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USING HELIUM TO PREDICT THE MASS PROPERTIES OF AN OBJECT IN THE VACUUM OF SPACE

by

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Abstract -- How can the mass properties of objects designed to operate in space best be measured in an earth based lab? Mass properties measurements of lightweight objects designed to operate in the vacuum of outer space have traditionally been made in a vacuum chamber, in order to eliminate the errors due to the mass of the air surrounding the object. Vacuum chambers are expensive and inconvenient to use. The novel method described in this paper eliminates the effect of the air mass without requiring a vacuum chamber. This method works for any shape object.

Summary of Boynton's helium method

(Space Electronics is applying for a patent on this method.)

1. Measure the object in an air environment.

2. Measure the same object in a helium environment. Since the helium is at atmospheric pressure, there is no need for a thick-walled chamber. Even a thin plastic enclosure will work.

3. The MOI of the test object in a vacuum can then be calculated from these two measurements, using the following formula:

$$I_V = 1.2\ I_H - 0.2\ I_A$$

where;
I_V = MOI (predicted) in a vacuum
I_H = MOI measured in helium
I_A = MOI measured in air

Since the mass properties instruments have an on-line digital computer, these calculations can be done automatically.

4. Buoyancy effects on CG unbalance moment can be corrected using a similar procedure.

Introduction -- Measuring the mass properties of objects designed to operate in the vacuum of outer space poses problems not encountered when performing similar measurements on earth-based test objects. There are five primary sources of error introduced to the measurement by the air atmosphere. These are:

1. the effect of air entrapped within the test part, thereby adding to the **actual** mass of the test part

2. the effect of the atmospheric gas entrained on the outer surfaces of the test part adding to the **effective** mass of the test part.

3. the effect of the **damping** term on the equation of motion of a torsion pendulum.

4. the **deflections** of the test item due to the drag forces.

5. the **buoyancy** effect on CG moment

For large lightweight objects such as decoys, the magnitude of these errors can be considerable. The degree to which entrapped and entrained air influence the test results is a function of the shape and structure of the test part. A solid object will experience only the effect of entrained air, while a hollow cylindrical object with interior baffles will have an error due mostly to entrapped air. The percentage measurement error is a function of the relative mass of the entrapped or entrained air vs the mass of the solid portion of the test part. Smooth-surfaced, dense objects, such as solid cylinders, will show negligible difference in MOI (or POI) when measured in air or vacuum. On the other hand, large lightweight objects may show more than 15% difference in MOI when measured in air vs vacuum, and the buoyancy effect on **sealed** lightweight objects can cause CG measurement errors of several inches.

For the test objects we considered, the error due to damping and deflection were less than 0.1%, and we will ignore these effects in the remainder of this paper.

Problems associated with measuring in a vacuum -- You can eliminate the effect of air by measuring the moment of inertia of an object in a vacuum, but this leads to a number of problems:

1. The objects to be tested which are most affected by air tend to be large. This requires large vacuum chambers which are massive, expensive, and

require long setup and evacuation time for each test.

2. Most high accuracy MOI and POI instruments are built with gas bearings. That means that the gas discharged from the bearing must be continually pumped out in order to maintain a vacuum, making it difficult to obtain a good vacuum.

3. A vacuum chamber requires a large expensive vacuum pump. Considerable electrical power is expended every time the vacuum chamber is evacuated, and additional energy is required to keep the pumps running so the air flowing through the gas bearing is removed.

4. There is no convection cooling in a vacuum, so motors and electronic circuits in standard mass properties instruments will tend to overheat and fail. Some components can be moved outside the evacuated space, but others have to be protected by intermittent, low service factor operation, or special cooling methods. These components introduce some measurement uncertainty due to temperature variation during the operating cycle.

5. The gas bearing in the instrument works very differently in a vacuum than in air, so that a special bearing design is required for use in a vacuum.

6. The cost of a special mass properties instrument for use in a vacuum is at least 10% higher than a conventional instrument.

