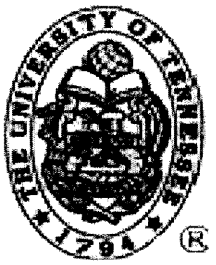
NASA REDUCED GRAVITY STUDENT FLIGHT OPPORTUNITIES

H.E.R.C.U.L.E.S. Returns

"**H**eat **E**xchange **R**esearch and **C**ondensation (evaluation) by **U**tilizing a **L**iquid/fog **E**xperimental **S**et-up **Returns**"

Topic Area: Heat Transfer / Fluid Dynamics



University of Tennessee, Knoxville
Department of Mechanical, Aerospace, and Biomedical Engineering
414 Dougherty Engineering Building
Knoxville, TN 37996

Faculty Advisors:
Dr. Viatcheslav Naoumov
Professor, MABE
nvi2000@mail.ru /(865) 974-7675

Dr. Masood Parang
Professor, MABE
mparang@utk.edu /(895) 974-5259

Team Contact:
Lauren R. Jean*
Flight Crew
**(Alternate Flight Crew, Spring 2003 Campaign)*
Junior, Electrical Engineering
ljean@utk.edu / (865) 394-9201

Team Members:
Dan Passmore
Flight Crew
Junior, Physics
dpassmo1@utk.edu

Jay Stembridge
Flight Crew
Junior, Computer Engineering
jstembri@utk.edu

Sheena Edwards
Flight Crew
Junior, Biomedical Engineering
sedwards@utk.edu

Nathan Fortner
Alternate Flight Crew
Sophomore, Aerospace Engineering
nfortner@utk.edu

Faculty Adviser Endorsement:
"As primary faculty advisor for the HERCULES undergraduate student research project, I endorse the submission of this proposal."

Dr. Viatcheslav Naoumov, Professor, MAES Date

TABLE OF CONTENTS

List of Table ii

Flight Week Preference 1

Mentor Request 1

Abstract 2

Chapter I ***Technical Overview***

1.1 Background 4
1.2 Test Objectives 8
1.3 Test Experiment Description 10
1.4 Test Description 14
1.5 Justification for Follow-Up Flight 15
1.6 References 18

Chapter 2 ***Experiment Safety Evaluation***

2.1 Flight Manifest 19
2.2 Experiment Description/Background 19
2.3 Equipment Description 19
2.4 Structural Design 20
2.5 Electrical Analysis 31
2.6 Pressure Vessel Certification 34
2.7 Laser Certification 34
2.8 Crew Assistance Requirements 34
2.9 Free Float Requirements 34
2.10 Institutional Review Board (IRB) 34
2.11 Hazard Analysis 35
2.12 Tool Requirements 39
2.13 Ground Support Requirements 39
2.14 Hazardous Materials 39
2.15 Experiment Procedures Documentation 40

Chapter 3 ***Outreach Plan***

3.1 University Outreach 43
3.2 Community Outreach 45

Chapter 4 ***Administrative***

4.1 Institution Letter of Endorsement 46
4.2 Statement of Supervising Faculty 46
4.3 Funding/Budget Statement 46
4.4 Institution Review Board (IRB) 48

4.5 NASA/JSC Human Research Subject Consent Form.....48
4.6 Institutional Animal Care and Use Committee (IACUC)..... 49
4.7 Parental Consent Forms..... 49

Appendices

A. Participant Information
B. Original Institution Letter of Endorsement
C. Original Statement of Supervising Faculty

FLIGHT WEEK PREFERENCE

The HERCULES team requests the following flight date preferences beginning with the most desired week. It is understood that these dates represent the start of the flight weeks. We have requested the March 4th flight date at the request of our professors so as to coincide with the week of our spring break. The HERCULES team would also like to request to be placed in Flight Group A.

March 4, 2004
July 8, 2004
July 22, 2004

MENTOR REQUEST

The HERCULES team would like to request the "services of a JSC scientist or engineer to augment the guidance given by faculty members and/or the KC135 program staff."

ABSTRACT

Two-phase systems are of great importance, especially when coupled with heat transfer and the management of fluid movement. One key area of interest is that of power generation in micro gravity conditions, as many power cycles take advantage of a phase change. A saturated vapor undergoes a multi-step process as it is cooled and condensed, and the flow regimes that are present during condensation are dependant upon gravity.

As a follow-up of last year's HERCULES experiment, the first objective of this experiment is to accurately simulate forced flow condensation of a saturated vapor in micro gravity by using a mixture of heated water and a heated fog. This setup allows for the simulation of all phases of condensation, as the ratio of water to fog will be adjustable. This adjustment also makes it possible to observe many different flow regimes and to measure their respective heat transfer rates. It is expected that in the absence of gravity, the liquid will form a liquid film along the inside wall of the pipe and annular flow will be established. Therefore, the heat transfer from the fluid inside the pipe to the cooling surface is expected to differ greatly from normal gravity.

The second objective of this experiment is to measure the change in temperature of the liquid and fog as they exit the cooling section by inserting thermocouples into the flow. It is hypothesized that the simulated liquid condensate in gravity conditions will be warmer than that in micro gravity due to the increased surface area that is in contact with the cooling element in micro gravity conditions.

The third objective of this experiment is to investigate the influence of the ratio of the water to fog. The changing of this ratio will result in the changing of flow regimes, which will drastically change the heat transfer possibilities of the system. This will also provide excellent visual data of the formation of different condensation driven flow regimes such as annular, drop-wise, and slug flows.

CHAPTER 1 TECHNICAL OVERVIEW

1.1 Background

Thermal management in spacecrafts is primarily handled by systems that do not operate differently in micro gravity, such as solar arrays, fuel cells, and other low-density power generators. Currently multiple flow and heat transfer processes designed for micro gravity conditions face many unsolved issues. Future space exploration, colonies, and spacecrafts motivate investigation into large-scale power generation in a low gravity environment.

Of great interest is the Rankine cycle because it uses the available heat transfer of a phase change. The process of changing phases produces two-phase flows, which have not been fully explored in micro gravity. Two-phase flow systems are superior to single-phase systems because they carry more energy per unit mass and require less pumping power per unit of thermal energy (1). Unfortunately, as Bousman has stated, two-phase systems behave differently in different gravity. More research about two-phase heat transfer in micro gravity needs to be done in order to harness the ample power available. This needed research includes the process of condensation. Dealing with two-phase flows in micro gravity conditions is fundamentally more difficult because of the effects of surface tension, wetting forces, and the drastic decrease of buoyancy forces.

When a saturated vapor collides with a surface below the saturation temperature of that vapor under normal gravity conditions, the latent energy of the vapor is released and transferred to the surface, forming condensation (3). Condensation is defined as the removal of heat from a system in such a way that a vapor is converted into a liquid (11). The condensation in our system, the mixture of water and vapor and the interior wall of the condenser, forms because the vapor transfers heat to the cooled wall, thus removing heat from the system.

Under Earth gravity conditions, saturated vapor within a cooled pipe is condensed and falls to the base where the liquid can then be collected via a simple gravity driven system. This outcome is desired since the fallen condensate leaves the cooled pipe surface exposed to the flow of the gaseous mixture. Since the inner wall is exposed, the process of heat exchange from the saturated vapor to the wall may continue. This process will not work in the same manner in micro gravity conditions since the saturated water vapor entering the cooled section of the pipe will condensate and then cling to the wall due to an absence of buoyancy and the increased effect of surface tension and wetting forces. These forces are present in normal gravity conditions but become inconsequential with the exception of small containers and boundary layer conditions (5,13). Since the magnitude of the gravity vector is small when compared with the forces related with surface tension phenomena in micro gravity, these forces are ignorable in micro gravity conditions.

In the annular flow regime, condensate film forms on the periphery of the tube (11,13). When the saturated vapor first enters a cooled section of pipe, it begins to condense along the walls of the pipe in the form of droplets. This is due to the transfer of heat by natural and forced convection to the wall from the saturated vapor. Once the droplets begin to form on the surface of the pipe there is an added convective heat transfer between the formed liquid droplet and the wall. As the two-phase mixture continues to flow inside the cooled pipe, it is continuously being cooled and condensed. As stated by Lixin You and Hongtan Liu, inside the two-phase region, the liquid saturation increases along the flow direction (10). Therefore, the film thickness will also increase in the direction of the flow. The only force that is creating the movement of the fluid film in micro gravity is the shear force that acts upon the film as imposed by the vapor flowing in the middle of the pipe. Therefore, the movement of the liquid film is relatively slow.

There are two basic forms of condensation that are of interest: drop-wise and film-wise. Drop-wise condensation occurs when the cooling surface is not easily wetted, and film-wise condensation occurs when the cooling surface is easily wetted (11), or when the vapor does not contain enough liquid to sufficiently form a liquid film around the entire inner surface of the cooling pipe. In drop-wise condensation, liquid drops condense and roll over the cooling surface as they grow (11). This growth, and movement allows for other vapor particles to come in contact and exchange heat with the cooling surface. Film-wise condensation essentially operates in the same manner except that as the vapor is condensed, the liquid tends to stick to the inner wall of the pipe due to wetting forces and insulate the wall from the rest of the vapor flow.

The liquid film on the inside of the pipe poses a problem in the area of heat transfer because it does not allow the vapor inside the pipe to come in contact with the wall as in the normal gravity condition, which would lead one to expect that the heat flux will be greater in the conditions of micro gravity. Excluding the latent heat of condensation, there are two heat fluxes that are important. First is the heat flux that is associated with the heat transfer between the liquid water and the pipe, and the second is between the forced flow of the vapor and the cooling surface of the pipe. In micro gravity conditions, the liquid will have an increased heat flux due to the hypothesized formation of annular flow, and therefore, the formation of a greater contact area with the cooling surface. However, the heat flux associated with the vapor will be decreased because when annular flow is established there will be a liquid barrier on the inside of the pipe and the vapor will not come in contact with the cooling surface. With this said, the anticipated results are that there will be a decrease in the temperature of the condensate in micro gravity and that the temperature difference, defined as the change in temperature from the inlet to the exit of the cooling section, in the vapor flowing on the inside of the pipe will be smaller.

By following a parabolic flight path, NASA's KC-135 research aircraft produces 15-25 seconds of micro gravity. This technique currently produces the longest period of reduced gravity available without resorting to space flight (1). However, the complete condensation of a saturated water vapor would require water to be boiled and steam generated in the conditions of micro gravity in order to produce the saturated water vapor. The issues surrounding film boiling and the previously mentioned difficulties

with the associated two-phase flow make it impractical to expect reasonable results with so many variables. Therefore, in order to simplify the experiment, eliminate unnecessary hazards, and to reduce the overall cost, this experiment will attempt to simulate the dynamics of condensation using an air and water mixture as opposed to generating the condensate from vapor.

