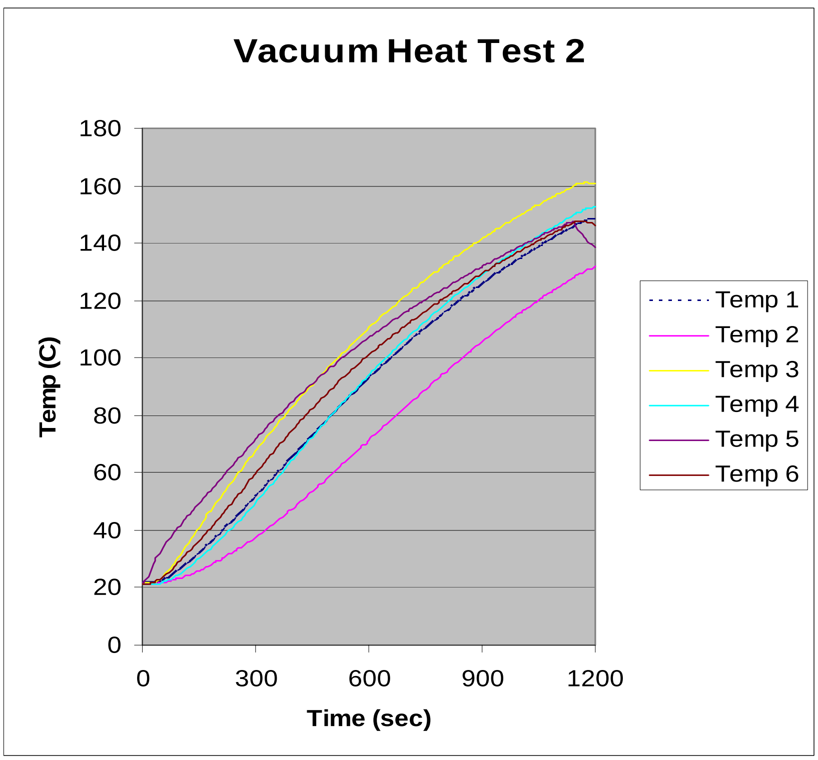




C.2 Vacuum Heating Test Results



Vacuum Heat Test 1
Temp (C)
180
160
140
120
100
80
60
40
20
0
0
300
600
900
1200
Time (sec)
Temp1
Temp 2
Temp 3
Temp 4
Temp 5
Temp 6



Vacuum Heat Test 2
Temp (C)
180
160
140
120
100
80
60
40
20
0
0
300
600
900
1200
Time (sec)
Temp 1
Temp 2
Temp 3
Temp 4
Temp 5
Temp 6

Appendix C. Inflation Test Results

Appendix D. Success Criteria

Parameter	Complete Success	Marginal Success	Unsuccessful
Heating	Correct design temp level achieved	Transition temp level achieve, but below expected	Transition temperature never achieved
Pressurization	Correct design pressurization profile (4psi) achieved +/- 25%	Pressure sufficient to inflate tube but outside of design bounds (+/- 25%)	Insufficient pressure to fully inflate tube, or high pressure causes failure
Tube Inflation	All tubes fully inflate	At least 1 tube fully inflates	No tube inflation (heat point not reached or inflation system malfunction)
PC/104 Computer	PC/104 computer systems correctly implement all required operating algorithms and gathers all data needed including video data.	PC/104 computer systems implement all required operating algorithms but only gathers data from some sensors and is unable to gather video data	PC/104 is unable to perform its required operation or is able to operate the experiment but fails to gather necessary data.
Power System	Provides the required amount of DC power to all onboard systems	Able to only provide enough power to run one tube experiment	Unable to provide enough power to run any of the tube experiments
Documentation	Provide written as well as visual descriptions of all designs and algorithms. Provide programming code with full comments	Provide only written descriptions of algorithms and designs. Poorly commented programming code	Poor descriptions of designs and no code at all.
Structural Design Loads	Maintain appropriate factor of safety with a 10 G load applied		
Structural Design	Reduce structure weight to 40 lbs. and maintain appropriate factor of safety with a 10 G load applied	Retain structure weight at 58 lbs. and maintain appropriate factor of safety with a 10 G load applied	Unable to meet factors of safety on yield and ultimate strength within limits of project weight
Vibration Testing	Published NASA vibrations specifications met through analysis and testing	Published NASA vibrations specifications met through testing only. Vibration analysis incomplete.	Published NASA vibrations specifications not met through either analysis or testing.
Structural Safety Documentation	Provide structural analysis/ vibration analysis & test documentation for NASA Safety review and verification.	Provide structural analysis/ vibration analysis documentation for NASA Safety review and verification. Analysis only test data not included	Structural analysis/ vibration analysis documentation incomplete. No data on vibration testing included.

Appendix E. DoD SERB Briefing Slides

Rigidizable Inflatable Get-Away-Special Experiment

RIGEX (AFIT-0301)

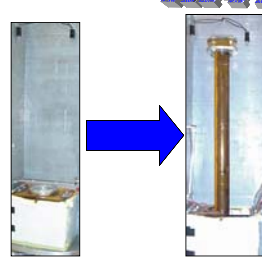
DoD SERB
4-6 Nov 03

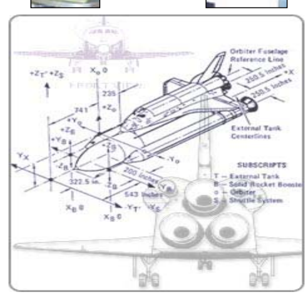
Capt Steve Lindemuth
Lt David Moody
Lt Ray Holstein
Air Force Institute of Technology

PI, Maj Rich Cobb
richard.cobb@afit.edu

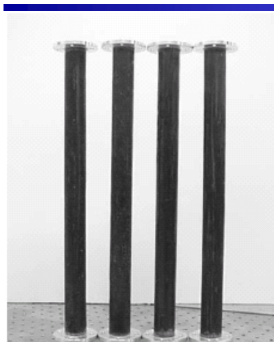
Concept

- Objective: Produce and fly experiment to collect data on inflatable rigidized structures in the space environment
- Concept:
  - Launch on Shuttle in self-contained Get-Away-Special (GAS) canister
  - Heat and inflate individual tubes
  - Cool tubes to make them structurally stiff
  - Vibrate stiffened tubes using piezoelectric patches
  - Collect data on inflation and vibe with environmental, video, and vibration sensors





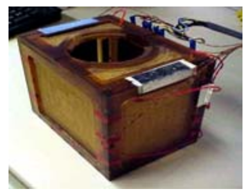
Key Components



20" GraphiteTubes

Folded Tubes

- InflatableTubes
  - Graphite/epoxy
  - Thermoset plastic
  - 125°C Transition temp
  - Excited with piezoelectric patch for characterization



Flight Oven

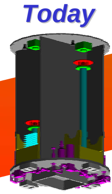
- Advantages over Mechanical Systems
  - 50% Weight
  - 75% Volume
  - 50% Engineering Cost
  - 90% Production Cost

  = Large $$$$$ Savings

Why Launch RIGEX?