How good a vacuum do you need? -- To eliminate the effect of air, you do not need to create the near perfect vacuum of outer space. The relationship between air mass error and atmospheric pressure is linear. For example, reducing the atmospheric pressure from 14.7 psia to 2 psia will reduce the effect of the entrained and enclosed air by a factor of 7.25. By measuring the moment of inertia first at atmospheric pressure, and then at 2 psia, you have two data points from which to extrapolate the measured value in a vacuum.

Using Helium to simulate low atmospheric pressure -- If a 2 psia atmosphere can be used to obtain one of the data points, then it follows that any other method yielding the equivalent of 2 psia can also be used. This led us to believe that testing in a helium atmosphere had the potential to simulate testing in a reduced pressure atmosphere of about 2 psia, since the density of helium is about one seventh that of air. There are two major sources of measurement error in air (entrained and entrapped air). For the helium method to be successful, it must reduce both by the same percentage. Our experiments show this to be the case. The percentage reduction in MOI was the same whether we reduced the pressure to 2 psia or replaced the atmosphere with helium. We repeated this experiment with a number of test object shapes.

Advantages of helium atmosphere testing over vacuum testing -- The primary advantages are lower cost and greater convenience.

1. The massive, expensive vacuum chamber and the vacuum pump are eliminated. Helium testing can be done in a simple, lightweight, sealed chamber. For very large parts, the entire test area can be sealed with plastic film and serve as a space environment.

2. Less operator time is required to run a test. Evacuation time for a vacuum chamber is far greater than helium purge time. Helium is introduced at the top of the chamber and when it is detected flowing out of a vent at the bottom, the chamber is ready for testing.

3. Test setups in a vacuum chamber cannot readily be changed without re-introducing air and re-evacuating the chamber. A glove box can be used in the helium chamber. For large test chambers, technicians can work in scuba gear or with Scott packs in a helium environment. Realistically, technicians cannot work in a vacuum chamber and the vacuum must be released and the chamber re-evacuated for any adjustment to the test. In a helium filled room, a simple airlock can

be used, so the room need not be purged and refilled.

4. The MOI (or POI) instruments require little redesign. A proprietary Space Electronics gas bearing design works equally well in air or helium and the electrical components are equally well cooled in either atmosphere.

Results of low pressure simulation using a helium atmosphere -- It was determined by these tests that measuring MOI in a helium environment of 1 atmosphere pressure is equivalent to operating in air at a pressure of about 4 inches of Mercury (2 psia). Even though we had chosen test objects which had different proportions of entrained and entrapped air, the results were the same for all tests. This is exactly what one might suspect based on the relative density of air and helium.

As our test data shows, the data points using helium appear on each curve at a density which is slightly greater than would be predicted from the theoretical density of helium. We were puzzled by this at first, but then it occurred to us that the helium is probably mixed with a small amount of air, increasing its density. In any event, the magnitude of error which results was less than 0.08% for the cone shaped objects.

NOTES

In the process of performing these tests, a number of interesting effects were observed.

Temperature effect -- When the MOI measurements were first performed, there seemed to be considerable drift. We also noticed when the cover of the test chamber was removed, the escaping helium was quite cold. We questioned whether the drift was due to temperature variation. Two modifications were made:

1. A thermometer was mounted in the side of the chamber to monitor temperature.

2. The helium was passed through a copper coil in a room-temperature water bath before entering the test chamber.

The effect of these changes was minimal but gave us additional confidence in the test setup. We then were able to determine that the drift was due to humidity (see next paragraph).

Humidity effects -- The drift was finally traced to a humidity effect. Our first test objects were made of paper and cardboard. These had apparently achieved moisture equilibrium with the ambient atmosphere. The vacuum, with zero humidity, drew moisture from the test objects, reducing their weight and MOI. This effect was measurable. The tests were re-run with non-adsorbent test objects and we observed that the humidity effect was eliminated.

