#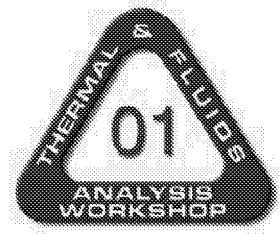 ASSESSMENT AND ACCOMMODATION OF THERMAL EXPANSION OF THE INTERNAL ACTIVE THERMAL CONTROL SYSTEM COOLANT DURING LAUNCH TO ON-ORBIT ACTIVATION OF INTERNATIONAL SPACE STATION ELEMENTS

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ABSTRACT

The International Space Station (ISS) employs an Internal Active Thermal Control System (IATCS) comprised of several single-phase water coolant loops. These coolant loops are distributed throughout the ISS pressurized elements. The primary element coolant loops (i.e. U. S. Laboratory module) contain a fluid accumulator to accommodate thermal expansion of the system. Other element coolant loops are parasitic (i.e. Airlock), have no accumulator, and require an alternative approach to insure that the system maximum design pressure (MDP) is not exceeded during the Launch to Activation (LTA) phase. During this time the element loop is a stand alone closed system. The solution approach for accommodating thermal expansion was affected by interactions of system components and their particular limitations. The mathematical solution approach was challenged by the presence of certain unknown or not readily obtainable physical and thermodynamic characteristics of some system components and processes. The purpose of this paper is to provide a brief description of a few of the solutions that evolved over time, a novel mathematical solution to eliminate some of the unknowns or derive the unknowns experimentally, and the testing and methods undertaken.

FOREWORD

This document was prepared for the Internal Active Thermal Control System (IATCS) Subsystem Manager for George C. Marshall Space Flight Center of the National Aeronautics and Space Administration. The NASA Task Initiator for this effort is Mr. Joseph B. McConnell of ED25. This report documents some aspects of the International Space Station Internal Active Thermal Control System compliance testing over the time frame of late 2000 through mid 2001.

The authors wish to thank the following individuals for their contributions:

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ACRONYMS

ACOMC	Assembly Checkout Operations and Maintenance Configuration
EADU	Entrained Air Detection Unit
EATCS	External Active Thermal Control System
FH	flexhose
GSE	Ground Support Equipment
HATS	Hardware Acceptance Team(s)
IATCS	Internal Active Thermal Control System
ISS	International Space Station
JSC	Johnson Space Flight Center, Houston
KSC	Kennedy Space Center, Florida
LTL, LT	Low Temperature Loop
LP-EADU	Liquid Piston Entrained Air Detection Unit
MDP	Maximum Design Pressure
MSFC	Marshall Space Flight Center, Huntsville
MTL, MT	Moderate Temperature Loop
MP-EADU	Metal Piston Entrained Air Detection Unit
NASA	National Aeronautics and Space Administration
PPA	Pump Package Assembly
psia	pounds per square inch (absolute)
psid	pounds per square inch (differential)
QD	Quick Disconnect
USL	Unites States Laboratory module
cc	cubic centimeter
scc	standard cubic centimeter
sci	standard cubic inch
ft^2	square feet (area)
ft^3	cubic feet (volume)
in^2	square inches (area)
in^3	cubic inches (volume)
	fluid density

1.0 SUMMARY

The International Space Station (ISS) employs an Internal Active Thermal Control System (IATCS) comprised of several single-phase water coolant loops. These coolant loops are distributed throughout the ISS pressurized elements. The primary element coolant loops (i.e. U. S. Laboratory module) contain a fluid accumulator to accommodate thermal expansion of the system. Other element coolant loops are parasitic (i.e. Airlock), have no accumulator, and require an alternative approach to insure that the system maximum design pressure (MDP) is not exceeded during the Launch to Activation (LTA) phase. During this time the element loop is a stand alone closed system. The solution approach for accommodating thermal expansion was affected by interactions of system components and their particular limitations. The mathematical solution approach was challenged by the presence of certain unknown or not readily obtainable physical and thermodynamic characteristics of some system components and processes. The purpose of this paper is to provide a brief description of a few of the solutions that evolved over time, a novel mathematical solution to eliminate some of the unknowns or derive the unknowns experimentally, and the testing and methods undertaken.

2.0 INTRODUCTION

The ISS employs an IATCS comprised of several single-phase water coolant loops. These loops are distributed throughout the various ISS pressurized modules and provide coolant to various heat exchange devices. Examples are electronics cooling coldplates, carbon dioxide removal assembly, cabin air heat exchangers, research experiment payload racks, a heat exchanger to prepare the Astronauts' space suits for Extra Vehicular Activities (EVAs), and a compact cross-flow interface heat exchanger which transfers the internal waste heat from the IATCS outside to the External Active Thermal Control System (EATCS) for radiation to space.

During on-orbit assembly of the ISS, the IATCS coolant loop network undergoes incremental build-up. This build-up occurs along with the addition of new pressurized elements or modules. At present, the U. S. Laboratory (USL) module, Airlock and Node 1 are on-orbit and operating as one system.

The IATCS utilizes a dual-loop internal architecture which allows segregation of a low temperature loop (LTL or LT) and a moderate temperature loop (MTL or MT). The primary loops contain fluid accumulators in the Pump Package Assembly (PPA) in each loop. The parasitic elements have no accumulator in their respective sub-loops prior to being connected to the primary loops. As a result, the thermal expansion of the coolant must be accommodated if these elements' loops experience temperature excursions prior to being connected to the primary loops. If there was no accommodation for the volumetric increase of the coolant, the internal loop pressure could potentially exceed the system MDP. A solution is needed to ensure the MDP of the system is not exceeded during the LTA phase for the ISS elements without an integral accumulator. An alternative fluid mechanical compliance is incorporated into each element's sub-loop during LTA to solve this challenge. The solution adds no additional hardware to the element.

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3.0 REQUIREMENTS AND ENGINEERING CHALLANGE

3.1 COMPLIANCE

The term compliance, as used here, means the ability of the IATCS loop hardware to accommodate thermal expansion of the coolant during LTA. In a rigid system thermal expansion of an internal fluid would cause the internal pressure to rise. If the compliance of the loop is sufficient, the internal loop pressure is prevented from increasing to the point where the MDP of the system is exceeded.

The loop piping is comprised of rigid tubing, rigid devices and flexible hose. The compliance of the rigid tubing is insignificant in its effect to accommodate thermal expansion of the coolant. The flexhose provides some degree of compliance to accommodate volumetric expansion. If a loop is comprised of pure rigid tubing, the thermal expansion would cause MDP to be exceeded. If the loop is pure flexhose the compliance of the flexhose is sufficient to accommodate the thermal expansion for the temperature excursions expected. The temperature differential under consideration is 70 deg F to 110 deg F. As an example, the USL module has about 2500 inches of flexhose in a 40 gal. capacity system. Therefore, depending upon the ratio of flexhose to rigid tubing volume in the sub-loop, more or less auxiliary compliance is needed.

The solution implemented to solve this engineering challenge is to allow an air bubble in the element sub-loop during LTA. The air then acts in place of an accumulator to accommodate the thermal expansion of the coolant. The size of the air bubble must be large enough to accommodate the expected expansion of the coolant plus a safety margin. This establishes the lower limit to the size of an allowable compliance air bubble. The bubble also must be small enough not to exceed the IATCS gas trap capacity to remove the bubble upon loop activation and subsequent circulation of the bubble in the loop. This prevents the bubble from reaching the PPA inlet and/or impeller. The mass of air bubble which the gas trap can remove over a short time frame is limited. This establishes the upper limit of allowable compliance air bubble.