- Relatively simple experiment (ready to go Mar 04)
- GAS launch economical (approx $200K) and convenient (h/w purchased)
- Data valuable in near term
- University payload

Today



RIGEX rides on shuttle

- *Gain data on deployment and vibration characteristics*
- *Compare data to ground tests and analytical models*

Tomorrow

Use data for risk reduction on upcoming missions

- *JPL/DARPA interest*
- *Possible NRO applications*

The Future

Dynamics of space inflatables are well understood

- *Imagery applications enhanced*
- *Solar sails/collectors available*
- *Wide variety of large, light-weight applications*

Military Relevancy

- Specific AF Prioritized Needs (collection resolution improved by larger apertures)
  - Any need that relies on remote monitoring and collection
    - Near Term

      #6, 7, 16, 17, 22, 23 - Collect on and monitor various events,
    - Mid Term

      #20, 21, 22, 23, 29, 30 – Collect on and monitor various events
- RIGEX data is a step toward making all types of inflatable space structures more viable
    - Large aperture sensors, large space structures, solar sails, solar power collectors, space telescopes, etc.
- Efforts currently supported by NRO and JPL
  - Letters of support as recent as Oct 03

Need For Space Test

- Correlate behavior of inflatable rigidizable structures in the space environment and on the ground
  - Record deployment characteristics
    - Deployment is critical, previous experiments have had unexpected deployment behavior (Inflatable Antenna Experiment)
    - Light weight and flexibility of materials makes zero-gravity testing essential
  - Determine modal characteristics of deployed tubes to compare with ground test results
    - Modal characteristics crucial for space antennas and other highly sensitive sensors

Test Like You Fly

History

- Some inflatables in space

ECHO I

IAE

- Some rigidizables on Earth

IRSS

IRD

RIGEX will test rigidizable inflatables in the space environment

Detailed Overview

Flight / Experiment Data

- 1 self-contained experiment sized for Shuttle GAS canister, 3 experiment replications
  - No external power
  - No specific orbital requirements
  - No pointing or stabilization requirements
  - No telemetry requirements
  - 1 day mission and return
- Volume: 141783 cc, Mass: 80.92 kg

Funding

Funding Source	Prior FY ($k)	FY03 ($k)	Future FY ($k)	Total
AFOSR	23.8			23.8
DARPA	20			20
NRO		30		30
AFIT/EN	19.2	65	30	114.2
TOTAL				188

Status

- Initial design complete, planned completion of flight article in Mar 04

Priority

- First year presented to SERB

Requested STP Services

- Launch Services and Integration

Summary of Data Application

- Air Force Institute of Technology will use the data from this experiment to validate ground testing methods for determining deployment and vibration characteristics of inflatable rigidizable structural members
- Raw and analyzed data will be made available to JPL and NRO as soon as practicable for comparison with analytic models
- Applicable category is applied research

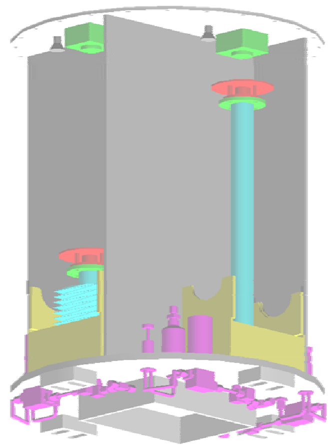
RIGEX (AFIT- 0301)
FLIGHT MODE SUITABILITY

Flight Mode	% Experiment Objectives Satisfied
Shuttle	100 %
Shuttle Deployable	0 %
Shuttle Deployable with Propulsion	0 %
International Space Station	0 %
“Piggyback” Free-flyer on ELV (GTO)	0 %
Dedicated Free-flyer on ELV (GTO)	0 %

- Value of Flight Hardware Retrieval: Absolutely necessary to retrieve this experiment since all data is collected internally (no telemetry)

Summary

- Inflatable rigidizable structures have definite potential in the future of space systems
- Could be a key technology in achieving AF and DoD future needs while lowering launch and life-cycle costs
- The data gained by RIGEX will be a stepping stone to understanding the behavior of inflatables in space and making their use more viable



RIGEX

Appendix F. System Architecture

Previous research on RIGEX identified a systems engineering approach to the experiment (12). This previous work identified the major physical areas of the RIGEX system and used classical systems engineering principles to analyze how they would best work together. This thesis will go a step further in defining a top level system Architecture for the RIGEX system.

System Architectures were developed by and for the Department of Defense in order to cope with several complications inherent in today's acquisition process. These complications include increasing uncertainty in requirements, rapidly evolving technology, major structural changes in the DoD, and the need for interoperability within the services and with coalition partners worldwide (16).

All of these issues require flexibility to address adequately. The approach used in Systems Architectures allows for maximum flexibility in system design (9).

The overall requirements of a system define its trade space. System Architectures provide a roadmap to navigate through that trade space and determine a solution space (17). This solution space infers flexibility and the ability to cope with changing requirements and changing environments.

It is Department of Defense policy that all DoD components shall develop and use architectures to support acquisition (16).

RIGEX does not fall under the category required to have a DoD architecture because of its relatively small size and complexity. Given this, a systems architecture is still useful for the RIGEX experiment in order to ensure proper connection of the various RIGEX functions as well as flexibility and longevity for the program as it progresses.

A systems architecture begins with identifying key top level functions of a systems and specifying the interactions between those functions. These functions are determined from the overall operational concept of the systems and from top level requirements. For RIGEX, this is shown in Figure 36

These top level functions are then broken into their component functions as a top-down derivation into more root level functions.