1.2 Test Objectives

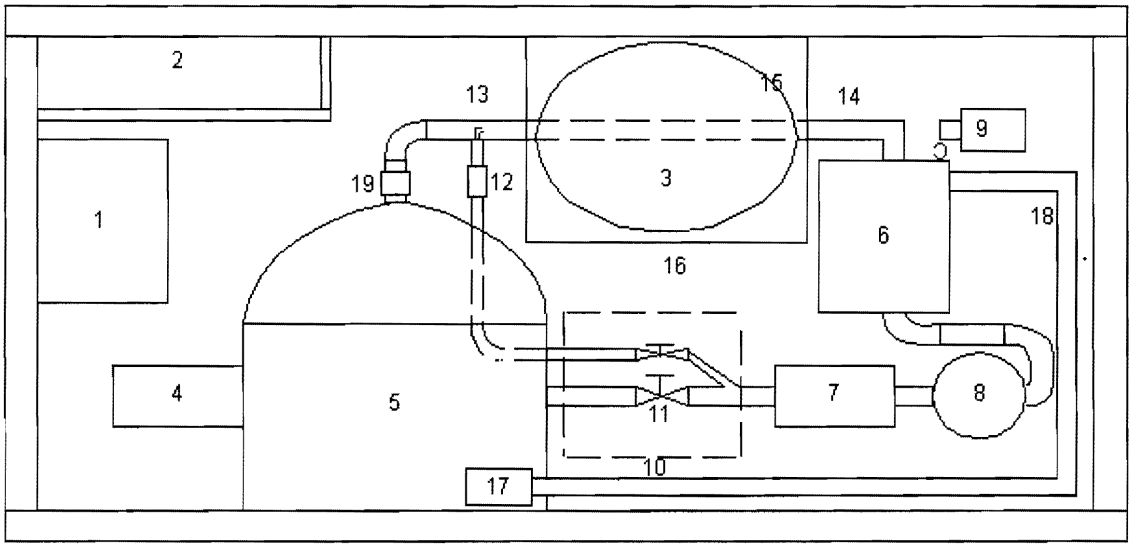
As a follow-up of last year's HERCULES experiment, the first objective of this experiment is to accurately simulate forced flow condensation of a saturated vapor in the presence of micro gravity by using a mixture of heated water and a heated fog. The fog will consist of water droplets that are approximately 25 microns in diameter and will simulate a saturated water vapor while the added water will simulate the liquid that would be condensing on the inside of the pipe during the actual condensation process. This setup will allows for the simulation of all phases of condensation, as the ratio of water to fog will be adjustable. This adjustment also makes it possible to observe many different flow regimes and to measure their respective heat transfer rates. In gravity conditions the liquid will simply flow along the bottom portion of the pipe and the fog will fill the volume above it. However, as it was observed in last year's HERCULES experiment (12) in the absence of gravity, the liquid will form a liquid barrier along the inside wall of the pipe and annular flow will be established. This flow regime is fundamentally different than that described for gravity conditions and, therefore, the heat transfer from the fluid inside the pipe to the cooling surface is expected to differ greatly as well.

The second objective of this experiment is to measure the absolute temperature of the fog and water before the cooling section and the change in temperature of the liquid and fog as they exit the cooling section by inserting thermocouples into the flow. It was hypothesized in last year's HERCULES proposal that the simulated liquid condensate in gravity conditions will be warmer than that in micro gravity conditions due to the increased surface area that is in contact with the cooling element in micro gravity conditions. The results from last year's experiment provided the primary data that confirmed this hypothesis (12).

The third objective of this experiment is to investigate the influence of the ratio of the water to fog. The changing of this ratio will result in the changing of flow regimes, which will drastically change the heat transfer possibilities of the system. This will also provide excellent visual data of the formation of different condensation driven flow regimes such as annular, drop-wise, and slug flows.

1.3 Test Experiment Description

The apparatus is made up of four systems, or five main components, that operate continuously through each test cycle, with no human intervention: the fluid transfer system, the condensation system, the data acquisition system, and the water/fog injection system. The components are the Mesh Separation Module (MSM), hydrofogger, pump, cooling module, air heater, and water heater, as seen in Fig.1.3.1



1	Electrical Box	6	SM	11	Variable Valve	16	Cooling Module
2	Laptop Station	7	Water Heater	12	Flow Meter	17	Small Water Pump
3	Ice Bath	8	Pump	13	Water Injector Nozzle	18	Water Bypass Pipe
4	Air Intake Heater	9	Digital Cameras	14	Flow Observation Section	19	Humidity Measurement Device
5	Hydrofogger	10	FRAD	15	Bladder		

Figure 1.3.1 – Experimental Apparatus

The fluid transfer system moves the water through the experiment. From the MSM, it is pumped through the adjustable water heating system. It then travels past the FRAD, or flow regulator and divider. Then the water is divided into two variable rate flows, which are manually controlled by variable valve flow regulators inside the FRAD. One of the flows travels to the hydrofogger fluid intake, and the other travels to the water injection system. The water flow rate is measured by a water flow meter and adjusted by the variable valve flow regulators (the water flow rate is kept around 1.2 gallons per second). The vapor leaving the hydrofogger is combined with an injected spray of water at the entrance of the test section and condenser. The water to vapor ratio is controlled by the positions of the flow valves in the FRAD. After the injection, the combined flow (water and vapor) passes through the condenser, where it is rapidly cooled to simulate condensation. Thermocouples are located at the entrance to and exit from the condenser, as well as on each variable flow loop described previously. The system of four thermocouples installed in the inlet and outlet sections of the condenser at 90° increments for the measurement of the change in temperature of water. Two thermocouples also installed in the inlet and outlet sections of the condenser measure the change in the temperature in the fog. The temperature of injected water is measured by our thermocouple at the inlet of the water injection system. Thusly the temperature of the mixture can be found, as well as the temperature changes of the vapor and the condensate across the condenser. The values found in micro gravity conditions can be compared to values measured in gravity runs. Soon after passing through the condenser, the water and vapor move through a short clear pipe, where they may be observed for visual confirmation of flow pattern. The valve at the end of the clear pipe leads straight to the

MSM, which uses a network of meshes to draw the water down to the bottom of the tank, where it becomes trapped by a set of screens for repumping. A vent located near the top of the MSM uses a series of screens to trap water while allowing air to escape into the ambient surroundings. This system allows separation of the water and air in a way that allows only the water to be pumped back into the system. The details of the mesh separation module are similar to the one outlined by Dodge, which is an example of a vaned Propellant Management Device (PMD) used in the Viking spacecraft (5). The performance from last year's MSM was acceptable and the same device has been employed in this year's experiment. The MSM proved in micro gravity conditions that it was able to keep the needed quantity water supplied to the water pump.

The water is pumped from the MSM to the heater. The heater raises the temperature between 88° and 90°F. The water is passed to the water/fog injection system, which creates a controlled mixture of water and vapor to pass through the condenser. Water is then delivered to the hydrofogger intake, via the fluid transfer system, where it passes through a set of thermocouples before being fed into the hydrofogger. Air is fed to the hydrofogger through the air intake. The air is then passed through a series of heating coils to raise the air temperature. The thermocouple at the exit plane of the air inlet measures the air temperature as it is fed into the hydrofogger. The hydrofogger combines the hot air and water to form a heavy fog. The fog then exits the hydrofogger and passes through a check valve where it is combined with water injected by the fluid transfer system. This mixture is then passed along to the condenser. The small pump

incorporated into the hydrofogger removes the excess water through a bypass pipe to the MSM.

The condensation system is made up of a straight piece of copper pipe, which passes through a cooling module. The cooling module consists of a well-insulated housing with a small refrigerant system to provide climate control. The cooling module contains a bladder, which surrounds the copper pipe and contains a mixture of salt and ice to form an ice bath. The ice bath is used to cool the copper pipe as it passes through the cooling module. The climate control inside the cooling module helps to maintain constant temperature for the ice bath. Thermocouples are placed at the entrance and exit planes of the cooling module. The thermocouples are inserted into the flow, with some close to the wall, in order to measure the temperature of the film, and some farther from the wall, in order to measure the temperature of the vapor. Under normal gravity conditions water flows along the bottom of the pipe, therefore only the two lower thermocouples are necessary. As the fluid mixture passes through the copper pipe, going through the cooling module, the temperature of the mixture is rapidly reduced to provide cooling for condensing.

The data acquisition system consists of several sets of thermocouples, a digital camera, and a laptop computer. The thermocouples are placed in sets at the following locations: at the entrance of the water injection system, the air intake of the hydrofogger, and the entrance and exit planes of the condenser. Using multiple thermocouples at the same location allows an average temperature to be measured. This prevents temperatures at

isolated points from misrepresenting the over-all temperature of the flow at the location of interest. The flow meter is located before the water injection system. The camera is located next to the clear pipe at the exit end of the cooling module and has two different mounting positions to provide various angles for collecting visual data of the film layer and flow conditions. The thermocouples are connected to the amplifiers, which are connected to the data acquisition board, which is then connected to the laptop for data collection and recording throughout each test cycle.

1.4 Test Description

About one gallon of water will be used to conduct this experiment. One gallon is sufficient for a continuous cycle of mixed vapor and mist with as much as 100 percent water. A more realistic model of condensation is created by variation of the amount of water in the mixture. Initially, the mixture will be largely vapor; it will be increased in small amounts, with a greater water flow rate and a lower vapor flow rate each cycle. The last cycle will have nearly all water, thus simulating full condensation. The heating elements in the intake segments for both air and water can be altered in flight as well, to affect the respective temperatures of the air and water flowing through the condenser, thus allowing a greater temperature difference from the wall of the condenser and a far more accurate measure of the actual heat transfer from the flow to the condenser wall.

Due to the increasing proportion of water to vapor in the mixture, the liquid film on the interior condenser wall will thicken. In the ground-testing phase, the liquid flowing

through the condenser will be on the bottom of the tube, exposing a greater surface to the vapor. A greater heat transfer from the vapor to the walls will therefore occur, as the contacting surfaces have a greater difference in temperature. The results from last year's ground testing confirms this effect (12).

It is hypothesized and verified that an annular flow will form a micro gravity run of the experiment; a liquid boundary layer will form on the inside surface of the pipe, leaving the vapor mixture to flow through the center. As the vapor mixture wont directly contact the condensing surface, an insulating effect occurs; as the liquid film thickness increases, it decreases the heat transfer rate from the mixture to the condenser wall. It therefore seems likely that the condensation rate would decrease with the increasing boundary thickness. Also, the fluid in an annular flow has a greater contact with the surface of the condenser, and so should be colder in micro gravity conditions. The primary set of experimental data from last year's flight (12) completely confirmed these expectations.

1.5 Justification for Follow-up Flight

The prior HERCULES experiment was accepted into the Reduced Gravity Student Flight Opportunity Program and has previously flown. The past experimental apparatus was successfully constructed in an attempt to measure the heat transfer of two-phase flow in conditions of microgravity. The experiments performed last year confirmed our expectations about air/liquid flow pattern in microgravity. Visual observations also confirmed annular liquid flow regime due to the dominance of surface tension forces.

The temperature measurements indicate lower water temperature and higher exit fog temperatures at microgravity when compared with results in normal gravity. This indirectly demonstrates that less condensate is expected to form under microgravity conditions when compared with normal gravity. While the heat exchange from the liquid to the pipe is enhanced, the saturated vapor heat exchange with pipe wall is reduced (12).

The proposed air heater for last year was not included in the previous experiment due to budget and time constraints; leaving the water and air at two different temperatures. The third objective was not realized last year since the objectives were planned for a three-year program and we were not able to complete all objectives during last year's experiment. No visual data of the flow patterns was recorded because of budget and time constraints.

We propose the modification of H.E.R.C.U.L.E.S. in two areas: the test equipment and the experiment data collection. We will first modify the test equipment by adding an air heater. This will bring the temperature of the air closer to the temperature of the water in order to stimulate condensation more precisely. During flight another problem was the viewing glass. The mixture of water and air would hit the perpendicular viewing glass and recoil towards the test section. We are modifying the visual data area so it will easily be changeable with several different versions of angled and curved clear PVC pipes, which we believe will eliminate the problem. We propose having several different sections so that if one section does not work as expected, we will be able to change it out with another after the first flight day and obtain better results the next day.

