Study of Pinch-Off and Reconnection of Liquid-Liquid Flows in Micro- and Macro-Gravity Conditions

Topic Area: Fluid Dynamics

University of Minnesota – Twin Cities
Department of Aerospace Engineering and Mechanics
107 Akerman Hall
110 Union Street SE
Minneapolis, MN  55455

Team Contact:
Eric Euteneuer
eute0002@umn.edu / (612) 378-5205

Supervisor:
Dr. Ellen Longmire
ellen@aem.umn.edu / (612) 626-7853

Team Members:

Eric Euteneuer, flight crew
Senior, Aerospace Engineering
eute0002@umn.edu / (612) 378-5205

Cecilia Ortiz, flight crew
Senior, Aerospace Engineering
orti0022@umn.edu / (612) 378-2466

Travis Schauer, flight crew
Senior, Aerospace Engineering
scha0459@umn.edu / (612) 378-9740

Christopher Teeuwen, flight crew
Senior, Aerospace Engineering
teeu0001@umn.edu / (281) 244-9871

Submitted on:
June 2, 2001
# Table of Contents

ABSTRACT ...............................................................................................................................................3

EXPERIMENT BACKGROUND ..............................................................................................................3

EXPERIMENT DESCRIPTION ....................................................................................................................3

JET STABILITY/PINCH-OFF EXPERIMENT ...............................................................................................4

RECONNECTION EXPERIMENT ..................................................................................................................4

EQUIPMENT DESCRIPTION .....................................................................................................................5

JET STABILITY/PINCH-OFF EXPERIMENT ...............................................................................................6

Tank .........................................................................................................................................................6

Nozzle and Honeycomb Assembly ..........................................................................................................6

Forcing System ..........................................................................................................................................8

Pump ..........................................................................................................................................................9

RECONNECTION EXPERIMENT ................................................................................................................9

Plexiglas Box ............................................................................................................................................9

Mixer .......................................................................................................................................................10

Attachments ..........................................................................................................................................11

OTHER ....................................................................................................................................................12

Fluids ......................................................................................................................................................12

Video .....................................................................................................................................................12

Frame .....................................................................................................................................................12

Entire System ........................................................................................................................................12

STRUCTURAL LOAD ANALYSIS .............................................................................................................14

STRUCTURAL DESIGN CALCULATIONS: .................................................................................................14

FULL ASSEMBLY AND FRAME: ..................................................................................................................15

STRUCTURAL ANALYSIS OF EXPERIMENT BOXES .............................................................................18

ATTACHMENT OF COMPONENTS TO FRAME .......................................................................................18

COMPONENT .........................................................................................................................................18

FLOOR ATTACHMENT ............................................................................................................................19

FLOOR LOAD ANALYSIS .........................................................................................................................19

FACTORS OF SAFETY .............................................................................................................................19

ELECTRICAL ANALYSIS ..........................................................................................................................20

POWER SOURCE DETAILS ......................................................................................................................21

LOAD ANALYSIS .....................................................................................................................................21

EXPERIMENTAL PROCEDURE & DATA ACQUISITION ........................................................................21

GROUND/PRE-FLIGHT PROCEDURES ....................................................................................................21

IN-FLIGHT PROCEDURES ........................................................................................................................22

DATA ACQUISITION ................................................................................................................................22

JET STABILITY & PINCH-OFF DATA & ANALYSIS ..............................................................................23

GROUND TESTS ....................................................................................................................................23

Needle Valve Calibration ..........................................................................................................................23

EXPERIMENTAL RESULTS – GROUND CONDITION ..............................................................................24

IN-FLIGHT TESTS & RESULTS ..................................................................................................................26

In-Flight Tests .........................................................................................................................................26

Macro-Gravity Results ............................................................................................................................26
Abstract

Topological transitions that occur in liquid/liquid flows with significant interfacial tension are found in many practical applications. For example, when crude oil is pumped from a well there exists an oil-water mixture. This mixture must in turn be separated before the oil is transported to a pipeline or tanker. However, current separation processes are hard to design without using expensive trial and error techniques. Because of this, numerical models for mixing and separation have been developed at the University of Minnesota. Preliminary experiments under normal gravity conditions were performed to serve as a foundation from which numerical techniques were developed. However, more tests under a variety of gravity conditions need to be performed so that the numerical model can be tested and made more applicable to a wider range of flows. We believe that testing these viscous flows under gradient gravity fields would increase the accuracy of the model and thus leading to less complex and more cost efficient models for separation processes.

Experiment Background

There are many industrial applications today related to energy production, conversion, and use where topological changes such as pinch-off and reconnection of immiscible fluids are an important factor in efficiency and performance. The goals for these applications vary from efficiently separating emulsions consisting of fine scale droplets to maximizing mass transfer rates (such as in waste processing systems). Since these processes are too complex to be computed based on first principles, models must be developed. Before a model is developed, however, we must have a firm understanding of the dynamics of these systems.

These systems are difficult to characterize experimentally and model theoretically and numerically for several reasons: (1) the number of independent parameters affecting the flow behavior can be large, (2) the transitions usually occur over very short time and space scales relative to those of the local flow, and (3) the classical mathematical description of fluid motion becomes much less reliable at transitions. It is for these reasons that these experiments were performed. Specifically, the flow structure and topology of immiscible liquid-liquid flows for a jet and a heterogeneous mixture was examined. The experiments performed will allow future researchers to study the importance of buoyancy forces. The results of these experiments will now be used to develop the numerical models for these transitions. Once the models are perfected, designers in various areas such as energy production and conversion, internal combustion engines, and nozzle-spraying technologies can come up with more efficient separation and mass transfer methods.

Experiment Description

The overall objectives for our experiments are to obtain qualitative and quantitative experimental data documenting the dynamics of real transitions that can serve as a benchmark for the computational study. Specifically:
• Characterize pinch-off, as well as the events surrounding pinch-off, under various gravity fields.
• Examine the interactions of two immiscible fluids with significant surface tension. i.e. quantify the time it takes for two liquids, a heterogeneous mixture of the two fluids, to separate/coalesce into two distinct fluids.
• Analyze data for future use in numerical computations and simulations.

**Jet Stability/Pinch-Off Experiment**

The experiment was designed so that it could be easily operated under the varying gravity conditions aboard the Weightless Wonder. This consisted of slightly modifying the systems used previously by Ellen Longmire and some of her students at the University of Minnesota. The final setup consisted of the closed loop system shown below in Figure 1.

A magnetic pump drives the flow. The flow, consisting of a water/glycerin mixture, first passes through a needle valve, which controls the mass flow rate. After passing through the needle valve, the flow encounters the forcing system. This system provides a sinusoidal forcing to the flow velocity, which causes repeatable pinch-off conditions. After traveling through the forcing system, the flow enters a honeycomb, which straightens the flow before it enters the nozzle. The flow is finally accelerated through the nozzle and injected into the mineral oil inside of the tank.

The water/glycerin mixture is denser than the mineral oil. Thus, it settles to the bottom of the tank, allowing it to be pumped through the system again. This provides a system that runs continuously, as long as the pump remains on.

**Reconnection Experiment**

In addition to the pinch-off experiment where the dynamics of pinch-off interfaces are examined, reconnection rates are studied. The idea of this experiment is to generate a heterogeneous mixture of immiscible fluid particles. The fluids used will also be mineral oil and a solution of water and glycerin. The container for these fluids was a cubical Plexiglas box with differential volume valve that was used to minimize the existence of air bubbles that could change the behavior of the fluids. The differential volume valve allowed for a slight change in volume due to our mixing device.

The mixing device was used to generate a heterogeneous mixture. The mixing device was started at the beginning of zero gravity portions of the flight parabola. The start of the experiment was identified when the mixing device stopped. All the data was then recorded on a video camera that ran continuously throughout the flight. (The original idea was to take gravity readings periodically. This proved not to be such a bright idea. The combined effects of the changing gravity with moving ones head around in order to see the gravity readings, the stop watch, and the paper which the readings were to be recorded to made the recorded nauseous. Thus, video results were relied upon for all data.)
Using dimensional analysis, we derived the following equation that relates the characteristic time and characteristic thickness of heterogeneous mixture we are going to measure as a function of other known quantities:

\[
\frac{H}{H_0} = g \left( \frac{\rho_a}{\rho_b}, \frac{\mu_a}{\mu_b}, \frac{t_r}{T_0}, \frac{t_m}{T_0}, \frac{\rho_a H_0^2}{\mu_a T_0^2}, \frac{\rho_a H_0^2}{\mu_b T_0}, \omega T_0 \right)
\]

Where the significant parameters are:

- **Fixed:**
  - \( \rho_a = \) density of fluid A
  - \( \rho_b = \) density of fluid B
  - \( \mu_a = \) viscosity of fluid A
  - \( \mu_b = \) viscosity of fluid B
  - \( g = \) gravity force
  - \( \sigma = \) surface tension between the two liquids

- **Varied:**
  - \( \omega = \) mixer frequency
  - \( t_m = \) mixing time

- **Dependent/measured:**
  - \( H_0 = \) initial thickness of heterogeneous fluid mixture
  - \( H = \) measured thickness of heterogeneous mixture
  - \( t_r = \) run time, time for the liquids to separate

In addition to obtaining the reconnection rate, the qualitative “nature” of the coalescence was also studied. i.e. The interfaces and drop shapes were looked at under different conditions. The results of this experiment will then be compared with separate tests done at normal gravity.

**Equipment Description**
The main elements of our experimental apparatus are:

**Jet Stability/Pinch-Off Experiment**

![Diagram](image)

**Figure 1:** Experimental assembly.

Tank

The tank is where the pinch-off occurs in the experiment. Its sides and bottom were made from ½” thick Plexiglas, while the top was made from ½” thick gray PVC. Each of the side pieces were glued together using Weld-On 3, manufactured by the IPS Corporation. The top of the tank was removable so that filling and cleaning the tank could be done with ease. Bolts were used to secure the top of the tank to the bottom portion during testing, with an o-ring providing a leak-proof seal between the two pieces. The inner dimensions of the tank were 16” tall x 8” wide x 8” deep, providing a total liquid capacity of 4.43 gallons.

