Orbital Flight Preparations of Get Away Special Payload G-572: Design and Testing of Mechanical Systems

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ABSTRACT

A need was identified to develop an build a completely self-contained experimental apparatus to investigate the cardiovascular response to the weightlessness of spaceflight. This experiment would fly aboard a NASA Get Away Special (G.A.S.) canister, which would require that the apparatus be fully self contained and automatic. This apparatus would need to include an artificial heart and heart driver, a compact integrated Mock Circulation System (MCS), an automated control system, a data acquisition system, and a self-contained power supply. The development of the MCS required the modification of a Penn State-type MCS to include the use of a coil spring in the compliance elements, an automatically controlled variable systemic resistance unit, and the integration of all elements of the MCS into a compact and lightweight package which could function effectively in microgravity. Testing showed that this MCS improved upon the functionality of the original Penn State design, since it incorporates automatic systemic resistance adjustment, and a reduction in fluid inertance with a corresponding improvement in pressure and flow waveforms. This MCS was successfully incorporated into an experiment package which fit into a cylinder 19 inches in diameter and 27 inches high, with a weight limit of 200 lb.

INTRODUCTION

Many different mock circulatory systems (MCS) have been used to develop and evaluate artificial hearts and ventricular assist devices over the past 20 years. These MCS have varied from simple fluid columns with an infinite arterial compliance[1] to complicated hydro-mechanical feedback models[2]. Each of these MCS was designed to simulate the human circulatory system under a variety of conditions. One of the most widely accepted MCS has been based on the design of Pennsylvania State University[3], which was originally developed in 1971 and has undergone considerable refinement since then. However, most of the mock circulatory systems in use today were designed to be used in a ground-based laboratory where size and weight were not critical considerations in their design, and the presence of a constant gravitational field was assumed. The Penn State MCS utilizes a leaf spring-loaded bellows as a compliance element, which is adaptable to microgravity environments, while others use an air-filled chamber, which will not function properly in microgravity. Furthermore, the Penn State MCS employs a series of rubber tubes compressed between two metal plates as a means of varying the systemic fluid resistance.

The University of Utah, in collaboration with Bellarmine College, Utah State University, and the NASA Johnson Space Center, has been conducting research into the effect of microgravity on diastolic heart function and the reduction of stroke volume observed in astronauts following adaptation to weightlessness[4]. Initial experiments using elements from the Penn State MCS demonstrated the "proof of concept" during parabolic flight experiments onboard the NASA KC-135 aircraft[5]. Subsequent flights have demonstrated the effectiveness of the integration of the experiment into a single compact and self-contained package using a compact MCS. This investigation will ultimately involve the insertion of an instrumented artificial heart and mock circulatory system into a microgravity environment via a NASA Get Away Special payload in the cargo bay of the space shuttle. The experiment requires that a complete artificial ventricle and driver, mock circulatory system, and all necessary batteries, data recorders, and control equipment fit into a container roughly the size of a 20 gallon trash can, and to weigh no more than 200 lb.

DESIGN CHALLENGES

Mock Circulation System

With space and weight at such a premium, one of the first tasks of the team at the University of Utah was to redesign the Penn State MCS into a single compact unit while maintaining the required physiologic characteristics. The first task was to reduce the size of the MCS from an apparatus that filled a tabletop to one which was roughly the size of a car battery. This unit needed to incorporate systemic and venous compliance elements, a fixed arterial resistance element, and a variable systemic resistance element. It was also decided that an important characteristic of the systemic fluid resistance unit was linear behavior across the wide range of flow conditions encountered in a pulsatile flow fluid circuit, which essentially means maintaining laminar flow at rates from 0 up to 20 liters/min.

An additional requirement for the MCS, dictated by the need for automatic operation, involved the automatic adjustment of the systemic resistance element, so that the mean aortic pressure in the circuit could be maintained at 95 mm of Hg throughout the range circulatory filling volumes used in the experiment. Essentially, this means that the resistance needs to be able to be varied using a servomotor controlled by some form of automatic feedback loop, tied to the mean outflow pressure at the heart.

As the development of the integrated MCS proceeded, it became apparent that an additional requirement was the ease of assembly and changeover of the resistance element. Since the resistance element is composed of a porous filter media, it was subject to frequent clogging which necessitated the complete disassembly of the MCS to change the filter media. In the initial stages of development of the MCS, it could take as long as three days to change a resistance element. It was decided that this time should be reduced to a few hours at most.

A final design challenge the team faced as the development progressed was the need for high reliability of the entire system. Since the experiment would be integrated into the G.A.S. can approximately three months before launch, the system needed to be able to remain dormant for that period and then be fully operational with no adjustment or maintenance before launch. This means that the system must be reliably leak-free, with a minimum of corrosion or bacterial growth.