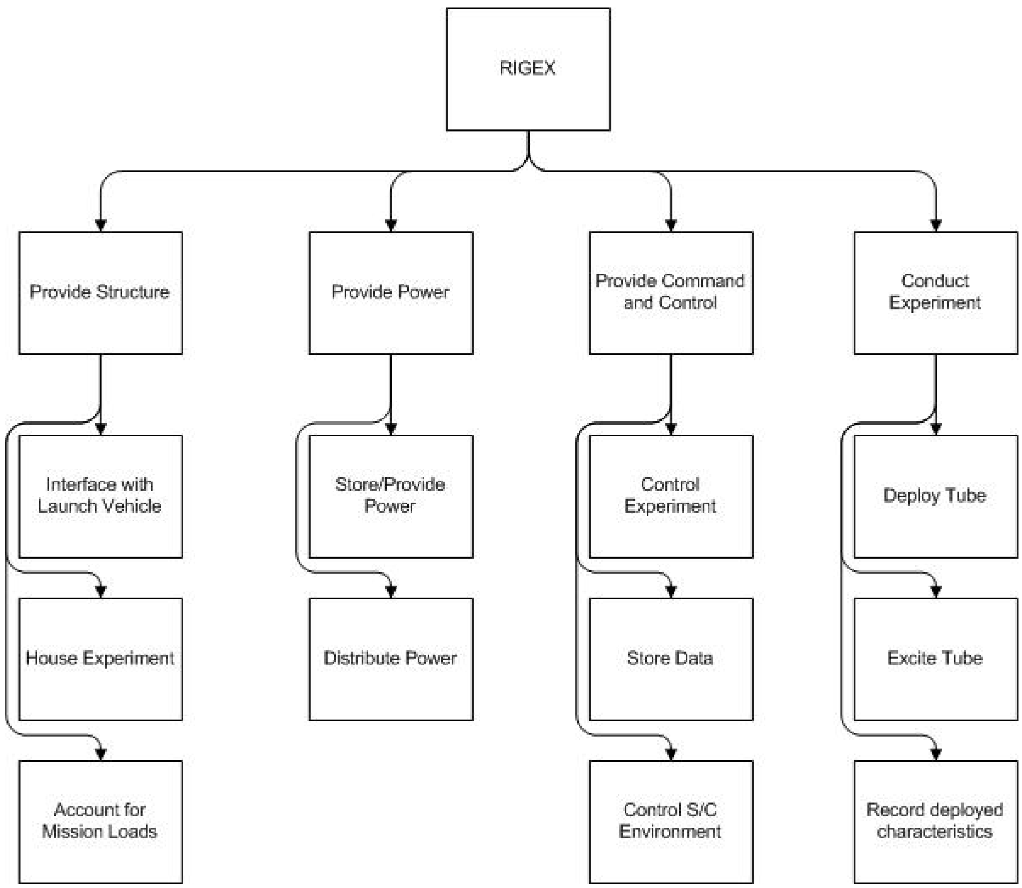


Figure 36. RIGEX Functional Hierarchy

Since further breakdown of the system architecture focuses on the transfer of information between functions, each main function will be decomposed with the exception of the "provide structure" function. This function is relatively stand alone, services all other areas, and does not have a requirement to receive or transfer information to or from the other functions. For this reason, the structure will not be included in further breakdown of the functional hierarchy for RIGEX.

The other main functions are broken down in a standard format known as IDEF0 that standardizes format for ease of use. IDEF0 was originally designed as a tool for software development (2). The IDEF0 model exposes the functions of a system through progressively more detailed layers of functions. The top two layers of key functions are shown in the following figures for RIGEX. The standard IDEF0 syntax is described in Figure 37 below.