Nozzle and Honeycomb Assembly

The nozzle for the system was designed to achieve a uniform flow at the nozzle exit. This led to a converging nozzle design, with the flow entering and exiting the nozzle axially, and the point of inflection in the nozzle at the midpoint of the nozzle’s overall length. The equation for the nozzle contour was as follows:

\[ y = A + Bx + Cx^2 + Dx^3 + Ex^4 + Fx^5 \]

Six unknown constants are present in this equation. Thus, six boundary conditions were needed to solve for the unknowns. Three of these boundary conditions have been described above. The other three conditions imposed on the nozzle were the inlet, exit,
and inflection point radii. All of the boundary conditions are listed below in Table 1, while the constants in the nozzle contour equation are given in Table 2. The nozzle contour is shown schematically in Figure 2.

Before entering the nozzle, the flow passed through a 2” section of honeycomb. The honeycomb straightened the flow so that it would enter the nozzle with very little rotation or turbulence. A picture of the nozzle glued into the top of the tank, along with the piping upstream of the nozzle, is shown below in Figure 3.

<table>
<thead>
<tr>
<th>Axial Boundary Condition</th>
<th>Radial Location [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>y = 0.500</td>
<td>x = 0</td>
</tr>
<tr>
<td>y = 2.032</td>
<td>x = 5</td>
</tr>
<tr>
<td>y = 1.266</td>
<td>x = 2.5</td>
</tr>
<tr>
<td>y = 0</td>
<td>x = 0</td>
</tr>
<tr>
<td>y = 0</td>
<td>x = 5</td>
</tr>
<tr>
<td>y = 0</td>
<td>x = 2.5</td>
</tr>
</tbody>
</table>

**Table 1**: Boundary conditions for nozzle.

<table>
<thead>
<tr>
<th>Constant</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.500</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>0.18384</td>
</tr>
<tr>
<td>D</td>
<td>-0.024512</td>
</tr>
<tr>
<td>E</td>
<td>0</td>
</tr>
<tr>
<td>F</td>
<td>0</td>
</tr>
</tbody>
</table>

**Table 2**: Solution of nozzle equation.
Forcing System

As was previously mentioned, the forcing system applied a sinusoidal perturbation to the flow, thus causing repeatable pinch-off conditions. The forcing system was nothing more than a plastic cup, which acted as a piston, sandwiched between an 8” speaker and a rubber gasket. The gasket was at the interface of the water/glycerin solution, thus any perturbations to the gasket were transferred directly to the flow.

A sinusoidal input to drive the forcing system was created by a function generator. The signal was then amplified by a home stereo amplifier before being sent to the speaker. A picture of the disassembled forcing system is shown in Figure 4 below.

Figure 3. Schematic of nozzle contour.

Figure 3: Nozzle and surrounding apparatus.
Figure 4: Exploded view of forcing system.

Pump

A 1/30 HP magnetically driven pump, manufactured by the Little Giant Pump Company (model 1.5-MDI-SC), was used to force the water/glycerin mixture through the system. This pump, as will be shown later, provided smooth, consistent performance over the range of gravity conditions encountered during the flight. A picture of the pump, along with some of the surrounding fittings, is shown below in Figure 5.

Figure 5: Pump and surrounding apparatus.

Reconnection Experiment

Plexiglas Box

The box was made from ½” thick Plexiglas. The box was filled with fluid A (mineral oil) and B (water/glycerin solution). Please refer to Figures 6 & 7 for more details. The
bottom of the box was made such that an aluminum plate can be attached to the box. This aluminum plate was used to attach the box to the main frame. The top of the box was designed in such a way as to make it removable. The top was attached to the flanges of the main box and was sealed using a rubber gasket. The top piece also contained holes to allow for the attachment of the mixer piston and a piston to allow for the internal change in volume. The inside dimension of our box is about 10 inches$^3$ in each direction.

**Mixer**

The purpose of the mixer is to create a heterogeneous mixture of the two viscous fluids. It is driven by a pneumatic circuit and an air piston with a ten-inch stroke. The schematic of the pneumatic circuit can be seen in Figure 8.

---

**Figure 6: Reconnection Box Schematic**
Figure 7: Picture of reconnection experiment without the two immiscible fluids.

Figure 8: Schematic of Pneumatic Circuit

Attached to the cylinder is a perforated ¼ in Lexan plate with ¼ in holes and a 50% open area. This plate moves up and down with a frequency, $\omega$, of 1Hz. After a heterogeneous mixture has developed, the mixer is turned off and the Lexan plate automatically returns to the top so as to not interfere with the flow.

Attachments
The attachments between and fitting for the air cylinder are made out of flexible plastic tubing fastened with plastic fittings that properly seal.

**Other**

**Fluids**

Two fluids, mineral oil and a water/glycerin mixture, were used in the experiment. The fluids were chosen based on their influence on the pinch-off process. Namely, these two fluids provided consistent and fairly crisp pinch-off regions during ground testing. The water/glycerin mixture used was 50/50 based on volume. The properties for the fluids used are given below in Table 3.

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Density, (kg/m$^3$)</th>
<th>Viscosity, (cP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water/Glycerin</td>
<td>1142</td>
<td>8.35</td>
</tr>
<tr>
<td>Mineral Oil</td>
<td>800</td>
<td>21.7</td>
</tr>
</tbody>
</table>

**Table 3**: Fluid properties.

**Video**

A digital video camera was used to capture images during the experiment. The camera used was a Canon ZR10. This camera captures images at a constant rate of 30 frames per second. However, the shutter speed can be varied. A shutter speed of 1/2000 was selected for this application. This shutter speed provided fairly crisp images with fairly little backlighting necessary to illuminate the experiment.

**Frame**

The frame was a structure made of Unistrut$^\text{TM}$ with a cross-section of 1 5/8 in$^2$. The outside dimensions of the frame are 61 5/8 in L x 40 in H x 21 in W. This structure supported our experiments and any sharp angles were rounded and padded in accordance with the hazard checklist.

**Entire System**

The frame dimensions and the locations of the main components inside the frame are shown in Figure 9.
Figure 9: Frame showing location of internal components. (Top and front view)
Structural Load Analysis

In order to meet NASA’s structural requirements of the experiment, structural load analysis was performed on our experiment frame.

**Structural Design Calculations:**

<table>
<thead>
<tr>
<th>Component Description</th>
<th>Weight (lbs)</th>
<th>Dimensions</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camera #1</td>
<td>1</td>
<td>5 1/4 in L x 3in W x 4in H</td>
<td>Aluminum mounting plate</td>
</tr>
<tr>
<td>Camera #2</td>
<td>1</td>
<td>5 1/4 in L x 3in W x 4in H</td>
<td>Aluminum mounting plate</td>
</tr>
<tr>
<td>Pinch-Off Tank</td>
<td>65</td>
<td>9in L x 9in W x 18in H</td>
<td>Plexiglas &amp; PVC box, aluminum mounting plate</td>
</tr>
<tr>
<td>Reconnection Tank</td>
<td>60</td>
<td>11in L x 11in W x 12 1/8 in H</td>
<td>Plexiglas &amp; PVC box, aluminum mounting plate</td>
</tr>
<tr>
<td>Speaker Assembly</td>
<td>18</td>
<td>8 3/16 in L x 8 3/16 in W x 20in H</td>
<td>Aluminum mounting plate</td>
</tr>
<tr>
<td>Amplifier</td>
<td>14</td>
<td>17in L x 11in W x 5.5in H</td>
<td>Aluminum mounting plate</td>
</tr>
<tr>
<td>Function Generator</td>
<td>5</td>
<td>11in L x 10in W x 4in H</td>
<td>Aluminum mounting plate</td>
</tr>
<tr>
<td>Frame</td>
<td>170</td>
<td>61 1/16in L x 19in W x 40in H</td>
<td>Steel</td>
</tr>
<tr>
<td>Pressure Circuit</td>
<td>3</td>
<td>6in L x 4in W x 6in H</td>
<td>Plastic plate with pressure valves</td>
</tr>
<tr>
<td>Pump</td>
<td>6</td>
<td>7in L x 3.5in W x 4in H</td>
<td>Aluminum mounting plate</td>
</tr>
<tr>
<td>Tubing, Clamps</td>
<td>10</td>
<td>N/A</td>
<td>plastic, aluminum</td>
</tr>
<tr>
<td>Other</td>
<td>15</td>
<td>N/A</td>
<td>various materials</td>
</tr>
<tr>
<td><strong>Total Weight</strong></td>
<td><strong>368</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4: Weights and dimensions of components.

![Figure 10: Free body diagram of assembly.](image-url)
**Full Assembly and frame:**

Figure 10 shows a free-body diagram of the frame and the main internal components. The components shown are the components that have a weight larger than 10 lbs. The location of these components is critical for the structural analysis. On the other hand the weight of the rest of the components is small compared to the main component’s weight and their location can be changed if needed.

\[
\begin{align*}
F_1 &= \text{Weight of Pinch-off tank applied at its center of gravity (cg).} \\
F_2 &= \text{Weight of Speaker assembly applied at its center of gravity (cg).} \\
F_3 &= \text{Weight of Reconnection tank applied at its center of gravity (cg).} \\
F_4 &= \text{Weight of Frame applied at its center of gravity (cg).} \\
F_5 &= \text{Weight of Amplifier applied at its center of gravity (cg).} \\
F_6 &= \text{Weight of Function Generator applied at its center of gravity (cg).}
\end{align*}
\]

The location of the center of gravity of the frame with respect to the x-y coordinate system shown in Figure 6 is:

\[
x = 30.82 \text{ in.} \quad y = 18.59 \text{ in.} \quad \text{which is the location of } F_4
\]

The location of the centers of gravity of each main component with respect to the center of gravity of the frame are shown in Table 5.

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight</th>
<th>Center of Gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lbs</td>
<td>x</td>
</tr>
<tr>
<td>Pinch-off Tank</td>
<td>65</td>
<td>-16.6285</td>
</tr>
<tr>
<td>Reconnection Tank</td>
<td>60</td>
<td>5.3125</td>
</tr>
<tr>
<td>Speaker Assembly</td>
<td>18</td>
<td>-5.27</td>
</tr>
<tr>
<td>Amplifier</td>
<td>14</td>
<td>21.1875</td>
</tr>
</tbody>
</table>

**Table 5:** Centers of Gravity of Main Components

The components are symmetrically located with respect to the centerline of the frame shown in the top view in Figure 6. Therefore, the moments in the z-direction are opposite and equal about the centerline.

