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Laboratory Memorandum LM-2004-21

Buoyancy Engine Construction and Design for an Underwater Glider

B. Skillings

August 2004

Canada

DOCUMENTATION PAGE

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SUMMARY

This report details the construction of a buoyancy engine. (See Janes, Nick. Design of a Buoyancy Engine for an Underwater Glider VM1 L121 LM-2004-13 for a previous study.) There is an introduction to the significance of a buoyancy engine to underwater glider technology as well as a description of some existing gliders. The following section describes the design challenge: to build a vertically translating programmable buoyancy engine capable of diving to maximum depth of 20 m. After identifying drawbacks of the original design, design changes were made and construction was undertaken. There was a setback in the choice of an ABS pipe as a structural member; however, a solution was identified and built. Conclusions and future work end this memorandum, identifying lessons learned and a path for further development.

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BUOYANCY ENGINE CONSTRUCTION AND DESIGN FOR AN UNDERWATER GLIDER

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LIST OF ABBREVIATIONS AND SYMBOLS

AUV.......................................Autonomous Underwater Vehicle
ABS.......................................acrylonitrile butadiene styrene
FIM ....full indicator movement
NRC-IOT ....National Research Council Institute for Ocean Technology
PVC.......................................polyvinyl chloride

1.0 INTRODUCTION

Underwater gliders are a relatively new development in Autonomous Underwater Vehicle (AUV) design. Henry Stommel and Doug Webb are credited with envisioning the underwater glider concept. Stommel imagined a world ocean observing network based on “a fleet of small neutrally-buoyant floats called Slocums” that “migrate vertically through the ocean by changing ballast, and they can be steered horizontally by gliding on wings at about a 35 degrees angle… During brief moments at the surface, they transmit their accumulated data and receive instructions *. . .* Their speed is generally about 0.5 knot.” (Rudnick 2004, 48) The significance of this inspiration to oceanographers is clear when the frequently exorbitant cost of ship time for small research budgets are compared to cost of available gliders. Although the initial cost is upwards of $75,000, these lightweight, reusable AUVs can be launched from a small boat with no special equipment for weeks at a time.

One of the first companies to pursue Stommel’s vision was the Webb Research Corporation in East Falmouth, Massachusetts. They currently have one commercially available glider on the market today, the Slocom Electric and one under development, the Slocum Thermal. As the informing names indicate, alkaline batteries power the Electric glider and a thermal energy harvesting engine powers the Thermal. The major advantage of the Thermal glider is the massive gain in range and duration due to the harnessing of environmental energy. Compared to the information in Table 1-1, the Electric glider has a range of 30 days over 1500 km and a maximum depth of 200 m.

Figure 1-1: Slocom Thermal Glider
http://www.webbresearch.com

Table 1-1: Slocom Thermal Specifications

• **Weight:**	60 Kg	• **Endurance:**	5 years
• **Hull Diameter:**	21.3 cm	• **Range:**	40000 km
• **Vehicle Length:**	1.5 meters	• **Navigation:**	GPS, dead reckoning, altimeter
• **Depth Range:**	4 - 2000 meters	• **Sensor Package:**	Conductivity, Temperature, Depth
• **Speed, projected:**	0.4 m/sec horizontal	• **Communications:**	RF modem, Iridium satellite, ARGOS

Another underwater glider, Seaglider, has been developed at the University of Washington (Seattle) by the Applied Physics Laboratory and the School of Oceanography. A unique feature is an isopycnal hull- the glider volume compresses at a rate to match the small changes in seawater density as it dives.