These two limits together outline the envelope of the Compliance Criteria. The criteria are stated in a maximum and minimum bubble volume V_b at standard conditions (STD).

3.2 REQUIREMENTS

The requirements for the Airlock allowable compliance was determined from the known volumes of the loops, the known volumes of flexhose in the loops, and the thermal expansion of the coolant over the required temperature range (70 deg F to 110 deg F). The allowable compliances are between 5.76 sci (94.4 scc) and 37.6 sci (616 scc) for the MT and between 2.25 sci (36.9 scc) and 46.4 sci (760 scc) for the LT[10].

3.3 THE CHALLENGE

The challenge arising out of this is how to test and verify prior to launch that an ISS element meets its particular and unique Compliance Criteria. The low end of the envelope ensures the system MDP is not exceeded during LTA. This might occur if the loop compliance was insufficient to accommodate thermal expansion of the IATCS coolant. This guards against loop

damage, which could lead to a leak in the system. The high end of the envelope ensures that the compliance air bubble is not so large as to exceed the capacity of the PPA gas trap. This guards against pump damage due to cavitation or depriming of the pump, which would lead to shutdown of the loop.

Information about the size of air bubbles in a sub-loop network is useful for purposes of predicting changes in the main loop accumulator quantity upon connection of the sub-loop to the primary loop and activation of the new element. This knowledge is helpful for such things as tracking of fluid inventories for re-supply logistics and software setpoints which utilize the accumulator quantity in leak detection algorithms.

There is currently no special equipment, fixturing, or access available to inject a known amount of air into a cooling loop. The presence of flexhose in the loop and dissolved gas in the loop introduces some difficulties discriminating the associated compliance from air bubble compliance.

There is some data available on the change in volume versus pressure for flexhose in a laboratory environment. Unfortunately this data is not directly applicable to flexhose that is installed in a system. The installed flexhose has various bend radii, mounting straps, is packed tightly against adjacent components, and other non-quantifiable parameters. This makes it difficult to characterize the response of flexhose under as-built conditions.

Also, an exact value for the elevation pressure head on the bubble(s) is not available. The piping and component fluid passageways in the networks are complex. The location and distribution of any entrained air is unknown. It may be distributed as several small bubbles. It may be present somewhere as a predominant large mass. Since the modules are up to 15 feet in diameter, any entrained air may not experience the same local ambient pressure.

These are some of the contributing factors which comprise the interesting engineering challenge to the ISS IATCS Thermal Team.

4.0 SOLUTION APPROACH - HISTORY

4.1 USL – NITROGEN DRIVEN LIQUID PISTON ENTRAINED AIR DETECTION EQUIPMENT

A compliance test was performed on the USL LTL and MTL IATCS systems on June 21, 2000[1]. This test was performed to determine the size of any existing gas bubbles in the system. In order to run these tests, the racks which contained the respective PPA accumulators were disconnected from the system. This prevented any movement of the accumulators due to pressure changes from impacting the system measurements.

The test setup for the USL (Figure 1) consisted of a fluid sight glass connected at one end to an IATCS loop, a tank of pressurized gaseous nitrogen connected to the other end of the sight glass, a pressure gauge to measure the nitrogen pressure exerted on the loop and a linear scale associated with reading the level of IATCS coolant in the sight glass.
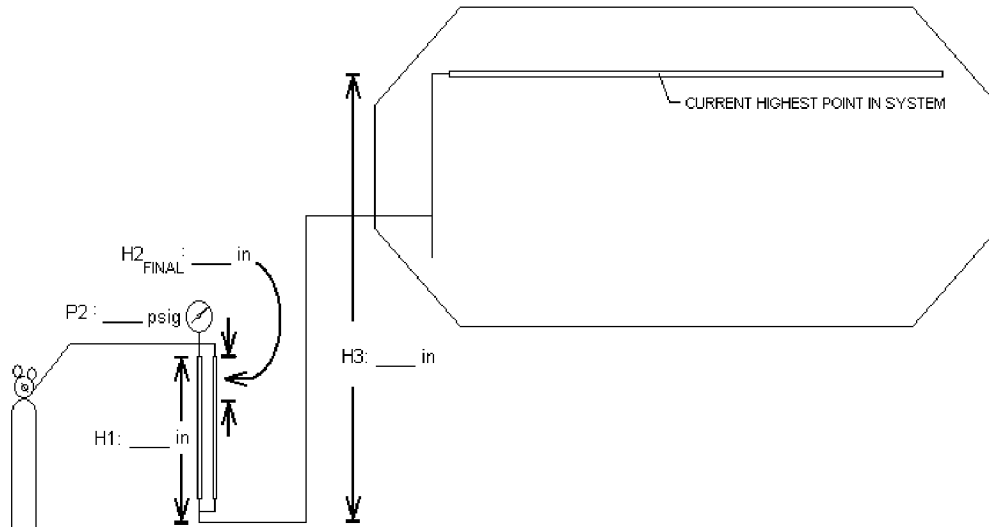
Figure 1. LP-EADU: USL Test Setup (from Reference 1)

The nitrogen pressure exerted on the IATCS coolant in the sight glass was varied through the range of 5 to 40 psig in 2.5 psig increments. The change in coolant level in the sight glass was determined. This pressure data was then corrected for elevation heads and yielded an overall ΔP and an overall ΔV. It was assumed that the air bubble was at the top of the loop. From these values the volume of air bubble in the loop was calculated via the Ideal Gas Law in isothermal form (Boyle's Law). The initial bubble volume is adjusted back to a standard reference.

$$V_{IN} = P_F \cdot \left(\frac{\Delta V_{meas}}{\Delta P_{meas}} \right) \cdot \left(\frac{T_{IN}}{T_F} \right) \cdot \left(\frac{P_{IN}}{P_{BAR}} \right)$$

(1)

where

V_{IN}	=	Initial volume of air bubble within the loop prior to compression (scc)
ΔV_{meas}	=	Measured amount of coolant injected into the loop (cc)
ΔP_{meas}	=	Measured resultant change in the pressure of the loop (psia), $P_F - P_{IN}$
P_F	=	Final pressure in the loop (psia)
P_{IN}	=	Initial pressure in the loop (psia)
P_{BAR}	=	Reference barometric pressure (psia)
T_{IN}	=	Local temperature prior to compressibility test (absolute)
T_F	=	Local temperature at the time of compression (absolute).

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The results were reported as "raw" values for V_{IN}. The term "raw" means that no adjustment has been made to account for compliance of flexhose aboard the USL module, or for the small amount of compliance measured within the test setup equipment itself [1] the "tare". Any effects due to dissolved nitrogen entering the loop coolant were neglected. The tests are run in a controlled environment so T_{IN} was assumed to be equal to T_F. The USL tests yielded the following results:

Sub-Loop Under Test	Data Set #1	Data Set #2
	Increasing Pressure	Decreasing Pressure
USL - LT	19.2 in^3	15.8 in^3
USL - MT	21.25 in^3	20.9 in^3

Table 1. USL IATCS Loop Bubble Volumes (from Reference 1.)