The forces caused by the moments under the 6g loading are small compared to the forces of the weights under the same loading. The location of the heavier components is close enough to the center of gravity of the frame so that the moments caused by the weights are not significant enough. The maximum force caused by the moments under the worst g loading condition (6g) is 56 lbs upward on the bolts that attach the frame to the airplane floor. This is well under the tensile strength of the bolts of 5000 lbs.
To do the rest of the structural analysis, it was decided to divide the assembly into three different components whose weight act in their respective center of gravity (see Figure 11).

**Assembly 1** includes the experiment boxes, cameras, pump and any necessary connections. The weight shown in the table is an estimated maximum weight. **Assembly 2** includes the speaker assembly, function generator, amplifier and any necessary connections. The weight shown in the table is an estimated maximum weight.

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight (lbs)</th>
<th>Center of Gravity x</th>
<th>y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame</td>
<td>170</td>
<td>30.82</td>
<td>18.59</td>
</tr>
<tr>
<td>Assembly 1</td>
<td>144</td>
<td>-5.98</td>
<td>7.543</td>
</tr>
<tr>
<td>Assembly 2</td>
<td>54</td>
<td>8.372</td>
<td>4.875</td>
</tr>
</tbody>
</table>

Table 6. Centers of Gravity of Assemblies
The connections are defined as follows:

- **Lower connections**: are the brackets between the four pieces that bolt to the floor and the two long cross members on the bottom.
- **Mid-connections**: are the brackets that hold the side pieces to the two cross members that hold the speaker assembly.
- **Mounting connections**: are the corner brackets that hold the bottom of the frame together.

Assembly 1 applies an approximately uniform load to the two members on which they are mounted. The maximum load on these members is applied under a 6g downward loading. The load per member turns out to be 430 lbs under this g-load. For these beams, the maximum allowable load is 1690 lbs.

Assembly 2 applies column loads to the four side members. Under the maximum 6g loading condition, a load of 80 lbs is applied to each member. The maximum allowable load is 2570 lbs.

The four support beams that are bolted to the aircraft floor support the entire assembly weight under a 6g downward loading. This corresponds to a maximum load of 560 lbs per member. For 24” members the maximum allowable load is 1690 lbs.

The connections between the members which supports assembly 1, lower connections, can support a maximum downward load of 1000 lbs, a maximum upward load of 3000 lbs, a maximum forward or backward load of 1200 lbs, and a maximum lateral load of 1500 lbs. The maximum loads applied at these joints under the worst g-loading situations are 215 lbs for a downward load, 72 lbs for an upward load, 320 lbs for a forward load, and 72 pounds for a lateral load.

The connections between the members which support the assembly 2, mid connections, can support a maximum downward load of 1000 lbs, a maximum upward load of 1500 lbs, a maximum forward or backward load of 1200 lbs, and a maximum lateral load of 1500 lbs. The maximum loads applied at these joints under the worst g-loading situations are 80 lbs for a downward load, 27 lbs for an upward load, 120 lbs for a forward load, and 27 pounds for a lateral load.

The connections between the members that bolt to the aircraft floor, mounting connections, can support a maximum downward load of 1000 lbs, a maximum upward load of 1500 lbs, a maximum forward or backward load of 1200 lbs, and a maximum lateral load of 1500 lbs. The maximum loads applied at these joints under the worst g-loading situations are 280 lbs for a downward load, 95 lbs for an upward load, 420 lbs for a forward load, and 95 pounds for a lateral load.

Note that the force applied to each connection was found by taking the component weights attached to each member and dividing by the number of connections that hold the members together.
Structural Analysis of Experiment Boxes

The individual components that could fail are the Plexiglas boxes. The boxes were glued together using Weld-On 3, manufactured by IPS Corporation. This adhesive has a maximum strength of 3100 psi after 14 days of cure time at room temperature. The highest stress on the seams of the boxes occurs under a 9g forward loading. The reconnection box holds 41 lbs of fluid while the pinch-off box holds 42 lbs of fluid. For the reconnection experiment, the maximum stress under a 9g loading is:

\[
\sigma = \frac{\text{force}}{\text{area}} = \frac{41 \times 9}{2 \times 11 \times .5} = 33.5 \text{ psi}
\]

The maximum stress applied to the seams of the pinch-off box is:

\[
\sigma = \frac{\text{force}}{\text{area}} = \frac{42 \times 9}{2 \times 16 \times .5} = 23.6 \text{ psi}
\]

These stresses are well under the maximum allowable stresses dictated by the adhesive.

Attachment of Components to Frame

The Plexiglas boxes and pump was attached to the frame using four 3/8” bolts through ¼” thick aluminum plates. The speaker was mounted using a ½” thick aluminum plate with four 3/8” bolts. A 9g forward loading leads to the maximum bearing stress applied to the aluminum plates. Pull-out forces occur when an upward g-loading in encountered. The maximum stresses and pullout forces are summarized in the table below, which were calculated using the following equations:

\[\text{Bearing Stress} = \frac{\text{force}}{\text{area of bolt in contact with plate}}\]

\[\text{Pull-Out Force} = \frac{\text{force}}{\text{# of bolts}}\]

<table>
<thead>
<tr>
<th>Component</th>
<th>Bearing Stress</th>
<th>Pull-Out Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reconnection Plate</td>
<td>1440 psi</td>
<td>30 lb</td>
</tr>
<tr>
<td>Pinch-Off Plate</td>
<td>1560 psi</td>
<td>32.5 lb</td>
</tr>
<tr>
<td>Pump Plate</td>
<td>144 psi</td>
<td>3 lb</td>
</tr>
<tr>
<td>Speaker Plate</td>
<td>216 psi</td>
<td>9 lb</td>
</tr>
</tbody>
</table>

Table 7: Bearing Stresses

The bearing stress values are well below the ultimate stress of aluminum, which is 27000 psi, while the pullout forces are well below the maximum allowable pullout loads supplied by the frame material manufacturer of 1000 lbs.
The amplifier, function generator, and signal analyzer was housed in a wooden box, with each component secured down using straps. The cameras were mounted to plates that were built so that the camera height is adjustable. These components were tested at the University of Minnesota to ensure they can withstand the g-loading requirements.

**Floor Attachment**

Forward, backward, and lateral g loading conditions cause a shear stress in the floor attachment bolts. The maximum shear stress is in the 9g forward loading case. The thickness of the steel frame is 0.106 inches, with the entire experimental assembly weighing 370 lb. This leads to a shear stress per bolt of:

\[
\tau = \frac{f_{\text{bolt}}}{A_{\text{area}}} = \frac{370 \times 9}{8 \pi \left(0.375^2\right)} = 3.8\text{ksi}
\]

The shear strength of steel is 58 ksi, which leads to a factor of safety of 15.

The maximum shear strength provided by NASA is 5000 lbs per bolt. Under a 9g loading, our experiment applies 416.25 lbs/bolt.

An upward g loading applies a tensile force to the bolts. A 2g upward loading applies a tensile force of 92.5 lb/bolt, well under the NASA supplied maximum value of 5000 lb/bolt.

The maximum bearing force on the frame attachment locations is under a 9g loading condition and can be calculated as follows:

\[
F_b = \frac{F_{\text{load}}}{\text{bolts}} = \frac{370 \times 9}{8} = 416.25\text{lb}
\]

This is well below the maximum allowable load of the frame at a slot face, which is given by the manufacturer as 2300 lb.

**Floor Load Analysis**

The frame was resting on 8 floor spacers. Our equipment weighs 370 pounds, which gives a load of 46.25 lbs/spacer. This is well within the 200 lb/spacer requirement.

**Factors of Safety**

The corresponding factors of safety for each calculation performed above are shown in the table below.
<table>
<thead>
<tr>
<th>Component</th>
<th>Factor of Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reconnection box seam</td>
<td>92</td>
</tr>
<tr>
<td>Pinch-off box seam</td>
<td>130</td>
</tr>
<tr>
<td>Reconnection base plate</td>
<td>18</td>
</tr>
<tr>
<td>Pinch-off base plate</td>
<td>17</td>
</tr>
<tr>
<td>Pump base plate</td>
<td>187</td>
</tr>
<tr>
<td>Speaker mounting plate</td>
<td>125</td>
</tr>
<tr>
<td>Lower connections</td>
<td>3.75</td>
</tr>
<tr>
<td>Mid connections</td>
<td>10</td>
</tr>
<tr>
<td>Mounting connections</td>
<td>3.5</td>
</tr>
<tr>
<td>Floor attachment shear force</td>
<td>15</td>
</tr>
<tr>
<td>Floor attachment bearing force</td>
<td>5.5</td>
</tr>
<tr>
<td>Box support beams</td>
<td>3.9</td>
</tr>
<tr>
<td>Speaker, Electronics support beams</td>
<td>32</td>
</tr>
<tr>
<td>Frame supports</td>
<td>3</td>
</tr>
<tr>
<td>Lower connections</td>
<td>4.6</td>
</tr>
<tr>
<td>Mid connections</td>
<td>12.5</td>
</tr>
<tr>
<td>Mounting connections</td>
<td>3.5</td>
</tr>
<tr>
<td>Reconnection base plate bolts</td>
<td>33.3</td>
</tr>
<tr>
<td>Pinch-off base plate bolts</td>
<td>30.7</td>
</tr>
<tr>
<td>Pump base plate bolts</td>
<td>333</td>
</tr>
<tr>
<td>Speaker mounting plate bolts</td>
<td>111</td>
</tr>
<tr>
<td>Lower connections</td>
<td>41.6</td>
</tr>
<tr>
<td>Mid connections</td>
<td>55.5</td>
</tr>
<tr>
<td>Mounting connections</td>
<td>15.7</td>
</tr>
<tr>
<td>Floor attachment bolts</td>
<td>54</td>
</tr>
<tr>
<td>Lower connections</td>
<td>20.8</td>
</tr>
<tr>
<td>Mid connections</td>
<td>55.5</td>
</tr>
<tr>
<td>Mounting connections</td>
<td>15.7</td>
</tr>
</tbody>
</table>

**Table 8: Factors of Safety**

**Electrical Analysis**

An electrical schematic showing each electrical component along with its unique wire identifying number is shown below in Figure 9. The cord from the surge protector will go to a 115 VAC, 60 Hz outlet. The cords for each electrical device were included with the equipment when it was purchased and so they are adequate for carrying the current needed to power each device. The gauge size and current carried by each wire is shown below in Table 9. The surge protector we are using has the master kill switch for our system.
Figure 12: Electrical schematic.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Wire Gauge Size</th>
<th>Current Carried</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cameras</td>
<td></td>
<td>0.04 A Each</td>
</tr>
<tr>
<td>Function Generator</td>
<td>18</td>
<td>0.75 A</td>
</tr>
<tr>
<td>Amplifier</td>
<td>18</td>
<td>1.3 A</td>
</tr>
<tr>
<td>Pump</td>
<td>18</td>
<td>1.1 A</td>
</tr>
<tr>
<td>Lights</td>
<td></td>
<td>0.275 A Each</td>
</tr>
</tbody>
</table>

Table 9: Listing of equipment with wire gauge size and current carried.