Sensing when the chamber was filled with helium -- Our normal procedure was to introduce helium into the evacuated chamber. When the pressure returned to 1 atmosphere, the escape of gas from the vent was proof that the chamber was filled with helium. However, in those tests where we did not evacuate the chamber, we filled it with helium from the top to minimize the mixing of air and helium. We used 3 methods to determine when the chamber was filled with helium.

1. We placed a deflated plastic bag loosely over the vent. When helium started to flow from the vent, it rose into the bag, filled it, and eventually caused the bag to rise in the air, much as a hot air balloon is filled and rises.

2. The second method was to place a candle in an inverted jar at the vent. When helium rose into the jar and displaced the air, the candle went out.

3. The two previous methods work well but do not lend themselves to continuous use in a production environment. Commercial oxygen sensors are available. We have installed two of these on our measuring instruments. The first sensor is placed in the chamber and

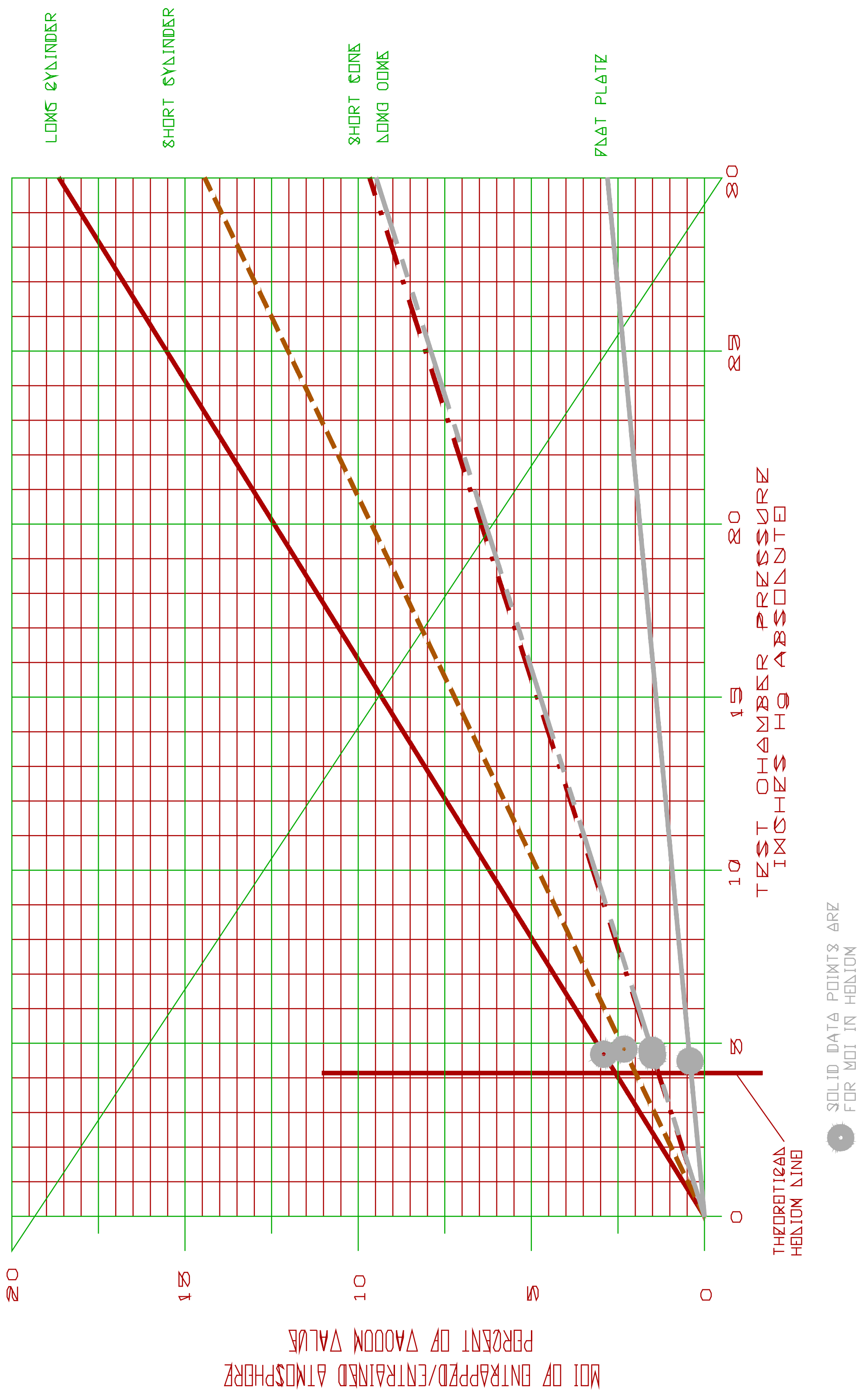

Figure 1 - MOI of Entrapped/Entrained Air

Property	**Air**	**Helium**
Density (lb/ft^3) at 20°C	.0754	.0104
Absolute Viscosity at 20°C Micropoise	181	194
Specific Heat joule/gm °C Constant Pressure at 20°C	1.006	5.24
Thermal Conductivity at 0°C joule/cm sec°C	2.41	14.15

used to verify when the oxygen has been displaced by helium. The second sensor is mounted outside the instrument and is used to warn the test operator if the oxygen level is reduced to 90% of its normal level per OSHA standards.

Purging air from sealed test objects -- This is a measurable effect when air is entrapped inside a lightweight, high volume test object. If the helium method is to be fully effective, this air must be replaced by helium. If the test object is not tightly sealed, this can be accomplished by simply waiting until the air has dispersed into the helium atmosphere. If there are any openings in the test object, they should be oriented down so the helium will rise through them and displace the air inside. It should be noted that if the test object is tightly sealed, air may be intentionally trapped inside when the vehicle is in space and no attempt should be made to purge it.