The results of the USL tests appeared to be near three times larger than some other indications. This was inferred from dynamic experimental test data from operational tests of the USL. Due to this unexplained difference and the spread in the results (Table 1) it was decided to implement a different compliance testing tool for the Airlock module tests.
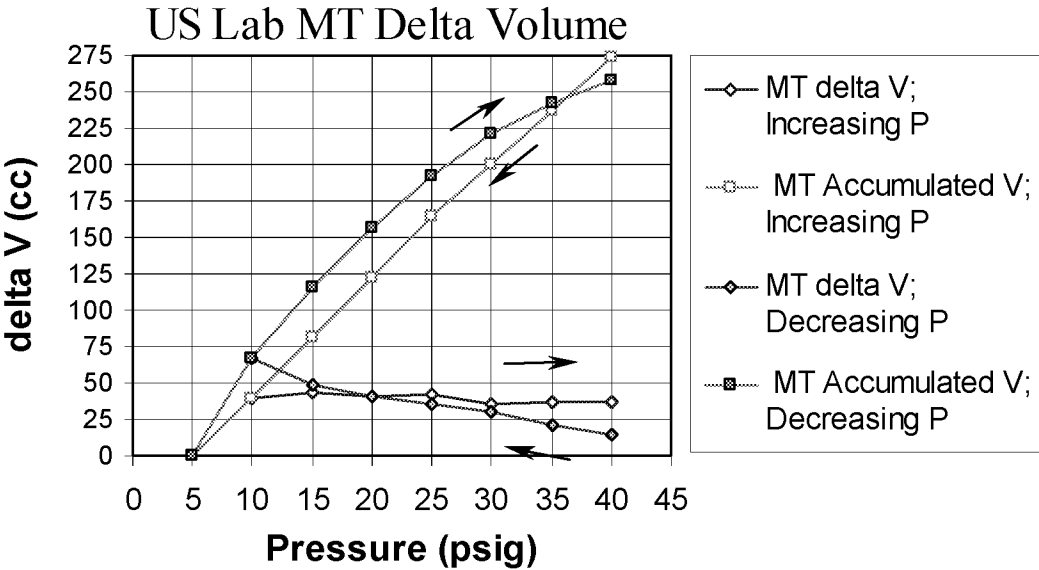

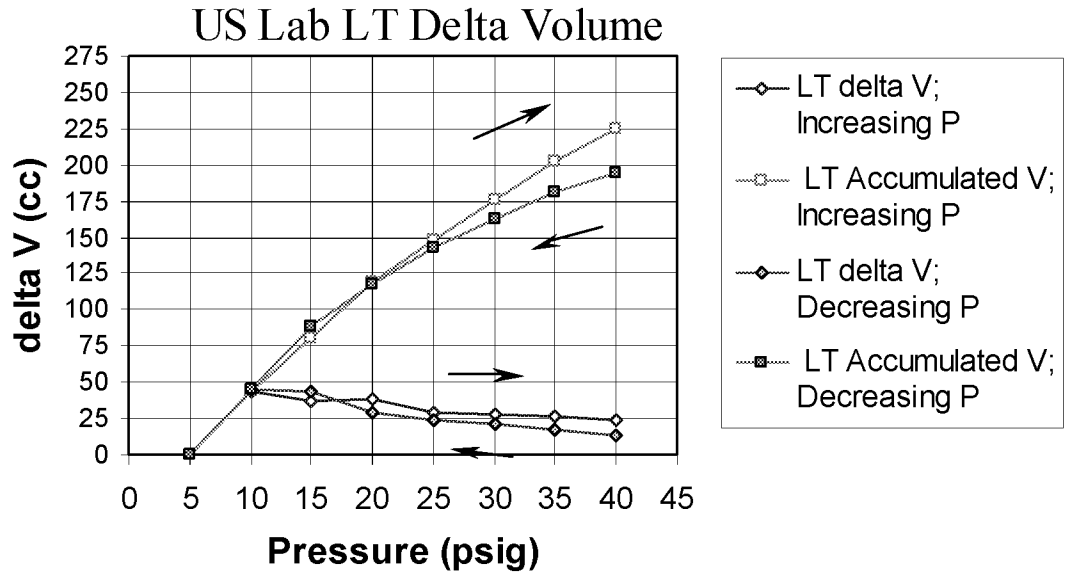Figure 2. USL MT delta V vs Pressure

Figure 3. USL LT delta V vs Pressure

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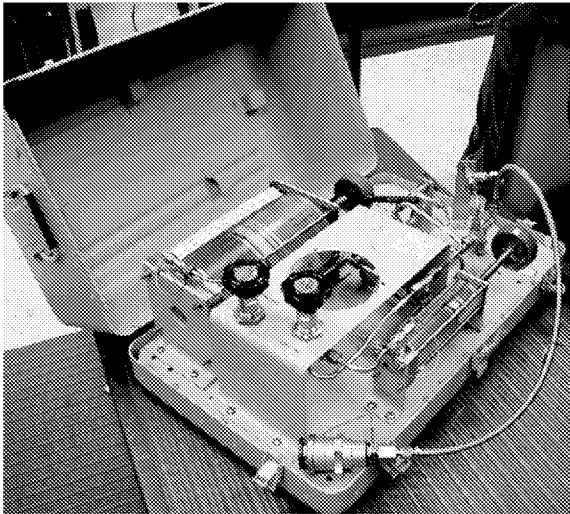## 4.2 AIRLOCK – POSITIVE DISPLACEMENT METAL PISTON ENTRAINED AIR DETECTION UNIT

Figure 4. MP-EADU - pressure gauge removed for calibration.

Compliance tests were performed on the Airlock module LTL and MTL IATCS systems in April, 2001. These tests were performed to determine the size of any existing gas bubbles in the system. Rather than a liquid piston driven by nitrogen pressure to affect a change in pressure in the system, a positive displacement metal piston and cylinder tool, the Entrained Air Detection Unit (MP-EADU) (Figure 4), was used in the Airlock compliance test set-up.