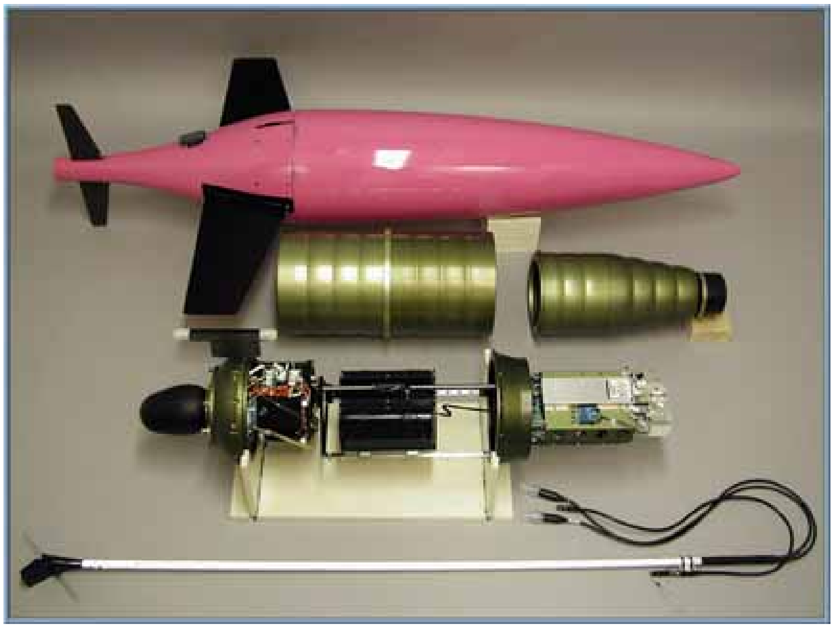

Figure 1-2: Seaglider: visible components include the antenna at the bottom of the image as well as the pressure vessels
http://www.apl.washington.edu/projects/seaglider/summary.html

Table 1-2: Seaglider Specifications

• **Weight:**	52 Kg	• **Endurance:**	1-6 months
• **Hull Diameter:**	30 cm	• **Range:**	6000 km
• **Vehicle Length:**	1.8 meters	• **Navigation:**	GPS, dead reckoning, magnetic
• **Depth Range:**	1000 meters	• **Sensor Package:**	Conductivity, Temperature, Depth
• **Speed, projected:**	0.25 m/sec horizontal	• **Communications:**	Iridium satellite, AMPS cellular

At the heart of any glider today is the ballast device – the buoyancy engine. By either changing the mass or volume of the submersed vehicle it changes the direction of the net buoyant force. If the vehicle is negatively buoyant, the glider sinks and is horizontally directed by the wings as water flows over them. Pitch is usually controlled by a sliding mass to adjust the centre of gravity and thereby creating a pitching moment. A rolling moment is generated by a rolling mass and with the wing lift and drag it turns like it possessed a conventional rudder. On these saw-tooth dives, information such as temperature, salinity and microscopic plant count can be gathered.

2.0 DESIGN CHALLENGE

The National Research Council's Institute for Ocean Technology (NRC-IOT)[1] is developing an underwater glider for research in dynamics and control. As part of the development process, the first objective is to build a vertically translating programmable buoyancy engine capable of diving to maximum depth of 20 m. In a previous study (Janes 2004), the best design out of five candidates was determined. In this chapter we present a brief overview of the previous work as well as additions for this report.

2.1 Design Constraints

1) **Size**
    - Design will fit in a standard 1 m long, 10 cm pipe.
        - Selected as a down scaled version of the Slocum Glider, as it also has a 10:1 length to diameter ratio.
2) **Depth**
    - Buoyancy engine module should be designed to operate to a depth of 20 m
        - Selected because the depth of the testing facility, the Towing Tank[2], is 7 m. This gives a comfortable 2.9 factor of safety.
3) **Centre of Gravity and Centre of Buoyancy Position**
    - For a vertically translating variable buoyancy vehicle, it is clear that the centre of buoyancy must be above the centre of gravity for a stable dive path.
4) **Mass of vehicle must be the same as the volume of water it displaces.**
    - Necessary condition for a neutrally buoyant body. This allows for a modification in volume that enables a change in the direction of the net buoyant force.