Product of inertia Spin balance machines are capable of very high sensitivity, particularly if the test item is rotated at a relatively high speed, since the force due to POI unbalance increases as the square of the speed. However, air turbulence has the effect of negating the advantage of higher spin speed. Air turbulence increases the noise floor of the measurement, so that the unbalance signal is obscured by the forces introduced by the air flowing past the outer surface of the test object. Placing the test object in a vacuum eliminates this problem. However, the same objections to a vacuum chamber listed earlier apply for this case. A helium environment has the effect of reducing this noise floor by approximately a factor of 7.

Center of gravity If center of gravity is measured by the spin process, then the same advantages listed above for POI apply to this process. If CG is measured by detecting static unbalance moments, then the weight of air introduces an error due to buoyancy. This buoyancy effect only occurs for sealed objects. The density of air is 0.075 lb/ft$_3$. If one side of an object displaces 1 ft$_3$ more than the other side, and the center of buoyancy of that side is at a radius of 3 ft, then a moment of 2.7 lb-inch is created. The significance of this moment depends on the weight of the test item. If the test item weighs 1000 pounds, then this results in an error in CG of 0.003 inch. If the test item weighs 100 pounds, then the error is 0.027 inch. If the test item is a thin lightweight space object such as a decoy, then it could weigh as little as 1 pound. The resulting error in CG would be 2.700 inch! Measuring the CG in helium will reduce the buoyancy error by a factor of 7.5. As in the case of the moment of inertia measurement, the measurement in air and helium can be extrapolated to yield the CG in a vacuum.

Effect of helium on the test operator The helium used in this test procedure will be exhausted to the atmosphere and will be mixed with the air that the operator breathes. Will this present a hazard? The answer is no, for the following reasons: Helium is not toxic, and in fact is intentionally used by scuba divers to reduce the incidence of the "bends". Helium rises very quickly, since it is so much lighter than air. In a large industrial building, the 1 CFM of helium used by the instrument will rise to the ceiling and not change the composition of the air the operator breathes. In a small room, the helium will eventually displace the air, so that the operator could experience a lack of oxygen. However, well before this happens, the operator will note that he is starting to sound like Donald Duck when he talks. As a further safeguard, we have installed an oxygen sensor on all of our instruments which use helium. A warning tone sounds when the oxygen level decreases to 90% of its normal concentration.