The MP-EADU is a suitcase-sized device. It consists of two graduated cylinders connected in parallel, a pressure gauge, and various isolation valves (Figure 5). Volumetric Cylinder 1 (VC1) has a displacement of 100cc and VC2 has a displacement of 1800cc. On each cylinder there is a micrometer adjustment for a fine measurement of the piston stroke and a linear scale on the side of the cylinder for a coarse measurement of the piston displacement. The calibration is such that each $1/50^{th}$ of a turn of the micrometer, one tick mark, is equal to only a fraction of a cubic centimeter of displacement by the piston.
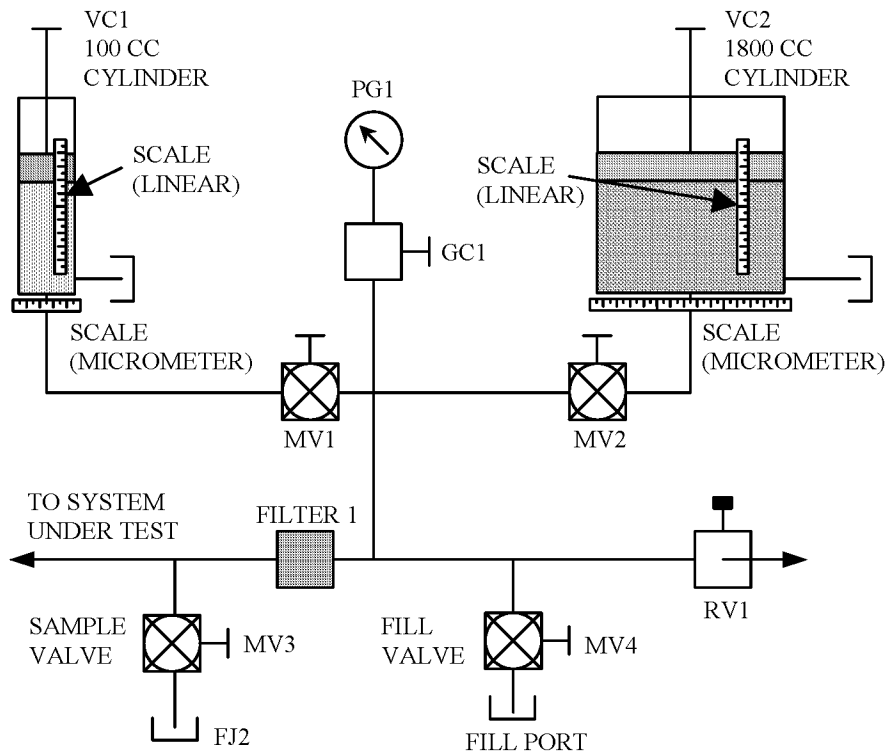

Figure 5. MP-EADU Schematic Diagram, from Reference (2)

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4.3 METAL PISTON ENTRAINED AIR DETECTION UNIT (MP-EADU) VALIDATION

The MP-EADU was required to be validation tested in order to qualify its use for this particular application on the ISS Program. The MP-EADU was originally designed and used in the early Shuttle and Spacelab programs and had been in storage for some time. Additionally the application to ISS was slightly different in that the volumes of entrained air to be detected were larger than previously considered.

The small 100cc displacement volumetric cylinder (VC1) is shown in Figure 6. Originally VC1 was used for making precision measurements and VC2 was used to make a final adjustment to the total coolant/fuel volume in the system under test (setting the fluid accumulator level). Because the air bubble volumes in the ISS elements are larger, VC2 needed to be used to make the measurement. The capability of the MP-EADU to perform these measurements sufficiently needed to be confirmed. In response to this need, MSFC, Boeing-Huntsville and KSC personnel designed, planned and executed a validation test of the MP-EADU. The test measured known volumes of air bubbles. Test volumes of 0, 33, 115, 200 and 280 cc air bubbles were used.

The test volumes were introduced into a rigid thick walled cylinder to avoid any system mechanical compliance similar to flexhose compliance. The test volumes were achieved by first filling the cylinders with IATCS coolant. Then an amount of coolant approximately equal to the nominal amount was drained into a graduated cylinder. The initial and final weight of the cylinders was measured. The weight of coolant drained was weighed. From these measurements, the bubble mass/volume in the cylinder was derived and cross-checked. The data was then adjusted to account for the mass of the air bubble remaining in the cylinder at temperature and pressure.
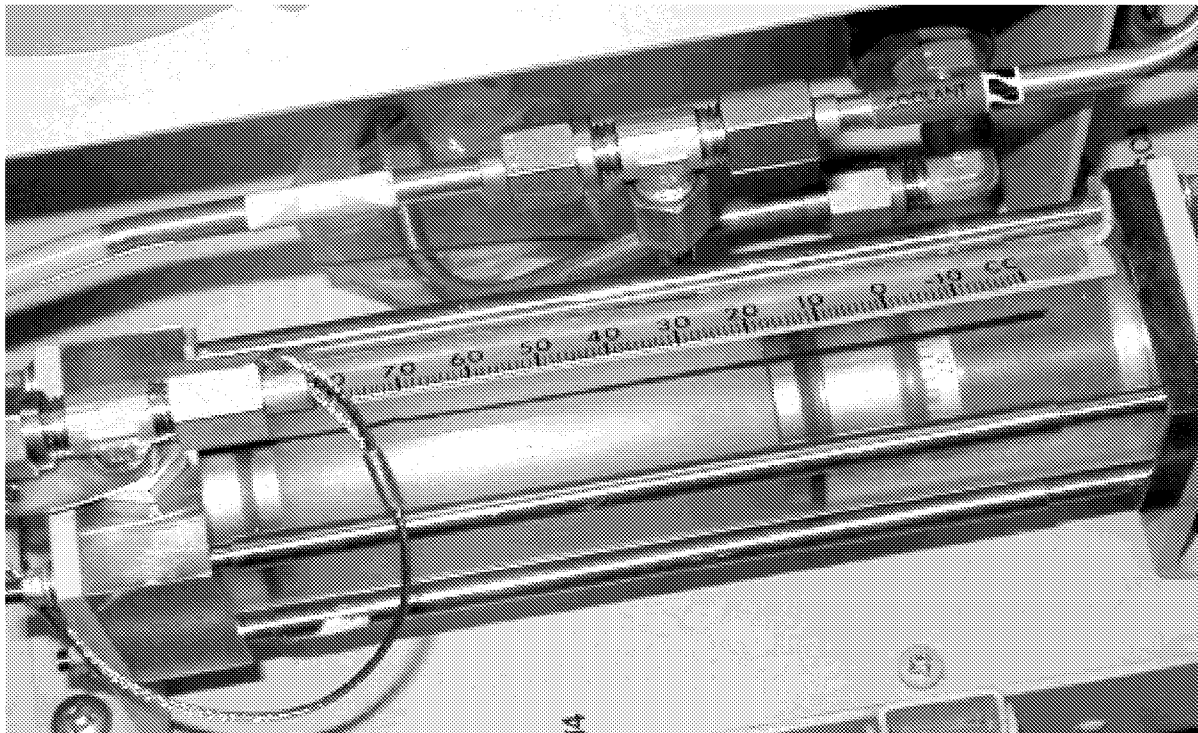

Figure 6. Volumetric Cylinder VC1

Prior to measuring the test air volumes, a tare of the validation setup was performed. This included the EADU and connecting lines minus the cylinder. The test was performed throughout the pressure range. This tare was subtracted from the measured test values.

The results are tabulated in Table 2 and shown graphically in Figure 7. The results were within the desired range of accuracy of 1 in^3. All but the 280cc run were less than 1.5%. The 280cc run was 3.3%. Shortly after this run was performed, a follow-up test was to be run. In the beginning of this follow-up test, a valve packing material failed and the second test was discontinued. It is believed that the incipient failure of the valve packing material contributed to the higher percentage error in the 280cc run. It was noted during the 280cc test that a small amount of fluid was observed around the base of the valve stem. The failure appeared to be due to the packing material drying out as a result of storage and then crumbling as a result of the recent use during this test. The packing crumbled and broke up internal to the valve. The MP-EADU was taken out of service to be rebuilt.

