An Investigation to Advance the Technology Readiness Level of the Centaur Derived On-orbit Propellant Storage and Transfer System

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An Investigation to Advance the Technology Readiness Level of the Centaur Derived On-orbit Propellant Storage and Transfer System

By:

Nathan L. Silvernail

A thesis submitted to the Graduate Studies Office In partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering

Embry-Riddle Aeronautical University
Daytona Beach, Florida
Spring 2013
An Investigation to Advance the Technology Readiness Level of the Centaur Derived On-orbit Propellant Storage and Transfer System

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This thesis was prepared under the direction of the candidate's Thesis Committee Chair, Dr. Sathya Gangadharan and Thesis Committee Members, Mr. James Sudermann and Mr. Brandon Marsell. It was submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering.

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Acknowledgements

I would like to convey my deepest appreciation to all of those that have helped to make this research a success and who have provided guidance along the way. Thank you to my advisor and mentor, Dr. Sathya Gangadharan for all of his support and motivation. Thank you to Bernard Kutter and Peter Wilson for the amazing opportunities they provided me and all of the help and support they gave throughout the years. Thank you to my Committee members, James Sudermann and Brandon Marsell, for all of their guidance and assistance with the microgravity research conducted and the models developed. Thank you to my friends, Brian Lenahen, Dhawal Leuva, Anita Solanki and Tyler Hamlin, for all of their support throughout the life span of this research. Thank you to the faculty members and staff at ERAU that have kindly put up with all of my requests and last minute deadlines to help make this research a success.
Mission Statement

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Title: An Investigation to Advance the Technology Readiness Level of the Centaur Derived On-orbit Propellant Storage and Transfer System

Institution: Embry-Riddle Aeronautical University

Degree: Masters of Science in Mechanical Engineering

Year: 2013

Advance the Technology Readiness Level (TRL) of on-orbit propellant storage and transfer technologies to develop and maintain the ability to refuel space systems in Low Earth Orbit (LEO) and Geo-Synchronous Orbit (GSO) so as to further extend the mission capabilities of modern day Commercial Launch Vehicles (CLV's); such as the Atlas V, Delta IV Heavy, and future Falcon Heavy.

Abstract

This research was carried out in collaboration with the United Launch Alliance (ULA), to advance an innovative Centaur-based on-orbit propellant storage and transfer system that takes advantage of rotational settling to simplify Fluid Management (FM), specifically enabling settled fluid transfer between two tanks and settled pressure control. This research consists of two specific objectives: (1) technique and process validation and (2) computational model development. In order to raise the Technology Readiness Level (TRL) of this technology, the corresponding FM techniques and
processes must be validated in a series of experimental tests, including: laboratory/ground testing, microgravity flight testing, suborbital flight testing, and orbital testing. Researchers from Embry-Riddle Aeronautical University (ERAU) have joined with the Massachusetts Institute of Technology (MIT) Synchronized Position Hold Engage and Reorient Experimental Satellites (SPHERES) team to develop a prototype FM system for operations aboard the International Space Station (ISS). Testing of the integrated system in a representative environment will raise the FM system to TRL 6. The tests will demonstrate the FM system and provide unique data pertaining to the vehicle's rotational dynamics while undergoing fluid transfer operations. These data sets provide insight into the behavior and physical tendencies of the on-orbit refueling system. Furthermore, they provide a baseline for comparison against the data produced by various computational models; thus verifying the accuracy of the models output and validating the modeling approach. Once these preliminary models have been validated, the parameters defined by them will provide the basis of development for accurate simulations of full scale, on-orbit systems. The completion of this project and the models being developed will accelerate the commercialization of on-orbit propellant storage and transfer technologies as well as all in-space technologies that utilize or will utilize similar FM techniques and processes.
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Chapter I

Commercial Benefits of Technology

The current Evolved Expandable Launch Vehicle (EELV) program was developed in the 1990’s to ensure continued and affordable space access for the United States Air Force (USAF) and other organizations. Under this program, the current Atlas V and Delta IV launch systems were developed. Currently, these launch systems provide the ability to place spacecraft in Geo Synchronous Orbit (GSO). However, the ability to place heavier satellites and space systems to and beyond GSO, such as NRO satellites and future lunar missions declared by Shackleton Energy, Bigelow Aerospace, EarthRise Space Inc. and other organizations, is not yet possible.

For this reason, plans for development of upgraded performance Commercial Launch Vehicles (CLV’s) and Heavy Lift Vehicle’s (HLV’s) have come into focus with an estimated cost of anywhere between $3 Billion for low end performance CLV’s to $24 Billion for a 70 mT HLV (providing lift capabilities approximately 2.5 times greater than the Delta HLV). In fact, NRO just spent $350 Million to upgrade the capabilities of the Delta IV Heavy to provide for a larger payload mass. This $350 Million upgrade increased the Delta IV Heavy’s delivery payload capability by about 1,400 lbm’s, i.e. NRO spent an additional $250,000 per added pound of payload weight in order to deliver their payload to GSO.

Additionally, Operations and Service Infrastructure for Space (OASIS), a project promoted under the International Space Exploration Coordination Group (ISECG) of 14 space agencies worldwide, is progressively developing a network of spaceports that
utilize similar FM Technologies that are being advanced through this proposal. These spaceports support the theory of utilizing existing launch vehicles in correlation with on-orbit propellant storage and transfer technologies to introduce a cost effective means of traveling between Earth, Mars and the moon. This program estimates an initial investment of only $296.3 million with a return in 7 years and an annual profit of $42 million.¹

By developing the ability for launch systems to refuel once they reach LEO, the orbital capabilities of these existing launch systems will effectively double. Providing a near term opportunity for current launch systems to deliver payloads to GSO and beyond with an estimated development cost of only $500 Million. However, on-orbit refueling technologies are not limited to current launch systems. In fact, when this technology is implemented with the future advanced CLV’s and HLV’s, it will complement those launch systems by expanding their mission capabilities and providing advanced orbital placement of much heavier payloads than current launch capabilities and future designs can handle.

**Background of Technology**

The Centaur derived system (illustrated in Fig. 1) is composed of three main modules, to enhance storage efficiency and available storage volume, these modules include: the Centaur module, the mission module and the upper liquid hydrogen storage module. During launch, the LO₂ and LH₂ sections of the Centaur module will be filled to maximum capacity. After separation of the Solid Rocket Boosters (SRB), approximately
50% of the propellant being stored in the Centaur module will be burned to allow the system to reach LEO.

Figure 1. Centaur derived on-orbit propellant storage and transfer system being developed by ULA.¹

Upon reaching LEO, the system will be placed into a transfer spin, or a spin about its minor axis, to allow the centrifugal force of the system to pull the propellant to the outer poles of the fuel tanks where FM hardware is located. This innovative settling approach not only creates a type of low-consequence propellant settling (settling requiring minimum additional propellant expulsion) but also allows the system to operate in an energetically stable state; allowing the energy of the system to correct any instability’s experienced from internal or external perturbations. Once the system is
rotating at the proper angular velocity it will undergo four propellant transfers by the means of a gaseous helium and oxygen pressurant, these transfers are outlined below:

**Transfer One** will be conducted to cryogenically cool the upper liquid hydrogen storage module and will consist of transferring a small percentage of the remaining liquid hydrogen in the Centaur module to the upper storage module and allowing the storage module to vent to vacuum.

**Transfer Two** will be conducted to move all of the remaining liquid hydrogen from the Centaur module to the upper storage module once it has been sufficiently cooled. Once the liquid hydrogen has been transferred, residual gaseous hydrogen will be vented to space to prepare the tank to receive liquid oxygen.

**Transfer Three** will be done to relocate all of the liquid oxygen from the Centaur module’s LO\(_2\) tank to its LH\(_2\) tank. After these three transfers have been completed, the system will simply maintain its set trajectory on-orbit and await rendezvous with the subsequent mission elements (spacecraft needing to be refueled). Once rendezvous is complete, the system will perform one last propellant transfer.

**Transfer Four** includes transferring the remaining liquid oxygen from the LO\(_2\) module and liquid hydrogen from the LH\(_2\) storage module to the docked spacecraft.