A summary of the electrical load analysis is given below in Table 10. All of our electrical equipment was plugged into a surge protector that is equipped with a kill switch.

In the case of a power loss, our amplifier, pump, and lights would stop operating. However, this is in no way an unsafe configuration. Our digital video cameras were equipped with batteries, which provide back-up power. This will allow the cameras to operate during a power loss, thus keeping all the settings on the cameras from changing to default power-up settings.

<table>
<thead>
<tr>
<th>Power Source Details</th>
<th>Load Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name: Power Cord A</td>
<td>Cameras #1 &amp; #2: 0.04 A Each</td>
</tr>
<tr>
<td>Voltage: 115 VAC, 60 Hz</td>
<td>Lights #1 - #4: 0.275 A Each</td>
</tr>
<tr>
<td>Wire Gauge: 12</td>
<td>Function Generator: 0.75 A</td>
</tr>
<tr>
<td></td>
<td>Amplifier: 1.3 A</td>
</tr>
<tr>
<td></td>
<td>Pump: 1.1 A</td>
</tr>
</tbody>
</table>

| Max Outlet Current: 20 A | Total Current Draw: 4.33 Amps |

Table 10: Electrical load table.

Experimental Procedure & Data Acquisition

Ground/Pre-Flight Procedures
Once the team had arrived in Houston, the race to prepare the experiment and the team had begun. In general, the procedure used to ready the experiment was:

1. Buy small items such as distilled water for the experiment.
2. Unload and ready the experiment for the Test Readiness Review (TRR)
   - Set up and calibrate the experiments.
   - Demonstrate that the experiments don’t leak by rotating the experiments on all axes of the test frame.
   - Round and cover and remaining sharp corners.
3. Make adjustments to the experiment as suggested by the TRR review panel.
4. Load experiment and run experiments while plane is grounded.

**In-Flight Procedures**

The experimental and in-flight test procedures were made as automated and simple as possible so that the experiments can be run easily under the constantly changing gravity environment. The step-by-step process once we are in the air and able to move about the cabin is:

1. Supply power to the amplifier and pump. This was in the closed loop circulation of fluids in the pinch-off experiment that will run continuously during the flight. Also, open the compressed air regulator to supply compressed air to our pneumatic circuit.
2. Turn on the digital video cameras.
3. Right before zero gravity conditions, start the mixing of the two fluids in the reconnection experiment. This will last approximately 1-3 seconds.
4. Repeat steps 3 & 4 for other parabolas. However, there were slight variations in the reconnection experiment between parabolas. See Appendix A for individual parabola details of the Reconnection Experiment.
5. After all of the parabolas are completed, turn off the power to the instruments and make sure secure for landing.

NOTE: Individual experimental procedures can be found in the experiment descriptions.

**Data Acquisition**

As was previously mentioned, a digital video camera was used for recording flow images. The relevant camera settings used for data collection are given below in Table 11. Professional grade cassettes were used for recording the images onto tape.

The software used for analyzing the data was PhotoDV and IntroDV, manufactured by Digital Origin. Various options were available in this program for capturing still images and recording video. A capture size of 604 x 454 (square) was used so that the images would not be distorted. Due to the nature of how digital video cameras work and the fact that pinch-off images change rapidly with time, a field interpolation needed to be done on the images. The even fields in the images were eliminated during this process in all of the images shown throughout this report.
Video was transferred to Quicktime format, so that the video may be seen on any common platform.

<table>
<thead>
<tr>
<th>Function</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shutter Speed</td>
<td>1/2000</td>
</tr>
<tr>
<td>Recording Mode</td>
<td>LP</td>
</tr>
<tr>
<td>White Balance</td>
<td>Indoor</td>
</tr>
<tr>
<td>Focus</td>
<td>Manual</td>
</tr>
</tbody>
</table>

Table 11: Digital camera settings.

Jet Stability & Pinch-Off Data & Analysis

Ground Tests

Needle Valve Calibration

The needle valve needed to be calibrated so that flow rates could be determined for data analysis purposes. Calibration was performed by pumping the water/glycerin mixture through the entire system except the nozzle and honeycomb. 200 mL of the water/glycerin mixture was pumped into a beaker and the time recorded to pump this amount of fluid was recorded. This process was repeated several times for various needle valve settings. The data was then averaged for each needle valve setting. The results are shown below in Table 11 and Figure 13. Note that the Reynolds and Strouhal numbers use the density and viscosity of the water/glycerin mixture (the moving fluid). Also, the characteristic velocity and diameter (D) used for these numbers was the nozzle exit velocity and diameter, respectively. It can be seen that the flow velocity changes approximately linearly with the valve setting for the valve used. The forcing frequency was kept at a constant value of 12 Hz during calibration.

<table>
<thead>
<tr>
<th>Valve Setting</th>
<th>Re</th>
<th>St</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>52.2</td>
<td>3.2</td>
</tr>
<tr>
<td>7.5</td>
<td>73.9</td>
<td>2.2</td>
</tr>
<tr>
<td>8</td>
<td>96.2</td>
<td>1.7</td>
</tr>
<tr>
<td>8.5</td>
<td>121.2</td>
<td>1.4</td>
</tr>
<tr>
<td>9</td>
<td>140.7</td>
<td>1.2</td>
</tr>
<tr>
<td>9.5</td>
<td>158.2</td>
<td>1.0</td>
</tr>
<tr>
<td>10</td>
<td>187.7</td>
<td>0.9</td>
</tr>
<tr>
<td>10.5</td>
<td>198.2</td>
<td>0.8</td>
</tr>
<tr>
<td>11</td>
<td>226.1</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Table 11: Summary of needle valve calibration data.
**Experimental Results – Ground Condition**

A range of conditions were tested on the ground that would fully encompass the range of flow conditions that would be tested in-flight. This allowed the results found during various g level conditions to be correlated to normal, 1 g conditions. Pictures of the pinch-off region are shown for various flow rates in Figure 14. Gravity acts downward in this figure and in all flow figures that follow. The width, w (measured horizontally), and length, l (measured vertically), of the drops at pinch-off were measured and are given in Table 12. Two angles were also measured in the pictures. $\beta_u$ is the angle between the horizontal and upstream jet boundary, while $\beta_d$ is the angle measured between the horizontal and the downstream drop boundary. These values are also given in Table 6. All of the values in Table 6 are averages based on the analysis of multiple drops.

Note the presence of satellite drops (small drops that form before the large drop pinches off) in all but the rightmost image. Also note the change in shape of each drop at pinch-off. At a Reynolds number of 52, the drop is nearly spherical at pinch-off. However, as the Reynolds number is increased to 121, the drop tends to flatten out on the upstream side. For Reynolds numbers equal to or above 141, the drop begins to lengthen drastically and eventually form a teardrop shape. The pinch-off angles also show an interesting phenomenon: as $\beta_u$ increases, $\beta_d$ decreases and vice versa. The maximum $\beta_u$ and minimum $\beta_d$ also appear to occur at approximately the same Reynolds number. This can be seen in Figure 15, which shows all of the data used in calculating the average values listed in Table 12.

It should be noted that the pinch-off angles were extremely hard to measure with any degree of accuracy. The clarity of the images near the pinch-off region simply was not good enough to measure the angles with a high degree of accuracy. Additionally, the stage that the pinch-off is in (i.e. right at pinchoff, slightly before pinch-off, etc.) has a strong impact on the measured pinch-off angles. This caused some problems since the digital camera only had a frame rate of 1/30. Thus, it was hard to obtain images where the drops were at the very brink of pinch-off. With this taken into account, an estimation on the error in the angle measurements is $\pm 5^\circ$. 

![Figure 13: Plots of needle valve calibration data.](image)
Figure 14: Ground test (1 g) results. From left to right, Re = 52, 74, 96, 121, 141, and 158. Length of each image is 10D.

Table 12: Averaged pinch-off characteristics during ground testing.
In-Flight Tests & Results

In-Flight Tests

Testing aboard the Weightless Wonder occurred on two consecutive days. Video images were captured during both flights. However, during the first flight the flow rates were not recorded and so the results cannot be attributed to a specific Reynolds number. Important information, such as approximate flow rates needed for pinch-off, was found during the first flight. This gave a good starting point for the next flight. On flight day two, the flow rates were recorded by verbally announcing them to the camera for recording purposes. For this reason, the results presented below are from day two only.

Only two flow rates were tested on flight day two, namely Reynolds numbers of 96 and 141. Additionally, only two parabolas were flow at a Reynolds number of 96. This was due to the fact that pinch-off did not occur consistently for a Reynolds number of 96 during zero g. At a Reynolds number of 141, however, pinch-off seemed to occur more often. Further details will follow below.

A couple of words are appropriate at this point concerning the performance of the pump during various portions of the flight. After looking at the transitions from 1.8 to zero g, it was found that the performance of the pump was fairly constant over the range of g levels encountered.

In some of the images presented below, it may appear than some “bubbles” are present in the flow that do not move with time. While this may be the case in the zero g pictures, most of the time the “bubbles” are actually drops of the water/glycerin mixture that clung to the side of the tank. It should be obvious when observing sequences of pictures which bubbles are actually bubbles near the center of the tank and which bubbles are clung to the side of the tank.