The absence of mechanical compliance in the validation setup thick walled cylinder can be seen in the flat nature of the graphs. No expansion of the system shows up with increasing pressures. The flatness of the curves is an indication that the process was indeed isothermal and that the mathematical method of Boyle's Law works well for a rigid system. The calculation methods will be discussed later in the Airlock section. The data yielded excellent results being within about 9.24 cc (0.6 in^3) or 3.3 % in the worst case at the largest volumes.
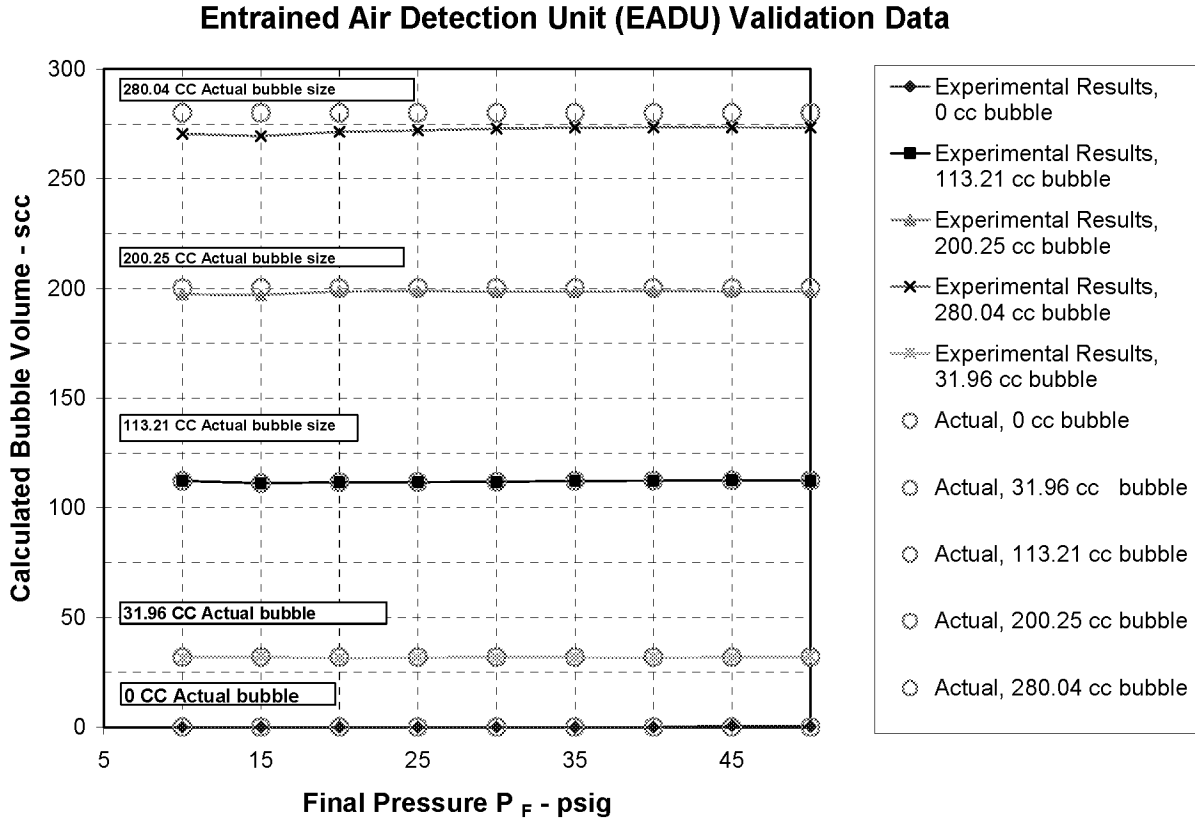

Figure 7. MP-EADU Validation Test - Comparison of Results (from reference [5])

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Nominal Size V_{IN}	Largest Experimental Error $\lvert V_{meas} - V_{actual} \rvert$	Percent Error
(cc)	(cc)	(%)
0	0.65	-
33	0.32	1.0
115	1.70	1.5
200	2.65	1.3
280	9.24	3.3

Table 2. MP-EADU Validation Test Results[6]

4.4 Metal Piston Entrained Air Detection Unit Accuracy

The accuracy of the initial volume calculation obtained from data provided by the MP-EADU is derived from equation (1) [2]. The error bound in the measurement result of the initial volume of air bubble within the loop prior to compression , V_{IN}, is

$$\delta V_{IN} := \left(\frac{\Delta V}{\Delta P} \cdot \delta P_F \right) + \left(\frac{P_F}{\Delta P} \cdot \delta \Delta V \right) + \left(\frac{P_F \cdot \Delta V}{\Delta P^2} \cdot \delta \Delta P \right) \tag{2}$$

where

δV_{IN} = Error bound for the initial volume of air bubble within the loop prior to compression
ΔV = Measured amount of coolant injected into the loop (cc)
ΔP = Measured resultant change in the pressure of the loop (psia), $P_F - P_{IN}$
P_F = Final pressure in the loop (psia)
δP_F = Uncertainty in the pressure measurement, due to the pressure gauge
$\delta \Delta V$ = Uncertainty in the volume measurement, due to VC2
$\delta \Delta P$ = Uncertainty in the change in pressure between P_{IN} and P_F,
    since the pressure gauge is read twice for a differential pressure $\delta \Delta P = 2\ \delta P_F$

The predominate term is the error due to the bourdon tube pressure gauge. The gauge has a one half minor division equal to 0.25 psig. The inherent error of the MP-EADU varies depending on the inter-relation of the above parameters. To examine the error, the data was evaluated for experimental error using the data points with the largest difference between the measured bubble size and the actual bubble size. The results are summarized in Table 3. The table shows that the MP-EADU Validation Test actual experimental error was in all cases within the maximum calculated error bound capability of the tool.

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Nominal Size V_{IN}	Experimental Error $\lvert V_{meas} - V_{actual} \rvert$	Max Error Bound δV_{IN}	Experimental Error as Percent of Max Error Bound
(cc)	(cc)	(cc)	(%)
0	0.65	0.721	90.2
33	0.32	2.34	13.7
115	1.70	6.70	25.4
200	2.65	10.4	25.5
280	9.24	13.6	67.9

Table 3. MP-EADU Validation Test Results, Typical MP-EADU Error[6]

4.5 AIRLOCK TEST SET-UP

Since the MP-EADU is a portable suitcase sized device (Figure 4) it could be situated centered at the mid-level of the Airlock. This provided minimal elevation differences between the EADU and the extremes of the Airlock cooling loops. This minimized any effects due to elevation heads. Any elevation heads that may have been present were neglected. Because the actual location of any bubbles within the loop was unknown the elevation head was also unknown. The Airlock was positioned about 12 to 15 feet above the manufacturing floor, on the manufacturing support scaffolding, as shown to the right with your humble narrator.
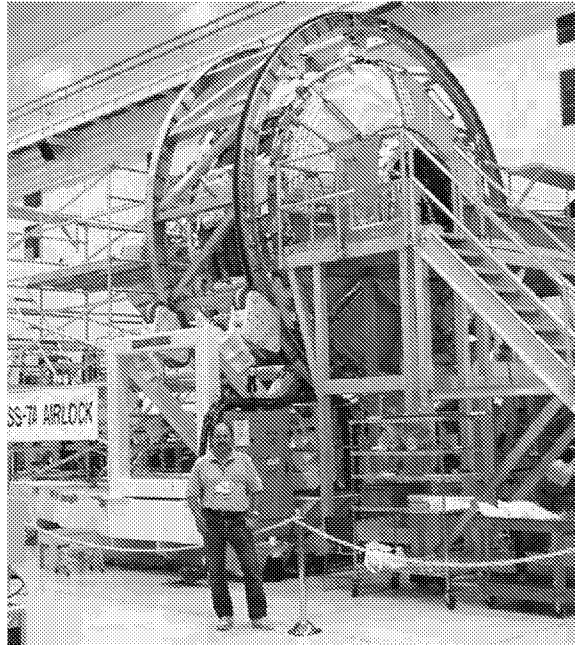
4.6 AIRLOCK PROCEDURES

Figure 8. One of the authors at KSC during Airlock testing.