2.2 Design Fundamentals

Disregarding the dynamic effects of drag or the added mass due to the blunt cylinder accelerating in water (for more information on the analytical dynamic information, see Janes), there are only two basic methods of changing the net force acting on the vehicle:

1) Change the volume while maintaining constant mass.
2) Change the mass while maintaining constant volume.

---

[1] NRC-IOT was previously known as the Institute for Marine Dynamics (NRC-IMD).
[2] The Towing Tank is a rectangular tank 200m (656 ft) in length, 12m (39 ft) in width and 7m (23 ft) in depth capable of wave and wind generation. Models are towed through still water or waves by a carriage spanning the width of the tank. Model rigging is facilitated by two trim docks and a moveable overhead crane (4000 kg).

There are several methods used to accomplish this direction change in the net force. The second method has no variations, as it can only be accomplished by dropping weight. Clearly this is not an option for a long range, lightweight vehicle capable of hundreds of dives over its mission. This method, however, is used by most submersibles to recover the vehicles in an emergency situation.

The first method has many variations. It can be a pump to move oil from an internal to external bladder; it could be a release of air into a bladder by means of a chemical reaction or by a release of compressed air; or it could be an actuator driven piston to move a diaphragm. Of the five design concepts considered in a previous study (Janes

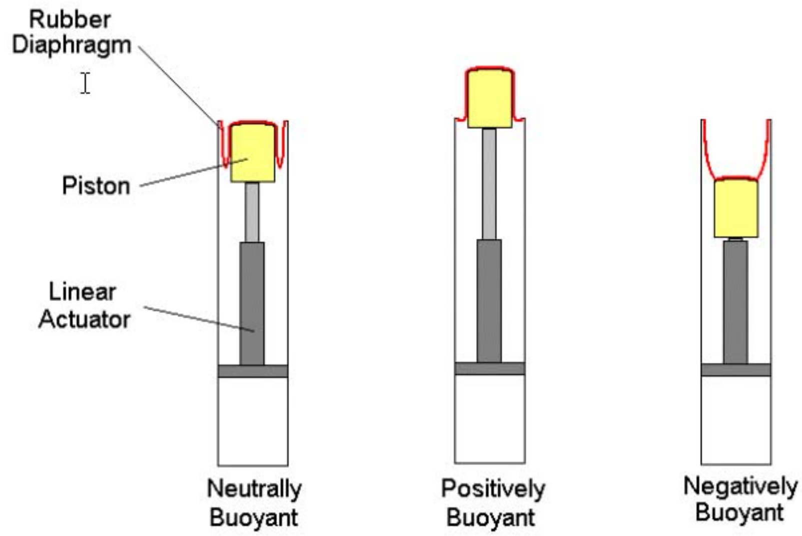

Figure 2-1: Nick Janes' winning design concept:

linear actuator and rolling diaphragm.

2004), an electromechanically driven actuator pushing a rolling diaphragm was selected as the best candidate. It was selected because of the quick response time, projected medium cost of the vehicle and considered the easiest to manufacture.

2.3 Previous Design

The previous design had a 1 m long 10 cm diameter PVC pipe encasing all of the major components. The linear actuator is an eight inch stroke UltraMotion® Digit with a NEMA 23 stepper motor and an Applied Motion 3540M controller. The rolling diaphragm is a 80 mm long, 95 mm diameter Dia-Com Type D-300-300. Inside the pipe was a 70% partial vacuum to keep the diaphragm attached to the piston without the use of adhesives. The other components (diaphragm fastener, diaphragm mount, piston,