Macro-Gravity Results

Pinch-off images for a Reynolds number of 96 are given in Figure 16 below, with the corresponding numerical results given in Table 13. Going from left to right, the pictures are taken every two cycles (every 1/6 of a second). Note that the images are very similar, even though there was a fair amount of vibration induced in the experiment by the airplane. Also note that the size of the drops are quite a bit smaller than they were during ground testing. However, the satellite drops are fairly larger. This can be explained by the fact that, since the forcing frequency, and thus the pinch-off frequency was the same in this case as it was during ground testing, the mass flow rate per drop cycle must be the same. Thus, if the mass flow rate of the main drop decreases, the mass flow rate of the satellite drops must increase.
Figure 16: 1.8 g results at Re = 96. Length of each image is 10D.

<table>
<thead>
<tr>
<th>Image Number</th>
<th>β_u (degrees)</th>
<th>β_d (degrees)</th>
<th>w/D</th>
<th>l/D</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>88.7</td>
<td>5.6</td>
<td>0.59</td>
<td>0.71</td>
</tr>
<tr>
<td>2</td>
<td>88.2</td>
<td>6.1</td>
<td>0.61</td>
<td>0.68</td>
</tr>
<tr>
<td>3</td>
<td>88.5</td>
<td>6.5</td>
<td>0.59</td>
<td>0.68</td>
</tr>
</tbody>
</table>

Table 13: Numerical results for Re = 96 at 1.8 g.

Various images at a Reynolds number of 141 are given in Figure 17. Image 4 was taken on a different parabola than the other three images. Note the drastic difference between image 4 and the other three images. The flow rate was not even slightly adjusted between any of the images shown. This suggests that at this flow rate, the jet is quite unstable and very susceptible to minor fluctuations in exterior vibrations or other outside forces. Numerical measurements in this case were not even attempted to be made because of the large variations in jet shape. It should be noted that in image 4, the waviness of the jet is due to the forcing applied to the system, not by vibrations induced in the experiment.
Figure 17: 1.8 g results at Re = 141. Length of each image is 11D.

Micro-Gravity Results

The results presented in this section occurred well after the transition from 1.8 to zero g. During this portion of time, the process of pinch-off is dramatically different than it was at zero and 1.8 g’s. For example, rather than the jet pinching off at a steady rate, fairly long portions of time would go by before a large drop would form and pinch-off. In fact, in many cases pinch-off was due to subtle changes in gravity that caused the large drops to begin to slowly move and eventually pinch-off. This was one of the minor problems encountered during testing: the slightly varying gravity environment at “zero gravity.” However, this was expected before the flight occurred. Important results were still found during this portion of the flight, (results which would have been virtually impossible to obtain anywhere else on earth) which are discussed below.

Three images at a Reynolds number of 96 are given in Figure 18 below. Image 8 is a different drop than images 9 and 10. Images 9 and 10 are actually a sequence of images taken one frame apart (1/30 of a second). Note the remarkable similarity between images 8 and 9. The results given in Table 14 verify the similarity numerically. None of the images are extremely close to pinch-off so angle measurements are not presented in Table 14. Note that the shape of the drops before pinch-off (images 8 and 9) resemble
prolate spheroids, while immediately after pinch-off (image 10) the drop comes closer to becoming a symmetric sphere. A symmetric sphere after pinch-off was expected due to interfacial tension along with the absence of gravity forces.

![Images of drops at pinch-off](image1)

**Figure 18:** Zero g results at Re = 96. The length of each image is 5D.

<table>
<thead>
<tr>
<th>Image Number</th>
<th>W/D</th>
<th>l/D</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>2.93</td>
<td>3.42</td>
</tr>
<tr>
<td>9</td>
<td>2.69</td>
<td>3.37</td>
</tr>
<tr>
<td>10</td>
<td>2.67</td>
<td>3.18</td>
</tr>
</tbody>
</table>

**Table 14:** Numerical results in zero g for Re = 96.

Unlike the results for a Reynolds number of 96, the results at a Reynolds number of 141 varied quite a bit. Images of various drops at pinch-off are shown in Figure 19. All three of these images are of different drops during different parabolas. Note that while the downstream pinch-off distance is fairly constant, the drop shape and size varies quite a bit. In image 11, the upper surface of the drop is at a fairly large angle from the horizontal, while in images 12 and 13 the same surface is nearly parallel to the width of the drop (where width is measured perpendicular to the axis of the jet at pinch-off). The size of the drops vary due to the length of time they remained attached to the jet. It was found that the longer the jet was subjected to zero g, the less waviness there was in the jet. This phenomenon indicated a relative time scale as to how long the drops remained attached to the jet in the pictures below (the drop in image 12 remained attached for a fairly long period of time while the drop in image 13 is pinching off much closer to the beginning of zero g. The numerical results for the images in Figure 19 are given in Table 15.
Figure 19: Zero g results at Re = 141. Length of each image is 11D.

<table>
<thead>
<tr>
<th>Image Number</th>
<th>( \beta_u ) (degrees)</th>
<th>( \beta_d ) (degrees)</th>
<th>( w/D )</th>
<th>( #D )</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>86</td>
<td>27</td>
<td>2.23</td>
<td>2.98</td>
</tr>
<tr>
<td>12</td>
<td>87</td>
<td>12</td>
<td>3.64</td>
<td>4.33</td>
</tr>
<tr>
<td>13</td>
<td>81</td>
<td>11</td>
<td>2.49</td>
<td>2.25</td>
</tr>
</tbody>
</table>

Table 15: Numerical results in zero g for Re = 141.

Transition Results

The transitions from 1.8 g to zero g provided interesting results. The images during transition for a Reynolds number of 96 are given in Figure 20. The images are the closest images of each successive drop to pinching off. They are arranged chronologically as one would read normal print. The time between each consecutive image, along with other important parameters, is given in Table 16. A time equal to one half of a frame was assigned to the time of pinch-off when the verge of pinch-off was missed in the image. Some angle measurements in the table are left blank because the image was not close enough to pinch-off for an accurate measurement to be taken.
**Figure 20:** Transition from 1.8 to zero g for Re = 96. Length of each image is 10D.

<table>
<thead>
<tr>
<th>Drop Number</th>
<th>Time (seconds)</th>
<th>$\theta_u$ (degrees)</th>
<th>$\theta_d$ (degrees)</th>
<th>w/D</th>
<th>l/D</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.000</td>
<td></td>
<td></td>
<td>0.61</td>
<td>0.71</td>
</tr>
<tr>
<td>2</td>
<td>0.100</td>
<td></td>
<td></td>
<td>0.59</td>
<td>0.73</td>
</tr>
<tr>
<td>3</td>
<td>0.200</td>
<td></td>
<td></td>
<td>0.54</td>
<td>0.66</td>
</tr>
<tr>
<td>4</td>
<td>0.267</td>
<td></td>
<td></td>
<td>0.59</td>
<td>0.66</td>
</tr>
<tr>
<td>5</td>
<td>0.367</td>
<td></td>
<td></td>
<td>0.56</td>
<td>0.78</td>
</tr>
<tr>
<td>6</td>
<td>0.433</td>
<td>86.8</td>
<td>7.9</td>
<td>0.59</td>
<td>0.66</td>
</tr>
<tr>
<td>7</td>
<td>0.533</td>
<td>86.2</td>
<td>7.9</td>
<td>0.61</td>
<td>0.68</td>
</tr>
<tr>
<td>8</td>
<td>0.633</td>
<td></td>
<td></td>
<td>0.59</td>
<td>0.68</td>
</tr>
<tr>
<td>9</td>
<td>0.700</td>
<td></td>
<td></td>
<td>0.59</td>
<td>0.71</td>
</tr>
<tr>
<td>10</td>
<td>0.800</td>
<td>83</td>
<td>13.5</td>
<td>0.59</td>
<td>0.73</td>
</tr>
<tr>
<td>11</td>
<td>0.900</td>
<td></td>
<td></td>
<td>0.56</td>
<td>0.66</td>
</tr>
<tr>
<td>12</td>
<td>1.100</td>
<td></td>
<td></td>
<td>0.73</td>
<td>0.88</td>
</tr>
<tr>
<td>13</td>
<td>1.200</td>
<td>78.7</td>
<td>12.4</td>
<td>0.59</td>
<td>0.66</td>
</tr>
<tr>
<td>14</td>
<td>1.367</td>
<td>74</td>
<td>52.6</td>
<td>0.64</td>
<td>0.83</td>
</tr>
<tr>
<td>15</td>
<td>1.500</td>
<td></td>
<td></td>
<td>0.68</td>
<td>0.90</td>
</tr>
</tbody>
</table>
The images in Figure 20 show the last pinch-off that occurred during the transition period. Additional drops may have pinched off further into zero g as described above. Note the downstream pinch-off distance is fairly constant until the last few images. Also note that the size and shape of the drops remain fairly constant, except again for the last few images. It is seen that gravity plays a large role in this flow. Zero g is attained near the left of the bottom row of images in Figure 20. Thus, the inertia of the jet, due in large part to gravity, causes the jet to persist for some time before being slowed by viscous forces.

Images for a Reynolds number of 141 are given in Figure 21. It is immediately seen that this case is quite different than the case at a Reynolds number of 96. The images are arranged in the same way they were in Figure 20, with zero g again occurring near the leftmost image in the bottom row. Note that the length of the jet begins to increase as the transition begins to occur (inertia dominates). As gravity dissipates, viscous forces become more important and the jet begins to contract in length. Waviness in the jet initially dissolves away at the beginning of the transition period, but then reappears in the last few images. This is most likely due to the recoil of the jet after pinch-off. Table 17 lists important numerical properties for this flow case. Note some dimensions are not given because they could not be found; the drops pinched-off outside the image recorded by the camera.

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>1.600</td>
<td>0.59</td>
<td>0.64</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>1.733</td>
<td>77.5</td>
<td>13.7</td>
<td>0.78</td>
</tr>
<tr>
<td>18</td>
<td>2.067</td>
<td>0.86</td>
<td>1.08</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>2.267</td>
<td>76</td>
<td>19</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Table 16: Numerical results for transition period for Re = 96.
Figure 21: Transition from 1.8 to zero g for Re = 141. Length of images for the upper row is 10D, 11D for the lower row.