In addition to those aforementioned, further benefits of CLV’s and the utilization of on-orbit propellant storage systems include low cost development of hardware with a low turnaround in production time, the utilization of vehicles and hardware with flight ready status and high reliability, and the potential for advanced space missions on a near-term basis.
Physical Testing Overview

The primary focus of this investigation is to validate the means of utilizing a combination of spin stabilization about the vehicle’s minor axis and pressure gradients to transfer liquid propellants between subsequent tanks on the on-orbit propellant storage and transfer system detailed in the above section. To accomplish this, a successive testing approach was implemented that would advance this technology’s TRL to a point that full scale on-orbit testing is possible. This “from the ground up” approach involves the design and fabrication of scale prototypes of the on-orbit system that are equipped with the functionality to validate the transfer techniques being investigated. These prototypes are put through a successive testing sequence (illustrated in Fig. 2) that evolves from ground or laboratory testing to scale on-orbit testing onboard the International Space Station (ISS) with parabolic flight testing and sub-orbital flight testing in between. The successive nature of this approach allows for the development of performance predictions for subsequent test elements to be developed from the analysis of prior testing and applied to future experimental designs; thus increasing the rate of success and maximizing data collections for all future tests.

Figure 2. Successive testing "from the ground up" approach timeline.
During the ground testing and parabolic flight testing phases of this investigation, the prototype performed two operationally similar propellant Transfer Scenarios (TS). These scenarios include Transfers Two and Three as discussed previously. TS-1 involves transferring a very small amount of liquid propellant to the adjacent tank. This is assumed to create internal perturbations that can be considered negligible when compared to that of the following transfer operations. For this reason, TS-1 was not conducted during this investigation. Furthermore, TS-4 includes a transfer between two docked systems (the Centaur derived system and a simulated docked spacecraft) and is expected to require additional testing time to complete. For this reason, TS-4 will remain a secondary test objective and will be investigated during the later stages of this successive testing approach. The primary and secondary test objectives for this investigation are outlined below:

*Primary Test Objectives:*

1) Successfully perform TS-2 and TS-3 while the mock-up is filled to 50% of its maximum capacity in both LH$_2$ and LO$_2$ tanks.

2) Measure energy dissipation rate of the mock-up while TS-2/TS-3 are performed.

3) Determine the rotational stability of the test model spinning about the minor axis.

*Scale Prototype*

Three identical 1:37 scale mock-ups of the Centaur derived on-orbit propellant storage and transfer system were created utilizing the manufacturing facilities at ERAU. These mock-ups were fabricated from 6061-T6 Aluminum and Polycarbonate to maintain high survivability throughout all phases of this investigation. The fully
operational on-orbit system will utilize materials with far different physical properties so adjustments had to be made to the prototype to ensure the Center of Gravity (CG) of the full system was realized during scaled testing. Additional characteristics such as transfer pipe thickness and diameter as well as transfer valve locations were all taken into account. All propellant transfers were controlled via a specially designed flight computer mounted within the mission module section of the prototype. A cross sectional image of the scaled prototype used during testing is illustrated in Figure. 3.

Figure 3. Cross sectional view of 1:37 scale prototype of the on-orbit propellant storage and transfer system.
Chapter II

Ground Testing Approach

To accurately determine performance predictions for the upcoming phases of this investigation as well as to verify the safety and reliability of the test equipment, ground testing was performed. This testing was conducted in the Fuel Slosh Laboratory at ERAU and involved mechanically spinning the scaled mock-ups about their minor axis via the use of a DC direct drive electric motor and sprocket system (shown in Fig. 3). The mock-up was spun at varying rotational rates and the transfers were conducted. During the transfers, angular acceleration changes of the system were wirelessly transmitted to the data acquisition system (DAQ) via a 2.4 GHz Bluetooth transmitter. Wireless cameras were mounted to the scaled mock-up to provide visual information of the liquid during the transfers. The video footage, along with the transmitted angular acceleration rates, provided insight as to the benefits and drawbacks to this innovative method of rotational settling.

Figure 4. Ground experimental apparatus developed at ERAU.
Ground Testing Data and Observations

While on-orbit, these systems will be spun at relatively low rates; however, the gravitational component present during ground testing created a problem. The FM processes and techniques being investigated require the liquid propellant, within the tanks, to be settled at the outer poles of the system prior to the opening of the transfer valves. This causes the liquid to fully envelope the transfer valves and allows the liquid to remain in that state during the course of the transfer operations; thus preventing an instantaneous pressure collapse within the tanks.

To overcome the force of gravity and allow the liquid within the tanks of the prototype to remain at a settled state, the scale prototype had to be spun at a very high angular velocity. This high rate of spin had a very large impact on the propellant transfers being conducted. The large angular velocity used during testing imposed a large Centrifugal Force (CF) on the liquid within the transfer lines of the prototype.

Take, for example, the test conducted for the TS-2 transfer operation. The pressure within the LH$_2$ tank on the Centaur module was at approximately 45 psi while the pressure in the subsequent tank on the upper liquid hydrogen storage module (the tank the liquid was being transferred to) was at atmosphere. In this scenario, the force introduced onto the free surface of the liquid, within the transfer lines, by the pressure acting on the liquid mass is approximately 0.554 lb. Seeing that the cross-sectional area of the transfer line is 0.012 in$^2$. By utilizing Eq. 1, the total force introduced onto the free surface of the liquid within the transfer lines due to the angular velocity at which the prototype is being spun can be determined.
\[ CF = m \left( \frac{v^2}{r} \right) \]  \hspace{1cm} (1)

Where \( m \) is the mass of the liquid within the transfer lines, \( r \) is the distance between the CG of the prototype and the free surface of the liquid within the lines, and \( v \) is the angular velocity at which the system is being spun. If \( v \) is taken to be the angular frequency in rad/sec multiplied by \( r \), then Eq. 1 can be written as:

\[ CF = m \left( \frac{v^2}{r} \right) = m \left( \frac{(\omega r)^2}{r} \right) = m\omega^2 r \]  \hspace{1cm} (2)

Where \( \omega \) becomes the angular frequency of the system in rad/sec. By plugging in the values for the ground test performed for the TS-2 transfer operation into Eq. 2, it can be determined that:

\[ CF = m\omega^2 r = (0.002 \text{ lb}_m) \left( 12.6 \frac{\text{rad}}{\text{sec}} \right)^2 (0.595 \text{ ft}) = 0.189 \frac{\text{lb}_m \cdot \text{ft}}{\text{sec}^2} = 6.08 \text{ lb}_f \]

This calculation shows that the total CF introduced onto the liquid surface in the transfer line is approximately 11 times greater than the pressure force used to transfer the liquid; thus resulting in higher than anticipated transfer times during the ground testing portion of this investigation. In fact, an onboard video camera, mounted to provide a “bird’s eye view” of the tank during the transfer process, showed the impact of the CF on the liquid in the transfer lines during the time of the transfer. In this video, the free surface of the liquid within the transfer lines can actually be seen inching forward from the pressure force and then being reduced backward from the CF.
Though an elementary concept, the impact of the CF on the transfer process for this type of space system is significant and must be taken into account. From the above equation, it is clear that the slower the system can be spun the less significant the CF will be. However, with full scale systems, the liquid mass within the transfer lines and the distance from the free surface of the liquid to the vehicle’s CG will be significantly higher; therefore, larger pressure gradients between tanks may be required to reduce the total amount of time for a complete transfer.

For any particular system these parameters remain completely dependent upon the envelope of operations set forth for their particular mission requirements and objectives. However, in this investigation the lowest angular frequency that can provide complete rotational settling of the liquid, in microgravity, is of particular interest. A range of angular spin rates for ground and microgravity testing as well as the CF associated with those spin rates is provided in Table 1.

Table 1. Experimental spin rates and calculated CF.