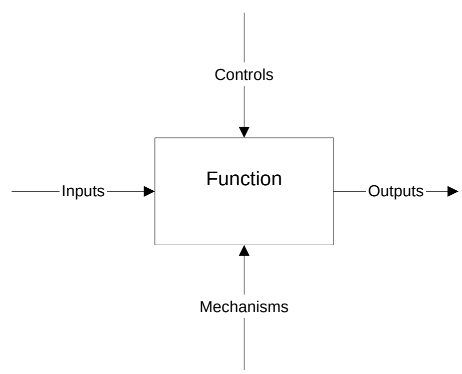


Figure 37. Basic IDEF0 Syntax

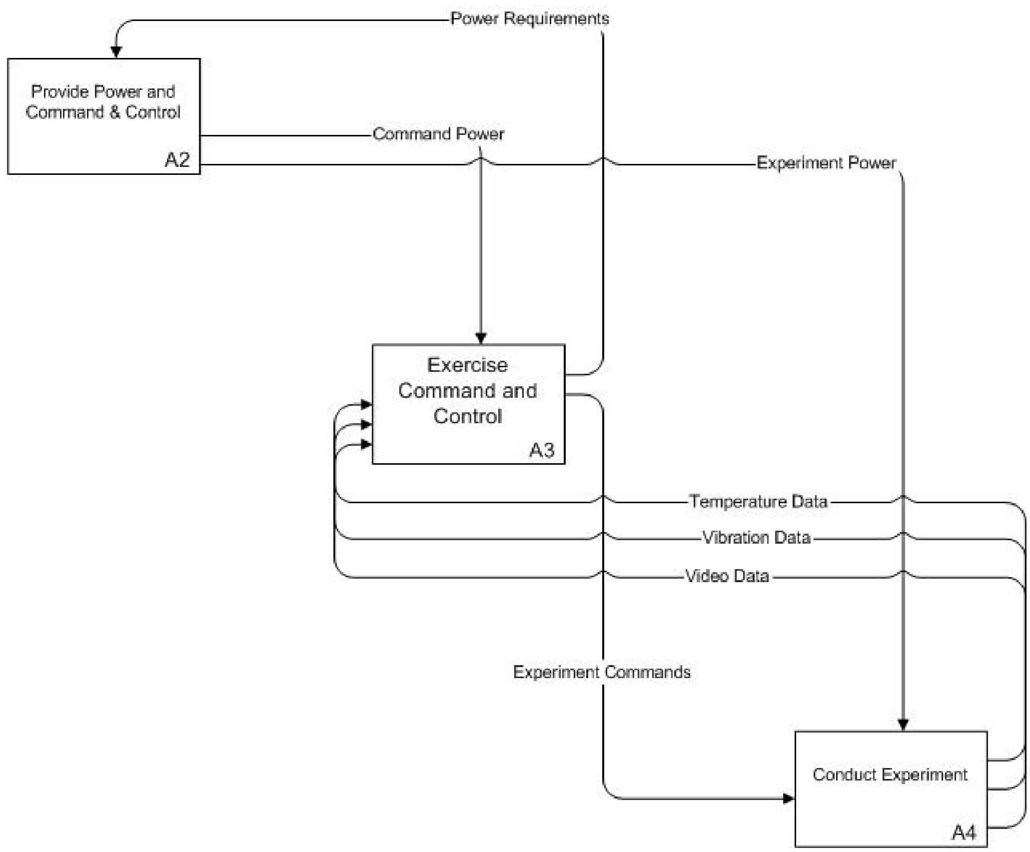


Figure 38. RIGEX A-0 Diagram

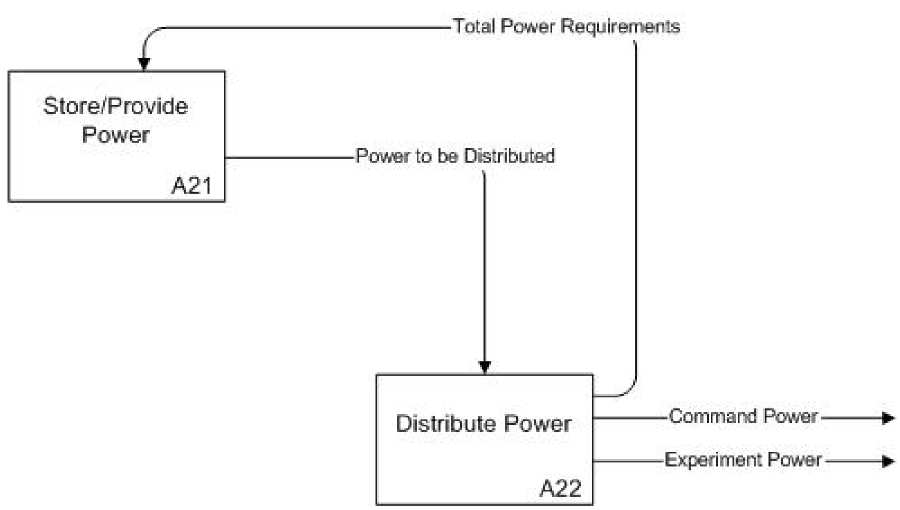


Figure 39. RIGEX A-2 Diagram

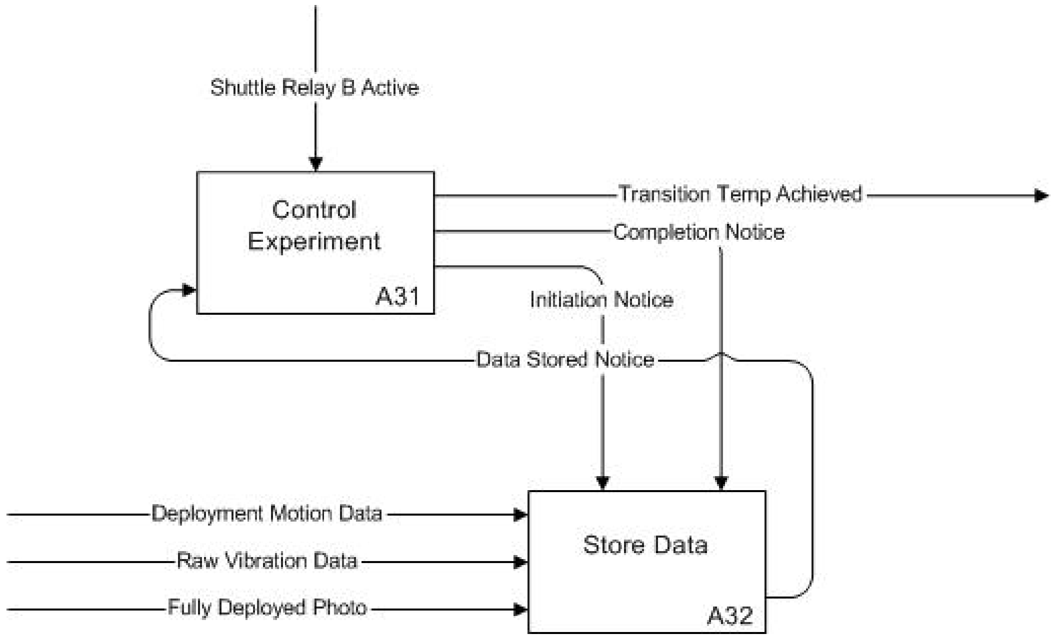


Figure 40. RIGEX A-3 Diagram

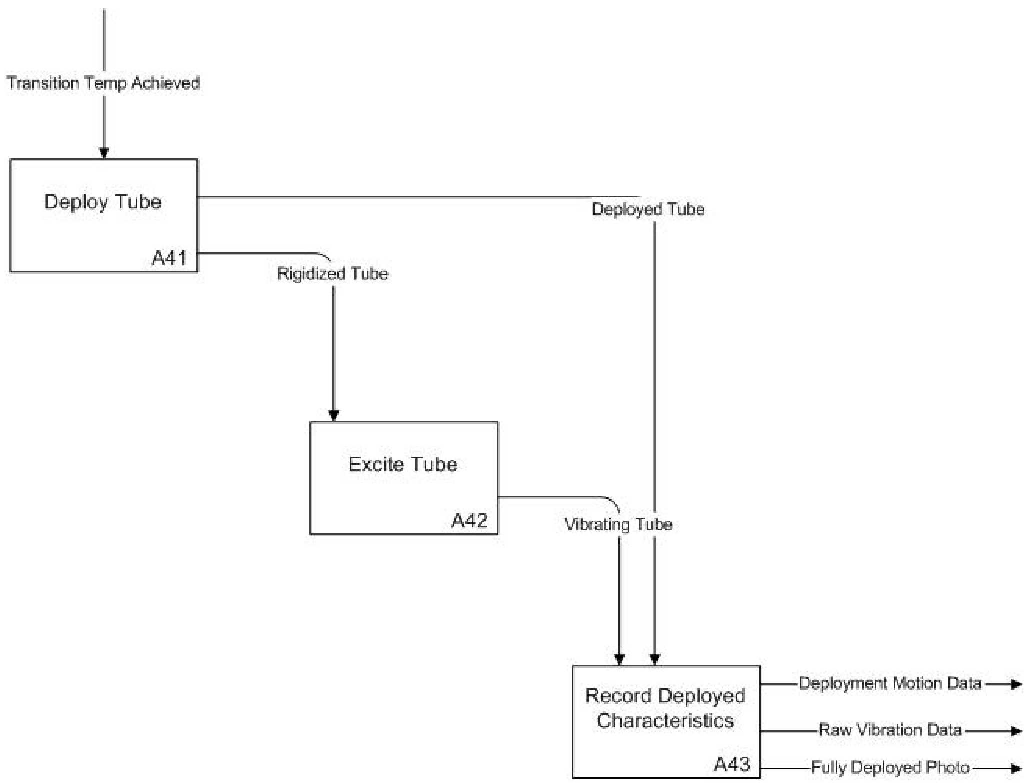


Figure 41. RIGEX A-4 Diagram

Appendix G. Updated NASA Payload Accommodations Requirements

The Payload Accommodations Requirements document is the initial step in preparing a GAS payload to launch on the Space Shuttle. It identifies the RIGEX system in general terms and addresses any possible hazards that RIGEX may pose to the Space Shuttle. A first draft of this document was accomplished as part of previous thesis work (12). This appendix is an update to the document to bring it in line with recent changes in RIGEX configuration and design.