<table>
<thead>
<tr>
<th>Drop Number</th>
<th>Time (seconds)</th>
<th>w/D</th>
<th>l/D</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.000</td>
<td>0.83</td>
<td>1.00</td>
</tr>
<tr>
<td>2</td>
<td>0.100</td>
<td>0.78</td>
<td>1.00</td>
</tr>
<tr>
<td>3</td>
<td>0.167</td>
<td>0.83</td>
<td>0.98</td>
</tr>
<tr>
<td>4</td>
<td>0.300</td>
<td>0.78</td>
<td>1.08</td>
</tr>
</tbody>
</table>
Table 17: Numerical results for transition period for $Re = 141$.

<table>
<thead>
<tr>
<th></th>
<th>0.400</th>
<th>0.81</th>
<th>0.95</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0.533</td>
<td>0.81</td>
<td>1.05</td>
</tr>
<tr>
<td>7</td>
<td>0.633</td>
<td>0.76</td>
<td>0.95</td>
</tr>
<tr>
<td>8</td>
<td>1.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>1.267</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1.767</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>2.100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>2.800</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>3.033</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>3.300</td>
<td>1.44</td>
<td>1.44</td>
</tr>
<tr>
<td>15</td>
<td>4.467</td>
<td>1.71</td>
<td>1.93</td>
</tr>
<tr>
<td>16</td>
<td>5.600</td>
<td>2.47</td>
<td>2.27</td>
</tr>
</tbody>
</table>

A few key comparisons can be made between Figures 20 and 21. First, the size of the drops are much larger for the larger flow rate, both initially and at the end of the transition period. Second, the downstream distance at which pinch-off occurs is much larger in the case of the higher Reynolds number. Finally, the shape of the drops in the lower Reynolds number case are slightly more spherical than in the higher Reynolds number case, where they are generally more prolate.

Pump performance was also looked at by analyzing the images above. By approximating the drops as ellipsoids that are radially symmetric, an estimation for the volume of each drop can be obtained. Knowing the volume of each drop and the time for each drop to form, an estimation for the volumetric flow rate can be determined. Note that this analysis disregards the fact that the drops are not exactly ellipsoids. This analysis also neglects the volume of satellite drops and the growth and shrinkage of the jet upstream of pinch-off. However, the assumption of ellipsoids is fairly good and does not introduce an overly large amount of error in the analysis, except for the last couple of drops where there is a large change in the jet length and diameter. For the purpose of this analysis, it is adequate. With this in mind, the results are given in Figure 22 below. Note that the volumetric flow rate is approximately constant. This suggests the changing gravity levels do not drastically affect the performance of the pump. Thus, the error due to pump performance in the results presented throughout this paper is minimal.
Other Interesting Events

The previous results were examples of “normal” occurrences throughout the flight. However, the changing gravity fields led to some events that would be hard to reproduce. Two of these examples are given below.

Figure 23 is a picture taken during zero g. In the upper right hand corner of the picture is an air bubble. This bubble was due to a small pocket of air in the tank after it was filled and could not be avoided. Perhaps this was a good thing, since this image, along with the following sequence of images were made possible by the bubble. The bubble is moving up and to the right at the instant this image was taken. This was caused by a slight increase in the g level. Some of the water/glycerin mixture got trapped in the bubble’s wake and followed the path of the bubble (lower right portion of image). Eventually, pinch-off occurred at the instant shown in the figure. Note the bean-shaped drop, which is quite different than all of the results presented earlier. Also note the presence of mineral oil inside the drops coming out of the nozzle (upper portion of image). This was due to a small amount of mineral oil present upstream of the nozzle. This could not be avoided since the mineral oil is lighter than the water/glycerin mixture. Thus, it tends to propagate towards the top of the system even when the pump is running.
A similar event as the one shown in Figure 23 is given in Figure 24. In this case, however, the water/glycerin caught in the wake of the bubble actually intersects the jet coming out of the nozzle. A sequence of 12 images is shown to illustrate the event. These images are taken 1/6 of a second apart. What is interesting is that the intersecting jets do not coalesce. They do not, however, bounce off of each other.

The clarity of these images is less than the previous images presented due to the fact that this event happened near the end of the flight. Because the transitions between zero and 1.8 g’s occur fairly rapidly, the fluids tend to mix slightly. The air bubble was sometimes caught in this mixing process, leading to small air bubbles getting scattered throughout the tank. These air bubbles were small enough to stay mixed in the mineral oil for long periods of time, thus building up throughout the flight and leading to grainy images.
Figure 24: Intersection of two jets in zero g. Length of each image is 11D.
Ground Test & Parabola Data

Since the flight crew experienced disorientation, the test condition (the number of cycles the two fluids were mixed) varied over time. To see which test conditions were performed during any given parabola, please refer to Appendix A.

Empirical Results

![Figure 25: Test condition comparisons.](image)

![Figure 26: 1-Cycle of Mixing](image)
Figure 26 Comparison between Flight and Ground Data for 1 Mixing Cycle

Figure 27 Comparison between Flight and Ground Data for 2 Mixing Cycles
The above figures show the average behavior for the respective test conditions. The data can be matched to a 4\textsuperscript{th}-order polynomial using least-squares fitting. The general formula can be seen below. The coefficient values for the best-fit lines for the appropriate test conditions are displayed in Table 7.

\[ y = Ax^4 + Bx^3 + Cx^2 + Dx + E \]

<table>
<thead>
<tr>
<th></th>
<th>1-Cycle</th>
<th>2-Cycles</th>
<th>3-Cycles</th>
<th>1-Cycle</th>
<th>2-Cycles</th>
<th>3-Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A )</td>
<td>8.00E-08</td>
<td>1.00E-08</td>
<td>7.00E-09</td>
<td>1.00E-05</td>
<td>1.00E-05</td>
<td>2.00E-06</td>
</tr>
<tr>
<td>( B )</td>
<td>-3.00E-05</td>
<td>-6.00E-06</td>
<td>-4.00E-06</td>
<td>-0.0015</td>
<td>-0.0013</td>
<td>-0.0003</td>
</tr>
<tr>
<td>( C )</td>
<td>0.0042</td>
<td>0.0013</td>
<td>0.001</td>
<td>0.0629</td>
<td>0.0551</td>
<td>0.0205</td>
</tr>
<tr>
<td>( D )</td>
<td>-0.2757</td>
<td>-0.1349</td>
<td>-0.1149</td>
<td>-1.1277</td>
<td>-0.97</td>
<td>-0.5618</td>
</tr>
<tr>
<td>( E )</td>
<td>7.7619</td>
<td>7.9689</td>
<td>8.1078</td>
<td>7.9732</td>
<td>7.9864</td>
<td>7.8445</td>
</tr>
<tr>
<td>( R^2 )</td>
<td>0.9885</td>
<td>0.9942</td>
<td>0.9938</td>
<td>0.9961</td>
<td>0.9989</td>
<td>0.9865</td>
</tr>
</tbody>
</table>

**Figure 28** Comparison between Flight and Ground Data for 3 Mixing Cycles

Figure 14 and Table 7 show the time required for a 100% completion (reconnection of the two fluids) for the various test conditions.
Figure 29: Comparison of ground tests to in-flight data.

<table>
<thead>
<tr>
<th># of cycles</th>
<th>1-cycle (sec)</th>
<th>2-cycles (sec)</th>
<th>3-cycles (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground Tests</td>
<td>50</td>
<td>50</td>
<td>76.67</td>
</tr>
<tr>
<td>In-Flight Data</td>
<td>133.5</td>
<td>204.2</td>
<td>237.5</td>
</tr>
</tbody>
</table>

Table 19: Time to 100% for empirical data.

Flow Visualization

This report takes a closer look at the four particular test cases.
1. Ground Tests: How the fluids behave under normal conditions
2. No mixing in zero gravity
3. 1-Cycle of mixing in both micro- and macro-gravity.
4. 2-Cycles of mixing in zero gravity
The first set of images displays the results of the reconnection experiment under normal, 1g, conditions with one two cycles of mixing.

As you can see, under normal gravity conditions, it only took about 50 seconds for the two liquids to completely separate. This led us to the assumption that the two liquids would fully separate before the start of the next micro-gravity portion of the flight parabola assuming that the liquids separated at a faster rate in macro-gravity.

No Mixing; Zero Gravity

The second case, flow of two immiscible fluids in zero gravity without any mixing, is an important part of this experiment. Before any kind of analysis can be done on flow with a heterogeneous mixture of the two fluids (as displayed in the ground tests above) in the varying gravity conditions, we must understand how the flow naturally behaves. This can be examined visually by looking at the following pictures of the fluid flow in zero gravity.
These pictures show how the two immiscible fluids interact in zero gravity without any kind of mixing. While looking at these pictures, you may notice a small metallic looking sphere floating around. This is a result of a small air pocket we were not able to remove from the system in our preflight set-up. While this bubble exists, it does not appear to cause an adverse effect to our experiment. In fact, the bubble tends to almost act like a third fluid and doesn’t appear to interact or perturb the system.

After repeated evaluation of the video displaying the “no mixing” test cases, there appear to be small buoyancy driven flows. It is also important to note that the aircraft did not create a completely zero gravity environment. There were points in the flight path where small amounts of positive and negative forces were acting on the system. The resultant of these time-varying forces created the flow visualized above. As you can see, the two fluids stay mostly separated with fingers of the more dense fluid, the water/glycerin solution, penetrating the oil.

Notice that at t = 30 sec, when the transition between micro- and macro-gravity occurs, there is a small layer of bubbles. However, the size of the bubbles are relatively large and the layer dissipates within a second or two in macro-gravity. Knowing this, we decided to neglect any kind of additional mixing that may have occurred during the micro-gravity portions of the experiment.

1-Cycle of Mixing; Micro- and Macro-Gravity

Now that it is known what happens to the fluids in micro-gravity without any mixing, it is time to examine the flow with one cycle of mixing in micro- and macro-gravity.
$t = 1$ sec; $\delta = 8''$

$t = 3$ sec; $\delta = 8''$

$t = 5$ sec; $\delta = 8''$

$t = 9$ sec; $\delta = 8''$

$t = 11$ sec; $\delta = 8''$

$t = 19$ sec; $\delta = 8''$
Here, it appears that a very small amount of reconnection occurs before the macro-gravity conditions occur. The first seven images show how the blobs/bubbles of like fluid tend to come together and how, as time increase, the flow tends to look more like the flow condition of “No Mixing” in micro-gravity shown above. As the macro-gravity portion of the ensues, the flow tends to behave more like the flow shown in the Ground Test images shown above, only, the flow reconnects at a slower rate.
2-Cycles of Mixing; Zero-G

When the two fluids were mixed longer, i.e. there were more cycles of mixing, we noticed something unique and unexpected. This can best be described by looking at the following images.