In the data collection area we propose the addition of one or more digital cameras positioned to capture different angles of annular flow. They will be integrated with the data acquisition system through the laptop and will be fully automated, eliminating the variables associated with the humanly controlled image collecting. We plan to add the thermocouples to the air after heating and to the water before the injection of the air. This will enable us to measure the absolute temperature of the air and water to make adjustments to the heaters of both during flight and supply us with additional data for the analysis of condensation and the calculation of heat flux from the fog to the water and from the water to the test section walls. The addition of more thermocouples increases the amount of raw data received and the accuracy of the final result. We will add a humidity-measuring device because it will be useful to measure the humidity of fog in order to have more information for the analysis of condensation.

The main goal of modification is to achieve more accurate data and additional parameters for the process of condensation. We can use the extra data from repeating the experiment with the new additions to perform a more accurate quantitative analysis of the condensation.

1.6.1 References

1. Bousman, W.S., Studies of Two-Phase Gas-Liquid Flow in Microgravity. NASA Contractor Report 195434. 1995.

2. Carron, Igor, and Best, Frederick R. "Gas-Liquid Annular Flow Under Microgravity Conditions: A Tempral Linear Stability Study". *International Journal of Multiphase Flow*. Vol. 20, No. 6, 1994. pp. 1083-1093.

3. Incropera, Frank P. and DeWitt, David P. Fundamentals of Heat and Mass Transfer, John Wiley & Sons, 2002

4. Lee, Jinho. Prediction of Gas-Liquid Two-Phase Flow Regime In Microgravity. NASA Contractor Report 106274. 1993

5. Low Gravity Fluid Dynamics and Transport Phenomena. Progress in Astronautics and Aeronautics. Volume 130. Washington, D.C.: American Institute of Aeronautics and Astronautics, Inc., 1990.

6. Lu, Quing. Film Condensation In A Horizontal Rectangular Duct. NASA Contractor Report 1999044. 1992

7. McQuillen, J.B. et al NASA. Flow Research Using The Learjet Apparatus. NASA Contractor Report 106814. 1995

8. Microgravity Research in Support of Technologies for the Human Exploration and Development of Space and Planetary Bodies. Committee on Microgravity Research, Space Studies Board and Committee on Physical Sciences, Mathematics, and Applications, National Research Council. Washington, D.C.: National Academy Press, 2000.

9. Norton, L. Robert. Machine Design: An Integrated Approach Second Edition. Prentice-Hall Inc. 2000

10. You, Lixin and Liu, Hongtan. *A two-phase flow and transport model for the cathode of PEM fuel cells*. International Journal of Heat and Mass Transfer. Volume 45 number 11. Elsevier Science Ltd. May 2002 pp. 2278-2301

11. Wallis, Graham B and Collier John G. Two-Phase Flow and Heat Transfer, Department of Mechanical Engineering Stanford University, 1967.

12. Garth, Hutchinson, Morgan, Peeler, Spencer. Heat Exchange Research and Condensation evaluation by Utilizing a Liquid/fog Experimental Set-up. HERCULES Final Report.

13. Thermal-Hydraulics for Space Power, Propulsion, and Thermal Management system design. V.122. Edited by William J. Kzotiuk. AIAA Inc. Washington D.C, 1990.

CHAPTER 2 EXPERIMENT SAFETY EVALUATION

2.1 Flight Manifest

The HERCULES team is made up of the following team members:

Flight Day 1	Flight Day 2
Dan Passmore	Lauren Jean
Sheena Edwards	Jay Stembridge

Flight dates, in order of preference, are March 4th as the first choice, July 8th as a second choice, and July 22nd as a third choice. Lauren participated in the reduced gravity program last year as a member of "MAMMOTH Flow: Revisited" alternate flight crew. None of the other members shown above have previous experience with the reduced gravity environment on board the KC-135. Team HERCULES has requested the first choice in flight dates to coincide to our school's spring break at the request of our professors. Due to budget and logistical issues, team HERCULES also has the preference of flight group A.

2.2 Experiment Description/Background

Please refer to chapter 1 for a full description of background information by the HERCULES team.

2.3 Equipment Description

Please refer to chapter 1 for a full description of the equipment used by the HERCULES team.

2.4 Structural Design

The experiment is housed in an extruded aluminum framework. The framework will have dimensions of 24"x24"x50" and the entire experiment will weigh 248 lbs. All parts of the experiment are mounted to the frame using SAE grade 5 bolts (5/16"-18), and these same bolts are used to hold the frame together. The frame is made of one square inch extruded aluminum and then will be bolted to the KC-135's frame using four (4) NASA supplied 3/8" diameter bolts.

2.4.1 Free Body Diagrams

The free body diagrams used in this section show that the experiment as proposed is capable of sustaining the required forces without failure. The free body diagrams were drawn for the cases where the maximum load would occur, the 9g forward loading and 2g upward loading. These diagrams show that the experimental apparatus will not fail under the most strenuous loading conditions predicted and, therefore, it will also meet the loading requirements for those cases of lower stress. Figure 2.4.1 shows the loading of the entire system for the 9-g forward loading condition, where Figure 2.4.2 shows the entire system under a 2-g upward load. Figure 2.4.3 shows the entire system as subjected to a 6-g downward loading.

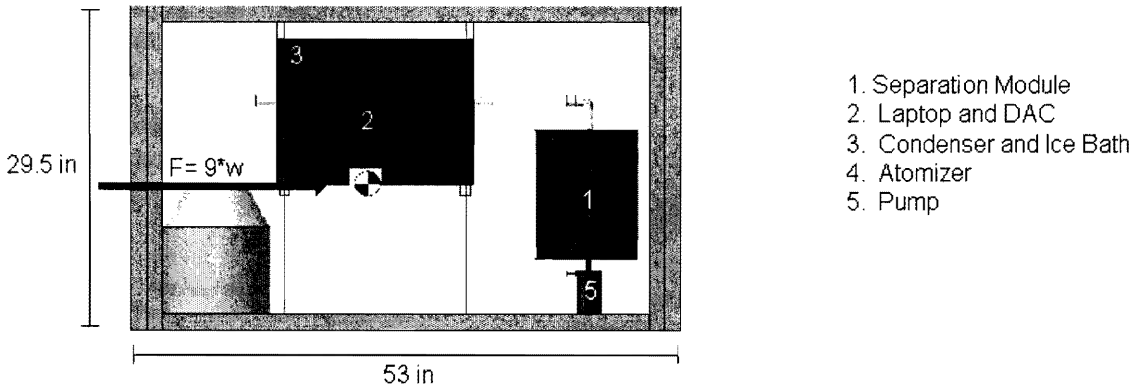


Figure 2.4.1: Free Body Diagram for 9g Forward Loading of the Complete Assembly

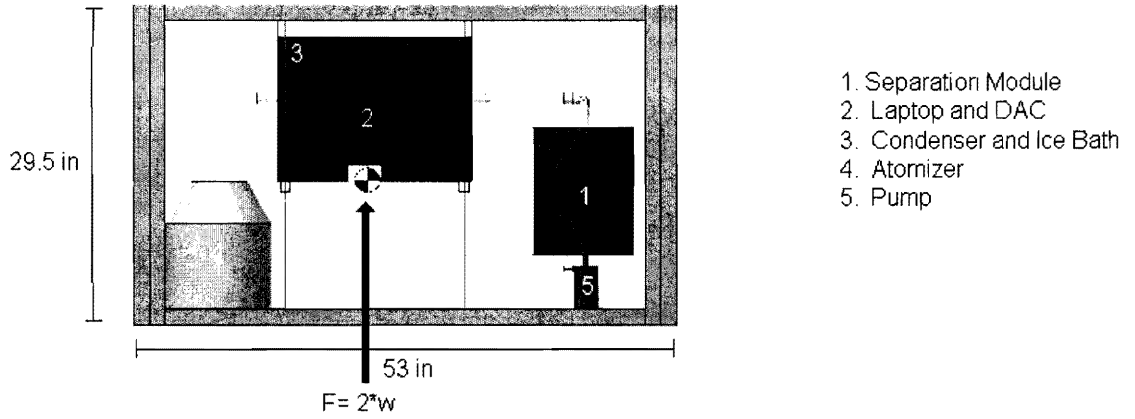


Figure 2.4.2: Free Body Diagram for 2g Upward Loading of the Complete Assembly

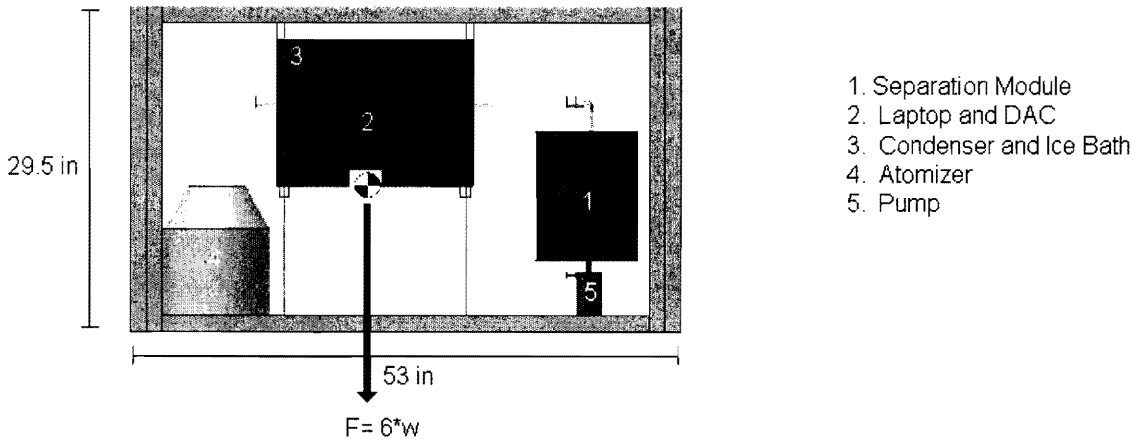


Figure 2.4.3: Free Body Diagram for 6g Downward Loading of the Complete Assembly

The center of gravity of the assembly is assumed to be at the geometrical center of the assembly. Because the heavier parts are on the lower half of the assembly, the center of gravity will actually be lower than the geometric center. However, assuming a geometric center yields a worst-case scenario, the moment arm will be longer in this condition than in the actual experimental setup. For the components attached to the frame, the free body diagrams for the heaviest component are shown. From this free body diagram, all other components attached to the frame will have the same attachments with smaller forces, so no free body diagram is needed. Figures 2.4.5, 2.4.6, and 2.4.7 show the loading cases on the MSM for the conditions of 2-g upward loading, 6-g downward loading, and the 9-g forward loading respectively.