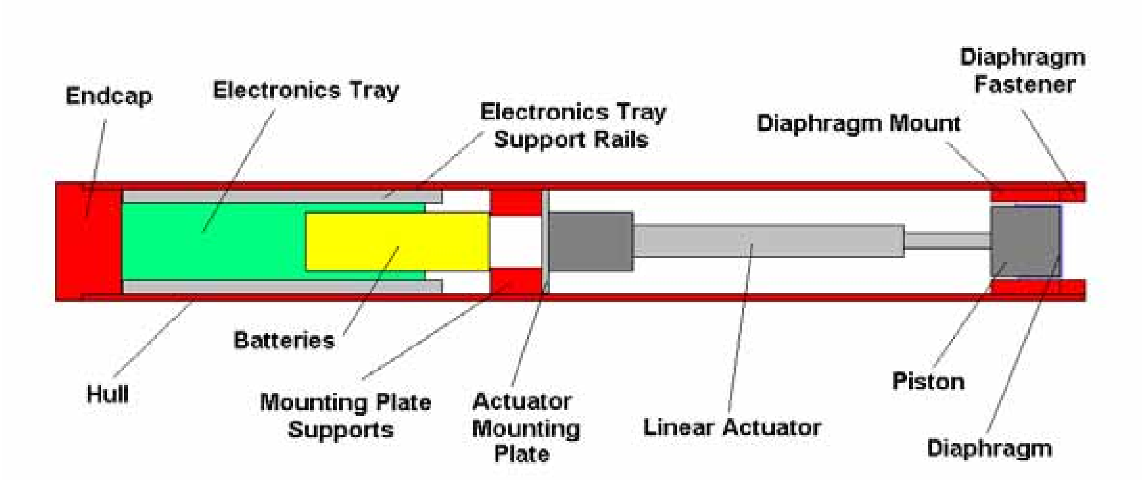

Figure 2-2: Nick Janes' design of a buoyancy engine.

actuator mounting plate, mounting plate supports, electronics tray and end cap) were to all be custom made in-house. For construction, the end cap, rolling diaphragm mount and the linear actuator mount were all to be bonded to the interior of the pipe by means of PVC glue.

With respect to this design, there were two serious drawbacks:

1) **It required assembly with PVC glue**
   - PVC glue sets in approximately five minutes. This does not leave enough time to accurately position parts deeper within the pipe.
2) **The design was not modular**
   - Due to the permanently bonded construction of the assembly, it was not possible to access all components after assembling the system. (i.e. rewiring of the actuator)

These two issues needed to be addressed in a design modification. In addition, more detailed drawings were required to begin construction.

3.0 DESIGN MODIFICATIONS AND CONSTRUCTION

To deal with both of these design issues, two changes were made. First, a mid-body section was inserted into a newly split section of pipe to address issue two, and second, strap clamps were to run axially along the hull to pull the unit together to address issue one. Although the strap clamps are not visible in Figure 3-1, all of the main components are visible. (See Figure 3-6 on p. 9 for strap clamps and Appendix D for drawings.) All of the components (linear actuator, rolling diaphragm, ect.) that were considered for the