<table>
<thead>
<tr>
<th>Spin Rate (RPM)</th>
<th>Angular Velocity (rad/sec)</th>
<th>Centrifugal Force (lbf)</th>
<th>Difference Between CF and Pressure Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>12.56</td>
<td>6.039</td>
<td>5.485</td>
</tr>
<tr>
<td>110</td>
<td>11.52</td>
<td>5.075</td>
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<tr>
<td>80</td>
<td>8.373</td>
<td>2.684</td>
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<td>70</td>
<td>7.327</td>
<td>2.055</td>
<td>1.501</td>
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<tr>
<td>60</td>
<td>6.280</td>
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</tr>
<tr>
<td>40</td>
<td>4.187</td>
<td>0.6711</td>
<td>0.1171</td>
</tr>
<tr>
<td>30</td>
<td>3.140</td>
<td>0.3775</td>
<td>-0.1765</td>
</tr>
<tr>
<td>20</td>
<td>2.093</td>
<td>0.1678</td>
<td>-0.3862</td>
</tr>
<tr>
<td>10</td>
<td>1.047</td>
<td>0.0419</td>
<td>-0.5120</td>
</tr>
</tbody>
</table>
The highlighted portion of the table depicts the target spin rates for microgravity testing. The negative value in the far right column denotes the spin rate at which the CF becomes less than the force exerted by the pressure in the tank.

The successful completion of the ground tests not only validated the test hardware and functionality of the scale mock-ups but served as a validation for the FM techniques and processes defined. Lastly, the ground testing brought the TRL for the on-orbit propellant system’s FM techniques and processes to 4 and served as a baseline test, allowing performance predictions to be developed for the system prior to parabolic flight testing.
Chapter III

Parabolic Flight Testing Phase I Approach

Once the proposed transfer methods had been verified in a laboratory environment, the same transfer methods must then be verified in a simulated operational environment, microgravity. To achieve this, NASA’s Reduced Gravity Aircraft (RGA) was utilized.

A Tri-Axis Spin Rig (TASR) was developed to mechanically spin the scale prototype to a predetermined angular velocity about its minor axis in microgravity. Once the required angular velocity was achieved, the prototype was released and allowed to spin unharnessed within the test enclosure.

Before flight, the LO$_2$ and LH$_2$ tanks of the Centaur module on each mock-up were filled to 50% capacity with water and then pressurized with air. Once this was completed for all prototypes, the “charged” test models were securely fastened into the designated stowage area of the TASR.

During flight, each mock-up was tested individually beginning with TS-2. Therefore, one mock-up was removed from the storage area and placed within the test enclosure. Once in place, the mock-up was mechanically captured and spun about its minor axis. Upon induction of microgravity, the mock-up was released while the required TS’s were simultaneously triggered. The triggering of the TS was done remotely and utilized electronic solenoid valves to allow the fluid transfer to occur only when required. Once triggered, the TS commenced while onboard gyroscopes and accelerometers recorded
the changes to the system’s angular acceleration/velocity and wirelessly transmitted them to the data acquisition system. Once each particular TS was complete, the mock-up settled at the bottom of the test enclosure, allowing the next test to be initialized. This process was repeated for each mock-up and TS.

An image taken during parabolic flight testing is provided below, in Fig. 4. This figure shows the TASR mounted to the floor of the RGA and one of the scale prototypes floating unharnessed during testing in the microgravity environment.

![Figure 5. Parabolic flight testing being carried out onboard NASA’s RGA.](image)

**Parabolic Flight Testing Phase I Data and Observations**

Shown in Fig. 6, is a graphical representation of the angular acceleration changes measured during the flight testing conducted on the scaled prototype. The
solid blue line represents the angular acceleration changes of the prototype while no liquid was contained within the tanks and no transfers were conducted. This data set was measured to provide a control that all other sets could be compared against to ensure any instabilities observed were not due to mechanical or integration problems.

The dashed red line represents the angular acceleration changes of the system while the liquid from the LO₂ tank on the Centaur module was transferred to the LH₂ tank on the same module. The comparison of this data set with the control proves that the system demonstrates certain internal perturbations. These perturbations are due to the motion of the liquid within the tanks and transfer lines of the system and they are strong enough to inhibit its rotational stability. However, it is important to note that the graph denotes a decaying angular acceleration. This proves that the hypothesis, which stated that the act of spin stabilizing the system along the vehicle’s minor axis, rather than the major axis, will result in a self-stabilizing behavior, is correct.

Figure 6. Accelerometer output from RGA flight testing.
The graphical representation of the angular velocity changes measured during flight testing is shown below, in Fig. 7. This data set, when compared to the control, provides that same evidence as seen before with the angular acceleration measurements. When a transfer is initiated, the system experiences an internal perturbation that destabilizes its rotation which is then corrected by the natural rotational dynamics of the prototype as the test continues.

![Figure 7. Gyroscope output from RGA testing.](image)

**Parabolic Flight Testing Phase II Approach**

The second phase of RGA testing performed was done completely supplementary to the research. In the original project outline, this phase of testing was not included. However, it performed to attempt to gather larger amounts of empirical data sets that could be used to validate the computational modeling effort that went
along with the research outline. This section will discuss the details of the experiment and how it was carried out.

To mimic the transfer process, that is fluid transfer via the means of a gaseous pressurant, a simple geometry transfer system was devised. This system consists of two 3 inch diameter cylindrical tanks that are 12 inches long and connected to each other via 0.5 inch pipe, this section makes up the transfer line and is intersected with a solenoid valve and a mass flow sensor. The solenoid valves provide transfer control and the mass flow sensor was utilized to record the mass flow rates of the transfer at various pressures.

Each tank is fitted with an electronic pressure gauge to digital record the instantaneous pressure drop in each tank at the moment of transfer. So, there are two parameters being recorded, mass flow rate through the transfer line and pressure gradients in each tank at the time of transfer.

The tanks are composed of acrylic tubing and Poly Vinyl Chloride (PVC) plastic. This provides for visual verification of the transfer processes as well as visual comparison between the actual movement of the liquid in microgravity and the movement of the liquid portrayed in the computational simulations.

The testing processes is quite simple compared to the first phase of RGA testing. In this testing, the tanks are rigidly attached to the test frame (shown in Fig. 8, 9 and 10) and do not float freely at any time. This was done to reduce the complexity of the system as to attempt to reduced the computational cost during the simulation phase.
Additionally, these tanks were not spun to settle the liquid, liquid control was done utilizing gravity during the non-microgravity portions of the flight.

Figure 8. Phase II microgravity flight experiment outside view.

Figure 9. Phase II microgravity flight experiment inside view.
To begin the tests, the upper tank was pressurized to 28 psi and the bottom tank was vented to atmospheric. Once microgravity set in, the solenoid valve, in the middle of the transfer line, was opened and the fluid was transferred into the bottom tank. During this process, mass flow rates and pressure gradients were recorded by the data acquisition system (shown in Fig. 11). Once the transfer was complete, equilibrium pressure was reached and the test was reset for the next microgravity parabola.
Parabolic Flight Testing Phase II Data and Observations

During the second phase of parabolic testing, the pressure in the upper and lower tanks of the system and the mass flow rate of the liquid through the single transfer line. During each parabola, the upper tank was pressurized to 28 psi while the lower tank was left at atmospheric pressure; this is denoted by the approximate 0.875 voltage reading for the upper tank and 0.105 voltage reading for the lower tank as shown in Fig. 12. Prior to microgravity, the motion of the RGA would provide a gravity force 2 times higher than normal gravity. This portion of the flight was utilized to settle the liquid in the tanks so that a transfer could occur. Approximately, 7 seconds after a microgravity environment was induced, the transfer valve was opened and the propellant transfer commenced. After the transfer was complete, the pressure sensors recorded the
pressure difference between the two tanks to be approximately 0.653 psi, this is
denoted by the difference of 0.393 volts between the upper and lower tank after the
instantaneous pressure collapse was observed from the transfer.

Similarly, the mass flow of the liquid was recorded through the 0.5 inch diameter
transfer valve that connects the upper tank to the lower tank. By comparing the graphs
illustrated in Fig. 12 and Fig. 13, it can be seen that the mass flow fluctuates away from
zero at the same time the instantaneous pressure collapse occurs. The maximum
frequency observed from the mass flow measurements was approximately 2.5 Hz which
then denotes an approximate mass flow rate of 0.75 gallons per minute. These results
are lower than anticipated, however the expected pressure drop in the lower tank was
10 psi and ended up averaging at approximately 8.5 psi for all tests run. The lower
average pressure drop in the upper tank supports the lower mass flow rates recorded.