In order to measure the Airlock compliance, the piston was manually displaced via the micrometer. This directly displaced IATCS coolant fluid into the Airlock loops and raised the loops internal pressure. An initial motion of the piston, enough to move the pressure from 0 psig to the starting pressure of 5 psig, was advanced to take up any mechanical backlash or stiction in the system. Then the pressure was increased via additional forward piston displacements, which resulted in 5 psid pressure increments. The incremental displacement of the piston was recorded at each pressure increment. A set of ΔV and ΔP data was thus obtained for the Airlock.

The tare for this test setup is defined as any measured volumetric change in the test setup, occurring in the ground support equipment (GSE) or lines connecting the GSE to the loop under test, as a result of the test pressures. Alternately it can be defined as any measured volumetric change in the test setup, occurring in any equipment attached to the test setup that is not part of the object under test, as a result of the test pressures.

In order to obtain the experimental change in volume of the item under test it is necessary to subtract any tare volumetric change from the experimentally measured change in volume.

$$\Delta V_{meas} = \Delta V_{item.under.test} + \Delta V_{tare} \quad\quad\quad (3)$$

$$\Delta V_{item.under.test} = \Delta V_{meas} - \Delta V_{tare} \quad\quad\quad (4)$$

A tare change in volume can occur because of air in, or mechanical compliance of the GSE and test setup equipment. The procedure to determine the tare value is included as part of the test procedure. The test procedure is essentially the same as the tare procedure described earlier, in the MP-EADU validation section, with the addition of item under test connected to the GSE and test equipment.

A volume of coolant is injected into the system by way of the volumetric cylinder's piston stroke. The piston is advanced with a micrometer device. It is advanced until the pressure in the system achieves 5 psig, which is the starting point. From here the piston is slowly advanced in measured volume displacement increments necessary to achieve 5 psi increases in the system pressure. Readings of volume of coolant injected are taken at 10 psig through 50 psig in 5 psig steps. The measurements thereby obtained are the volumetric change of the GSE and connecting lines, the "tare", over the range of the test pressures. The changes in pressure are performed slowly to keep the system in the thermal equilibrium necessary to apply Boyle's law.

The tare measurement procedure is performed immediately prior to taking the test measurements of the item under test. This provides an opportunity to observe, screen out, and/or correct any undesirable functional performance with the test setup, procedures or GSE prior to performing the test on flight hardware.

The tares in the Airlock tests utilizing the EADU were in the range of 18.4 cc to 71.4 cc total at 50 psig. The variation is due to varying amounts of air that was present in the EADU volumetric cylinders. The tests were run over the course of several weeks and in the interim the EADU had been emptied and refilled with IATCS coolant.

The tares in the EADU validation test setup (described below) were in the range of 10.1 cc to 13.2 cc at 50 psig. The validation setup was performed on a lab bench rather than on the Airlock manufacturing scaffolding. As a result the test setup flexible lines were shorter and the test line diameters were smaller yielding the lower tare values. Also, during the validation test, additional care was taken to minimize air in the system.

4.7 AIRLOCK TEST RESULTS

Data from the Airlock LTL and MTL compliance tests are shown in Figure 9. The figures contain the raw tare data for the compliance tool, the raw data for the Airlock loops, and the volumes calculated using equation 4. Because the loops were each split into two sections for testing, the tare was taken twice, once on each section, and was applied along to the appropriate section data in the calculation.
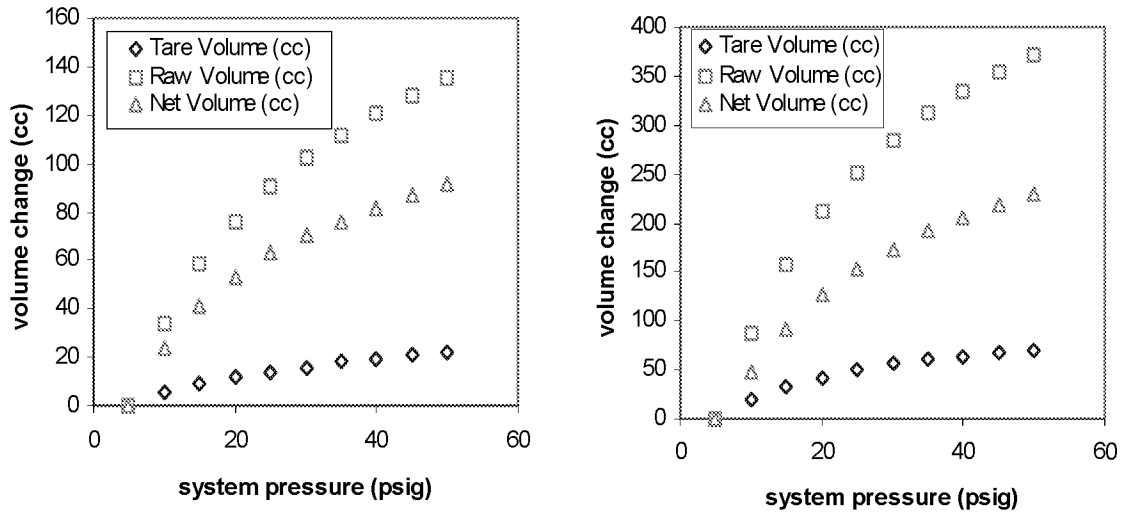
12

Figure 9. Airlock LTL (left) and MTL (right) Compliance Test Measured delta V

4.8 AIRLOCK ANALYSIS

4.8.1 BOYLE'S LAW

Because the validation tests showed that the compression process was in fact isothermal, proper application of Boyle's law can be used to calculate the air bubble mass. If system compliance is ignored, the application of Boyle's law is straightforward

$$pV = p_0 V_0 \qquad (5)$$

where the subscript "0" denotes the reference state. Substituting $\Delta V = V_0 - V$ and converting to standard conditions yields

$$V_{std} = p \cdot \left(\frac{\Delta V_{meas}}{p - p_0} \right) \cdot \left(\frac{p_0}{p_{std}} \right) \qquad (6)$$

where ΔV_{meas} is the measured change in volume. However, the choice of the reference state greatly affects the results of the analysis. Figure 10 shows the calculated bubble mass using different reference pressures for state 0.