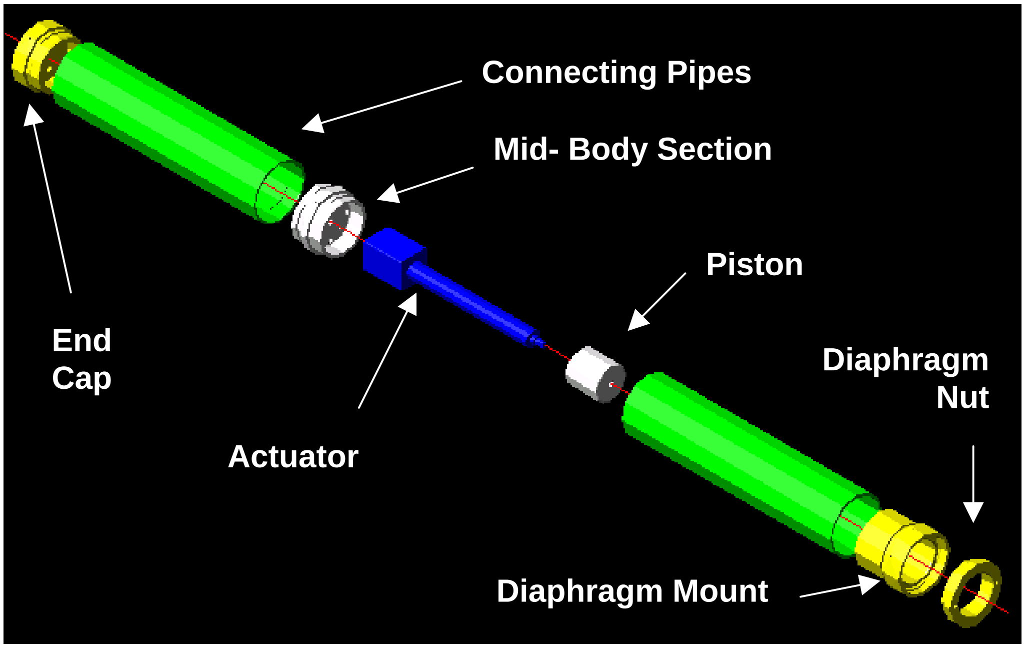

Figure 3-1: Original design modification.

previous design were used in the design modification. In addition, the basic cylindrical form was kept the same. All of the purchase orders are in Appendix B.

Further to these changes, there were design modifications of the diaphragm nut and mount to ensure proper threading detail and proper specifications for the end cap fitting locations. Keeping the mass of each component as small as possible was a guiding design principle in order to leave extra room for further development such as the mass of a computer, batteries and sensors for the final vertically translating vehicle. See Appendix A for the mass of each component and the available "ballast tolerance." Note that the manufacturing tolerances were taken into account - regardless of each feature size when assembled the ballast requirement for neutral buoyancy will fall within these extremes.

3.1 Construction Overview

From the required drawings, a materials list was produced. All of the parts were machined in the machine shop at IOT. There were, however, some manufacturing challenges. Specifically, the required tolerances of the radial face groove on the diaphragm mount needed a special lathe bit ground; see Figure 3-3. Figures 3-2 to 3-6 are a selection of construction photographs.

Figure 3-2: PVC Parting on the lathe – notice the PVC streamer coming off the tool.

Figure 3-3: The nearly complete diaphragm mount – specially ground lathe bit is being used to produce radius.

Figure 3-4: Drilling the piston lightening holes – center-drilling operation.

Figure 3-5: Trimming to length, facing and boring of the connecting pipes.

Figure 3-6: Strap clamps – modified hose clamps. Two lengths are used for the diaphragm and electric end pipes.

Unfortunately, the connecting pipe machining became problematic. ABS pipe was used instead of PVC because of availability. Upon receipt of this material, it was clear that the pipe was significantly bowed and elliptical. In addition, there was not a lathe available with a five inch through bore (the hole through the lathe spindle) making it necessary to mount the pipes to right-angle plates on a milling machine, align the average center of the pipes and size the bore with a micro boring head; see Figure 3-5. It was during this operation that it became suspect that ABS pipe had the desired mechanical properties. After the initial assembly of all the parts, it was evident that there was a significant flaw in the choice of materials– one that should have been obvious in the previous design. In order for the unit to operate properly, it is required that the diaphragm mount be parallel and concentric with the axis of the actuating cylinder within 0.025 inch. During the course of the pipe investigation, it was found that the pipe was on average 1/16 of an inch per foot bowed; had a minor inside diameter of 3.963 in and a major inside diameter of 4.020 in; and the FIM (full indicator movement) when measuring of the pipe between size averaged plugs was between 0.030 in and 0.040 in. (Size averaging means taking the average of the inside elliptical diameter, turned a plug with that average diameter and pressing it in.) Compounding the pipe bow problem was the manufacturing operation. Due to the bow, the ends of the pipe could not be machined parallel. Adding to the alignment problem was the strap clamp arrangement. It was possible to pull the pipe away from a position by tightening or loosening the clamps. (See Figure 3-7)

3.2 Connecting Pipe Solution Development

After several attempts at finding a solution, it was determined that ABS is too weak a material to be held for a machining operation without a significant change in dimension – it is, after all, intended for a sewer pipe. Therefore, a machinist has to contend with a material that will flex significantly for work piece holding. As a result, even though the pipe may be machined round and to the correct dimensions, it will inevitably flex and return to its elliptical shape.