These pictures represent the flow during the second period of micro-gravity with two cycles of mixing. What makes these pictures interesting is that the layer of bubbles tends
to act as a third immiscible fluid. This is apparent after examining the pictured from the other test conditions shown above. What was originally expected is that the bubbles would have been evenly disbursed throughout their perspective fluids.

Conclusions

Jet Pinch-Off & Stability Conclusions

Jet dynamics under a variety of gravity levels were studied aboard NASA’s Vomit Comet. Images were captured on a digital video camera and compared to normal, one g conditions. The shape and size of the resulting jet and droplets was analyzed. Additional analysis was performed using the separation angle between the jet and the droplet immediately after pinch-off.

It was found that gravity plays an important role in the flow analyzed. While repeatable pinch-off conditions could be obtained under a variety of flow rates under 1 g conditions, the same cannot be said about other gravity conditions, both higher and lower in g level. The flow was found to be rather unstable under 1.8 g’s, with pinch-off conditions varying drastically during different periods of time. During zero g, the flow was found to be drastically different than both the 1 and 1.8 g conditions. Under zero g, pinch-off did not occur at the forcing frequency. Rather, large drops formed that pinched off at an irregular rate. Most of the time the drops pinched off because of slight changes in the gravity level.

Reconnection Conclusions

The purpose of the experiment was to study the qualitative and quantitative reconnection motion of a heterogeneous mixture of two immiscible fluids in micro- and macro-gravity. The two fluids used in the experiment were mineral oil and a solution of distilled water and glycerin (1:1). The fluids were mixed up using a pneumatic circuit in series with an air piston. This piston moved a perforated plate that mixed the fluids into various scales of droplets depending on the number of mixing cycles. (The more mixing that occurred, the finer the fluid particles.) This mixing occurred at the beginning of the micro-gravity portion of the flight path.

What was seen is that the fluids reconnected at a much slower rate in the micro- and macro-gravity conditions of the KC-135 than they did in normal ground conditions. (See Results for details on the reconnection rates) What was important to notice, however, is the two fluids did reconnect, even slightly in micro-gravity. This was seen in the flow visualization. Assuming the mixing devise creates an 8” layer of bubbles immediately after mixing, it is shown that the fluids have a bubble layer of only a couple of inches at the start of the macro-gravity portion of the flight path.
Another unexpected result seen in the flow visualization is that the bubbles tend to act as an third immiscible fluid. This differed from the expectation that the bubbles would disperse evenly throughout the fluids.

In general, the data is valuable date because we were able to examine how the fluids separated in varying gravity conditions. Also, any new data in the scientific world that can help create better numerical fluid mechanic models is always a great resource.

Outreach Program

Outreach Goals
The main goal of this program is to transfer the knowledge and experience gained to all types of audiences, ranging through high school students, the general public, the scientific community, and the industrial community.

**Outreach Plan**

Because we seek to reach the widest audience possible, different means of communication were used, including a web page, newspaper, magazines, and presentations.

**Web Page**

The address of our website is:

http://www.aem.umn.edu/proj-prog/sfo/micro_flows/index_lf.html

which can be reached directly or through a link in the U of M Aerospace Department web site in the highlights section:

“AEM Students Participated in Micro-gravity Experiments in the "Weightless Wonder" Program at NASA”

http://www.aem.umn.edu/info/highlights.shtml

The web site main page is shown below. The main page shows an overview of the experiment, an introduction to the team, and the latest news about the team. This main page includes a link to the Reduced Gravity Student Flight Opportunities Program, as well as links to some of our sponsors:

- UROP – Undergraduate Research Opportunity Program
- Minnesota Space Grant
- Aerospace Engineering and Mechanics Department
- Institute of Technology
- University of Minnesota

Sponsors mentioned without a link:

- AEM Richard and Shirley DeLeo Scholarship & Engineering Fund
- AEM Alumni Program Support Fund
- Student Affairs Dean's Office
PROPOSED EXPERIMENT:

"Study of Pinch-Off and Reconnection of Liquid-Liquid Flows in Micro- and Macro-Gravty"

TEAM:

Eric Estense, Travis Schauer, Christopher Tessemen and Cecilia Ortiz. Professor Ellen Longmire is mentoring this team. Jill Barron from the Star Tribune is the journalist who went with us.

NEWS:

We just came back from participating in the Reduced Gravity Student Flight Opportunities Program! It was the best experience of our lives (at least for me). You can check out the articles that ran in the newspapers here in Minneapolis. I'll keep updating the webpage to include all the pictures that we have and all the things we did.

FALL 2000:

Our team was recently selected to participate in the February 2001 Reduced Gravity Student Flight Opportunities Program! This program allows undergraduates students to fly and test their experiments aboard a KC-135A, better known as the "Vomit Comet". This aircraft operates as a reduced gravity laboratory and provides a true weightless environment.

Newspaper Articles

MN Daily:  
Feb 19, Falling to Earth  
Feb 7, Hold on to your Coasters!

Star Tribune:  
Feb 9, Vomit Comet: Zero G in no place for weak
Feb 12, Facing up to the challenge of the altitude chamber
Feb 14, A few pointers on barfbag etiquette before  
Sat Night
Feb 14, Vomit Comet: Embellishment over Chief of Mexico

Modified by Cecilia Ortiz Duenas on April 8, 2001
The links to the secondary pages are:

Pictures – this page includes pictures from the flights, pictures from the trip down to Houston, building of the experiment and more.

Proposals – includes the original proposal and the final proposal sent to NASA. These proposals include an overview of the experiment and detailed descriptions of the experiment.

Outreach Program - this page lists all the outreach activities that the team is involved.

Results – Page that includes movies and still pictures of the experiments. It also includes the results obtained. Updated frequently.

Nitinol Vibration Damping Experiment - link to the web page of the other U of M team that participated in the program.

Star Tribune – link to the newspaper that covered our team.

MN Daily – link to the University’s student newspaper.

**Press and Radio Coverage:**

Newspapers

Two newspapers covered our team’s participation in the RGSFOP Program. Both journalists that wrote the articles accompanied our team during our participation.

From the Star Tribune, Jill Burcum, our official journalist, flew with two of our members. She completely covered our participation. The articles she wrote are shown below. A copy of the front-page article is included.

Feb 7, Hold on to your Cookies!
Feb 8, 4 U students will ride NASA's 'Vomit Comet'
Feb 9, 'Vomit Comet': Zero G is no place for wimps
Feb 12, Facing up to the challenge of the altitude chamber
Feb 14, A few pointers on barf-bag etiquette before the flight
Feb 16, Vomit Comet: Exhilaration over Gulf of Mexico

During our participation in the program, these articles would appear in the electronic version of the newspaper. There was also a question/answer option, where people who read the articles could send us an email to ask any questions. Most of the questions we got were from kids asking mostly astronaut related questions. It was a fun way to interact with kids.

*Published: February 16, 2001, STAR TRIBUNE*
One wild ride

Jill Burcum; Staff Writer

After a week's training at NASA, a group of University of Minnesota aerospace students and I have heard all about the potential downsides of hitching a ride on the plane used to train astronauts in weightlessness.

What the space agency didn't tell us was that riding the plane, dubbed the Vomit Comet, produces these effects:

Euphoria.
Giddiness.
A sense of wonder.
Superman impressions.
Serial somersaults.
An irresistible urge to yell, "Do it again!"

Housed near the Johnson Space Center in Houston, the KC-135 plane is one of NASA's most valuable scientific laboratories, and by virtue of what it does, the world's most exclusive roller coaster. On Thursday, it was all systems go for two members of a team of University of Minnesota aerospace engineering students to test their fluid-dynamics experiment on board.

Because NASA requires an official journalist to go with them, I got to go, too. The team was one of two groups from the university to win a NASA-sponsored science competition that let them aboard the plane. Their experiment will test how fluid acts in zero gravity.

It was, we agreed, the trip of a lifetime.

"This was so awesome," said Eric Euteneuer, 21, a senior from Maple Grove. "This is one of the highlights of my life."

"It's one of the best things that ever happened to me," added Chris Teeuwen, 23, a senior from Alexandria, Minn.

Ditto was all I could add as I stepped off the plane with a silly grin and shaky legs after a nearly two-hour flight.

In addition to Teeuwen and Euteneuer, the team also includes Travis Schauer, 21, of Thorp, Wis., and Cecilia Ortiz-Duenas, 21, of Mexico City. Ortiz-Duenas and Schauer will fly Friday to run another part of the experiment again.

Preflight jitters

Thursday morning was a different story compared with the postflight euphoria. At the 7:30 a.m. preflight meeting, it was easy to tell there were fleeting misgivings about the flight. There were more than a few pale faces and jittery legs.

John Yaniec, the gruff but knowledgeable test director, had assured everyone the day before that the plane is one of the safest in the air. It sounded good at the time, but his words' ability to reassure diminished Thursday morning when NASA staff members handed out the paperwork.

Among other things, those going up were asked to designate a beneficiary and to sign a paper stating...
that they understood that the plane doesn't fly according to normal aviation regulations.

Then there's the motion sickness. Yaniec claims that the plane doesn't deserve the Vomit Comet nickname. But after days of training on motion sickness and rumors that NASA refers to those who get sick on board as "kills," you start to wonder.

Fortunately, the preflight meeting went fast. After putting on the NASA-issued olive green flight suits and swallowing anti-nausea capsules, it was time to board the KC-135.

A few minutes after we strapped ourselves into regular passenger seats, the plane was airborne and soon reached cruising altitude.

"Time to rock and roll," Yaniec said as students rushed to the experiments parked in the padded, wide-open front area of the plane.

The plane flies in a special area designated for it over the Gulf of Mexico. It takes about 15 minutes to get there and begin the flight pattern—a series of parabolas, essentially climbs and dives. There is about 25 seconds of float time at the top of each parabola. Typically, each mission flies 30 parabolas.