Cost of Helium In March, 1991, the cost of helium was $84 for a 291 ft^3 bottle. About 1 CFM is required for the instrument. In addition, a volume of helium equal to the volume of the test chamber will be required. Typically, about $15 worth of helium is required for one measurement. This is a tiny fraction of the cost of buying a vacuum chamber and expending the energy to pump the air out.

Description of test method

It was the intent of these tests to determine the feasibility of measuring MOI of various test parts designed for use in space in a helium atmosphere at 1 atmosphere pressure (nominally 14.7 Psia) as a substitute for measuring these parts in a partial vacuum. The objectives of this study were:

1. To determine the level of reduced pressure air (vacuum) equivalent to the helium environment for various test part shapes. The shapes measured were; 2 cones, 2 cylinders, 1 solid sphere, and 1 flat panel.

2. To determine correction factors to extrapolate test part MOI in vacuum based on helium atmosphere results

3. To develop a gas bearing MOI instrument suitable for operation with helium or air as the bearing gas, and to anticipate any other problems associated with the use of helium as the gas bearing medium.

For each test object, MOI was measured in air at atmospheric pressure. Barometric pressure was recorded. Pressure was then reduced, and measurements made at 15, 20, 25, and 28 inches Hg vacuum. The test chamber was then backfilled with helium to atmospheric pressure and MOI was measured. The data was plotted and extrapolated linearly to perfect vacuum conditions.

The change in MOI from the vacuum value for each of the vacuum conditions and helium was then plotted as % MOI error due to entrained and entrapped atmosphere vs absolute atmospheric pressure. The magnitude of the error due to air varied from nearly 19 percent of vacuum MOI for a very thin walled cylinder rotated about its transverse axis to near zero for a solid steel sphere. Most test items were made of 0.007 inch thick mylar, so that the effect of air would be more dramatic.

The helium atmosphere value of MOI was then plotted as a straight horizontal line. The intersection with the MOI vs air pressure line consistently fell at an air atmospheric equivalent pressure of 4 to 5 inches Hg absolute pressure. This agrees with the prediction of 4.25 inches based on the relative densities of helium and air.