Figure 3-7: Concentricity and parallelism Issue – the maximum gap is about 0.180 in compared to 0.042 in at the minimum.

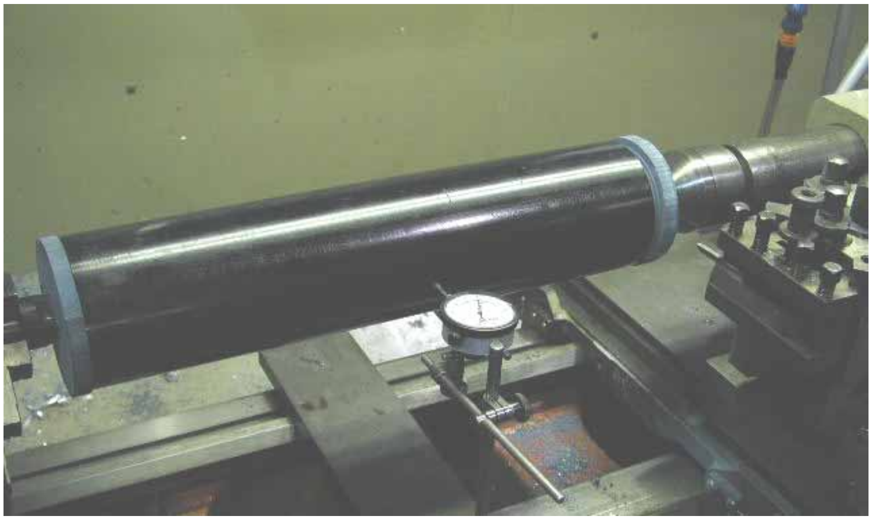

Figure 3-8: Pipe geometric inspection – measuring FIM.

It was finally concluded that a new approach would be needed. Using the actuator tube as a datum, a new alignment piece was designed and machined. As can be seen in the figure below, the alignment piece uses a hose clamp collet to compress and hold the diaphragm