**Float time**

Lights flash on during each parabola to announce the arrival of zero gravity. They aren't needed.

Suddenly, everyone is rising in the air, the way a hot-air balloon would over a Minnesota cornfield in mid-July. The sensation is the same, unless you give a little push, as I did. I soared uncontrollably and struck the ceiling butt-first.

Teeuwen and Euteneuer were up there, too, amazed looks on their faces as they kicked around in futile attempts to stay near their experiment and to avoid playing "bumper bodies" with others. That was nearly impossible to do.

Preflight, I had thought of the Greek myth of Daedalus and Icarus, who soared elegantly through the air on homemade wings until Icarus fell. Now, watching Euteneuer, Teeuwen and the others, what came to mind were Disney characters who suddenly gain the ability to fly and spend a few hours being total klutzes while they learn to do so.

**Float-time on each parabola ends quickly and is announced by Yaniec, who yells, "Coming down, get your feet down" over the throbbing engines each time. Then, macrogravity, zero G's nasty sister, sets in.**

Macrogravity simply refers to conditions in which the force of gravity is greater than Earth's. Those aboard the KC-135 experience macrogravity at the bottom of each parabola. During this time, passengers plummet to the floor Icarus-style, and they feel as if they weigh twice as much as they usually do.

It's also difficult to keep breakfast down. The nausea gods love macrogravity for some reason, and it's at this point that KC-135 passengers are mostly likely to get sick. No one did at first, but something NASA calls "stomach awareness" definitely sets in.

At first, the zero G is too shocking to enjoy it much. Weightlessness goes from the theoretical to the real in a big hurry. It takes some time to adjust. But after a few parabolas, everyone gets the hang of things. Amazement and delight set in.

Teeuwen, who was attending to the experiment, perfected the art of turning upside down during float time and then right side up again before macrogravity set in.
Others did spins and somersaults, or one-handed push-ups that shot them to the ceiling. Delighted shrieks and "Wows!" accompanied each of them. Some soared through the cabin, arms outstretched like superheroes. All that was missing was the cape.

After doing a swan dive from the ceiling, I took my camera and tape recorder out and set them spinning in opposite directions in front of me. At one point, when I wasn’t looking, the tape recorder sneaked away and started floating down the cabin before somebody snagged it.

That wasn’t true for the coins, bits of foam and lint that came out of pockets. They floated around in packs, like schools of bizarre, misshapen fish.

The 'kills'

All too soon, we were on our last set of parabolas and heading back to Ellington Air Force Base. At this point, there were a few people on the kill list. This was the Vomit Comet after all.

Euteneuer, despite ribbing others about how fast they’d get sick before the flight, developed stomach awareness and then vomited during the first 10 parabolas. However, he recovered well enough to stand inverted during zero Gs by the end.

I was one of the other kills. Having survived 20 parabolas, macrogravity nailed me on the 21st. NASA was right: Having a barf bag in the chest pocket of the flight suit is a good idea. After that, I was fine. Pretty good for someone who usually gets sick on the Tilt-A-Whirl at the county fair.

Back at Ellington, the first question from everyone waiting there was, of course, what was it like?

Teeuwen and Euteneuer, along with Jeff Rollins and Tim Jackson, two other Minnesota students who flew that day, were at a loss for words. So was I.


``I don't think there are words to describe it,'" Rollins said. "'You just have to do it to understand.'" To learn more about the University students' experiment, go to http://www.aem.umn.edu. Click on `highlights," then click on `fluids experiment.'"

Jill Burcum can be contacted at jburcum@startribune.com.

Ultimate roller coaster
The NASA airplane simulates zero gravity by flying in a pattern of 10,000-foot waves.

1. When the KC-135 plane, dubbed the `Vomit Comet," reaches about 34,000 feet, it pitches downward at 40 degrees. It is at that point that its passengers experience weightlessness.

2. When the plane pulls out of the dive, it pitches upward at about 40 degrees. At that moment, the force of gravity is almost twice that on Earth.

The sudden shifts in direction and gravity play havoc with the body's balance system. Those aboard are advised not to move their heads during the pullouts or face the nauseating consequence.

© Copyright 1998 Star Tribune. All rights reserved.

From the University of Minnesota Daily, Mike Stenerson, a photography student, did the coverage for the student point of view. His article appeared in the central page of the “Daily” on February 18, a copy of his article is included.
Monday, February 19, 2001
U of M Daily

*Falling to Earth*

Photos and Story by Michael Stenerson

*Cecilia Ortiz-Duenas experienced what most in this world never will: pure weightlessness.*

*Ortiz-Duenas, an aerospace engineering senior who came to the University three and a half years ago, this experience was her last chance. Due to a change in NASA's policy, this is the last year international students are allowed to participate in the program.*

*Staying in such close proximity to Johnson Space Center and participating in all the activities let students feel they were part of NASA.*

*I thought that there would be much more work, but it just feels like we're waiting to fly.* Ortiz-Duenas and Eric Euteneuer formed one team and worked on an experiment to study the separation of glycerin-water and oil. Chris Teeuwen and Travis Schauer headed up the other team, conducting a study on the pinch-off and reconnection of liquid-liquid flows.

The experiments are modifications of several already running at the University.

Teeuwen and Schauer had to deal with grimaces and wary eyes from the KC-135 flight operations crew on account of the 50 gallons of oil they took on the plane. During a previous flight, a different team of students miscalculated while assembling their experiment and emptied most of their 10 gallons of oil into the plane’s interior.

Luckily for the flight crew -- and the Teeuwen-Schauer team -- their experiment went off without a similar incident.

During their 10 days at NASA the students participated in several activities, including the 7-hour-long "physiological training." For this training, speakers used PowerPoint presentations, hands-on examples and a bit of old-fashioned storytelling for a crash course on KC-135 protocol.

The training also explained why some students would not feel normal, or, more specifically, why they would vomit.

NASA officials also required time in the altitude chamber, a rectangular, airtight room with controlled air pressure that simulates the effects of flying at different altitudes. Students put on oxygen masks and breathed at sea level air pressure for a half hour before it was lowered to simulate an altitude of 2500
feet.

The students then took turns removing their oxygen masks for up to five minutes.

When exposed to the diminished air pressure found at high altitudes, the brain becomes hypoxic, a condition where red blood cells are not able to reach the brain.

Hypoxia severely hinders the brain’s normal functioning, causing simple arithmetic, writing, and navigating a short maze to become extremely difficult.

"You start to think this (simple arithmetic) is really hard. I feel tired, what was I doing again?" Ortiz-Duenas expressed a desire to travel to primary and secondary schools to give small presentations on their trip.

Questions can be directed to orti0022@umn.edu

Other Newspapers

Local newspapers from the hometowns of the team members are currently conducting interviews to prepare an article.
Magazines

Two magazines from the Institute of Technology, University of Minnesota have covered our experience.

*Items*

A monthly newsletter for the IT community—current issue and archives. Article appeared in April’s issue.

*Inventing Tomorrow*


Radio

A small presentation was done for a local radio station. Eric Euteneur was the representative of the team.

*Activities:*

- IT Week Technology Fair, sponsored by the Plumb Bob student organization, is primarily a technology showcase, but also provides opportunity for employer representatives to meet with IT students as well as providing students to get acquainted with student organizations and activities. This fair is also targeted to high school seniors and college freshman students. We thought that this showcase would give a great opportunity to show and let students know about the program and our experience. The fair lasted 2 days. We designed a display showing pictures, contact information, newspaper articles, video footage from the flight, and an email contact list. We posted flyers in the main engineering buildings, which helped bring students, and professors that were interested in this project from different areas of study. The flyer is shown in the next page.


This gallery is part of the International Conference of Multiphase Flow where our advisor, Dr. Longmire was invited. The Gallery of Multiphase Flow is a gallery where Fluids experiments results are presented in the form of a poster or a video. We decided to send two posters, one for each of our experiments. A smaller presentation of the posters is attached in the next pages. These posters were completely designed and edited by us.
Presentations:

- March- April. Presentations were done in Aerospace Engineering low-level classes (sophomore and juniors from all types of engineering), as well as in higher-level classes (aerospace students).

- May 7th. Presentation in Local Middle School, ninth graders.
• May 21st. Presentation Edina High School, advanced placement physics classes.

• Ongoing Display at the Aerospace Engineering Department, showing newspaper articles and contact information.

When the time came for the community outreach portion of the program, the Community Resources Pool in Edina Minnesota contacted our group about arranging meetings for both junior and senior high school students. The resource center arranged two different meetings. In preparation for these meetings a short outreach video was made from both NASA and local news footage. The first presentation was made on May 7th to ninth graders for a local career fair. The presentation went well, but the interest level just wasn’t there. The second presentation was much more effective however. On May 21st a presentation was made to four Edina High School advanced placement physics classes. These students were very receptive to the presentation and had numerous questions about the experience and the program in general. Since all of these students are going to college, the interest level was much higher and the presentations were far more fun. There are future plans to visit some of the high schools attended by the team members. The group has also been contacted by the Community Resources Pool to do more presentations in Edina.

**Outreach Audiences:**

Taking the wide variety of activities and outreach projects that we have done, we think we have managed to reach all types of audiences.

High school students and college freshmen: IT Week, low-level engineering classes, and presentations.


General Public: Newspaper articles, Web page, and Radio coverage.

University of Minnesota Students: University of Minnesota Daily, Web Page, Presentations, IT Week, IT magazines, etc.
UNIVERSITY OF MINNESOTA
Department of Aerospace Engineering and Mechanics
participating in

NASA Reduced Gravity Student Flight Opportunities Program
A NASA sponsored program administered by the Texas Space Grant Consortium

February 2001

Study of Pinch-Off and Reconnection of Liquid-Liquid Flows in Micro- and Macro-Gravity

Nitinol Vibration Damping in Microgravity.

Eric Euteneuer
Cecilia Ortiz
Travis Schauer
George Teeuwen

Jeffrey Rollings
Dakri Nelson
Nick Velander
Tim Jackson
Will Hambleton

Visit us at I.T. WEEK
April 11 and 12, 2001 in the tent in Northrop Mall

Sponsored by

AEM Richard and Shirely DeLeo Scholarship & Engineering Fund
AEM Alumni Program Support Fund
Institute of Technology
Student Affairs Dean's Office
Bibliography