NASA SMALL SELF-CONTAINED PAYLOAD (SSCP) PROGRAM

GET AWAY SPECIAL (GAS)

G-0321

PAYLOAD ACCOMMODATIONS REQUIREMENTS (PAR)

1.0 INTRODUCTION

This accommodation plan defines the technical agreement between NASA/Goddard Space Flight Center (GSFC) and the GAS Customer concerning the unique information needed for the preparation, flight, and disposition of this GAS payload. The general plans for handling of GAS payloads are described in the GAS Experimenter Handbook and the Payload Integration Plan (PIP) Space Transportation System and Get Away Special Carrier (NSTS-44000).

Appropriate information from this accommodation plan will be used for a GAS payload unique PIP to the GAS Carrier/STS PIP and its associated annexes.

By signing this PAR, the Customer Contact and Payload Manager hereby certify that this payload and none of its components as flown on the Shuttle shall be sold, donated, or otherwise transferred for use as a commemorative item or work of art.

2.0 PAYLOAD DESCRIPTION

2.1 Size and Weight

The experiment is contained in the 5.0 ft^3 canister and has a maximum weight of 200 pounds.

2.2 Experiment Description(s)

The purpose of the experiment is to collect data on the inflation, rigidization, and modal analysis of several rigidized inflatable tubes.

2.3 Device Description(s)

The experiment can be divided into seven subsystems: structure, power, inflatable tubes, inflation & rigidization, excitation, command and control, and sensors. The preliminary design and layout of the components and subsystems is shown in Figure 2.3-1.

The structure is made primarily of 1/4 inch aluminum that is welded at the joints. The top plate has a bolt pattern and opening for vent tubing that matches the EMP. Four lateral support bumpers are attached to the underside of the bottom plate, to allow for adjustment during the canister integration.

The center area of the structure houses the power subsystem. The power system consists of three 30V DC cells, each comprised of 20 D-size alkaline batteries. The three battery cells are diode isolated and wired through Relay A on the GCD.

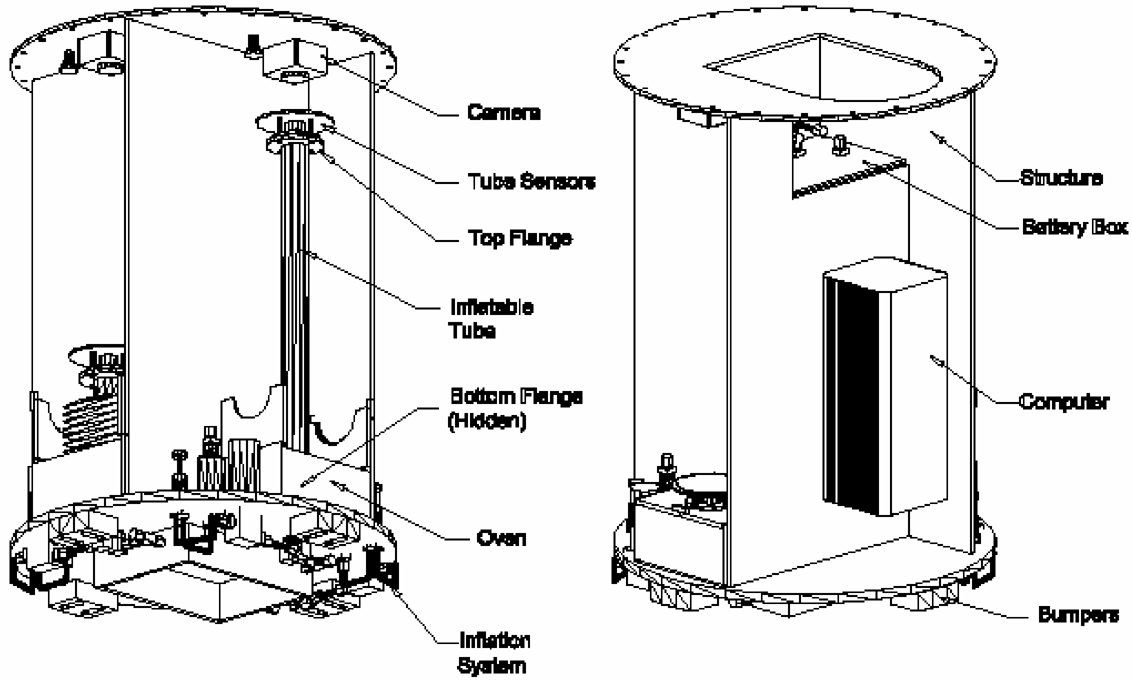


Fig 2.3-1 RIGEX Assembly

The height of the structure is divided into four equal wedge-shaped sections. Three of the sections are used for the inflatable structure assemblies. The inflatable tubes are 22 inch long and 1.375 inch diameter tubes that are flattened and accordion folded for packaging. The tubes are connected to the experiment by a flange which connects to the bottom plate. The top flange on the tube is cantilever and contains an excitation system and sensors.

The packaged tubes are stored in a thermoplastic oven, which is held closed by two retractable pins. Prior to inflation, the tube is warmed above the transition temperature by heating pads in the oven. Once the temperature reaches an adequate level, the tubes are pliable and ready for inflation.

The inflation system provides for a controlled pressurization of the tubes. A pressure cylinder releases air through a solenoid and pressure reducing valve to maintain 4 psia inside the tube. As the nitrogen expands inside the warmed tube, a relief valve regulates the pressure. After inflation, the tube begins to cool until it reaches an equilibrium with the canister. Once the tube has cooled below the transition temperature, it has rigidized and the inflation gas is vented.

To test the structural response of the rigidized tubes, a modal analysis is performed. A piezoelectric excitation device causes an arbitrary vibration in the tubes, which is monitored by an accelerometer.

The command and control of the experiment is performed by a PC/104 computer system. The computer executes an event calendar once it is activated by Relay B. All sensor data is collected by the computer during operation.

The sensors used in the experiment are divided into four categories: environmental, inflation and rigidization, modal analysis, and video. The environmental sensors collect data on the temperature of several components, the pressure inside the canister, and the voltage of the power system. The inflation and rigidization sensors collect temperature and pressure data on the inflatable tubes. The modal analysis sensors used tri-axial accelerometers on the tubes and the experiment stucture, as well as a force gauge. Finally, a digital video system is used to monitor the inflation and rigidization process.