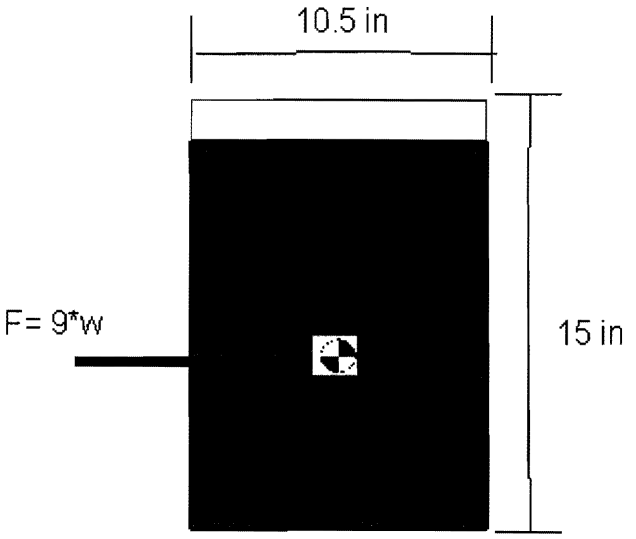


Figure 2.4.4: Free Body Diagram for 9g Forward Loading on Mesh Separator

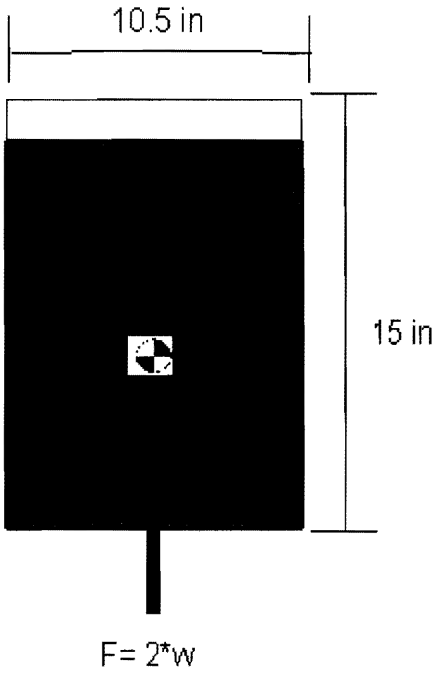


Figure 2.4.5: Free Body Diagram for 2g Upward Loading on Mesh Separator

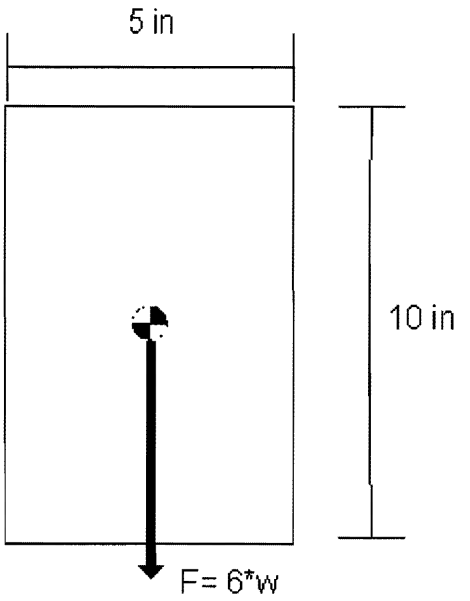


Figure 2.4.6: Free Body Diagram for 6g Downward Loading on Mesh Separator

2.4.2 Component Information

Each component's individual weight and mounting information is documented in Table 2.4.1. The given weights are rounded upward to the nearest pound.

Table 2.4.1 Individual Weights and Mounting Information for all Parts

Component	Weight (lbs)	Location on Frame
Frame	65	N/A
Condensator and Ice Bath	50	Supported from beams spanning height
Plexiglas	44	N/A
Separation Module	30	Supported from base
Piping and FRAD	10	Supported from bottom of frame
Atomizer	10	Supported from base
2 Cameras	5	Supported from top of frame
Water Pump	10	Supported from top of frame
Laptop	8	Supported from beams spanning height
Padding	5	All around frame
Surge protector	2	Resting on base
Water Heating Device	2	Supported from base
DAQ Board	1	Supported from base
Thermocouple Probes	1	Attached to piping
Air Heating Module	5	Attached to piping
Total Weight	248	

2.4.3(a) Attachment of Components

To determine if the attachment of the components to the frame is structurally sound, the Grade 5 bolts will be analyzed in tension and shear. The bolts will also be analyzed to determine the minimum engagement length of the bolt needed to prevent stripping. For these analyses, the proof strength for a Grade 5 bolt is used as the maximum allowable stress.

The minor diameter of the bolt of 0.2464 inches and the maximum component weight of 50 lbs were used to analyze the bolt in tension. From this, the safety factor for a single bolt holding the heaviest component to the frame can be found.

S_p = Grade 5 Bolt Proof Strength = 85,000 psi
$\sigma_{max} = F_{max}/A = 27 \text{ lbs} \times 9 / (\pi(.2464/2)^2) = 9437.16$ psi
$SF = S_p / \sigma_{max} = 9.01$

At 9g the heaviest component can be held to the frame with one bolt and will have a safety factor of 9.01 for failure in tension. Assuming a minimum safety factor of four, the maximum allowable force is also found.

$SF = 4 = S_p / \sigma_{max}$
$\sigma_{max} = 21{,}250$ psi
$\sigma_{max} = F_{max}/A = F_{max}/(\pi(.2464/2)^2)$
$F_{max} = 1013.28$ lbs

With a safety factor of 4, a single bolt can hold 1013.28 lbs in tension.

For failure due to shear stress, the same approach is taken. Using the minor diameter of the bolt as 0.2464, and the maximum component weight of 50 lbs, the safety factor for a single bolt holding the heaviest component in shear was found.

$S_{shear} = 0.5\ S_p$
$S_{shear} = 42{,}500$ psi
$\tau_{max} = F_{max}/A = 50 \text{ lbs} \times 9 / (\pi(.2464/2)^2) = 9437.16$ psi
$SF = S_{shear} / \tau_{max} = 4.5$

At 9g the heaviest component can be held to the frame with one bolt and will have a safety factor of 4.5 for failure in shear. Assuming a minimum safety factor of four, the maximum allowable force is also found.

$SF = 4 = S_{shear} / \sigma_{max}$
$\sigma_{max} = 10{,}625$ psi
$\tau = F_{max}/A = F_{max}/(\pi(.2464/2)^2)$
$F_{max} = 506.64$ lbs

With a safety factor of 4, a single bolt can hold 506.64 lbs in shear.

The minimum engagement length required to prevent the steel bolts from stripping through the aluminum thread must be calculated. The following equation is used, with the given values taken from the Machinery's Handbook.

$L_e = 2(A_t)/[\pi\ K_{nmax}\ (0.5+0.57735n(E_{smin}-K_{nmax})]$
$L_e = 0.1764$ in

Where

$A_t = 0.0524\ in^2 \equiv$ tensile stress area of screw thread
$K_{smax} = 0.2464$ in $\equiv$ max minor diameter of external thread
$K_{nmax} = 0.2524$ in $\equiv$ max minor diameter of internal thread
$E_{smin} = 0.2764$ in $\equiv$ min pitch diameter of external thread
$E_{nmax} = 0.2764 \equiv$ max pitch diameter of internal thread
$D_{smin} = 0.3125 \equiv$ min major diameter of external thread
$n = 18$ tpi

Because the internal threads are made of aluminum while the external threads are made of steel, the relative strength of the external and internal threads (J) must be calculated to determine if the engagement length is sufficient.

$$J = (A_s \text{ x Tensile strength of external thread material})/(A_n \text{ x Tensile strength of internal thread material})$$

$$A_s = \pi\, n\, L_e\, K_{smax}[(1/2n) + 0.57735(E_{smin} - K_{smax})] = 0.10482 \text{ in}$$
$$A_n = \pi\, n\, L_e\, D_{smIN}[(1/2n) + 0.57735(D_{smin} - E_{nmax})] = 0.15156 \text{ in}$$

$$J = (0.10482 \text{ in x } 85{,}000 \text{ psi})/(0.15156 \text{ x } 19{,}000 \text{ psi}) = 3.094$$

The engagement length required to prevent stripping is given below.

$$Q = J\,(L_e) = 0.5458 \text{ in}$$

In order to prevent stripping, every screw will have an engagement length of at least 0.5458 inches.

2.4.3(b) Assembly Calculations

It must be show that the fully assembled experiment is capable of withstanding a 9g forward load and a 6g downward load. Because these cases are the most extreme, if the frame withstands the 9g forward and 6g upward loading it will also withstand the other required loads. The frame is composed of extruded aluminum and will be attached by the same Grade 5 SAE bolts analyzed in Section 2.4.3(a).

For the 9g forward loading, the failure in the frame would result from the moment induced by the top of the structure. The total weight of the top portion of the frame, refrigerator and ice bath, piping and electronics is 70 lbs. In 9g loading that would become 630 lbs. The moment induced on the frame with a 29.5" moment arm would be 18,585 lb-in. The bolts attaching the side of the frame to the bottom of the frame would experience a 630 lb tensile load. Section 2.4.3(a) shows that each bolt can sustain a load of 1013.28 lbs in tension with a safety factor of four, so it is apparent that the bolts will not fail. The frame will experience an 18,585 lb-in moment, causing a bending stress that is found below.

M per beam = 18,585 / 4 beams = 4646.25 lb-in
σ_{max} = My/I = 2,970 x (1.5) / (1.37264) = 5940 psi
$\sigma_{yeild,extruded\ aluminum}$ = 34,800 psi
SF = $\sigma_{yeild,extruded\ aluminum}$ / σ_{max} = 5.86

The frame will hold when a 9g force is applied with a Safety Factor of 5.86.

For the 6g downward loading, the failure would result from the weight of the top of the experiment on the frame. For the bolts, this would result in a shear stress of 330 lbs. From Section 2.4.3(a) the maximum allowable force for a bolt in shear with a safety factor of four is 506.64 lbs. Therefore, the bolts will not fail in shear stress.

It is also possible that the 6g downward loading will cause the sides of the frame to fail in buckling. The maximum allowable force that the side of the frame can sustain without buckling is found below. The side of the frame is modeled as a fixed-free column for this analysis.

$$P_{cr} = \pi^2 EI/l^2$$
$$P_{cr} = \pi^2 (10{,}200{,}000 \text{ psi})(0.1853 \text{ in}^4)/(2.4 \text{ x } 24 \text{ in})^2$$
$$P_{cr} = 5{,}623 \text{ lbs}$$

$$SF = 5{,}623 \text{ lbs} / (55 \text{ lbs x } 6) = 17.0$$

In order for buckling to occur, the force required is 5,623 lbs. The maximum force that the sides of the frame will sustain is 330 lbs, at a 6g downward loading, so buckling will not occur.

2.4.3(c) Floor Attachment

The experiment will be attached to the floor of the KC-135 with four NASA supplied mounting bolts. The attachments could fail in tension, in shear, or by the bolts shearing through the experiment frame. Because the weight of the experiment is evenly distributed, the weight of the experiment will also be distributed evenly to the four bolts. According to NASA supplied information, the bolts are rated for a 5,000 lb tensile load and a 5,000 lb shear load. The safety factor for the bolts in tension is calculated for the maximum tensile loading, the 2g upward loading case.

Shear Bolt Safety Factor = 5000 lbs x 4 bolts / (248 x 9) = 8.96
Hold Down (Tension) Bolt Safety Factor = 5000 lbs x 4 bolts / (248 lbs x 2) = 40.32

The Bolts will not fail in tension or shear.

The shear force applied during the 9g forward loading is found below. From this, the safety factor for the bolts shearing through the frame can be calculated.

σ_{shear}= F / (Thickness of Frame x Diameter of Bolt x Number of Bolts)
σ_{shear}= 248 lbs x 9 / (0.372 in x 0.375 in x 4) = 4000 psi
SF = Yield Stress in Shear for Aluminum / σ_{shear} = 19,000 psi / 4000 psi = 4.75

The bolts will not shear through the aluminum frame.

2.4.3(d) Free Floating Hardware Calculations

The AERO team is not using any free-floating hardware, so no hardware calculations are needed.

2.4.3(e) Aircraft Floor Loading

The bolts will attach to the KC-135 floor via aluminum floor spacers. According to NASA supplied information, the spacers can withstand 200 lbs in 1g conditions (and 1200 lbs in 6g conditions). Therefore with each of the four spacers taking one fourth of the weight of the experiment, the safety factor for the spacers is calculated below.

SF = 200 lbs/spacer / (62 lbs/spacer) = 3.23

The experiment will not cause the aircraft floor loading to fail.