Batteries

As the needs of the control system were developed, it became apparent that a large amount of battery power would be required to operate the system. Of particular concern were the temperature requirements of the system, since the outcome of the experiment depends heavily on the viscosity of the blood analog fluid used in the MCS and heart. The heating element needed to control the experiment temperature, combined with the high power requirements of some of the other electronic control and measurement equipment, dictated the use of over 54 lbs of alkaline batteries to power the experiment. This number of batteries presented a number of design challenges. The first of these challenges involved the mounting of the batteries, which had to be securely fastened without puncturing or damaging the batteries, and in such a way that a battery could be changed easily and quickly. A second problem stemmed from a NASA requirement which stated that the battery box had to be sealed in an airtight container and separately vented in the event of a battery leak or short-circuit. The size of the box needed to enclose all of the batteries proved to be a particularly challenging design problem.

Size and Weight

As the development of the experiment progressed, one of the most significant problems faced by the design team was the size and weight restrictions imposed by the G.A.S. can in which the experiment was to be housed. Since the battery box would take up nearly half of the usable experiment volume, the team faced several tradeoffs when determining the final functionality and layout of the equipment. The first tradeoff involved the duration of the experiment and the temperature range over which the experiment could operate. Since longer run times and colder starting temperatures required more batteries, a balance had to be selected which allowed for the experiment to fit the size and space requirements, while maximizing the operational temperature window and experimental run times. The next design tradeoff involved the elimination of variable control for the aortic resistance element, which would have made the MCS too large to be housed in the structural design dictated by the large number of batteries. This design decision resulted in a significant reduction in the size and weight of the MCS, and added another round of design to the development process.

NASA Requirements

There were several other design challenges presented by NASA requirements for safety and structural integrity. The need to minimize volatile emissions from plastics required the use of controlled volatility sealant and wire insulation, which significantly increased the material costs of the package. In addition, NASA required that the inside of the battery box be covered with a non-conductive coating, which added to the complexity of sealing the battery box. Finally, NASA requirements prohibited the use of welds in any of the structural components, which meant that the battery box (which is a part of the structural system) had to be bolted together and then sealed with controlled volatility sealant and PTFE Gasket material.

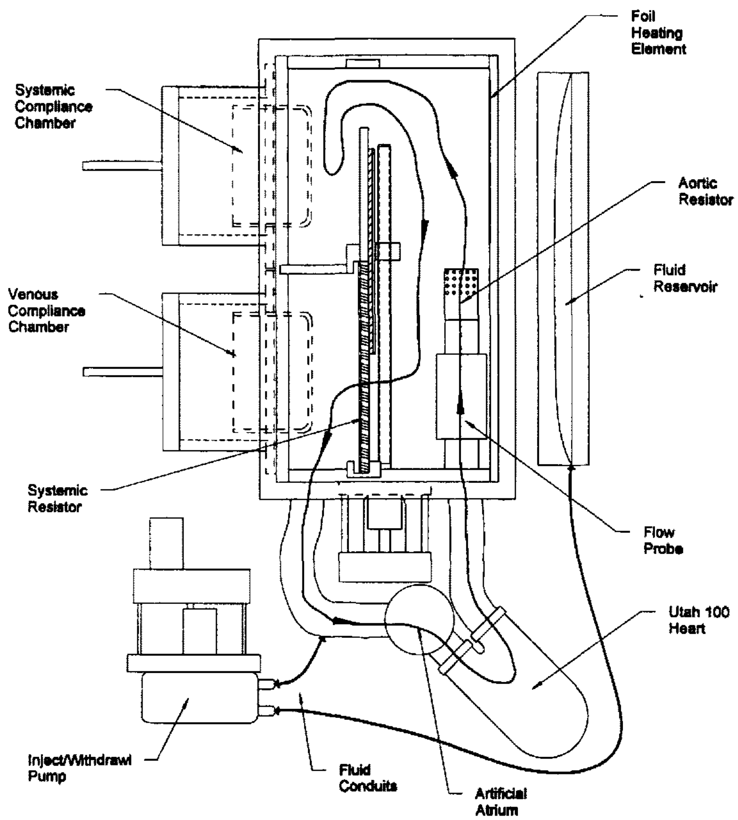

Figure 1 - Integrated MCS

EXPERIMENT PROTOCOL

The purpose of this experiment is to determine the effect of microgravity on diastolic heart function, and to attempt to quantify the reduction in stroke volume observed in this environment. The experiment attempts to produce a ventricular function curve by varying the mean circulatory filling volume and measuring the flow through the system after adjusting the systemic resistance to give a mean pressure of 95 mm of Hg at the outflow of the heart. By examining the data, a function curve can be produced which plots the mean flow out of the heart with the mean atrial pressure at the inflow to the heart. Since the lack of a gravitation vector eliminates the assistance of hydrostatic pressure in the filling of the heart, it is postulated that the ventricular function curve will shift to the left when compared to tests conducted under normal gravity.