2.4 Operational Scenario

After launch, the experiment is designed to use the baroswitch option to activate Relay A and provide power to the environmental heaters. These heaters maintain the temperature of critical components above $O_o C$ *during the flight. The filtered relief valve is used to vent the canister during ascent and repressurizes during reentry and landing.*

When Relay B is activated, the computer proceeds with control, operations, and data collection until either the event calendar is completed or the experiment is deactivated. During this time, the environmental sensors collect data on the canister temperature and pressure, as well as the battery voltage.

As the inflation and rigidization process is begun, heaters warm the inflatable above its transition temperature. Once warmed, air slowly inflates the structure, while the video sensors record the inflation. After inflation, the structure will radiate and cool until an equilibrium temperature is achieved. After the rigidization is complete, the inflation gas is vented. During the entire process, temperature, pressure, and displacement sensors will collect data.

To test the structural properties of the rigidized structure, an excitation device is placed at the cantilever end of the inflatable tube to cause vibration. During each excitation cycle, the accelerometers collect data on the modal response of the inflatable structures. Once all activities in the event calendar are complete, the computer will enter an inactive state until power is disconnected for reentry.

3.0 STANDARD SERVICES

3.1 Container Accommodations

3.1.1 Internal Atmosphere

The container will be purged with *Dry Nitrogen* and sealed at one atmosphere pressure prior to installation into the Orbiter.
AND
The container will incorporate a filtered relief valve so that it will evacuate during ascent to orbit and will repressurize during reentry and landing.

3.1.2 Insulated End Plate Cover

An insulated end plate cover with a silverized Teflon exterior coating will be installed over the container Experiment Mounting Plate (EMP) exterior.

3.1.3 Battery Box Venting

The battery box in this payload will be vented through the upper end plate via two 15 psid
pressure relief valves.

3.1.4 Baroswitch

The GAS Control Decoder (GCD) altitude switch *will* be used to turn on Relay A.

3.2 Flight Operations

3.2.1 Flight Design

NASA will identify a Shuttle flight opportunity appropriate to the following payload requirements and within the constraints of the SSCP queue.
Orbit:
Altitude *No requirement*
Inclination *No requirement*

Orientation: *No requirement*

Stabilization: *No requirement*

Other: *No requirement*

All of the above requirements that cannot be accomplished by NASA within the established plans for the identified flight will be accomplished as optional services delineated in section 4 of this document.

3.2.2 Flight Activity

The assignment of GAS Control Decoder (GCD) relay states to specific payload functions is shown in Table 3.2.2-1. The required payload crew activities during the flight are shown in Table 3.2.2-2. All relay operations beyond the first six (6) will be delineated as *optional services* in section 4 of this document.

RELAY	STATE	PAYLOAD FUNCTIONS
A	By Baroswitch HOT (H)	Power provided to environmental heaters, which maintain minimum temperature of critical components within the experiment.
	LATENT (L)	All power removed from the experiment
B	HOT (H)	Power provided to experiment computer. Computer remains active until event-calendar complete or power removed.
	LATENT (L)	Removes power supply to the computer
C	HOT (H)	Not used at this time
	LATENT (L)	Not used at this time

Table 3.2.2-1 PAYLOAD CONTROL FUNCTIONS FOR G-0321

RELAY OPERATION SEQUENCE	GCD RELAY (A,B, OR C)	STATE (TO H OR TO L)	MISSION CONDITIONS AND CONSTRAINTS
01	A	TO HOT	Baroswitch at 50,000 ft
02	B	TO HOT	At start of minimum "g" period. Less than 0.01 g's during operation
03	B	TO LATENT	Approximately 6 hrs after 02
04	A	TO LATENT	Prior to shuttle re-entry
05			
06			

Table 3.2.2-2 PAYLOAD OPERATIONS PLAN FOR G-0321

FOR A NOMINAL DURATION MISSION, THE MINIMUM ACCEPTABLE OPERATING TIME FOR THIS PAYLOAD IS *4 HOURS*.

IN THE EVENT OF AN ON-ORBIT ANOMALY, THAT RESULTS IN A SHORTENED DURATION MISSION, THE MINIMUM OPERATING TIME FOR THIS PAYLOAD IS *2 HOURS*. IF THIS TIME IS NOT ACHIEVABLE, THIS PAYLOAD WILL NOT BE ACTIVATED/WILL BE DEACTIVATED AS SOON AS POSSIBLE.

ALL GCD RELAYS WILL BE IN LATENT STATE AT LAUNCH

3.2.3 Payload Power Contactor (PPC) Malfunction Inputs

PPC Malfunction inputs will not be used.

3.3 Ground Operations Requirements

3.3.1 Storage, Handling, and Integration of Customer Hardware

PREFERRED INTEGRATION SITE:
Kennedy Space Center

MAXIMUM AND MINIMUM ALLOWED STORAGE TEMPERATURES:
30 deg C / 10 deg C

MAXIMUM AND MINIMUM ALLOWED RELATIVE HUMIDITY:
70% / 30%

CLEANLINESS REQUIREMENTS FOR PAYLOAD INTEGRATION:
Class 100,000 Clean Room

REQUIREMENTS FOR GASES OR LIQUIDS:
Pressurized air for Pressurized Cylinders

SPECIAL REQUIREMENTS FOR CUSTOMER HARDWARE HANDLING:
None

3.3.2 Payload Final Preparation

The customer plans to install the following items into his payload just prior to payload installation into the GAS flight container:

Battery Cells, Inflatable Tubes, Pressurized Gas (into storage cylinders)

3.3.3 Leak Test Levels

After payload installation, the container *will not* be pressurized for the purpose of leak testing. Pressurization of no more than 10 psig for no more than 20 hours will be permitted by the customer.

3.4 Safety

3.4.1 Inspection

Assemblies that cannot be opened and examined during safety inspection at the launch site must be sent to NASA for inspection and sealing prior to shipment of the payload. These assemblies will not be further opened by the customer prior to flight. The following assemblies fit this category *(if none, write* none*)*:
None

3.4.2 Preliminary Hazard Analysis

Figure 3.4.2-1 is the completed Payload Safety Matrix resulting from a preliminary hazard analysis on this payload. Figure 3.4.2-2 is the associated Hazard List for this payload.