2.4.4 Safety Factor Table

Table 2.4.1 Safety Factors for all Structural Analyses

Attachment of Components to Frame		
Location	Load Case	Safety Factor
Bolts in Tension	Forward 9g	9.01
Bolts in Shear	Forward 9g	4.5
Assembly Calculations		
Location	Load Case	Safety Factor
Frame	Forward 9g	5.86
Frame	Downward 6g	6.1
Floor Attachment		
Location	Load Case	Safety Factor
NASA Supplied Bolts	Forward 9g	8.4
NASA Supplied Bolts	Upward 2g	40.32
Frame (bolts shear through)	Forward 9g	4.75
Aircraft Floor Loading		
Location	Load Case	Safety Factor
NASA Supplied Spacers	Downward 6g	3.23

2.4.5 Component Pull Test Documentation

The HERCULES team has not performed any pull tests on any components, so not pull test documentation is needed.

2.4.6 Component Pull Test Documentation

The HERCULES team has not performed any pull tests on any components, so no pull test documentation is needed.

2.5 Electrical Analysis

2.5.1 Schematics

The setup of the electrical system for the experimental apparatus is detailed in figure 1, which shows the voltage and current required by each component of the system. It is divided into two main busses named A and B. Each bus is a surge protector with a 120-Vac operating voltage and a 15-A maximum current.

2.5.2 Load Table

Table 2.5.1 Electrical Power Source and Power Loads

Power Source		Load Analysis	
Name	Bus A	CAH	.833 A
Voltage	120	WP	.18 A
Frequency	60	Flow Meter	
Wire Gage	12	TCs x 12	1 A
		Laptop	1.5 A
Current Supply	15	Current Draw	3.51 A
Name	Bus B	Heaters x 6	10 A
Voltage	120	Air Heater	5 A
Frequency	60		
Wire Gage	12		
Current Supply	15	Current Draw	15 A
Name	Laptop		
Voltage	100-240 Vac		
Frequency	50-60		
Wire Gage	18		
Current Supply	1.5 A	Current Draw	
		Aircraft Power Requirement	
		Current Draw	18.51 A

2.5.3 Emergency Shutdown Procedure

An emergency shutoff switch will be affixed to the apparatus, allowing it to be immediately disconnected from the aircraft power supply, shutting down all portions of the experiment except for the computer, which operates on a battery. The switch will be placed near the laptop, easily reached by either member of the flight crew. Once the experimental system is disconnected, the crew members will switch all individual systems to their respective off modes. Before reactivating the system, the crew will perform a complete visual inspection, to make sure that all systems are down and that no damage previously incurred would prevent the system's operation.

2.6 Pressure Vessel Certification

This experiment is classified as a category E Pressure Vessel because of the components being used in the experiment. There are two primary pressure systems, an air system and a water system. The air system is composed of a Hydrofogger, which is a commercially manufactured ventilation system and will be used for its express purpose in this experiment. Therefore, the air system is considered to be a Category E classification. The water system also meets the requirements of a Category E classification (less than 150 psig max pressure and less than 110° C max Temperature).

2.7 Laser Certification

Team HERCULES does not need the use of any Lasers in this experiment.

2.8 Crew Assistance Requirements

Team HERCULES does not require any special attention from the reduced gravity office or the test directors before, during, or after the flight.

2.9 Free Float Requirements

Team HERCULES does not have any free floating parts associated with the proposed experiment.

2.10 Institutional Review Board (IRB)

Team HERCULES does not perform any biological testing.

2.11 Hazard Analysis

Hazard Number: 1
Title: Failure of the Superstructure

Hazard Description:

In the event that failure occurred in the superstructure, the system would collapse resulting in failure of the experiment. The risk would be due to floating debris, including components and fluid.

Hazard Cause(s):

1) Unsecured fasteners
2) Overstressed fasteners
3) Impact of superstructure to fuselage

Hazard Control(s):

Numerous calculations were made during the design process to ensure that failure would not occur. All materials that are used will meet industry standards.

Hazard Number: 2
Title: Fluid Leakage

Hazard Description:

The fact that we are circulating distilled water through a closed system; there are many pipe/hose connections that are critical to the experiment. A possibility exists that a fitting could break apart or loosen, causing water to escape from the system. In addition, fluid leakage near electrical devices can result in personnel shock, which will be addressed next.

Hazard Cause(s):

1) Inadequate Design
2) Accidental impact to system
3) Pressure build-up

Hazard Control(s):

The design indicates that all system components and piping will be located centrally in the superstructure, isolating it from personnel with distance. All piping/tubing will meet industry standards. All joints will be properly sealed and checked before flight. In the previous run of HERCULES, leakage occurred in the region of the viewing port at the end of the test section. Improvements have been made to prevent backflow and leakage due to excess pressure.

Hazard Number: 3
Title: Electrical Shock

Hazard Description:

Several electrical devices will be used in the experiment. With this, a possibility exists that a crewmember may be shocked.

Hazard Cause(s):

1) Frayed wires/cables
2) Improper connections at electrical devices
3) Uncovered power strip outlets
4) Fluid on a device

Hazard Control(s):

The experiment will be equipped with a surge protector and master kill switch. There is a built in circuit breaker that will shut down the experiment in the event

of a power surge through the aircraft. Prior to flight, all cords/cables will be inspected and replaced or corrected if necessary. All unused power strip outlets will be plugged with a plastic stopper to prevent the entry of any foreign objects.

Hazard Number: 4
Title: Sharp Corners on the Superstructure

Hazard Description:

The superstructure will be made up of extruded aluminum beams. It is configured as a cube, with eight exposed potentially sharp corners, and numerous 90-degree angles of the beams.

Hazard Cause(s):

1) Nature of design.

Hazard Control(s):

All exposed aluminum of interest will be shielded with a foam rubber padding, with emphasis on the corners.

Hazard Number: 5
Title: Burning of Personnel

Hazard Description:

Since the air inlet and a section of the pipe itself will be heated, a danger exists that a crewmember may be burned due to contact.

Hazard Cause(s):

1) Exposed surface

Hazard Control(s):

The majority of the system will never reach a temperature to be of concern. The air inlet however, will be insolated, shielding the personnel from danger. In addition the heater will be located away from the perimeter of the superstructure. The water heater will have sufficient insulation and shielding that the possibility of a burn will be drastically reduced as well.

Hazard Number: 6
Title: Overheating of Components

Hazard Description:

In the experiment, the inlet air will be heated. This section has a heating element in its center. It requires a minimal flow rate in order to keep the element from overheating and burning out or causing a fire.

Hazard Cause(s):

1) Inlet restricted

Hazard Control(s):

The heater will be equipped with a constraint that limits minimal inlet area of the system. All efforts will be made to ensure that foreign objects to not impede the inlet air.

2.12 Tool Requirements

Tools Being Carried During Flight
1. Duct Tape
2. Miniature (3mm) Flat Head Screwdriver
3. Zip Ties
4. Plastic Storage Bags With Sponges/Paper Towels Inside

Tools Being Brought to Reduced Gravity Facility (the above plus the following)
1. PVC Sealing Compound
2. PVC Hand Saw
3. Various Wrenches
4. Various Pliers
5. Various Clamps
6. Electric Drill
7. Various Drill Bits

No tools will need to be borrowed from the Reduced Gravity Office (RGO).

The HERCULES team will label all tools that are brought to Houston by marking them clearly. An easily readable and clearly marked inventory list will also accompany the above tools.

2.13 Ground Support Requirements

Team HERCULES requests the use of a standard freezer in order to maintain approximately 1.5 ft^3 of ice. This ice will be used to create the temperature gradient necessary for the desired measurements to be made.

2.14 Hazardous Materials

Team HERCULES does not utilize any hazardous materials in this experiment.

2.15 Experiment Procedures Documentation

2.15.1 Ground Operations

Upon arrival in Houston, the experiment's construction will be 85% complete. No major assembly work will be required with the exception of a few details, such as padding, electrical connections, and general safety inspections to ensure that there are no loose nuts/bolts, etc. that would create a potential for FOD (Foreign Object Damage). The experiment will then be inspected and tested by both flight and ground crew members upon arrival at Ellington Field. In preparation for the Test Readiness Review, team members will require access to at least one gallon of water, one standard size bag of ice, a small box of rock salt, 18-A electrical power, and a location to test all mechanisms for securing the apparatus to the aircraft floor.

The following procedure will be observed by all team members for construction and testing of the apparatus prior to flight:

1. Electrical connections of components: once all components are mounted, all electrical connections will be made. Each system will then be tested individually to ensure proper connections have been made.

2. Full power electrical testing: once each component has been properly connected, the entire system will be powered up simultaneously. During this testing the master switch (which controls power to the entire apparatus) will also be tested to ensure that it is functioning correctly.

3. Fluid system testing: upon successful completion of the full power test, the water will be introduced to the system and testing will be conducted on all pipe fittings and measurement systems.

4. Full system test: once all systems are operational, a complete series of test cycles will be run and data collected. This data will then be compared to data collected prior to arrival at Ellington field.

2.15.2 Pre-Flight

1. Load and secure experimental apparatus.
2. Ensure master switch is off.
3. Ensure all component switches are off.
4. Make all required electrical connections.
5. Adjust both flow control valves on FRAD to initial test positions.
6. Adjust air and water heaters to initial test positions.
7. Fill MSM with water, up to the watermark.
8. Fill bladder inside cooling module with ice and salt solution.
9. Visually inspect all structural, electrical, and pneumatic connections for abnormalities.
10. Secure any loose connections.
11. Flush water through pump until MSM drops to primed mark.
    (This ensures that the hydrofogger and water injector have water when the experiment is started.)

12. Ensure all fluid valves are closed and locked into place using zip-ties.
13. Remove all tools and peripheries used in set-up that will not be used in flight.
14. Visually inspect work area for FOD.

2.15.3 In Flight

The laptop computer on the apparatus will remain powered-up during take-off due to its long start-up time. The computer will not draw electrical power from the aircraft at this time, but will run on its internal battery until in-flight experimentation is ready to begin. During landing, all systems including the laptop computer will be powered down.

1. Visually inspect apparatus for loose connections, leaks, or other abnormalities.
2. Open cooling module lid and visually inspect ice bath bladder for leaks and ensure that the ice bath is evenly distributed around the pipe. Then, close and secure the lid.
3. Turn on master switch.
4. Turn on water pump.
5. Turn on water heater
6. Turn on Hydrofogger and adjust to correct position
7. Turn on component circuits
8. Start Data Acquisition Procedures

2.15.4 Post Flight

To prepare the experiment for the next day□s flight, the water MSM may need to be partially replenished. Also, water from the ice bath will need to be drained and the bladder cleaned out for the next pre-flight. Visually inspect apparatus for damage, abnormalities or FOD.

CHAPTER 3 OUTREACH PLAN

3.1 University Outreach

The Aerospace Education Research Organization (AERO) was founded in 2001 in order to provide students with the opportunity to get involved with exciting research as well as help educate the community about current aerospace research. This year, AERO has had several meetings and membership is steadily increasing. AERO not only consists of aerospace engineers, but also involves computer science, biomedical engineering, physics and mechanical engineering majors in this project. The organization plans to host social and educational events on campus and around the community. Also, to further educate the student body, AERO has set up a micro gravity exhibit in a main display case in the Dougherty Engineering Building. This organization offers opportunities for students to get involved with NASA's Reduced Gravity Flight Opportunity, Human-Powered Moon-buggy, Space Academy, and AIAA design competitions. Information about this organization for students interested in joining AERO can be found at the club's website: http://web.utk.edu/~aero.