METHODS

Mock Circulation System

The solution to these design challenges incorporates a number of unique features which reduce size and weight, increase reliability and ease of maintenance, and meet the functional requirements of the experimental protocol (see Figure 1). By incorporating two resistance elements and two compliance elements in a single unit, the entire MCS was fit into a space approximately 7" by 8.5" by 13" inches. The systemic resistance element is composed of porous polyethylene cut into shape and fitted into a cartridge which seals around the element to prevent blow-by and ensure that all fluid circulating in the system passes through the resistance element. Variable resistance is achieved by the use of a rubber lined steel plate, which is moved up and down using a threaded rod attached to a DC servomotor. This arrangements varies the surface area of the polyethylene plate in contact with the flow, thus effectively changing the resistance seen by the fluid as it circulates through the MCS (see Figure 2). In order to provide a linear relationship between the amount of fluid added to the system during each experiment phase and the distance the sliding plate must move to equilibrate the system, the polyethylene plate is masked with controlled-volatility sealant in a "V" pattern to further reduce the surface area of the resistor in contact with the flow as the sliding plate is closed off. Finally, the porous polyethylene sheet is backed with a sheet of perforated 316 stainless steel, which adds rigidity to the plastic plate needed to maintain a seal between the resistor and the sliding plate.

In order to decrease maintenance time and difficulty, the entire systemic resistance element,

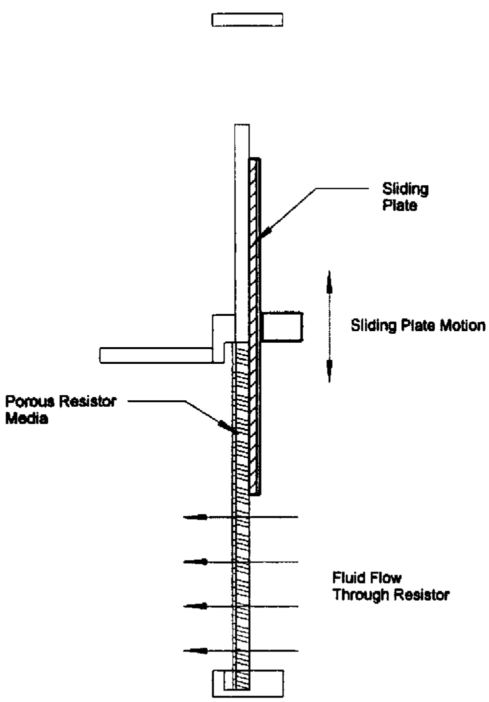

Figure 2 - Fluid Flow through Resistor

including the porous resistor, and sliding plate and track is incorporated into a removable stainless-steel cartridge. This cartridge is sealed around the edges with a rubber o-ring which prevents fluid from bypassing the cartridge, and yet permits it to be easily removed from the MCS box for maintenance. Furthermore, the cartridge itself is designed with GoreTex expanded PTFE sealing material around the porous polyethylene sheet. This effectively prevents fluid bypass of the resistor element while permitting the changeover of the porous

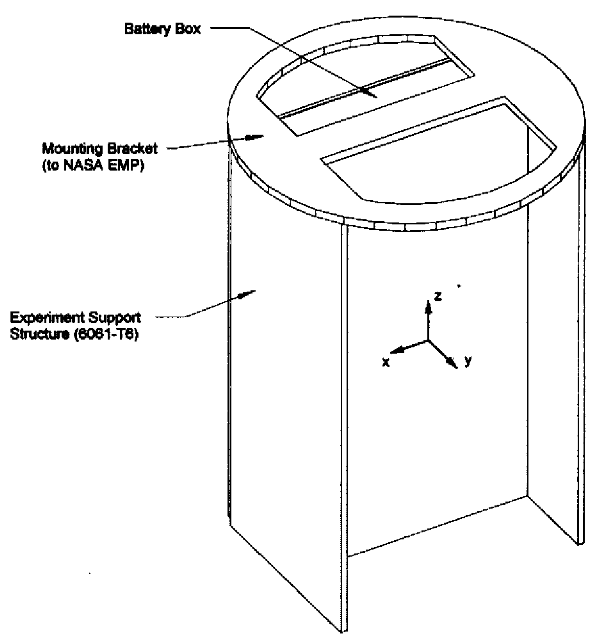

Figure 3 - Experiment Support Structure

plastic sheet without the use of RTV or other volatile sealing compounds.