Figure 12. Upper and lower tank pressure measurements during one parabola of RGA
testing.
Figure 13. Liquid mass flow rate measured during one parabolic fluid transfer test during RGA in-flight operations.
Chapter IV

Sub-Orbital Testing Approach

Current plans for suborbital flight testing are slated to take place during the summer of 2013. While size and mass restrictions of the present day suborbital test platforms severely limit the possible test configurations and applications to FM technologies, the increase in microgravity time associated with these types of flight tests will aid in the optimization of the parameters controlling the simulated output of the corresponding computational models. By performing sub-system testing, a simplistic approach will be taken to further advance the knowledge of the fluid dynamics associated with the full system and the related FM techniques and processes associated with it. By utilizing the suborbital flight testing, long duration based performance predictions can be made and applied to on-orbit testing; thus increasing the success rate of on-orbit testing and ensuring the reliability and applicability of all data sets collected.

Current plans for the suborbital testing phase of this project are to utilize the same hardware shown in Fig. 14. To do this, Virgin Galactic’s SpaceShipTwo will need to be utilized. This suborbital vehicle provides enough space and microgravity flight time that will be required to obtain sufficient data sets pertaining to the long term effects of on-orbit propellant transfers. Should this vehicle not be available for testing, a smaller, less complex testing apparatus will be designed that will be used to anchor the computational models being developed.
During this phase, the prototype will remain rigidly attached to the aircraft via the testing apparatus illustrated in Figure 14. This apparatus utilizes an electro-mechanical jaw-toothed clutch to spin the prototype to its required angular velocity where it will then disengage the spin shaft to allow the prototype to spin freely against the clutches frictionless bearings. During the time the prototype is spinning freely, two ball joints that connect the prototype to the spin shaft allow it to rotate 30 degrees in the vertical direction. This allows the prototype to maintain the ability to move as if unharnessed while it is rigidly contained within the test enclosure. While the first phase of testing was purely a “proof of concept” test, this phase of testing will be conducted to gather a maximum amount of data pertaining to the vehicle’s rotational dynamics during the on-orbit techniques and processes aforementioned.
Chapter V

Orbital Testing Approach

By utilizing the International Space Station (ISS) as an on-orbit testbed, the true operational environment of the on-orbit propellant storage and transfer system can be realized without the significant cost required for full scale development and integration. This type of testing will allow long term tests to be conducted to determine the dynamic characteristics of the propellant storage system while it undergoes the operational processes required for the on-orbit refueling of spacecraft. In order to accurately identify all parameters and behavioral characteristics of this system, specific primary objectives have been defined. In addition to the primary objectives, a series of secondary objectives will be defined that will provide a basis for further data collection and the advancement of an innovative technology pertaining to instantaneous liquid mass gauging in spacecraft.

Primary Objectives

The primary objectives for ISS flight testing consist of utilizing SPHERES, designed by MIT. These SPHERES maintain the ability to maneuver autonomously about the ISS with respect to each other, via the means of onboard control systems and advanced maneuvering algorithms. During this testing, the scale mock-up will be fastened to two SPHERES. The system will then be spun about the appropriate axis via the SPHERES’s onboard pressurized gas thrusters. All test operations of the scale mock-ups will be controlled utilizing the SPHERES’s onboard computer. The same means will
be used to record force responses, changes in the system’s angular velocity and acceleration, position, and pressure gradients between tanks. During ISS testing, water will be used to simulate the liquid propellant. This will minimize complications during testing and ensure the safety of the astronauts by not introducing toxic or harmful chemicals into the ISS environment. These SPHERES and the planned test configuration for ISS testing are illustrated in Fig. 15.

Figure 15. Conceptual Illustration of the experimental apparatus to be utilized during ISS testing.

Secondary Objectives

To compliment the primary test objectives, a set of secondary test objectives has been developed that will maximize the amount of data and knowledge gathered from
the on-orbit testing phase of this project. The first series of secondary objectives involve
the use of an experimental apparatus similar to the apparatus used during the second
phase of microgravity flight testing. This series of testing will be conducted with the
mock-up enclosed by an experimental apparatus that will be rigidly attached to one of
the walls of the ISS. This apparatus will control the mock-up and place it into a transfer
spin at a predetermined angular velocity. The mock-up will be attached to the apparatus
via a 6 DOF sensor that will relay force reactions from the mock-up to a nearby data
acquisition system. In the beginning stages of these tests, the mock-up will be spun at
relatively low rates to determine the proper speed for the system to quickly settle the
propellant at the poles of the tanks while exhibiting minimal internal perturbations from
the sloshing liquid. Several cameras will be attached to the experimental apparatus to
record the movement of the sloshing liquid to compare the liquid’s behavior on-orbit with
that depicted in the computational simulations.

The second series of tests introduced in the secondary objectives involves the
addition of a non-invasive approach to real time liquid mass gauging of spacecraft. This
system utilizes PZT health monitoring technology to actively measure a vessel’s fluid
mass in microgravity. The introduction of liquid to any structure changes the
corresponding resonant frequency of that system. By introducing a white noise signal
into the system with a PZT actuator, various PZT sensors are used to measure the
resulting vibrations of the system. These signals are then compared to the natural
frequency of the tank at various fill levels. It is anticipated that shifts in the resonant
frequency spectrum of the system are directly related to the system’s fill fraction. It is
important to note that, though this liquid mass gauging approach has successfully
completed RGA testing, its applicability to this testing is still under consideration and the tentative inclusion of this system will not hinder the success of the proposed ISS testing. Investigations during the suborbital flight testing will further advance the technology and provide a means to assess its applicability to testing on-orbit. The microgravity flight test configuration for the PZT mass gauging system is shown in Fig. 16.

Figure 16. PZT mass gauging microgravity flight test configuration.³

**ISS Hardware and Technical Specifications**

**a. Total mass and hardware dimensions for ascent**

It is important to note that this on-orbit experiment is a follow-up-payload to the FIT/KSC slosh experiment already designated for launch to the ISS in January of 2013. The experiment being proposed in this document will utilize the SPHERES, VERTIGO Computer, brackets, hardware, batteries, CO₂ tanks/ pressure system and HD cameras that are being sent up to the ISS for that project. In other words, the main components of the experiment will already be on the ISS from a previous experiment and will have already gone through all safety reviews and requirements for ISS operations.
Therefore, the total mass and size requirements for launch is minimal, the only components that will be required for launch and delivery are listed in Table 2:

<table>
<thead>
<tr>
<th>Item</th>
<th>Quantity</th>
<th>Estimated Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propellant Tank (w/ valve fittings installed)</td>
<td>2</td>
<td>0.9</td>
</tr>
<tr>
<td>Fluid Transfer Line (13 inch length)</td>
<td>2</td>
<td>0.08</td>
</tr>
<tr>
<td>Fluid Transfer Line (6 inch length)</td>
<td>2</td>
<td>0.05</td>
</tr>
<tr>
<td>Fluid Transfer Solenoid Valve</td>
<td>2</td>
<td>0.2</td>
</tr>
<tr>
<td>Pressurization Solenoid Valve</td>
<td>3</td>
<td>0.3</td>
</tr>
<tr>
<td>Pressurization Control Board</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>Fluid Transfer Control Board</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>Mass Gauging Sensor</td>
<td>2</td>
<td>0.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Factor of Uncertainty</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL ESTIMATED MASS</td>
<td>5.49</td>
</tr>
</tbody>
</table>

Table 2. Launch mass requirements for ISS experiment.

An estimated 480 in$^3$ will be required for ascent/delivery to the ISS. This volume encompasses all components listed in Table 2. Please refer to Fig. 17 for the corresponding dimensions.

![Figure 17. Estimated payload dimensions for launch.](image)
b. **Hardware dimensions for on-orbit operations**

As mentioned above, the on-orbit operations of this project will utilize hardware and components that will already be in the internal confines of the ISS prior to on-orbit operations. For this reason, the dimensions of the launch/ascent payload are less than the dimensions of the hardware to be utilized on-orbit. Please refer to Fig. 18 for the dimensions of the ISS experimental hardware to be used during on-orbit/ISS operations.