The reduced gravity project has been approved as both an independent research project and previously as a senior design project. The team plans several different ways of reaching the university's student population. The team will speak to freshman engineering students involved in the University of Tennessee's Engage engineering

program about AERO and the reduced gravity project and offer them the opportunity to become involved in the activities. The team plans to participate in this year's Exhibition of Undergraduate Student Research Fair that is held in April 2004. The results of the team's work will also be presented in a graduate seminar in the Mechanical, Aerospace, and Biomedical Engineering Department. The team will give short overview presentations of the project to the student clubs on campus, including but not limited to the following: Tau Beta Pi, American Institute of Mechanical Engineers, and The American Institute of Aeronautics and Astronautics. The team will follow with a more technical and detailed presentation at a later date for interested students.

The student newspaper on the University of Tennessee campus, *The Daily Beacon*, has been contacted to run a story on the project as well as the AERO organization. The *Knoxville News Sentinel* will be contacted and made aware of the project and the team's participation in the NASA Reduced Gravity Flight Opportunity. In addition, the yearbook staff has contacted us and has asked for pictures and more information for the 2003 yearbook. The honors program here at the University of Tennessee puts out a newsletter, *The Compendium*, and they too have expressed a great interest in our project. In September 2003 *U.S. News & World Report* published a picture of last year's HERCULES experiment onboard the KC-135 in their report of the University of Tennessee (see attached article). Team HERCULES plans to contact the local news affiliates for radio and television opportunities.

3.2 Community Outreach

Team HERCULES plans to educate our community about micro gravity research and other aspects of aerospace engineering. This outreach will be achieved by taking trips out to area high schools and middle schools and explain aerospace engineering using our project as an example. We plan to give a short presentation with video and pictures from previous years and a scientific overview of microgravity and the problems involved with it, and then we will have the class become involved in a short experiment from the NASA website, http://spacelink.nasa.gov. Last year's team saw a great response from the students when they were shown the video of the accelerometers they made attached to our project in flight. The response prompts this year's team to repeat along a similar route. The presentations and following experiment will be slightly different for the separate age groups, going into more scientific detail with the high school level. Perry County High School will be visited in December for a presentation to Mrs. Michelle Williams's senior physics class. Some schools also being considered include Karns High School, Bearden Middle School, Farragut High School, and Farragut Middle School. Also, middle schools and high schools in Knoxville's surrounding areas, such as Seymour, Sevierville, and Gatlinburg will also be considered.

On October 21st, 2003, the team will set up a booth at the Engineering's Day, an annual on-campus exhibit that showcases many different types of engineering projects to over 1,000 visiting high school students. A display about AERO and team HERCULES will be set-up for "Red Carpet Weekend", an on-campus event for high-school seniors to

learn about the College of Engineering. In the spring of 2003, team HERCULES participation in "Girl Scouts Discover-E Sunday" was a success. The team plans to participate in this event again in the year of 2004, because it educates young women, ages 11-17, about the opportunities available in engineering. Destination Imagination, the Science Olympiad, and the Science Fair are also being considered as places to reach out to our future engineers and encourage their interests in the sciences.

CHAPTER 4 ADMINISTRATIVE

4.1 Institutional Letter of Endorsement

Original signed copy can be found in appendix B.

4.2 Statement of Supervising Faculty

Original signed copy can be found in appendix C.

4.3 Funding/Budget Statement

The HERCULES team plans to receive $4500 from the Tennessee Space Grant Consortium upon acceptance into the 2004 RGSFO campaign. This money will be used as shown in Table 4.3.1. The total proposed expenses, seen in Table 4.3.1, shows an overestimation of maximum cost for all aspects.

Table 4.3.1 – Proposed Budget For Team HERCULES

Personnel

Expense	Quantity	Price	UT Cost Share	Industry Funding	Notes
Transportation	1	$ 90.00		$ 990.00	Van Rental for 11 days
Trailer	1	$ 10.00		$ 110.00	Trailer Rental for 11 days
Accommodations	1	$ 75.00		$ 825.00	Based on 10 day stay
Food & Expenses	5	$ 30.00		$ 1,500.00	Based on 10 day stay
TOTAL			**$0.00**	**$ 3,425.00**	Could decrease due to length of stay

Experimental Apparatus

Equipment	Quantity	Price	UT Cost Share	Industry Funding	Notes
Piping/Connections	Mult.	$ 100.00		$ 100.00	PVC
Air Heater	1	$ 50.00		$ 50.00	
Polycarbonate Sheet	2	$ 25.00		$ 50.00	
Various Hardware	1	$ 50.00		$ 50.00	Bolts, Washers, nuts, etc.
Padding	1	$ 50.00		$ 50.00	
Thermocouples	3	$ 20.00	$ 60.00		One package contains 5, need 12
Humidity Measurement Device	1	$ 500.00		$ 500.00	
Laptop Computer	1	$1,600.00	$ 1,600.00		Laptop provided by CFD Laboratory
Laptop A/D Board	1	$ 500.00	$ 500.00		
Accelerometer	1	$ 300.00	$ 300.00		
Miscellaneous	1	$ 200.00		$ 200.00	Unexpected costs
TOTAL			**$ 2,460.00**	**$ 1,000.00**	

TOTAL PROGRAM COST

UT Cost Share	**$2,460.00**	UT Cost Share provided through use of existing university owned equipment.
Industry Funding	**$4,500.00**	Funding to be provided from Engineering Development Office Corporate Sponsors.
Total Program Cost	**$6,885.00**	Could significantly decrease based on length of stay.

4.4 Institution Review Board (IRB)

Team HERCULES is not testing any humans or animals in this experiment.

4.5 NASA/JSC Human Research Subject Consent Form

Team HERCULES is not testing any humans or animals in this experiment.

4.6 Institutional Animal Care and Use Committee (IACUC)

Team HERCULES is not testing any humans or animals in this experiment.

4.7 Parental Consent Forms

All members of team HERCULES are over the age of 18 and therefore this section does not apply.

Appendices

A. Participant Information

The required photo identification and signature forms are all provided in this section. For proof of undergraduate status please refer to the included photo identification, which includes current student identification cards for all members of team HERCULES. Upon acceptance into the program a professional journalist will be designated for the team.

B. Institutional Letter of Endorsement

C. Statement of Supervising Faculty

NASA REDUCED GRAVITY STUDENT FLIGHT OPPORTUNITIES

H.E.R.C.U.L.E.S. Returns

"Heat Exchange Research and Condensation (evaluation) by Utilizing a Liquid/fog Experimental Set-up-Returns"

TEST EQUIPMENT DATA PACKAGE

Topic Area: Heat Transfer / Fluid Dynamics

University of Tennessee, Knoxville
Department of Mechanical, Aerospace, and Biomedical Engineering
414 Dougherty Engineering Building
Knoxville, TN 37996

Faculty Advisors:
Dr. Viatcheslav Naoumov
Professor, MABE
nvi2000@mail.ru /(865) 974-7675
vnaoumov@utk.edu

Dr. Masood Parang
Professor, MABE
mparang@utk.edu /(895) 974-5259

Team Contact:
Sheena Edwards
Flight Crew
Junior, Biomedical Engineering
sedwards@utk.edu / (865) 595-6345 / (901) 336-4530

Team Members:
Lauren R. Jean*
Flight Crew
Alternate Flight Crew, Spring 2003 Campaign
Junior, Computer Engineering
ljean@utk.edu / (865) 394-9201

Jay Stembridge
Flight Crew
Junior, Computer Engineering
jstembri@utk.edu

Dan Passmore
Flight Crew
Junior, Physics
dpassmo1@utk.edu

Nathan Fortner
Alternate Flight Crew
Sophomore, Aerospace Engineering
nfortner@utk.edu

Faculty Adviser Endorsement:
"As primary faculty advisor for the HERCULES undergraduate student research project, I endorse the submission of this proposal."

Dr. Viatcheslav Naoumov, Professor, MAES — Date

KC-135 QUICK REFERENCE DATA SHEET

Principal Investigator:	Dr. Viatcheslav Naoumov vnaoumov@utk.edu Adjunct Professor, MABE (865)974-7675
Contact Information:	606 Dougherty Engineering Building MABE Department University of Tennessee Knoxville, TN 37996-2200
Experiment Title:	Heat Exchange Research and Condensation (evaluation) by Utilizing a Liquid/fog Experimental Setup (HERCULES)
Flight Week:	March 4, 2004 through March 14, 2004
Overall Assembly Weight:	248 lbs.
Assembly Dimensions:	50" L x 24" W x 24" H
Equipment Orientation:	50" dimension should run forward to aft
Proposed Floor Mounting Strategy:	Bolts and Spacers
Gas Cylinder Requests:	None
Overboard Vent Request:	Yes
Power Requirement:	115 VAC, 20.1 A
Flyer Names for Each Day:	Day 1: Lauren Jean, Sheena Edwards Day 2: Jay Stembridge, Dan Passmore

TABLE OF CONTENTS

Quick Reference Sheet 2

Chapter 5 Test Equipment Data Package Requirements

5.1 Flight Manifest 4
5.2 Experiment Background 4
5.3 Experiment Description 7
5.4 Equipment Description 10
5.5 Structural Analysis 17
5.6 Electrical Analysis 27
5.7 Pressure Vessel Certification 30
5.8 Laser Certification 34
5.9 Parabola Details and Crew Assistance 34
5.10 Free Float Requirements 34
5.11 Institutional Review Board (IRB) 34
5.12 Hazard Analysis 35
5.13 Tool Requirements 41
5.14 Photo Requirements 42
5.15 Aircraft Loading 43
5.16 Ground Support Requirements 43
5.17 Hazardous Material 44
5.18 Material Safety Data Sheets (MSDS) 44
5.19 Experiment Procedures Documentation 44
5.20 Bibliography 47

List of figures

5.3.1- Comparison of Microgravity and Gravity Data
5.4.1 – Flow loop schematic
5.4.2 – Schematic of Separation Module
5.5.1 – Free body diagram for 9-g forward loading on complete assembly
5.5.2 – Free body diagram for 2-g upward loading on complete assembly
5.5.3 – Free body diagram for 6-g downward loading on complete assembly
5.5.4 – Free body diagram for 9-g forward loading on cooler
5.5.5 – Free body diagram for 2-g upward loading on cooler
5.5.6 – Free body diagram for 6-g downward loading on cooler
5.6.1 – System Circuit Diagram and Specifications
5.7.1a – Atomizer schematic
5.7.1b – Atomizer dome schematic
5.7.2 – Pressure Vessel free body diagrams

List of tables

5.5.1 – Individual Weights and Mounting Information for all Parts
5.5.2 – Safety Factors for all Structural Analyses
5.6.1 – Load Analysis
5.11.1 – Hazard Identification Table

5.1 Flight Manifest

The HERCULES team is made up of the following team members:

Flight Day 1	Flight Day 2
Lauren Jean	Dan Passmore
Sheena Edwards	Jay Stembridge

Lauren participated in the reduced gravity program last year as a member of "MAMMOTH Flow: Revisited" alternate flight crew. None of the other members shown above have previous experience with the reduced gravity environment on board the KC-135. Team HERCULES wishes to be placed in flight group A for monetary and logistical reasons.

5.2 Experiment Background

Future space colonies, spacecraft, and other extraterrestrial applications provide the motivation for large-scale power generation in the absence of gravity. The Rankine cycle is one of extreme interest because it takes advantage of the large available heat transfer due to a phase change in the form of evaporation and condensation. However, it is inherently more difficult to deal with two-phase flows in microgravity conditions due to the affects of surface tension, wetting forces, and the drastic decrease of buoyancy forces.