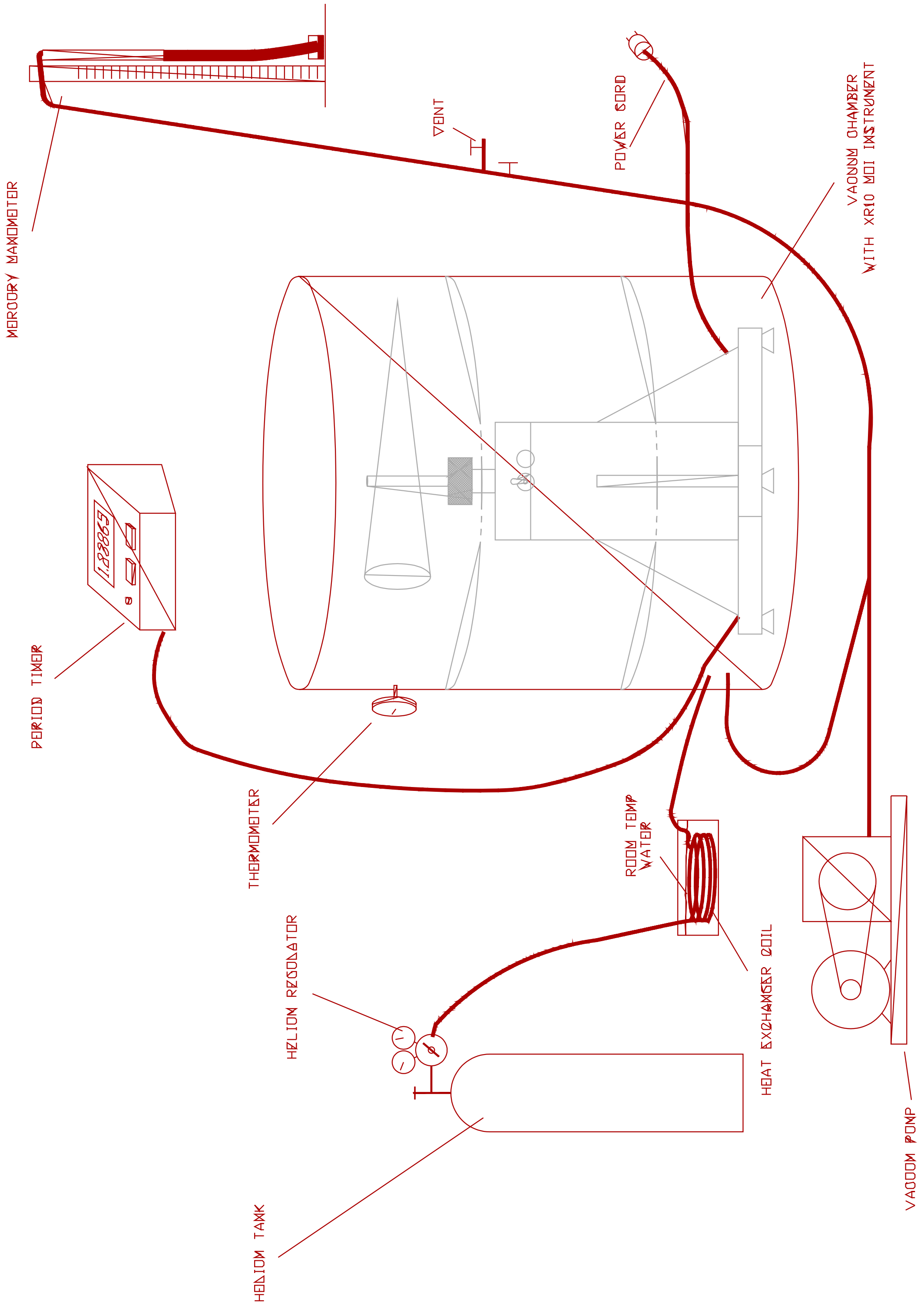

Figure 2 - Helium/Vacuum Test Setup

Test Results

Open Cones-- Thin walled cones are common shapes for certain types of space vehicles. Two cones were tested. One cone was 4.675 inch diameter by 16 inches long. The other cone was 5.75 inch diameter by 13.75 inches long. Both were open on one end and had a wall thickness of 0.007 inch. They were oriented to measure MOI about an axis parallel to the base at about 1/3 the height. This was nominally through the CG. Both cones exhibited slightly less than 10% error in air (this number could have been decreased by making the cone material thicker). For the shorter cone, the value of MOI in a vacuum was 0.61504 lb-in^2. If we calculate the MOI in a vacuum using the MOI in air and the MOI in helium, then this calculated value is within 0.12% of the true value in vacuum. For the longer cone, the value of MOI in a vacuum was 0.72390 lb-in^2. If we calculate the MOI in a vacuum using the MOI in air and the MOI in helium, then this calculated value is within 0.08% of the true value in vacuum. As described previously, the measured values in helium indicated a density slightly higher than would be predicted from the theoretical density of helium. We believe this is because the helium is probably mixed with a small amount of air, increasing its density. The helium data should fall on the curve at a pressure of 4.14 inches of mercury. Instead, the longer cone was at 4.77 inches and the shorter cone was at 4.73 inches. This small difference was not enough to cause a significant error in the predicted value of MOI.

Flat Plate-- The flat plate was a .120 inch thick lucite 5½ by 16 inches. MOI was measured about the short axis. The flat plate was selected as a test part because it had no entrapped air. Note that the relationship between the MOI measured in helium and that at an atmospheric pressure of 4.14 inches of mercury is the same as other shapes, indicating that the same formula can be used for any shape object (i.e. the same relationship exists for both entrained and entrapped air). The value of MOI in a vacuum was 9.71176 lb-in^2. If we calculate the MOI in a vacuum using the MOI in air and the MOI in helium, then this calculated value is within 0.05% of the true value in vacuum.