Again, the only equipment that will need to be launched to the ISS is listed in Table 2. The rest of the hardware and components will already be stowed in the designated stowage containers in the designated location on the ISS. The hardware to be launched, Table 2, will be secured with those components already in position onboard the ISS.

![Figure 18. Dimensions of hardware on-orbit.](image-url)
c. Power, data and other on-orbit resource requirements for operations

During on-orbit testing, MIT’s SPHERES VERTIGO hardware will be utilized to control the movement of the test article while on-orbit as well as to provide power to all fluid transfer and pressurization solenoid valves and associated control boards. The CO₂ this system has demonstrated on-orbit will be utilized to pressurize the experimental propellant tanks for on-orbit testing. Lastly, a laptop will be required to store approximately 12 GB of data at the conclusion of each test session. Once the data has been transmitted back to Earth and collected, the data can be deleted from the laptop; thus only 12 GB of storage space will be required for any one test session.

d. Anticipated stowage and operational location on ISS

All ISS testing hardware will be stored in a stowage bag when not in use. The storage location on the ISS is immaterial to project management; the storage location most convenient to the ISS directors and staff will be fine. Please refer to Section b, Hardware dimensions for on-orbit operations, for more information.

e. Anticipated crew interaction and operation requirements

During on-orbit operations, a crew member will be required to mount the experimental propellant tanks, transfer lines and valves, pressurization valves and all control boards to the SPHERES VERTIGO propellant slosh testing apparatus that will already be on the ISS. The crew member will also be required to fill one of the two propellant tanks with water (already onboard). Lastly, the crew member will be required to initialize the experiment by powering on the testing apparatus and uploading the control algorithms. During testing, when the SPHERES VERTIGO system is performing
maneuvers and propellant transfers, the crew member assistance will not be required. Post testing, crew member assistance will be required to download all experimental data to an ISS laptop and transfer that data back to the ground-based payload operations center. Upon completion of the data transmission, the crew member will be required to delete the test data from the ISS laptop.

**f. Crew training requirements, training timeframe and procedures**

An estimated 16 hours of total crew time will be required to complete the on-orbit testing phase of this project. A total of 4 on-orbit test sessions will be required with approximately 4 hours of crew time required during each test session. Test sessions will be conducted in 6 week intervals to allow for data transmission and analysis. On-orbit procedures and crew training requirements will be developed 6 months post project start and provided during the “ISS Procedure Development” milestone. Additionally, crew training will be initialized approximately 7 months post project start.

**g. Anticipated automation and plan for executing command and data control**

All data gathered during testing will be stored on the SPERES onboard VERTIGO computer. Upon completion of the tests, approximately 12 Gb of data will need to be transferred from the VERTIGO computer to an ISS laptop. That data will then be transferred from the ISS to a ground-based operations center. Post data transfer, all test data can be deleted from the ISS laptop.

Currently, KSC Launch Services Program and Florida Institute of Technology (FIT) are working on the slosh payload with MIT. This payload will demonstrate the data
transfer capabilities and VERTIGO computer prior to the Launch and ISS Testing Milestones for this project.

**h. Anticipated location for ground-based payload operations**

Currently, ground-based payload operation centers are being setup at FIT and KSC. One of these locations will be utilized for the ground-based payload operations for this project, with KSC being the primary choice and FIT secondary. Additionally, similar centers are already in use at MIT. Should the first and secondary ground-based payload operation centers become unavailable for any reason; the MIT center will be utilized.

**i. Safety and hazardous materials plan**

The Materials and Processes Technical Information System (MAPTIS) database has been utilized to determine the specific materials to be used during all ISS operations. This database shows that the materials selected are approved for use onboard the ISS.

NOTE: No hazardous materials will be used.
Chapter VI

This chapter is dedicated specifically to the computational models and simulations that were developed to predict the behavior of on-orbit propellant storage and transfer systems without the need to run further physical tests. Two different types of models were developed, a dynamic model utilizing MATLAB SimMechanics and a Computational Fluid Dynamic (CFD) model utilizing Ansys CFX. The CFD model was desired to predict the behavior of the full system as well as minor parameters such as pressure and temperature rates at certain locations whereas the dynamic model was developed specifically to determine the mechanics of the system and the rotational behavior of it during propellant transfers. This chapter will walk through the methods of performing both types of models as well as the setbacks to each.

Dynamic Modeling Methodology and Results

MATLAB SimMechanics was utilized to develop a physical or dynamic model of the on-orbit propellant storage and transfer system. This program employs a “block diagram” user interface that allows the programmer to manipulate various predefined blocks to represent a physical system in any type of environment. Once implemented, the model outputs a visual representation of the system being modeled; this is illustrated in Fig. 19.⁴
The major components or characteristics of the physical system that take precedence with this type of model are the system’s mass and inertial properties, CG location, spin axis and frequency, and any mechanical movements within the system that may hinder or effect the system’s behavior. In this case, the motion of the liquid within the propellant tanks of the system is of critical importance.

In the above section, the graphical results of the parabolic flight experiments prove that the system is stable when no liquid is present. Therefore, the dynamic model should exhibit the same behavior when the effect of the liquid movement is not taken into account, which it does. For this case, the physical properties and spin rate of the system as well as the gravitational loading (zero gravity) are the only aspects of the
system that is modeled. This produces a very simple model that is easy to validate. However, this is only the case with the control models of the experiment and in no way resembles the system in its full operation. Therefore, the motion of the liquid mass within the tanks must be accurately defined to allow the model to produce the same angular velocity and acceleration changes that the scale prototype experienced during testing.

Traditional methods of modeling the effects of liquid motion are to utilize a mathematical spring/damper and pendulum analog, where the pendulum is affixed to a mass that represents a specific percentage of the total liquid mass and allows that to rotate about a fixed point in space. This mass is referred to as the “slosh mass” while the remaining liquid mass is referred to as the fixed or “frozen mass”.

Figure 20. System prototype’s Centaur module cross sectional view with frozen mass, slosh mass, and connecting spring/damper.
The placement of the frozen mass within the propellant tank is completely dependent upon the type of tank being modeled as well as the amount of liquid within. In this case, the frozen mass is attached to the common bulkhead between the LO$_2$ tank and the LH$_2$ tank on the Centaur module. This is simply due to the type of spin that is being actuated. In most cases, the spin is about the major axis of the vehicle which would induce a CF normal to the major axis; however, in this case the spin is about the minor axis of the system. This, as mentioned before, induces a CF that is orthogonal to the major axis which pulls the majority of the liquid mass to the outer poles of the system; hence the placement of the frozen mass.$^5$

The last two components that are taken into account with this analog are the spring and the damper. As shown in Fig. 20, the spring and damper are attached to the pendulum and the major axis of the system. The combination of the spring and damper allows the motion of the pendulum to be inhibited in a way that mimics the viscous characteristics of the fluid. The spring constant and damping coefficients are the parameters that control the simulated liquids behavior.

With traditional models, it is typical practice for only one propellant tank to be modeled at a time. However, in this case, the entire system is composed of three different tanks, two of which are filled with liquid propellant at any given time. For this reason, traditional methods would call for the model to represent the physical aspects of the system as close as possible. This calls for two pendulum analogs in one model. While this is not difficult to setup, the process of estimating the parameters, utilizing the parameter estimation toolbox in MATLAB, becomes very difficult. The introduction of a
second pendulum tends to make the model chaotic, producing different results every run.

To overcome this problem, traditional methods could not be used and the model had to be developed implementing only one pendulum analog. The next step in the process was to determine a way to represent the entire system’s fluid mass with one pendulum, spring and damper. This became challenging, due to the fact that the dynamics of the system, while being spun, caused the two liquid masses to behave differently while the pendulum analog only allows for 1 Degree of Freedom (DOF). In order to overcome this problem and determine a way for the graphical output of this type of model to match that of the data produced by the parabolic flight experiments, the 1 DOF pendulum had to be manipulated.