The plots show three choices for the reference state, 5 psig, 50 psig and the initial pressure for a given ΔP increment. These choices are labeled, respectively, forward, backward, and piecewise. The calculated masses vary by as much as a factor of two. This is due to the effect of system compliance. Because the LTL has 165 ft of flexhose and the MTL has 245 ft of flexhose, the calculation of bubble mass using Boyle's Law is greatly affected by system compliance. The experimentally measured compliance consists of three main components: the bubble, the flexhose (FH), and the tare compliance.

$$\Delta V_{meas} = \Delta V_{FH} + \Delta V_{bubble} + \Delta V_{tare} \qquad (7)$$

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The tare fraction is subtracted out prior to applying Boyle's Law. The flexhose fraction of the measured compliance is not known. As a result Boyle's law produces a value for bubble volume that is in excess of the actual bubble volume. This occurs in the second factor of equations (1) and (6). In addition when the bubble volume determined by Boyle's Law is adjusted back to standard conditions from the reference state pressure, the flexhose fraction is amplified. This occurs via the fourth factor of equation (1) and third factor of equation (6). The term "flexhose amplification" has been coined to describe this effect. Both of these effects contribute to the upward trending of the data in Figure 10 with increasing pressure. As was seen in the EADU validation test, in an ideal system the data would be flat.

The forward and backward methods use the accumulated change in volume over the accumulated ΔP increments and tend to average out some experimental error. This is sometimes referred to as the "Summing" method. The piecewise method does not do this. Scatter in the piecewise plot is a good indication of experimental noise. The piecewise data tends to alternate high - low. This is because an error for example in ΔP on the high side in one piece (increment) tends to result in an error in ΔP on the low side in the next adjacent step. The piecewise calculations at each step share a common end data point.
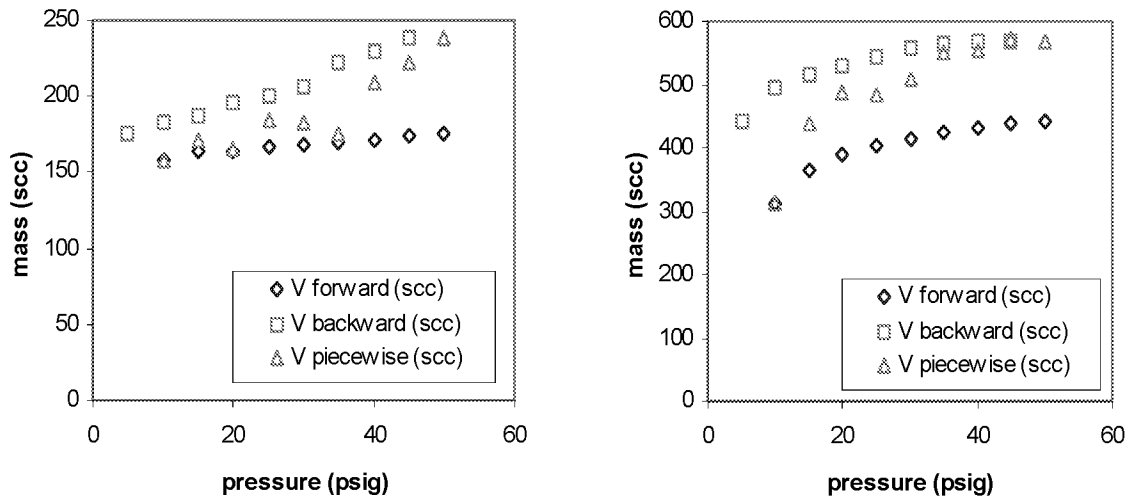

Figure 10. Airlock LTL (left) and MTL (right) Bubble Sizes, Boyle's Law

4.8.2 E. UNGAR METHOD

To account for the effect of flexhose compliance, the calculation can be done in another, more precise, way.

Testing using the compliance tool and single flexhoses showed that the flexhose compliance was proportional to $p^{0.92}$ [7]. The exponent is an average as there was significant scatter in this data. For MDP concerns it is desirable to use the minimum exponent. For gas trap capacity concerns it is desirable to use the maximum exponent. The compliance along with the tare was subtracted from the measured volume change using

$$\Delta V_{comp} = C_1 (p - p_{atm})^{0.92} \qquad (8)$$

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where ΔV_{comp} is the compliance volume change. In the analysis, the coefficient C_1 was adjusted to yield the lowest standard deviation among the forward, backward, and summing method results. The final calculated bubble masses are plotted in Figure 11.
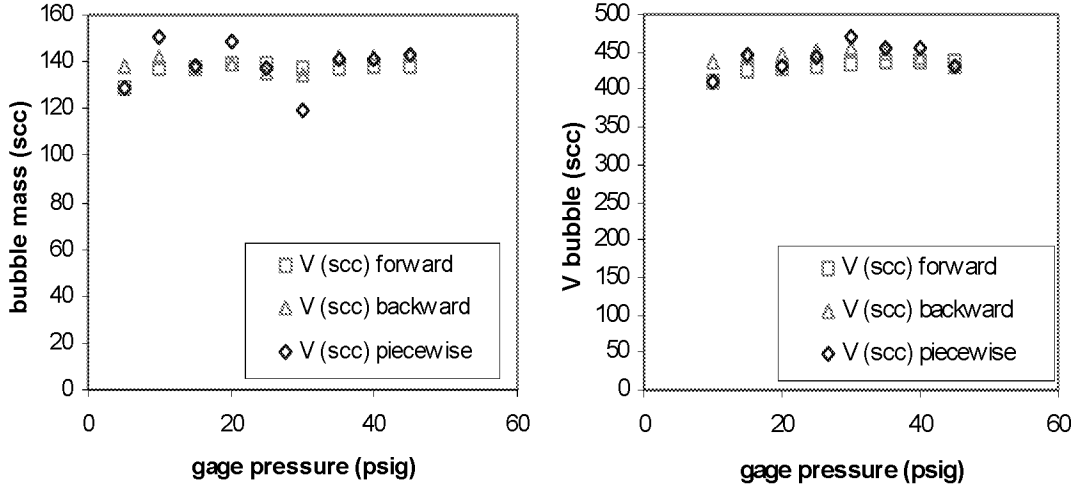

Figure 11. Airlock LTL (left) and MTL (right) Bubble Mass without System Compliance

The calculated bubble mass shown in Figure 11 is much more uniform than in Figure 10, both between methods and over the pressure range. The bubble masses are smaller than those shown in Figure 10 because the flexhose compliance has been removed from the result.

Although this method yields an excellent estimate of the bubble size, it was desirable to develop a simpler, more straightforward method that did not rely on the analyst's judgment nor requiring manual post-processing.

4.8.3 EDWARDS-UNGAR SEESAW METHOD

In this seesaw method, the system compliance is removed directly without having to ever know what its actual value is. The seesaw calculation is performed using three contiguous points along the pressure curve rather than two points. The method is based on the simplifying treatment that for the small ΔP of adjacent points and a flexhose compliance response with an exponent near 1.0, the flexhose contribution to compliance can be approximated as linear. The center point is the reference point. Using this simplification at each three-point ΔP step/increment, the flexhose contribution above and below the center reference point exactly cancel out. In mathematical terms the variable is eliminated. Using Boyle's Law for the bubble sizes

$$p_1 V_1 = p_2 V_2 = p_3 V_3 \tag{9}$$

For simplicity we have assumed that the system compliance is linear, so

$$\Delta V_{comp} = C_2 (p - p_0) \tag{10}$$

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where p_0 is any reference pressure. We denote the changes in bubble volume, V, by V_1-V_2 = ΔV_{12} = -$\Delta V_{12,tool}$-C_2(p_2-p_1), and V_2-V_3 = ΔV_{23} = -$\Delta V_{23,tool}$-C_2(p_3-p_2). Recasting equation 8 in terms of V_2 using these relations yields two equations with two unknowns, V_2 and C_2. C_2 can be eliminated, leaving a single equation for V_2.

$$V_2 = \frac{p_3 p_1}{p_3 - p_1}\left[\frac{\Delta V_{23,tool}}{p_3 - p_2} - \frac{\Delta V_{12,tool}}{p_2 - p_1}\right] \qquad (11)$$

When the calculations using equation 10 at each test point are averaged, they yield 142 scc and 402 scc for the LTL and MTL, respectively. Comparing these values to Figure 11 shows that the seesaw method yields an excellent estimate of the bubble mass.