Open Cylinders-- These test parts were thin-walled plastic tubes open at both ends. One had a 5.25 inch diameter and 14 inch height; the other had a 4.25 inch diameter and 17 inch height. Because of their shape, they had greater entrained and entrapped air than the cones (which were of the same thickness mylar). Therefore, the effect of air was greater (19% vs 10% for the cones). Even with this large error in air, we were still able to predict the MOI in a vacuum with high accuracy. For the shorter cylinder, the value of MOI in a vacuum was 1.68265 lb-in^2. If we calculate the MOI in a vacuum using the MOI in air and the MOI in helium, then this calculated value is within 0.14% of the true value in vacuum. For the longer cylinder, the value of MOI in a vacuum was 2.12335 lb-in^2. If we calculate the MOI in a vacuum using the MOI in air and the MOI in helium, then this calculated value is within 0.22% of the true value in vacuum.

Solid Sphere-- The precision-lapped stainless steel sphere had a diameter of 4.0078 inches and was round within 5 microinches. As would be expected, the effect of air was negligible (less than 0.01%). This data was not plotted.

Conclusions We have developed a new method of testing which simulates the vacuum of outer space without requiring a large expensive vacuum chamber. This method involves first measuring the object in air, then measuring it again in a helium environment, and extrapolating the values to yield the mass properties in a true vacuum. Experimental data on a number of shapes indicates that this method works very well. Space Electronics has developed instruments which use helium to lubricate the gas bearing in the instrument, so they are compatible with this method. This discovery should make it possible to measure very large objects (such as assemblies used in a space station) without requiring a vacuum chamber.