This was accomplished by introducing another variable that could be estimated to incorporate a simulated second degree of freedom by allowing the pendulum to rotate about the major axis of the system. By allowing the parameter estimation to vary the angle between the pendulum and the major axis, the model would find the best fit to the experimental data and provide the respective angle. The results of this modeling approach are illustrated in Fig. 21. The yellow plot is the post processed experimental data while the purple plot represents the models output.
CFD Simulation Methodology

To begin, the CFD modeling was developed to mimic the experimental tests as much as possible. That being said, each model utilizes two common things; a pressure gradient between each tank that drives the fluid transfer and a solenoid valve(s) that is(are) used to halt the fluid flow until a transfer is desired. That information is very important and will come into notice in the later part of this section.

There are 4 main parts to developing any CFD model, they are (1) developing the system mesh, (2) performing the system boundary initialization, (3) running the model or performing the simulation and (4) post processing the results. This section will discuss each part in detail and mention the key points for the models developed for this research. It is important to note that there were two different models that were created...
for this research. Each model will be discussed simultaneously while the results of each model will be discussed separately later on in the document.\textsuperscript{6}

\textbf{System Mesh Development}

The primary component of any CFD model is the boundary or mesh used to maintain the fluid or provide the boundary that each fluid touches. In this case, the internal geometry of the scaled prototype is what makes up the mesh. This is important because the mesh can only be composed of the areas that the fluid physically comes into contact with during physical testing; hence the reason the internal geometry is used.

To begin, an AutoCAD drawing of the fluid bulk must be created. In other words, the entire empty space within the system that the developer expects the liquid to, at one point, come in contact with must be drawn. For this research, there are two drawings that were created, one for the scaled system and one for the simple geometry transfer system. These are shown below in Fig. 22. It is important to note that these drawings must be saved as .igs files so that they can later be imported into the meshing software.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{Figure22.png}
\caption{Auto CAD representations of simple geometry transfer systems.}
\end{figure}
Now that the auto cad drawings have been developed, they need to be imported into the meshing software so that the mesh development can begin. The mesh for these CFD models was developed using Pointwise.

To begin, import the .igs file by clicking File then choose the Import Database option. A window will pop up and prompt you to choose your file. Once you have chosen your file and the database has been imported properly, begin the meshing sequence.

First, highlight every database line by clicking on the top of the main database list located in the panels section to the left of the meshing box, then click the “Connectors on Database Entities” icon located on the tool bar at the top of the window. Once that is complete, full list of connectors will appear just above the database list in that same panel. Highlight the entire connectors list and type in an arbitrary cell dimension. This dimension basically provides the amount of notes on each connector that will make up the entire mesh, so it is beneficial to choose an appropriate scale for the size of the mesh being developed.

Once that is complete, highlight the connectors list again and click on “Create” from the pull down at the top of the screen, then choose “Assemble Special” and choose “Domain”. A new side panel will pop up prompting the user to create the domain. This is done by starting at one side of the mesh and choosing the outward most connector and clicking on connectors adjacent to that one in any particular direction. Once all connectors and their adjacent connectors have been specified, the domain creation will be completed. It is important to note that when using interfaces in CFX, that will be discussed in the upcoming section, a particular meshing method must be used.
That is take a solenoid valve for example, it has an opening on each end with a specific flow direction that is specified by the manufacturer. The opening where the liquid flows in is called the inlet and the opening where the liquid flows out is the outlet. When meshing, the inlet and outlet need to be meshed to make them appear closed. This will allow you to create an interface at those locations later on in the CFD process as to provide the ability to open and close those sections when needed.

Now that the domain creation section is finished, the last part is the “Block” creation. This is simple in the fact that all the user must do is highlight the domain list and choose the “Block” option under the “Assemble Special” tab. Then the user till click on a mesh and choose the corresponding mesh directly adjacent to that mesh until all of the meshed sections in that black have been specified. Note that the user must maintain orientation and directional awareness of the mesh when creating the blocks. Also, when utilizing the interface approach in CFX, there will be more than one block created during the meshing sequence. This provides the option to initiate specific domains separately from each other. This comes in handy when one domain needs to have an initial pressure higher than another. Once all of the blocks have been created, the meshing sequence is complete. The last step is to export the mesh so that it can be imported into the CFD software. This is done by clicking “File”, “Export” then “CAE”. Be sure to choose the appropriate dimensions when exporting and choose the .cgns file option. Please refer to Fig. 23 and Fig. 24 below for the final meshing of the scaled mock up and the simple geometry transfer system.
Figure 23. Pointwise meshing of scaled mockup.

Figure 24. Pointwise meshing of simple geometry transfer system.
The next step in the CFD development stage is to begin the pre-initialization of the actual CFD model in Ansys. The program to be used is Ansys CFX Pre. This portion of the software is where all of the boundary conditions and initial parameters will be put in. For simplicity, only the simple geometry transfer system will be discussed. The number of interfaces, domains and the complexity of the initial parameters were less with this model but all of the methods were directly translated to the more complex model developed for the scaled mock up CFD.

To begin this phase, the user must start importing the mesh that was just created. That is the .cgns file that was exported from the Pointwise software aforementioned. This is done simply by choosing “File”, “Import” then “CCL”. A prompt then allows the used to select the file to be imported, be sure to choose the proper units when importing.

Once the mesh has been imported, each specific domain has to be created. Otherwise the software sees the entire mesh as one single domain; which will not work for fluid transfer modeling. Start by right clicking on the “File Analysis” text at the top of the tree on the left side of the window. Then choose “Insert” followed by “Domain”. The “Domain Creation Window” will then pop up and prompt the user to initialize the domain. There are a lot of different options that can be chosen, however, fluid transfer modeling only requires the user to be specific with a few. There will be five tabs in the “Domain Creation Window” that the user will need to be familiar with: Basic Settings, Fluid Models, Fluid Specific Models, Fluid Pair Models and Initialization. The Basic Settings tab and Initialization are the most important of the five.
In the Basic Settings tab, the fluids that will be used in the model must be initialized. In this case, water and air are the only two fluids that will be present. When getting into more complex models that deal with cryogenics, then the various fluids must be initialized and the parameters that govern those fluids must be specified. In this case, water and air make this step quite simple. Simply choose the two fluids from the drop down menu in the “Fluids and Particle Definitions” box and that is all. In this tab, the only other settings that are important are the relative pressure setting and the buoyancy setting. The relative pressure is just set to atmospheric pressure of 14.7 psi or 1 atm. The buoyancy setting must be selected and the gravitational constants for each axis must be specified. For this research, the testing takes place in microgravity, therefore, the buoyancy setting must reflect that. Thus, the vertical component of the gravitational setting is set to microgravity or -0.01*g (the negative represents the direction the gravitational constant is directed in) and the gravitational settings for the components horizontal are set to 0.

Next, the Fluid Models tab must be selected. Under this tab, the “Homogenous Model” box must be checked and the “Free Surface” set to “Standard”. The only other specification under this tab that is important is “Heat Transfer” option. This option must be set to isothermal with a reference temperature of 25 C.

The only option under the next tab, Fluid Specific Models, that is important is the “Fluid Buoyancy Model”. Make sure that “Fluid Density Difference” is selected and each fluid that will be within the domain during the simulation appears in the “Fluids” box at the top of the panel.
The “Fluid Pairs Model” tab should already have everything initialized properly. Just be sure all the fluids are present at the top of the panel and none of the below boxes are checked.

The Initialization tab is last, The “Domain Initialization” box must be checked to allow the user to see the available options. In this instance, the relative pressure will always be set to the same reference pressure that was used in the first tab, atmospheric. Unless otherwise required. For example, the simple geometry transfer system calls for a pressure of 28 psi to be initialized in the upper tank prior to the solenoid valves being opened. This pressure is what will drive the fluid transfer. So the upper tank’s domain is the only domain that will have anything different than atmospheric pressure in the relative pressure box. The last step is to specify how much of each liquid will be initialized in each domain. In each domain, other than the upper tank, there will only be air in the beginning of the simulation. So a 1 is put for air while a 0 is put for water. In the upper tank domain, the domain will be filled to some level with water. To represent how much water will be in the tank, an expression can be written or it can be represented fractionally. For instance, if the tank is to be half full with water than volume fraction for air will be 0.5 as well as water. Each method will work, if a specific fraction is required, an expression is the best way to initialize it.