In the annular flow regime, condensate film forms on the periphery of the tube (Lu 15). When the saturated vapor first enters a cooled section of pipe, it begins to condense along the walls of the pipe in the form of droplets. This is due to the transfer of heat by natural and forced convection to the wall from the saturated vapor. Once the droplets begin to

form on the surface of the pipe there is an added convective heat transfer between the formed liquid droplet and the wall. As the two-phase mixture continues to flow inside the cooled pipe, it is continuously being cooled and condensed. As stated by Lixin You and Hongtan Liu, inside the two-phase region, the liquid saturation increases along the flow direction (International Journal of Heat and Mass Transfer: *A two-phase flow and transport model for the cathode of PEM fuel cells*). Therefore, the film thickness will also increase in the direction of the flow. The only force that is creating the movement of the fluid film in microgravity is the shear force that acts upon the film as imposed by the vapor flowing in the middle of the pipe. Thus, the movement of the liquid film is relatively slow.

There are two basic forms of condensation that are of interest: drop-wise and film-wise. Drop-wise condensation occurs when the cooling surface is not easily wetted, and film-wise condensation occurs when the cooling surface is easily wetted (Wallis), or when the vapor does not contain enough liquid to sufficiently form a liquid film around the entire inner surface of the cooling pipe. In drop-wise condensation, liquid drops condense and roll over the cooling surface as they grow (Wallis). This growth, and movement allows for other vapor particles to come in contact and exchange heat with the cooling surface. Film-wise condensation essentially operates in the same manner except that as the vapor is condensed, the liquid tends to stick to the inner wall of the pipe due to wetting forces and insulate the wall from the rest of the vapor flow.

The liquid film on the inside of the pipe poses a problem with the exchange of heat between the liquid film and the cooled surface because it does not allow the vapor inside the pipe to come in contact with the wall as in the normal gravity condition. This would lead one to expect that the heat flux between the liquid film and the wall will be greater in the conditions of microgravity. Excluding the latent heat of condensation, there are two heat fluxes that are important. First is the heat flux that is associated with the heat transfer between the liquid water and the pipe, and the second is between the forced flow of the vapor and the cooling surface of the pipe. In microgravity conditions, the liquid will have an increased heat flux due to the hypothesized formation of annular flow, and therefore, the formation of a greater contact area with the cooling surface. However, the heat flux associated with the vapor will be decreased because when annular flow is established there will be a liquid barrier on the inside of the pipe and the vapor will not come in contact with the cooling surface. Defining the temperature difference as the change in temperature from the inlet to the exit of the cooling section the anticipated results are that the temperature difference in the condensate will be greater in the conditions of microgravity while the temperature difference associated with the vapor will be smaller. This means that the condensate that exits the cooling section will be colder in the conditions of microgravity, while the temperature of the vapor will be warmer due to the decreased surface contact with the cooling surface.

The complete condensation of a saturated water vapor would require water to be boiled and steam generated in the conditions of microgravity in order to produce the saturated water vapor. The issues surrounding film boiling and the previously mentioned

difficulties with the associated two-phase flow make it impractical to expect reasonable results with so many variables at this time. Therefore, in order to simplify the experiment, eliminate unnecessary hazards, and to reduce the overall cost, this experiment will attempt to simulate the dynamics of condensation using an air and water mixture as opposed to generating the condensate from vapor.

5.3 Experiment Description

The experiment is designed to simulate condensation in microgravity, which is done by pumping a liquid fog mixture through a cooling section. The liquid starts in a separating module, moves through a heated section of pipe, and splits into two flows. One flow moves to the atomizer, where it is mixed with the air to create an atomized fog. The rest of the liquid flows through the pipe and is inserted in the atomized flow to simulate the beginning of the condensation process. Then this combined flow continues through the pipe into the condenser. After the combined fluid flows through the condenser, it flows through a portion of clear pipe for observation and then back into the separation module. The observation portion and the condenser together make up the test section (TS).

One goal of this experiment is to gain a better understanding of the condensation process in microgravity conditions. While limitations on the working fluid and temperature ranges have prevented the use of a single material to perform actual condensation, the simulation of the condensation process should yield similar results. It is predicted that the heat transfer in microgravity from the condenser to the fluid will be higher, because the fluid will conform to an annular flow pattern. However, because the liquid coats the

entire pipe, there will be no contact between the vapor and the pipe, thus limiting condensation, and the ability of the air to be cooled.

In the previous run of this experiment, it was shown that these assumptions were indeed correct as seen in Figure 5.3.1. When annular flow was established, there was indeed an increased heat transfer from the water to the cooled pipe and a drastic decrease in heat transfer from the fog to the cooled pipe. Therefore, it is logical to conclude that the condensation process under the conditions of microgravity will produce less condensate than in normal gravity.

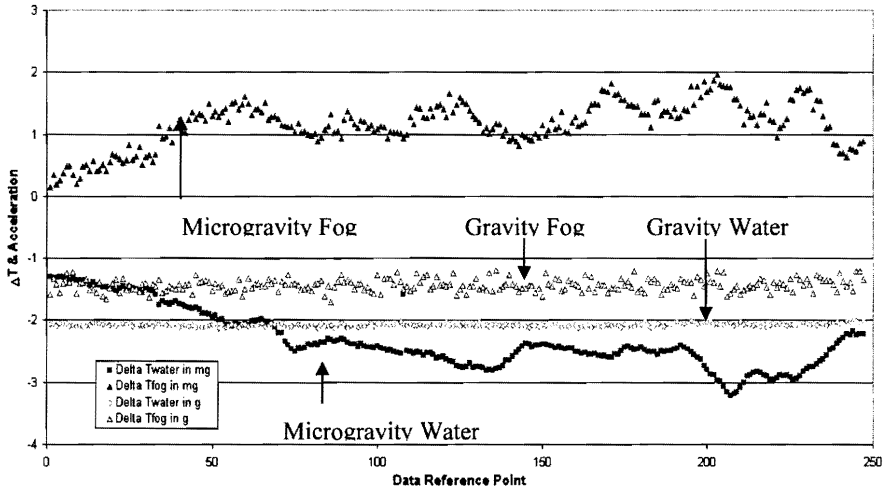


Figure 5.3.1 – Comparison of Microgravity and Gravity Data

A second objective of this experiment is to equalize the temperature of the water and the fog to more accurately simulate the heat exchange between the fog and the water and the water and the pipe. In the previous run of this experiment, the fog and water entered the condenser at different temperatures and heat was transferred between the heated water and unheated fog during the data acquisition stage thus changing the results. With the

temperatures equalized, this heat transfer should be minimized thus obtaining more accurate data. At the present time, our team is considering two different options for equalizing the temperatures. The first option is to add a heating device between the atomizer and condenser to raise the temperature of the fog to that of the water, approximately 85 ° Fahrenheit. The second option is to hold the temperature of the water and the fog at room temperature and lower the temperature in the condenser thus increasing the heat transfer between the pipe and the water flowing along it. To achieve this lower temperature, the ice in the cooler will be exchanged with solid CO_2 at -109.3 ° Fahrenheit. Due to sublimation of the CO_2, gas will be vented into the aircraft as detailed in section 5.11.

The third objective of this experiment is to investigate the influence of the ratio of the water to fog. The changing of this ratio will result in the changing of flow regimes, which will drastically change the heat transfer possibilities of the system. This will also provide excellent visual data of the formation of different condensation driven flow regimes such as annular, drop-wise, and slug flows.

The fourth objective of this experiment is to measure the absolute temperature of the fog and water before the cooling section and the change in temperature of the liquid and fog as they exit the cooling section by inserting thermocouples into the flow. It was hypothesized in last year's HERCULES proposal that the simulated liquid condensate in gravity conditions will be warmer than that in micro gravity conditions due to the increased surface area that is in contact with the cooling element in micro gravity

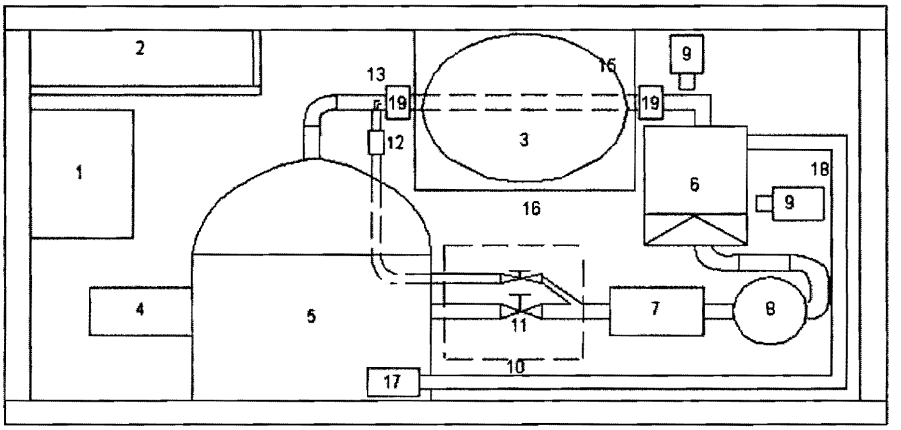
conditions. The results from last year's experiment provided the primary data that confirmed this hypothesis (12).

The fifth objective is to measure the humidity of the fog in order to investigate the rate of condensation. Again, this will be accomplished by adding specialized thermocouples throughout the condenser that will acquire the necessary data.

The sixth objective is to obtain digital photographs of the flow patterns simulated in microgravity in the transparent section of piping and in the Separation Module. These could then be analyzed and compared with the predicted flow patterns and with other published data on this subject.

5.4 Equipment Description

The experiment apparatus consists of four systems comprised of five major components that operate automatically and continuously throughout each test cycle as detailed in Figure 5.4.1. The four systems are: the fluid transfer system, water/fog injection system, condensation system, and the data acquisition system. The five major components are the Separation Module (SM), pump, fluid heater, atomizer, and cooling module.



1	Electrical Box	6	SM	11	Variable Valve	16	Cooling Module
2	Laptop Station	7	Water Heater	12	Flow Meter	17	Small Water Pump
3	Ice Bath	8	Pump	13	Water Injector Nozzle	18	Water Bypass Pipe
4	Air Intake Heater	9	Digital Cameras	14	Flow Observation Section	19	Humidity Measurement Device
5	Hydrofogger	10	FRAD	15	Bladder		

Figure 5.4.1 – Project Schematic

The fluid transfer system begins and ends at the SM. From the SM, water is pumped through an incremental flow valve and through a series of heating bands, which raises the water temperature. From there, the water travels across the flow regulator and divider (FRAD). At this point, the water is separated into two flows with variable flow rates. Two ball valve flow regulators inside the FRAD individually control the flow rates of the separated flow. After the flow is separated the water continues to flow along two separate paths. One path travels to the atomizer intake and the other path travels directly to the flow loop where it is injected into the flow stream by an injector nozzle. As described above, only 5.3% of the fog exiting the atomizer will be directed through the TS. The fog exiting the atomizer is separated into two streams of which one is vented outside the aircraft and the other passes through the TS where it is rapidly cooled. The

water vapor leaving the atomizer passes through a check valve where it is combined with the water injected on the exit side of the atomizer. The water to vapor ratio can be easily altered by varying the two valve positions in the FRAD. Thermocouples are located before and after the cooling section as well as in the fog leaving the atomizer. By using this setup it is possible to know the exact temperature of the mixture that is being used to simulate a saturated vapor. It is also possible to measure the change in temperature of the condensate in microgravity conditions, which can then be compared to those gathered in gravity conditions. After passing through the condenser, the mixture travels through a short section of clear pipe for observation. This section allows for visual confirmation of the boundary layer conditions and recognition of the desired flow regimes. The condenser and the clear pipe make up the test section in which the condensation simulation will take place. A check valve is located at the end of this clear pipe, leading directly into the SM.