PAYLOAD G-0321		PAYLOAD ORGANIZATION *Air Force Institute of Technology*				DATE *yy/mm/dd*		PAGE *1*	
		HAZARD CATEGORY							
		Collision	Contamination	Corrosion	Electrical Shock	Explosion	Fire	Temperature Extremes	Radiation
SUBSYSTEM	Inflation	X							
	Rigidization								
	Excitation								
	Electrical				X				
	Environmental Heaters							X	
	Pressure Systems					X			
	Materials								
	Mechanical								
	Structure	X							

Figure 3.4.2-1 Flight Operations

PAYLOAD G-0321		PAYLOAD ORGANIZATION *Air Force Institute of Technology*				DATE *yy/mm/dd*		PAGE *1*	
		HAZARD CATEGORY							
		Collision	Contamination	Corrosion	Electrical Shock	Explosion	Fire	Temperature Extremes	Radiation
SUBSYSTEM	Inflation								
	Rigidization								
	Excitation								
	Electrical				X				
	Environmental Heaters								
	Pressure Systems					X			
	Materials								
	Mechanical								
	Structure								

Figure 3.4.2-2 Ground Operations

GAS HAZARD DESCRIPTION – FLIGHT OPERATIONS		
PAYLOAD NUMBER & ORGANIZATION *G-0321 Air Force Institute of Technology*	SUBSYSTEM Ex: Electrical	DATE *yy/mm/dd*
HAZARD GROUP	BRIEF DESCRIPTION OF HAZARD	APPLICABLE SAFETY REQUIREMENTS
Inflation	During Inflation, the tubes will extend outward from their storage containers. The tubes will have insufficient force to breech the GAS canister	
Electrical	The battery system and power wiring will follow NASA standards and regulations.	
Environmental Heaters	The heaters used in the rigidization process will operate at approximately 150 C. The heating structure will be isolated to minimize heat transfer to the structure and the heaters will only operate for a short duration.	
Pressure System	The inflation cylinders will contain pressurized air. The cylinders are rated at 1800 psia, which is 450% greater than required. Any leaks in the pressure system will vent through the filtered relief valve.	
Structure	Failure of the structural frame. Any structural failure will be contained within the GAS canister.	

Figure 3.4.2-2 Flight Operations

GAS HAZARD DESCRIPTION – FLIGHT OPERATIONS		
PAYLOAD NUMBER & ORGANIZATION *G-0321 Air Force Institute of Technology*	SUBSYSTEM Ex: Electrical	DATE *yy/mm/dd*
HAZARD GROUP	BRIEF DESCRIPTION OF HAZARD	APPLICABLE SAFETY REQUIREMENTS
Electrical	The battery system will be installed in the experiment during integration. The battery system and power wiring will follow NASA standards and regulations.	
Pressure	The inflation cylinders will be charged to approximately 400 psia during integration. The cylinders are rated at 1800 psia, which is 450% greater than required.	

Figure 3.4.2-2 Ground Operations

3.5 Post Flight Shuttle Mission Data

GSFC will provide the customer with two types of data concerning the Shuttle mission on which this payload has flown:

a. Mission Elapsed Time (MET) for major attitude holds; with an indication when the Orbiter was pointing at the Earth, Deep Space, or the Sun.

b. Approximate time (±1min.) of GCD relay operations during the mission.

4.0 OPTIONAL SERVICES

All optional services provided by NASA will be at additional cost as negotiated between NASA and the Customer. The optional services charge for G-0321will be $0.00.

4.1 Additional Post-Flight Mission Data ***None***

4.2 Optical Window (10 lb. weight penalty) ***None***

4.3 Standard Door Assembly (SDA) (40 lb. weight penalty) ***None***

4.4 Special Launch Site Support Requirements ***None***

5.0 TECHNICAL SUPPORT SERVICES

Technical support services required by GAS users and provided by the GSFC (such as vibration testing, EMI testing, etc.) are provided at extra cost. Costs for these services are negotiated between the GSFC GAS project and the customer and are funded directly to the GSFC as a reimbursable effort.

5.1 The following items fit this category:

None at this time.

6.0 SCHEDULE

The earliest acceptable launch date for the G-0321 payload is 1 Apr 02.

It is understood that the GSFC is required to submit safety data, in accordance with NSTS 1700.7B and JSC 13830, to the Johnson Space Center's Payload Safety Review Panel *no later than* 60 days prior to delivery of a user's payload at the Kennedy Space Center. With the understanding that payload integration occurs nominally 2-3 months prior to a specific launch date, the following schedule represents the expected safety data submittals for the G-0321 payload:

<table>
<tr><th></th><th></th><th>EXPECTED COMPLETION DATE (fill in date for your payload)</th><th>DATE RECEIVED AT GAS PROJECT OFFICE (OFFICIAL USE ONLY)</th></tr>
<tr><td rowspan="8">DOCUMENT</td><td>Preliminary Safety Data Package (PSDP)</td><td></td><td></td></tr>
<tr><td>Final Safety Data Package (FSDP)</td><td></td><td></td></tr>
<tr><td>Materials List</td><td></td><td></td></tr>
<tr><td>Structural Analysis</td><td></td><td></td></tr>
<tr><td>Thermal Analysis</td><td></td><td></td></tr>
<tr><td>Energy Containment Analysis</td><td></td><td></td></tr>
<tr><td>Phase III Safety Data Package</td><td></td><td></td></tr>
<tr><td>Reflight Safety Data Package</td><td>Payload: G-0321
Date Submitted: _________</td><td></td></tr>
</table>

Table 6.0-1
MILESTONE SCHEDULE FOR GET AWAY SPECIAL PAYLOAD G-0321

THIS SCHEDULE IS FOR PLANNING PURPOSES ONLY. IT IS NOT AN OFFICIAL FLIGHT ASSIGNMENT.

Appendix H. Inflation System Calculations

The tubes used for RIGEX can be approximated as thin walled pressure vessels. Using this approximation, longitudinal and hoop stresses for the tubes can be calculated based on the expected pressures after inflation. This information is important to ensure that the tubes do not fail structurally due to internal pressure applied in a vacuum.

The pressurization system controls the inflated pressure of the tubes through the use of the pressure regulator. The location of the regulator within the system can be seen in the inflation system schematic, Figure 28. This regulator is fairly inaccurate at the low pressure levels being used. Pressure is entering the system at over 300psi and is regulated to approximately 4psi. During the inflation process, the inflation pressure at the tubes themselves changes rapidly as the tubes deploy and each folded section is filled with air.

Pressures at the tube interface can vary from 0psi to 10psi during inflation. Because of the inaccuracy of the regulator itself and the wide variations in pressure during inflation, it is necessary to understand the stresses placed on the tube. High stresses can cause damage to the tube while low pressure might not be enough to overcome the weight of the tube end caps during deployment. The methodology and results of the inflation stress calculations are shown in the following section.

The stresses in the tube are divided into two separate directions: hoop stress and longitudinal stress, as shown the figure below.