Now that all of those steps are completed, the last thing to do in CFX Pre is to check all of the solver settings and make sure the time steps are specified appropriately. It is important to note that fluid transfer models are quite computationally expensive in the sense that they cannot typically be ran as fast as most other models. This is due to the number of domains in the model as well as the complexity of the
background calculations that are being performed. For these reasons, a higher time step should be chosen in the beginning phases of the runs. Typically 1E-6 is chosen for the first time step. This was found to be the time step that provided the quickest results with the least amount of errors. Additionally, the “Residual Target” must be adjusted. A typical RMS type residual target is approximately 1E-4, but in the cases of higher complexity at higher target is needed, thus reduce this to 1E-2. This was the target that accounted for the quickest run with the least amount of errors.

The last thing to take into account is the total simulation run time and the parameters that will be monitored. Due to the fact that a full physical transfer occurred in the manner of a few seconds, the CFD simulation for the simple geometry transfer system was set to 10 seconds and the parameters that were monitored were the pressures in both the upper and lower tanks of the system and the mass flow rate of the water through the transfer line. Similar properties were chosen for the scaled mock up CFD simulation that is addressed in a later section. Please refer to Fig. 22 below for a screen shot of the completed Ansys CFX Pre for the simple geometry transfer system.

Figure 25. Ansys CFX Pre of simple geometry transfer system.
Once all of these steps are complete, the simulation can be ran. This is done using Ansys CFX Solver Manager. This section of the simulation is quite simple. The user must simply monitor the run and troubleshoot any error codes that are given. A graphical display provides the user monitor points as well as the system residuals for each domain. The simulation can be monitored in time steps or simulation time. Please refer to Fig. 26 below for a screen shot of the CFX Solver Manager run for the simulation.

![Figure 26. Ansys CFX Solver of simple geometry transfer system.](image)

Once the simulation has fully run, a pop up screen will prompt the user to run a post processing analysis of the simulation results. This is performed in Ansys CFX Post. There are no parameters to be initialized in the section of the CFD simulation, however, in order to determine the accuracy of the simulation the parameters that were initialized in the CFX Pre section have to be checked. This is done be creating a graphical
representation of the water inside the tank and rendering it to the tune of the pressures within each domain. By choosing “Location”, at the top of the screen, then “Volume”, an isovolume of the fluid bulk can be visually identified. This is used to check the fill level of the tank at the beginning of the run as well as during various time steps along the course of the simulation. Simply choose to display based on the volume fraction of the liquid to be above 0.5 for water and the amount of water in the domains will be shown. Then the user can render that bulk to be colored with a gradient map specifically to the pressure changes in the domains. Monitor the extreme high and low pressure in the domains to make sure they are not above or below the initialized pressures of atmospheric and 28 psi. Once that is complete, the monitored parameters can be exported to an excel file and a video of the simulation can be created. Please refer to Fig. 27 below for a screen shot of the Ansys CFX Post of the simple geometry transfer system.

![Figure 27. Ansys CFX Post of simple geometry transfer system.](image)
CFD Simulation - Parabolic Flight Testing Phase I Results

By utilizing Ansys CFX software, a computational simulation has been developed that will provide a method of performing the experimental tests in a virtual world rather than in the physical one. This will allow the tests to be conducted cheaper, quicker, and will provide data that physical testing could not provide. Current efforts focus on the simulation of the parabolic flight experiments mentioned in the above section.

This simulation has taken the inner geometry of the on-orbit propellant storage and transfer system prototype and performed the same operations that were performed in parabolic flight testing. The rate of spin, fill level, liquid propellant, pressure, and CG of the entire system were all taken into account. During the simulation various parameters are measured and recorded to later be compared to the data produced by the experiment to act as a method of validation. Figure 28 depicts the visual representation of the first 6 seconds of the TS-2 operation conducted in a virtual environment, utilizing the CFD modeling approach.

Unlike the dynamic model, CFD modeling encompasses all phases of the test; propellant transfers and flowing liquids are simulated. Also, the benefits of conducting the tests in a virtual world allow the user to monitor properties and parameters that would be difficult or even impossible to monitor in physical testing such as: the instantaneous pressure gradients between the tanks, instantaneous pressure at specific points in the fluid, temperature gradients along the tank boundary, mass flow rates, instantaneous mass gauging, and flow velocities along the boundary layer.
For the models developed for this investigation the only parameters that will be monitored are mass flow rates, pressure gradients, and instantaneous mass gauging. However, as the model advances and the simulation results are validated against experimental data, the simulation can be scaled up and the characteristics of a full scale on-orbit system can be taken into account. Once this is done, cryogenic fluids will be simulated and all of the various parameters associated with them will be monitored.

Figure 28. Visual representation of the first 6 seconds of the TS-2 transfer operation simulated in a virtual environment utilizing the CFD modeling approach.

Shown below, in Fig. 29, the absolute pressure, for each tank, is monitored during the CFD simulation. Prior to a propellant transfer, the pressure within the tank is defined to mimic the pressures utilized during testing; thus creating a point of validation between the model and the experimental approach. The pressure decay in the tank in which the liquid originated and the pressure rise in the corresponding tank can be determined in real time. This can be based against hand calculations to determine if the model is running properly. Furthermore, this parameter can provide data as to the amount of time it takes for the two tanks to reach equilibrium.\footnote{7}
Fig. 26 depicts the graphical output of the liquid mass flow rates through the transfer valves. While this parameter holds no significance for comparison against experimental data, it is of significance when being compared to the transfer times and the retardation of the liquids movement through the transfer lines from the CF associated with the spinning motion of the system.

As this model matures and this approach is applied to future experiments the accuracy of the simulation will increase. The methods developed to produce these accurate simulations will be documented and applied to the full scale system associated with this prototype as well as other full scale systems that utilize the same propellant transfer methods. When applied to these full scale systems, the liquid propellant being simulated will be switched to the actual cryogenic propellants that these systems utilize. In these scenarios, further validation attempts will be necessary to ensure the monitored parameters such as the temperature gradients along the domain of the tanks boundary as well as any effects that the pressure will have on the stability of the cryogenic fluids are correct. Once this level has been achieved, very accurate simulations of on-orbit propellant transfer operations can be run for almost any type of design and system configuration. System stability and the effects of boil off can be investigated thoroughly without the need for further experimental testing.
Figure 29. Graphical representation of the absolute pressure monitored for each tank on the prototype during the CFD simulation of the TS-2 transfer operation.

Figure 30. Graphical representation of the liquid mass flow rates monitored through the transfer line of the prototype during the CFD simulation of the TS-2 transfer operation.
CFD Simulation - Parabolic Flight Testing Phase II Results

To supplement this research, a series of RGA tests were conducted on a simple geometry transfer system to determine pressure gradients between two inline tanks as well as the mass flow of the fluid during the transfers conducted. A CFD simulation was then performed mimicking those tests to determine if the methods used could produce results similar to that gathered during physical testing. As mentioned before, this section of the research is, simply, supplementary to the research outline. The results gathered during testing were used to help conclude on the applicability of the simulation methods.

The methods utilized to model these types of systems were outlined in the above section. Once those methods were carried out for the simple geometry transfer system, a CFD model was formed and a computational simulation of the physical experiments was run. Similar to the physical tests, the mass flow rates of the liquid and the pressure gradients within the tank were measured. Additionally, the visual effects of the liquid flow that the simulation produced was compared to that observed during the RGA tests.

Due to the lesser complexity of the simple geometry transfer system and the tests conducted with it, the simulations were far less computationally expensive. While the simulations performed for the full system had to be run at 1E-16 time steps, these simulations could be run at a much more reasonable time step of 1E-2. This allowed for a full 10 second run to be completed in less than a day with a 4 core processing system. However, the results obtained from these simulations were far less than expected.

It was shown, during experimental testing, that the pressure within the upper tank would drastically reduce once the solenoid valve was opened and the transfer was
conducted. Similarly, the pressure in the bottom tank would increase until the transfer was complete and an equilibrium pressure was achieved. These results were as expected, however, when the solenoid valve was opened in the computational simulation the pressure in the top tank would immediately drop to a value that was less than the pressure in the bottom tank. The bottom tank's pressure would remain unchanged or only slightly affected. Once the simulation results were full post processed, the physical motion and behavior of the liquid could be visualized. This provided insight as to the problems occurring during the run.