The water/fog injection system creates a variable controlled mixture of water and vapor, which passes through the condenser. Water is delivered to the atomizer intake via the fluid transfer system and air is fed to the atomizer through the heated air intake. The atomizer combines the air and water to form a heavy fog. The fog then exits the atomizer and passes through a check valve and through a set of thermocouples to measure the temperature of the fog. The fog is then combined with injected water delivered by the fluid transfer system. After the water is injected into the air it is passed along to the condenser.

The condensation system is made up of a straight piece of copper pipe, which passes through a cooling module. The cooling module consists of a well-insulated housing filled with ice to provide rapid cooling as detailed in the calculations. The cooling module contains a bladder, which surrounds the copper pipe and contains a mixture of salt and ice to form an ice bath. The ice bath is used to cool the copper pipe and thus the fluid as it passes through the cooling module. The insulation of the cooling module helps to maintain constant temperature for the ice bath. A set of thermocouples is placed at the entrance and exit plane of the cooling module. As the fluid mixture passes through the copper pipe, going through the cooling module, the temperature of the mixture is rapidly reduced to provide cooling for condensing. The regular ice bath may be replaced with a dry ice bath depending on further ground testing at our home facility. If the dry ice bath is used, the air inserted into the atomizer will not be heated. The dry ice bath will be vented with extreme care that no moisture is released into the cabin due to the high altitudes achieved while in flight.

The data acquisition system consists of two sets of four thermocouples and one set of two thermocouples, a flow meter, two cameras, a humidity measurement device, and a laptop computer. The humidity measurement will be taken after the fog mixture leaves the atomizer and after it leaves the condenser in order to get the data about the rate of condensation. The thermocouple sets are placed in pairs at the following locations: a system of four thermocouples installed in the inlet and outlet sections of the condenser at 90° increments for the measurement of the change in temperature of water, and two thermocouples are also installed in the inlet and outlet sections of the condenser measure

the change in the temperature in the fog. Since the liquid and fog temperature difference across the condenser will be on the same order as the uncertainty of a typical thermocouple, the corresponding sets of thermocouples before and after the condenser are connected to the same amplifier and will be set to read the difference in temperature of water and fog. The flow meter will be located on the path of the flow divider that contains only water. The two cameras are mounted at 90-degree angles (with respect to one another) one looking at the pipe from the side and one looking inside the Separation Module. The thermocouples and flow meters are connected to the laptop for data collection and recording throughout each test cycle. The camera records visual data of the boundary layer of condensate flowing out of the condenser.

The SM is a passive separation system that works on the three main principles of centrifugal forces, surface tension, and wetting forces. The water and air mixture from the flow loop enters the SM tangent to the inside wall. Since the SM will be a cylindrical tank, the walls will be curved and the water will be forced to follow the curvature of the tank due to the momentum that it has been given by the pump. Because of this centrifugal action the heavier water will be pulled into the wall, thus separating it from the lighter air.

While this centrifugal action will separate the water from the air it will not provide the sufficient forces for the pump to operate properly, and ensure the pumping of only liquid water. Therefore, the tank will have a mesh system in the bottom that will hold the water at the inlet of the pump through wetting forces and surface tension as seen in Figure

5.4.1. The holes in the mesh will be small enough that the water will be pulled through the mesh in the high gravity portion of the flight but will not permeate through the mesh during the low gravity portion. The total amount of water that will be pumped through the system throughout a 30 second parabola is 0.58 gallons. Therefore, the mesh system in the bottom of the tank will contain approximately 0.65 gallons of water to allow for a liquid coating of the inside of the tank to occur. However, the total volume of the SM will be 3.5 gallons as detailed below.

Total length of one-inch diameter pipe: 100 inches

Total length of half-inch diameter pipe: 50 inches

Flow loop volume:

$$\frac{\pi}{4}\left(\frac{1}{12}ft\right)^2\left(\frac{75}{12}ft\right)+\frac{\pi}{4}\left(\frac{0.5}{12}ft\right)^2\left(\frac{25}{12}ft\right)=0.0349ft^3\cong 0.26gallons$$

The manufacturer's specification for the water flow rate of the atomizer is 5.8 gal/day, which leads to the following calculation.

$$\frac{5.8gal}{day}*\frac{1day}{24hr}=0.2416\frac{gal}{hr}$$

atomizer usage: $0.2416\frac{gal}{hr}*3hr=0.725\frac{gal}{flight}$ (Assumes a 3 hour flight time)

pump flow rate: $1.16\frac{gal}{\min}*\frac{1}{2}\min=0.58\frac{gal}{parabola}$ (assumes 30 second parabolas)

Total liquid volume = 0.26 gal + 0.725 gal + 0.58 gal = 1.565 gallons

Safety factor = 0.6 → Total Liquid Volume (TLV) = 2.5 Gallons

Total SM volume = TLV*1.3 → SM volume = 3.25 gallons

As the water is pumped from the tank the volume in the mesh section will be continually decreased. When the aircraft goes into the 1.8 g period, the water in the top of the tank will be forced through the mesh system and the tank will essentially reset for the next parabola. As the water and air mixture is pumped into the tank, the air will be allowed to leave the tank through a drain tube. This tube will have a diaphragm on the inside of the tank and will contain a series of meshes inside the tube. This system will allow the air to exit the tank into the cabin and the needed water to remain in the tank for pumping. In the event that water does get past the diaphragm it will be pulled back through the diaphragm during the 1.8 g portion of the flight.

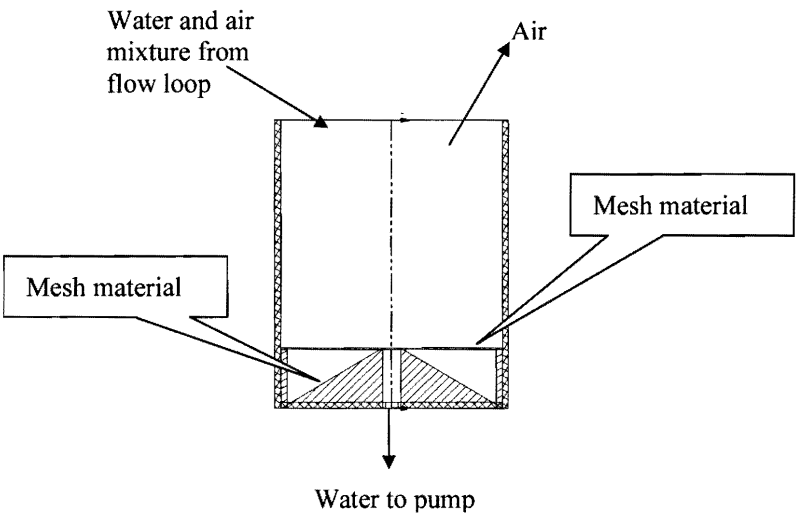


Figure 5.4.2 – Schematic of Separation Module

5.5 Structural Analysis

5.5.1 Experiment Frame Description

The experiment will be housed in an extruded aluminum framework. The framework will have dimensions of 24"x24"x50" and the entire experiment will weight 248 lbs. All parts of the experiment will be mounted to the frame using SAE grade 5 bolts (5/16"-18), and these same bolts will be used to hold the frame together. The frame will be made of 1.5" x1.5" extruded aluminum and will be bolted to the KC-135's frame using four (4) NASA supplied 3/8" diameter bolts.

5.5.2 Free Body Diagrams

The free body diagrams used in this section show that the experiment as proposed is capable of sustaining the required forces without failure. The free body diagrams were drawn for the cases where the maximum load would occur, the 9g forward loading and 2g upward loading. These diagrams show that the experimental apparatus will not fail under the most strenuous loading conditions predicted and, therefore, it will also meet the loading requirements for those cases of lower stress. Figure 2.4.1 shows the loading of the entire system for the 9-g forward loading condition, where Figure 2.4.2 shows the entire system under a 2-g upward load. Figure 2.4.3 shows the entire system as subjected to a 6-g downward loading.

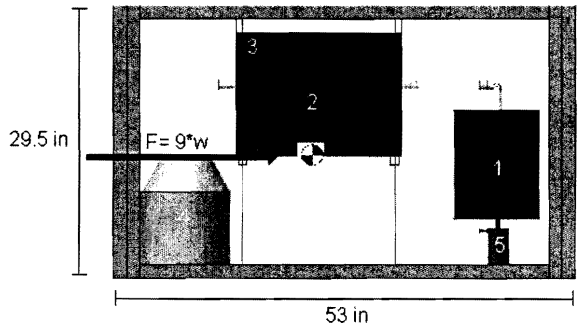


Figure 5.5.1: Free Body Diagram for 9g Forward Loading on the Complete Assembly

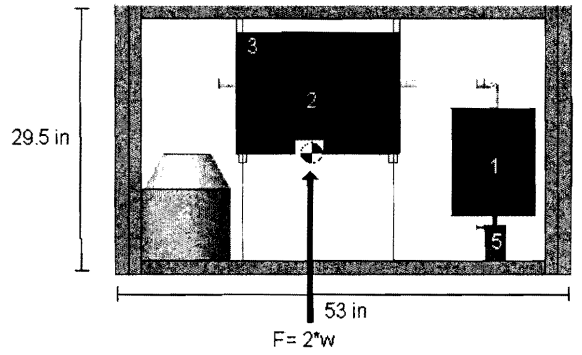


Figure 5.5.2: Free Body Diagram for 2g Upward Loading on the Complete Assembly

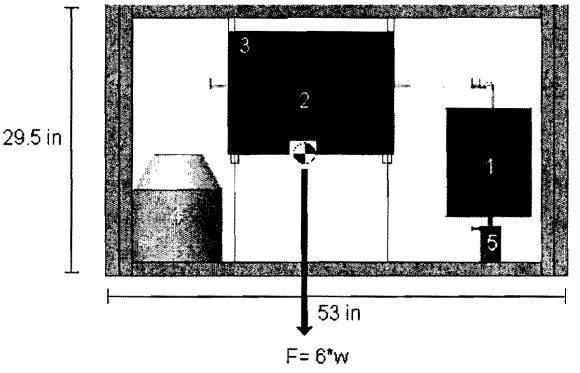


Figure 5.5.3: Free Body Diagram for 6g Downward Loading on the Complete Assembly

The center of gravity of the assembly is assumed to be at the geometrical center of the assembly. Because the majority of the weight is on the lower half of the assembly, the center of gravity will actually be lower than the geometric center. However, assuming a geometric center yields a worst-case scenario, the moment arm will be longer in this condition than in the actual experimental setup. For the components attached to the frame, the free body diagrams for the heaviest component are shown. From this free body diagram, all other components attached to the frame will have the same attachments with smaller forces, so no free body diagram is needed. Figures 5.5.4, 5.5.5, and 5.5.6 show the loading cases on the SM for the conditions of 2-g upward loading, 6-g downward loading, and the 9-g forward loading respectively.

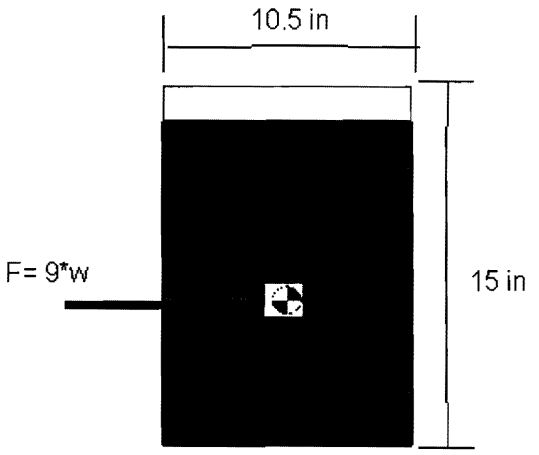


Figure 5.5.4: Free Body Diagram for 9g Forward Loading on Cooler