Early versions of the integrated MCS were constructed using aluminum plates coated with water-resistant paint to minimize corrosion. Maintenance difficulty coupled with the poor performance of the coating prompted the switch to

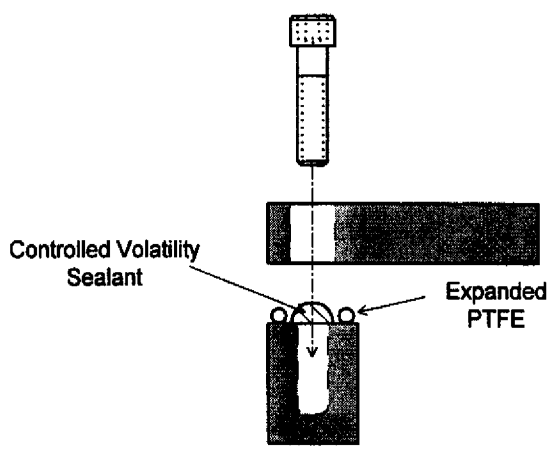

Figure 4 - Battery Box Seal

stainless steel as the method of construction of the MCS box. While this material reduced the corrosion problems, the increased weight, cost, and machining problems prompted the adoption of hard anodized aluminum as the final material for the MCS box.

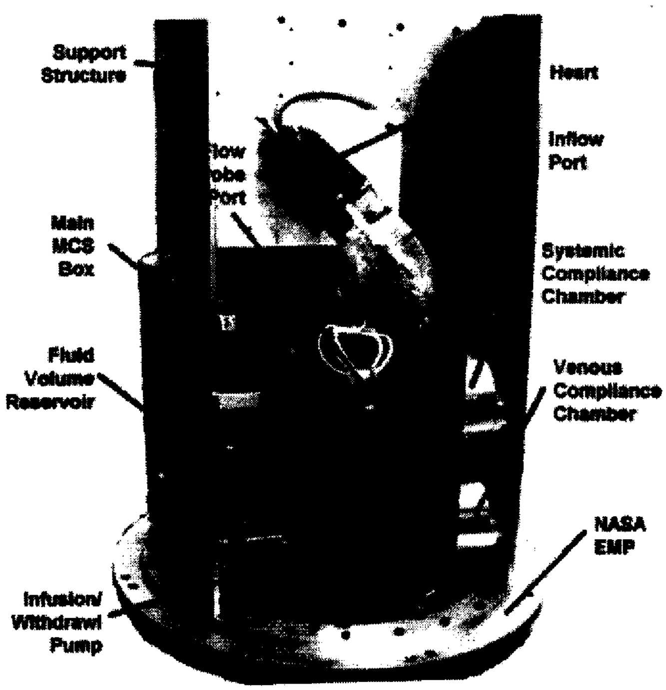

Figure 5 - Photograph of MCS

Furthermore, in order to increase the reliability of the sealing of the box, the box was designed with a single removable polycarbonate cover sealed with and o-ring, with the rest of the joints in the box permanently welded together. By anodizing the box after welding and then covering small breaks in the anodization with controlled volatility sealant, the MCS box becomes virtually maintenance-free.

These design features, when used with plumber's putty to seal any small leaks, permit the entire MCS to be sealed without the use of RTV sealant. This reduces the changeover time for the resistance element from three days to a matter of hours and increases the reliability of the MCS considerably.

Structure and Battery Box

The structure used to mount the entire experiment became of critical importance as the weight and size of the equipment began to approach the design limits. While many different structures were considered, the final solution is essentially an I-beam, mounted to the NASA Experiment Mounting Plate using a circular bracket (see Figure 3). This design permits the battery box to be incorporated as one half of the structure, while the other half houses the MCS, artificial heart, and control and data acquisition electronics. By using 3/8" aluminum plates for the flanges and a 1/2" aluminum plate for the web, a great deal of structural rigidity is achieved with a relatively small weight (59 lbs).

The battery box is essentially integral with the structure itself, since the back and sides of the box consist of the plates of the I-beam. By adding small top and bottom plates and a 1/4" aluminum cover plate, the batteries can be completely enclosed from the remainder of the experiment, ensuring that any fluid leakage from the MCS poses no danger of short-circuiting the batteries.