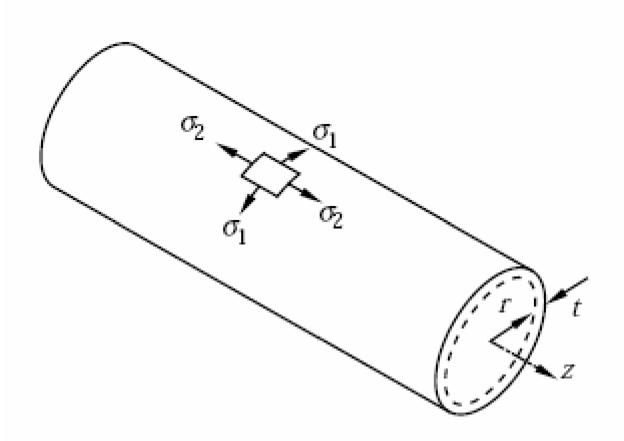


Figure 42. Model of Pressurized Tube Under Stress (5)

Looking at a differential element depicting hoop stress as shown in figure 43, and realizing that the element is stationary, we can say that

$$\sum F = 0 \tag{7}$$

and that

$$\sigma_1 A - pdA = 0 \tag{8}$$

Substituting in for the areas of the differential element we get

$$\sigma_1(2t\Delta z) - p(2r\Delta z) = 0 \tag{9}$$

Solving for Hoop stress, or the stress in the direction of σ_1,

$$\sigma_1 = \frac{pr}{t} \tag{10}$$

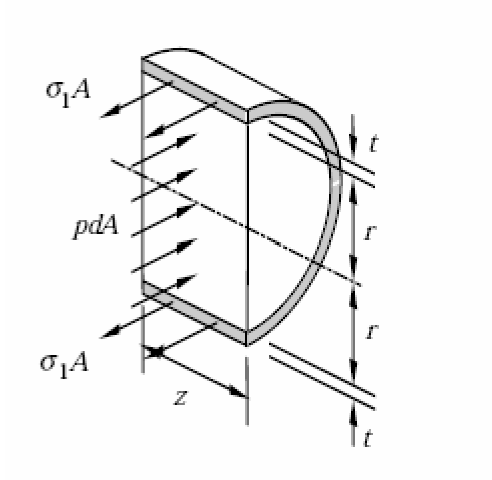


Figure 43. Hoop Stress Differential Element (5)

Using the same method for longitudinal stress, σ_2, we use the same basic equation,

$$\sigma_2 A_1 - pA_2 = 0 \tag{11}$$

substitute more appropriate areas for A_1 and A_2 from the longitudinal stress differential element, figure 21, to get

$$\sigma_2(2\pi rt) - p\pi r^2 = 0 \tag{12}$$

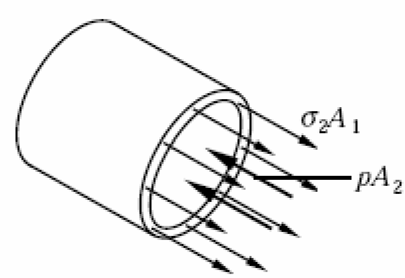


Figure 44. Longitudinal Stress Differential Element (5)

Solving for longitudinal stress, we get

$$\sigma_2 = \frac{pr}{2t} \tag{13}$$

These results show us that hoop stress in a thin walled pressure vessel is double the longitudinal stress, regardless of tube length or radius (5).

Appendix I. Failure Mode, Effects, and Criticality Analysis

Criticality are judged to be either low, medium, or high. Criticality is assumed medium if a single tube will fail due to identified failure mode.

Table 13. Failure Mode, Effects, and Criticality Analysis (FMECA)

Subfunction	Component	Failure Mode	Effect	Criticality	Mitigation Action
Provide Power					
Store/Provide power	Batteries	Batteries lose power due to overuse or long delay in launch	Insufficient power to at least one test	M	Used Multiple battery cells with long shelf life
Distribute Power	Wiring	Wiring breaks or loses connection due to launch loads or incorrect installation	Effects range from partial to full failure of single experiment based on specific wires compromised	M	Ground testing of wirigng including function tests before and after vibe test
Exercise C2					
Control Experiment	Flight Computer	Computer operational limits are exceeded	Failsafe points should preclude partial failure of computer system from causing failure of more than 1 experiment bay	M	Incorporate failsafe points in C2 software
Store Data	Flight Computer	Computer operational limits are exceeded	Stored data is compromised or lost	H	Test flight computer to all expected conditions where practicable
Conduct Experiment					
Deploy Tube	Tube	Tube is unable to deploy due to interference with other objects in experiment bay	Improper deployment of tube	M	Remove extraneous objects from all experiment bays to avoid sources of interference
Inflation System	Pressurized section of inflation system	Leakage of too much air from system	Tube in compromised section may not fully inflate	M	Recommend larger inflation system bottles to eliminate need for high pressure system
	Solenoid Valve	Valve won't activate due to insuffficient power supplied	Tube in compromised section will not fully inflate	M	Ground test of solenoid under flight-like conditions, using flight hardware
	Pressure Regulator	Regulator is set to allow too much pressure through	Tube in this section may fail structurally	M	Set regulator to correct setting during ground testing in flight-like conditions
	Pressure Regulator	Regulator is set to allow insufficient pressure through	Tube in this section may not fully inflate or may not inflate at all	M	Set regulator to correct setting during ground testing in flight-like conditions using flight hardware
Heating System	Heaters	Heaters debond from the oven sidewalls. New heating profile may cause early deployement of tube	Tubes may not be fully heated and may cause improper deployment of tube	M	Ground test of heaters beyond expected operational heating envelope
Excite Tube	PZT Patches	Patches lose sufficient bond to tubes	Tube vibration response data will be compromised or absent for single tube	M	Ground test of vibration system under flight-like conditions, using flight hardware
Record Deployed Characteristics	Cameras	Cameras fail to operate or field of view is obscured	Inflation dynamics and final deployed state will not be recorded for single tube	M	Ground test of cameras in flight-like conditions using flight hardware

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14. ABSTRACT
As greater capability is demanded of space based assets, their size and complexity are growing. Inflatable rigidizable structures offer significant improvements in the areas of weight, size and complexity over traditional mechanically deployed systems. These structures are not well understood and little testing of them has been done in the space environment. Widespread acceptance of these technologies will not be achieved without significant reduction in the risk of using inflatable rigidizable structures in space. The goal of this experiment is to verify and validate ground testing of small tubular truss structures for use in space. This experiment builds on previous research done in this area to reduce the risks involved in testing inflatable rigidizable structures in space. The Rigidizable Inflatable Get-Away-Special Experiment (RIGEX) is designed to launch as a self contained experiment on the Space Shuttle. It will inflate and rigidize three redundant experiments in the open space environment. Once these structures are deployed and rigidized, the experiment will vibrationally excite the deployed structures and record vibrational response in the space environment.

15. SUBJECT TERMS
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