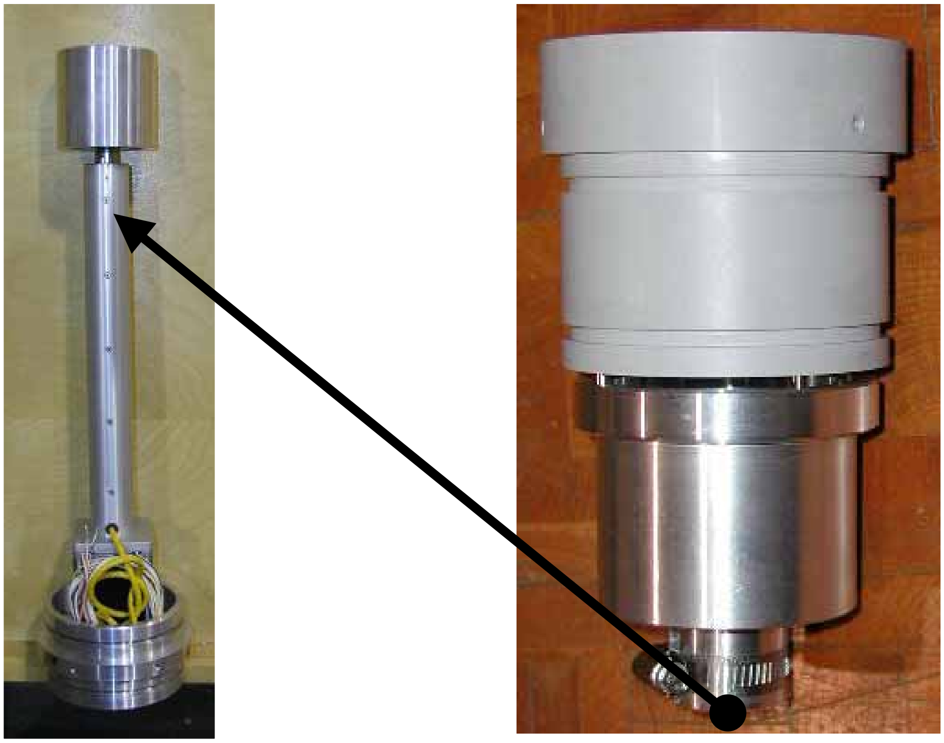

Figure 3-9: Illustration of the diaphragm alignment piece.

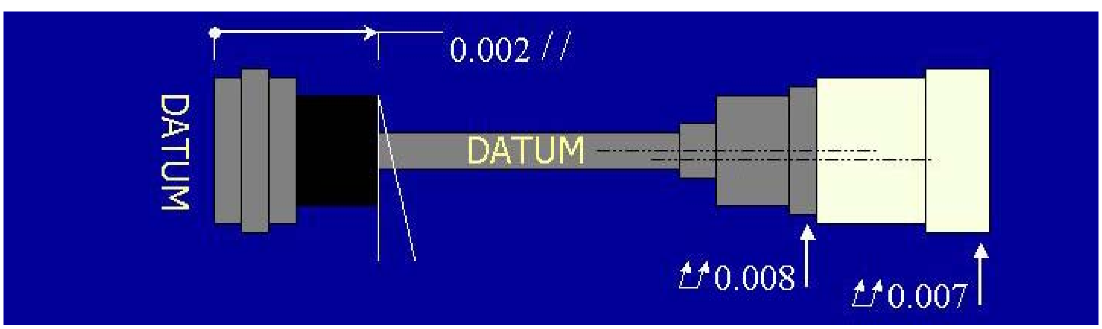

Figure 3-10: Parallelism and FIM readings of the forward assembly.

mount concentrically to the actuator tube.   From the surface table inspection measurements taken as illustrated in Figure 3-10 and 3-11, the form tolerance errors are now solved - the Diaphragm Mount is within 0.007 inches FIM. By assembling the buoyancy engine such that the gap between the diaphragm mount outside diameter and the mid-body section is slightly longer than the pipe (0.010 to 0.025 in), the diaphragm mount is now concentric.

Figure 3-11: Surface table inspection.

Although the alignment accuracy has significantly improved with the measures taken, the axial alignment of the piston due to the actuator manufacturer's ambiguous tolerance still needs to be addressed. Although the diaphragm mount is now sufficiently collinear to run true to the inside bore of the diaphragm mount, the piston rides at an angle relative to the axis of the actuator tube. However, the error is not sufficiently egregious to warrant an immediate fix.

4.0   FINAL DESIGN

The final design drawings are in Appendix D. Due to lack of available time, the Alignment Piece and Actuator Hold-Downs are only provided as sketches. Although these are not proper drawings, they do convey the geometric information.[3] The final design weighs 6.84 kg within a 1 m long, 10 cm diameter cylinder. To meet the condition that the centre of gravity is below the centre of buoyancy position at all actuator positions, a MATLab program was used (Appendix C). Missing from this code are the effects of the Alignment Piece, as the centre of gravity of this piece was not put into the code. (The code was written before the original design.) However, this was not added because the initial plot of the centre of gravity for all actuator positions was always below the centre of gravity. Given that the Alignment Piece position would only make the centre of gravity even farther below the centre of buoyancy, this work was not done.