Analysis Results Summary:

Loop	Method	Allowable		Average and/or Range of Calculated Values				
		Low	High	Forward	Backward	Piecewise	p_3-p_1=10 psid	p_3-p_1=20 psid
		(scc)	(scc)	(scc)	(scc)	(scc)	(scc)	(scc)
LTL	Boyle's Law (Eq. 5)	36.9	760	160-175	175-240	155-240	-	-
	E.Ungar (Fig 8)			137	136	139	-	-
	Edwards-Ungar, Seesaw			-	-	-	142	142
MTL	Boyle's Law (Eq 5)	94.4	616	305-420	440-580	440-580	-	-
	E.Ungar (Fig 8)			443	430	445	-	-
	Edwards-Ungar Seesaw,			-	-	-	402	409

Table 4. Summary of Airlock Results

As can be seen results summary, one single numeric value was not obtained for the compliance but rather a range of values depending on the method. In all cases the values obtained are well within the allowable range and have a small deviation. The difference in the MTL data between the E. Ungar and Edwards-Ungar Seesaw method was traced and attributed to a bad data point at 5 psig. Its effect manifested because it was the first point in the data set and subsequent values rely on it as a staring point. It was however concluded by consensus of the Thermal Team that the Airlock Compliance met the requirements for LTA.

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5.0 SUGGESTED IMPROVEMENTS

5.1 EADU

1) Some difficulty of repeatability was experienced with the pressure gauge of the EADU. Additionally this gauge introduces the primary error term in the systemic error calculations. This is the primary contributor to the noise that is seen in the data.   It would be beneficial to upgrade this pressure gauge to one with an increased precision and repeatability.

2) It was observed that the O-ring seal in the EADU has a significant amount of backlash by design when seating in the land in the piston.   This leads to limitations on the range of motion available for the tests and also to longer test procedures to accommodate the backlash and to avoid introducing error.   For example if the desired pressure level is overshot the piston needs to be backed up, unseating the o-ring. The ring-to-piston land clearance could be reduced to avoid these problems. A simple way to do this is to install a spacer between the ring and the edge of the land.

3) Currently the fill port is only used in the setup of the EADU prior to its use in a test. The fill port of the EADU could be utilized during testing to allow additional coolant into or out of the EADU. This would decrease the time required to perform certain tests. Currently when it is desired to set a specific pressure level, the EADU fluid has to be moved back and forth between VC1 and VC2 when setting the pressure to a desired level.   If the desired pressure level is overshot the piston is required to move backwards to lower the pressure. This looses the seating of the O-ring and invalidates the test. This would be avoided by utilizing the fill and drain ports to make certain adjustments to the pressure.

5.2 TESTING

The need for the compliance test comes about partly because of the inability to achieve a perfect hard-fill (no air in the loop) of the cooling loop with coolant and the inability to introduce a known amount of air into the loop. Improvements in the methods of introducing air into the loop could decrease testing time. At present the desired amount of air introduced varies widely. If the amount introduced is outside the allowable range, the fill, air introduction and testing has to be repeated. Ideally the fill, air introduction and testing would need to be executed only once.

1) An air injection tool to introduce controlled amount of air could be developed.

2) A recirculating coolant type system is currently used to remove air from the system after a fill. The amount of residual air has significant variance in this application. This system could be upgraded with the addition of a membrane contactor gas trap, or other methodology, to maintain a fixed known amount of air in the circulating coolant, and hence in the element loop in question

3)   The above two solutions occur after the fill operation and are additional steps. A method to reduce these steps would be ideal and would need to introduce the desired amount of air during the fill process. This could be accomplished simply by evacuating the loop to a predetermined vacuum level rather than to attempt to get a "perfect" vacuum and "hard-fill" with coolant. With knowledge of the loop volumes, the residual mass of air could be calculated directly via the gas laws.   For large systems with minimal flexhose compliance, the calculation should also include the amount of dissolved air in the fill coolant. De-aerated coolant which is then allowed to come to equilibrium saturation levels of dissolved air at ambient pressure could provide this information.

4) The need to perform the compliance tests is obviated in a system with a fluid accumulator installed.

5.3 ANALYSIS

When this task was undertaken the ACOMC specified the Allowable Compliance Criteria. It did not specify how to arrive at the compliance numerical value to compare against the criteria. Two methods were employed to measure the compliance and several different mathematical analyses were employed to arrive at the compliance numeric value. Each method has its strengths and weaknesses for a given system compliance measurement or application. A more formal guideline could be implemented which clearly delineates the way to arrive at the compliance numerical value under the given conditions of the system under test. Additional inspection of the various mathematical methods and their limitations would need to be undertaken in order to formalize this.

For example, the E. Ungar method directly incorporates the known physical phenomenon associated with the system such as flexhose expansion as a function of pressure, but it is mathematically cumbersome. The Edwards-Ungar Seesaw method is mathematically efficient, but makes simplifications which may or may not hold in all cases. Boyle's Law method is mathematically the simplest, but does not take into account flexhose expansion and in fact introduces the rather large error of "flexhose magnification".

6.0 CONCLUSIONS

*   The results obtained with these Allowable Compliance tests and analyses were sufficient to determine that the Airlock met the requirements for the LTA phase of the ISS.
*   The accuracy of the MP-EADU is sufficient for this task being within 3.5% for air bubble volumes over the range of 0cc to 280cc.
*   It is useful to perform a tare subtraction over the entire range of the test pressures. The MP-EADU validation test shows that this provides a good degree of accuracy. The MP-EADU validation also confirms the mathematical methods for a rigid system.
*   The system mechanical compliance must be taken into account if an accurate measurement of the bubble size is to be obtained.
*   The Edwards-Ungar Seesaw method yields an accurate bubble size calculation that does not require interpretation by the analyst. Further testing is required to determine the limitations of this method for non-rigid systems.
*   The E. Ungar method yields the most accurate result over a wide range of conditions and is suitable for non-rigid systems.
*   The Boyle's Law method does not yield an accurate result for a system with any degree of mechanical compliance in the system. Boyle's Law is suitable for rigid systems.
*   There is an inter-relation between the item under test, the analysis method used and the degree of precision required. At present this is not fully characterized. This inter-relation would be of significant impact if the test results were closer to the edges of the allowable compliance envelope. So far the results have, at random, not been significantly close to the margins for this to be a concern. If this were the case, it would be advisable to adjust the mass of air in the system to move away from the edges of the envelope and take care to incorporate the error bounds of the EADU.

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