Because space and weight limitations forced the battery box to be incorporated with the mounting structure, and NASA regulations prohibited the used of welded joints to seal the structure, the challenges posed by the need to seal the battery box were considerable. The battery container essentially consisted of a 24" by 14" by 8" butt-jointed box bolted together with machine screws. Since the box could be permanently sealed together along all joints but the cover plate, the seals consist of two lines of GoreTex expanded PTFE, with a bead of controlled volatility sealant in between (see Figure 4). This proved to be the most effective sealing technique, when combined with a Viton rubber gasket used to seal the removable cover plate.

RESULTS AND DISCUSSION

Mock Circulation System

Figure 5 shows a photograph of the completed MCS. The unit incorporates a sealing flange to seal the polycarbonate top plate to the rest of the box. The systemic and venous compliance elements are on one side of the box, and are separated internally by a dividing plate attached to the resistance cartridge (refer to Figure 1 for details of the cartridge design). Pass-through ports are used for de-bubbling, limit sensors for the sliding plate motion, the signal cable for the internal flow sensor, and wires for the heating element and a temperature sensor. The entire MCS occupies a space of approximately 7" by 8.5" by 13" (not including the resistor adjustment servomotor) and weighs approximately 45 lbs when full. The unit can be operated in full or zero gravity, and functions independently of experiment orientation.

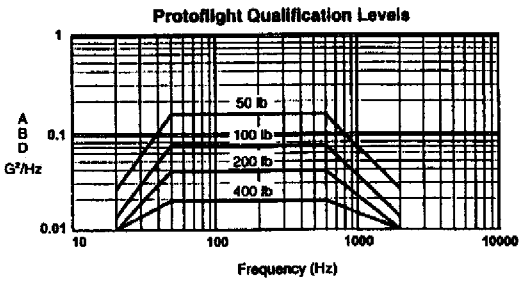

Figure 6 - NASA Protoflight Vibration Profile

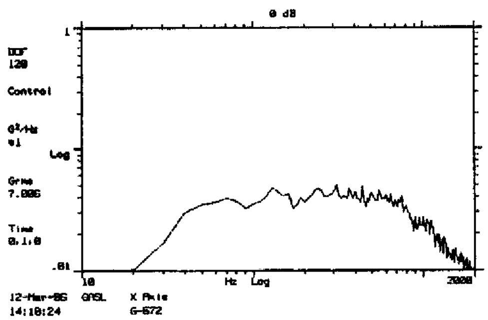

Figure 7 - X-axis vibration results

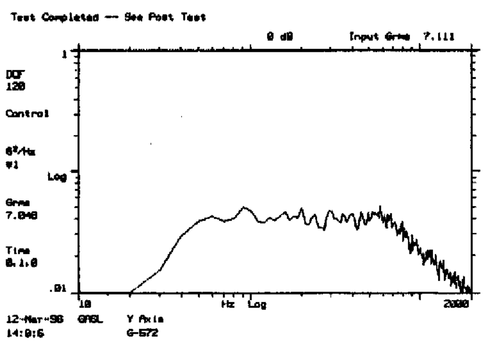

Figure 8 - Y-axis vibration results

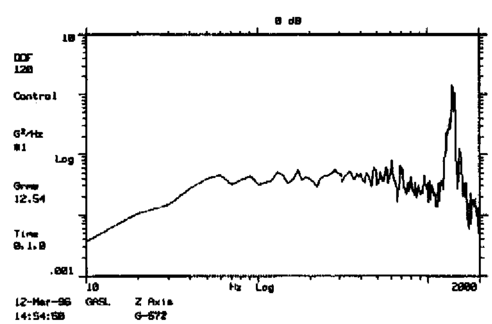

Figure 9 - Z-axis vibration results

Shake Table Test

On March 12, 1996 the experiment package, including the filled MCS and artificial heart, the batteries, and the support structure were subjected to a shake table test to simulate the effect of a shuttle launch on the complete experiment. A vibration profile specified by NASA (shown in Figure 6) was applied to the structure mounted in all three axes, and the response was measured using an accelerometer (see Figures 7 - 9). A small resonance was recorded in the z-axes at approximately 1300 Hz, which is well beyond the critical frequency of 35 Hz specified by NASA.

SUMMARY

In conclusion, the design and testing of mechanical systems for G-572 has resulted in a G.A.S. experiment that consists of a functional mock circulation system and artificial heart which is completely self-contained. The MCS approximates the fluid dynamics behavior of the human circulatory system, and is capable of operation in any orientation, and in microgravity. The MCS is capable of feedback control to allow the regulation of systemic resistance, which allows the experiment to automatically generate a ventricular function curve in the high-quality sustained microgravity environment of the space shuttle in orbit.

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