It was noticed during physical testing in microgravity that the fluid would maintain a settled state even once the transfer has begun. The motion of the aircraft and slightly positive or negative accelerations disrupted the fluids settled state slightly, but never enough to provide an instantaneous pressure collapse in the upper tank. However, the computational simulation is showing that the liquid is behaving erratically when microgravity conditions are present. This erratic behavior is inhibiting the transfer process and disallowing the accurate determination of pressure gradients and mass flow rates within the system. Because this type of CFD modeling is not standard, the code that drives the software is not completely developed to handle the physical laws that are required to provide proper results. It is interesting to note that the CFD simulations of the full system did denote a physical behavior that was seen during physical testing but the less complex run did not; even though both runs employed the same techniques. The only difference between the two simulations was the time step used to run them. This suggests that even though the simple geometry system was far less complex than the scaled prototype model, large time steps and computational
power will be required to observe any behavior that could be considered physically similar to the tests performed. Therefore, this method of simulating the behavior of on-orbit propellant transfer systems is not recommended unless the users conducting the transfer systems are utilizing a series of processors with the capability to run these simulations at a low enough time step without taking a large amount of physical time to complete.
Chapter VII

Conclusions

The successful completion of the ground and parabolic experimental testing portions of this research show that the methods of performing settled fluid transfers between two subsequent tanks on the same system are feasible. The act of utilizing a minor axis spin to perform fluid settling not only provides an active means of propellant management without the need for internal hardware, but it stabilizes the system on-orbit and mitigates propellant expulsion through an active Attitude Control System (ACS).

In addition, this method negates the need for cryogenic fluid pumps to perform cryogenic fluid transfers; thus minimizing vehicle upmass. Though the sub-orbital and orbital testing phases of the research outline have not yet been completed, sufficient data has been collected to deem the Centaur derived on-orbit propellant storage and transfer system a successful means of conducting controlled fluid transfer’s on-orbit. Although further testing must be completed to determine the performance characteristics of other sub-systems involved with this technology, the fluid settling and transfer sub-system in plausible.

Lastly, though the physical testing portions of this research were a success, the efforts to model these systems utilizing CFD and SimMechanics software have fallen short. The complexity of these systems along with the mathematics and calculations required to determine the physical behavior of the liquid being transferred are too cumbersome for modern processing systems to compute in a reasonable amount of time. Though these methods will produce results, it is concluded that further
computational method development must be completed to provide a fluid transferring modeling approach that will sufficiently predict the on-orbit behavior of these systems.
References

1 Larson, Wiley “Operations and Service Infrastructure for Space” International Space University SSP 2012


Appendix

Project Letters of Support
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July 17, 2012

Duane Ratliff, Director of Operations
Center for the Advancement of Science in Space (CASIS)
Space Life Sciences Laboratory
Kennedy Space Center, FL 32899

RE: ERAU project entitled Spacecraft On-orbit Advanced Refueling System for ISS Testing

Dear Mr. Ratliff and Associates,

The NASA Florida Space Grant Consortium (FSGC) is pleased to offer this letter in support of the proposal Dr. Sathya Gangadhara at Embry-Riddle Aeronautical University (ERAU) is submitting to the Center for the Advancement of Science in Space (CASIS) based on the on-orbit refueling project that Dr. Gangadhara and his student have been working for the past 2 years. In particular, I am pleased to see the new partnership with the Massachusetts Institute of Technology (MIT) Space Systems Lab and the enhancement of the working relationship between ERAU, the United Launch Alliance (ULA) and NASA.

As you know, FSGC is an association of seventeen public and private Florida Universities and colleges led by the University of Central Florida. The Consortium also includes all of Florida’s community colleges, as well as the Astronaut Memorial Foundation, Space Florida, Kennedy Space Center and the Orlando Science Center. FSGC supports the expansion and diversification of Florida’s space industry through providing grants, scholarships and fellowships to students and educators from Florida’s public and private institutes of higher education.

In recent years, FSGC has provided monetary support in the amount of $30K to support parabolic flights and the procurement of experimental sub-orbital flights for the Technology Readiness Level (TRL) advancement of the on-orbit refueling system being developed. Currently, I am working with the Director of the Massachusetts Space Grant Consortium to pursue the possibility of cost sharing between these two Consortiums.

Again, I am pleased to offer my support for this project and am excited to see the ISS being used for such innovative and game changing research.

Regards,

[Signature]

Jaydeep Mukherjee, Ph.D

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27th August 2012  

Dear Nathan  

ACES Cryogenic Modelling and Simulation Program  

SEC is very supportive of and interested in the results of your Government / Industry / Academia (ERAU, MIT, ULA, NASA) cryogenic storage and transfer technology development test program as it relates to accomplishing tangible (high TRL-level) proof-of-concept demonstrations in space. As you are aware, to implement and operate our commercial propellant depots in space, SEC will need robust, safe cryogenic propellant production, storage and pumping systems to service a wide variety of customer vehicles. High reliability, functionality and safety matched to economic pricing will be essential to provide the quality of service (QoS) our customers will demand.  

In particular, as part of our evolutionary propellant depot deployment operations, we will need to demonstrate and deploy several systems in sequence, while awaiting water to be mined and transferred to our LEO depots. By following this process, SEC gets a jump on propellant sales, albeit expensive at first, and customer cultivation on a global scale. First, we will launch, receive and process large quantities of LOX/LH2 at our LEO propellant depots for sale. Second, we will launch, receive and process large quantities of purified water that will be converted to LOX/LH2 at our depots for sale. Thirdly, when all systems are performing well, we will commence water transport from the Moon to the depots for mainstream 24/7 fueling operations. All of these steps require the best and safest cryogenic systems (e.g., cryo production, storage, transfer, thermal control, boil-off minimization and power control) that can be built and operated efficiently (initially with our crews, then fully robotically).  

As such, we would be very interested in your team's success in performing demonstrations of ever increasing capability leading to objective systems of commercial
value to us. Your step-wise approach to risk-reduction is important; however, because our schedule to get to market is very aggressive, we suggest your funding sponsors understand the value proposition of proceeding in an equally aggressive manner, if it is possible. If you are successful, and our schedules can be synchronized, it is highly likely that SEC will (via tech transfer) leverage your accomplishments to produce the systems we need for operations.

Therefore, we strongly support the team approach, especially with ULA and their enviable history of successful Centaur flights. You appear to have a good approach for which you and your customers should be proud.

Thanks and regards

Jim Keravala
COO Shackleton Energy Company
July 9, 2012

Duane Ratliff, Director of Operations
CASIS
Space Life Sciences Laboratory
Kennedy Space Center, FL 32899

RE: SPHERES Experiment on the International Space Station

Dear Mr. Ratliff,

The use of in situ International Space Station (ISS) experimental capability, namely Synchronized Position Hold Engage and Reorient Experimental Satellites (SPHERES), affords the opportunity to conduct slosh and fluid transfer experiments in a micro-g environment. In the near term, the data collected from these experiments will play an important role in anchoring analytical models. In the future, these data will help United Launch Alliance (ULA) plan for Atlas V and Delta IV missions that encompass complex scenarios like propellant transfer and on-orbit propellant management. ULA has invested over $150K of its own Internal Research and Development (IRAD) funds in related research topics over the past several years.

ULA sees these data as a valuable enhancement to data collected from Embry Riddle Aeronautical University’s (ERAU) submission for initiative NND111221100, “Opportunities for Payloads Requiring A Near-Zero Or Reduced Gravity Environment: Maturing Crosscutting Technologies That Advance Multiple Future Space Missions to Flight Readiness Status”. The aggregation of experimental data is a solid foundation of public domain information that cultivates the maturation of propellant transfer and on-orbit propellant management.

This project cultivates a partnership with Massachusetts Institute of Technology (MIT) Space Systems Lab and the Florida Institute of Technology as well as enhancing the existing working relationship between ERAU, ULA and NASA. This collaboration in turn supports a wide range of pressing issues facing the space transportation community. In addition, the partnership provides interesting, relevant Science, Technology, Engineering, and Mathematics (STEM) topics to engage students, our future workforce.

Sincerely,

[Signature]

Dr. George Sowers
Vice President
Business Development & Advanced Programs
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