Figure 3 - MOI vs. Chamber Pressure - Open Cylinders about Cross Axis

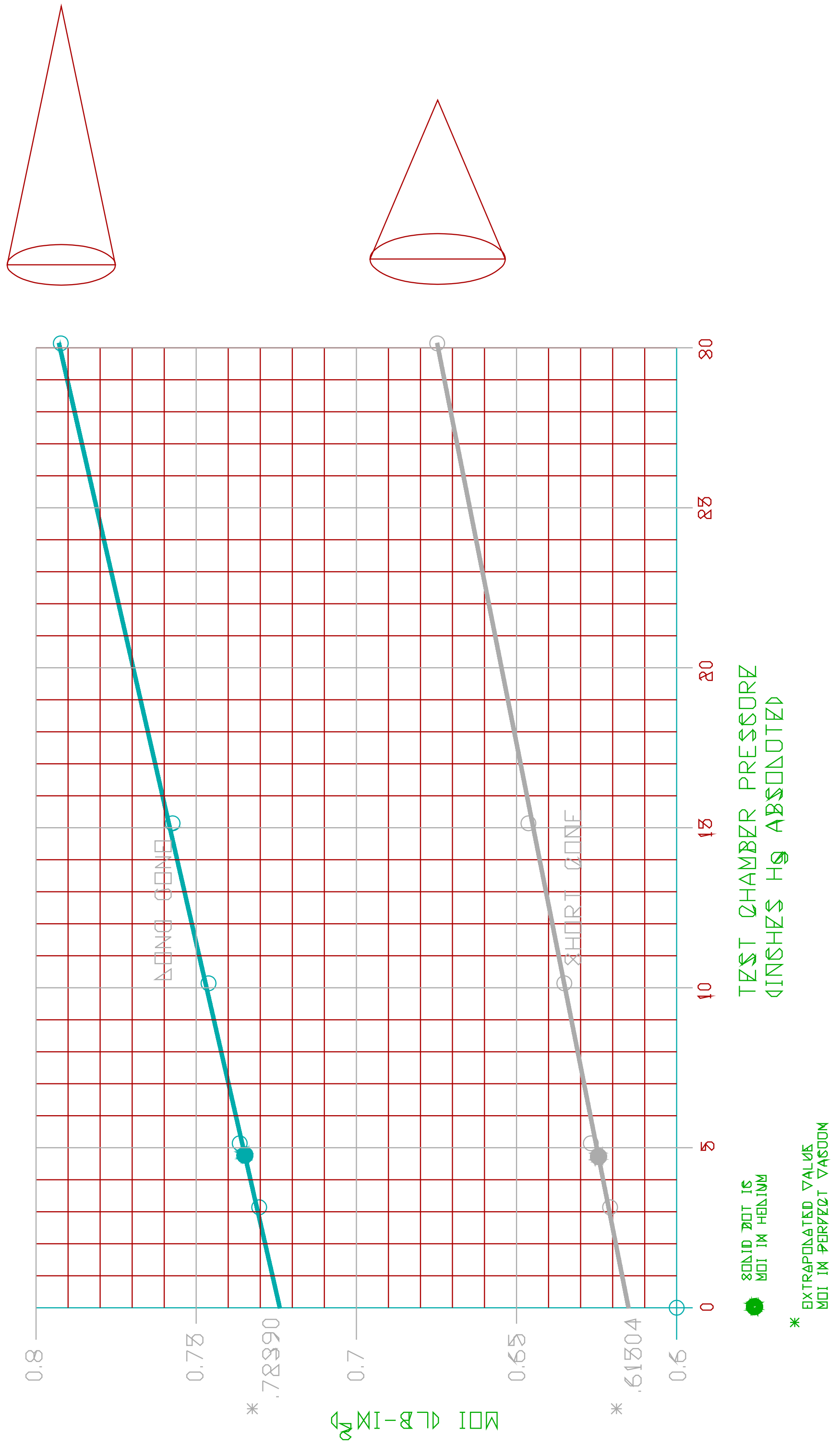

Figure 4 - MOI vs. Chamber Pressure - Open Cones about Cross Axis

Figure 5 - MOI vs Chamber Pressure - Thin Rectangular Plate

Test Data

Short Cylinder

Vac	Abs. Pressure	MOI	Calculated **	Deviation
0	30.14	1.92892		
15	15.14	1.81009		
20	10.14	1.77191		
25	5.14	1.72454		
28.5	1.64	1.68811		
30.14	0	1.68265 *	1.68033	-.14%
HE	30.14	1.72176		

Long Cylinder

Vac	Abs. Pressure	MOI	Calculated **	Deviation
0	30.14	2.51772		
15	15.14	2.33161		
20	10.14	2.25853		
25	5.14	2.18978		
28	2.14	2.14811		
30.14	0	2.12335 *	2.11864	-.22%
HE	30.14	2.18515		

* Extrapolated Data Point

** Calculated from Air and HE data at Atm. Pressure

Short Cone

Vac	Abs. Pressure	MOI	Calculated **	Deviation
0	30.14	.674765		
15	15.14	.646299		
20	10.14	.635092		
25	5.14	.626813		
27	3.14	.620793		
30.14	0	.615040 *	.614329	-.12%
HE	30.14	.624402		

Long Cone

Vac	Abs. Pressure	MOI	Calculated **	Deviation
0	30.14	.792282		
15	15.14	.757376		
20	10.14	.746159		
25	5.14	.736432		
27	3.14	.730344		
30.14	0	.723900 *	.723320	-.08%
HE	30.14	.734811		

* Extrapolated Data Point
** Calculated from Air and HE data at Atm. Pressure

Flat Plate

Vac	Abs. Pressure	MOI	Calculated **	Deviation
0	29.56	9.97983		
7	22.56	9.91993		
10	19.56	9.89673		
15	14.56	9.84724		
20	9.56	9.80396		
25	4.56	9.75381		
27.25	2.31	9.73270		
29.56	0	9.71176 *	9.70694	-.05%
HE	29.56	9.75242		

* Extrapolated Data Point

** Calculated from Air and HE data at Atm. Pressure