As the displaced mass of water is approximately 9.72 kg compared to the mass of 6.84 kg, this 2.88 kg difference can be filled with 20 D cell batteries to give about 100 Wh. Although these batteries are not able to fit around the actuator tube because of lack of space (this would be ideal as it would shift the centre of gravity even further to the bottom end) they are able to fit in an array of 4 in a cross pattern, five deep along the axis of the electronics end pipe.

Figure 4-1: All of the major components disassembled.

[3] The Diaphragm mount, drawing 891_10BS01 has to be altered to accept the ¼ dowels at the base.

5.0 CONCLUSIONS AND FUTURE WORK

The mechanical aspects of the buoyancy engine are almost complete. Although full mechanical drawings are not finished for the Alignment Piece and the Actuator Hold-Downs, the geometric information is supplied. The following is a list of future work that needs to be done to fully develop the vehicle:

1) **Pressure Testing of the Hull**
   - Before any electronic components are put in the water, the vessel should be pressure tested to 270 Kpa. (Gauge pressure at 20 m depth plus the 70% internal vacuum)

2) **Assemble and Program Electronic Components to Get the Unit Diving**

3) **Produce Position, Velocity and Acceleration Plots**
   - Producing position, velocity and acceleration information for the vessel will be a first step in an optimization process.

4) **Develop Control Interface and Control Algorithm to Optimize Convergence Time to the desired Depth**
   - Set up a computer terminal such that the vehicle performance was outputted in real time performance plots to ensure that the vehicle performs to expectations.

Further to these development goals, there are some specific recommendations for a future version of a buoyancy engine. Clearly, ABS pipe should not be used as a structural member. Instead, use the average of the major and minor diameter of the elliptical pipe and size the corresponding fittings to that diameter. The pipe would have to be pressed onto the matching bore, but this would significantly reduce the problems encountered in this design. In addition, the machined components could be reduced in mass, as the aluminum pieces are not fully engineered but designed from experience. There could also be a thermister installed in the electronics end to monitor the interior of the vehicle temperature to ensure that there are not over heating issues.

Perhaps the most important design change would be to use the actuator tube as the central datum and construction platform. Just as the Diaphragm Mount was cantered with a new Alignment Piece, the Mid-Body section could be attached in a similar manner. This gives the advantage of some axial movement in the sections to compensate for any fine changes in the centre of buoyancy due to manufacturing.

For future work beyond the goals of this design challenge, it would be desirable to have a unit that is more powerful than simply a buoyancy engine. It would be possible to add a pitch and roll control assembly around the actuator tube. A conceptual design is shown in Figure 5-1. As the final version of this buoyancy engine (and perhaps it will be a combination with a pitch and roll control system) will be installed in the IOT development glider, this unit may be the heart of this conceptual machine.

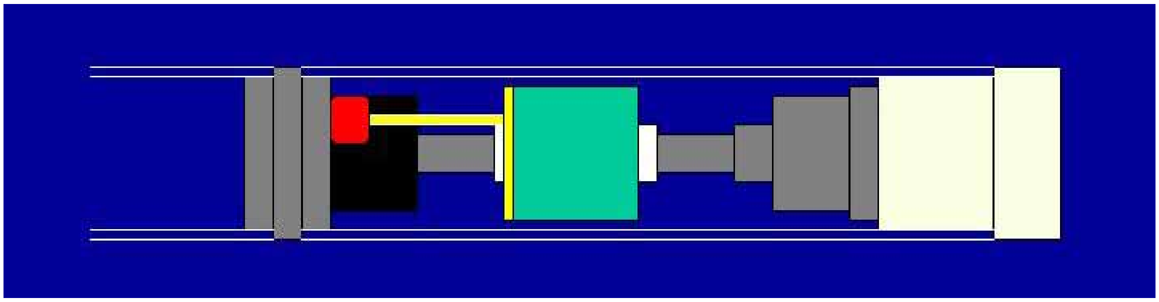

Figure 5-1: Simple concept of the pitch and roll assembly. Green square is a sliding and rotating mass on a plain bearing driven be a linear and rotary actuators (yellow).

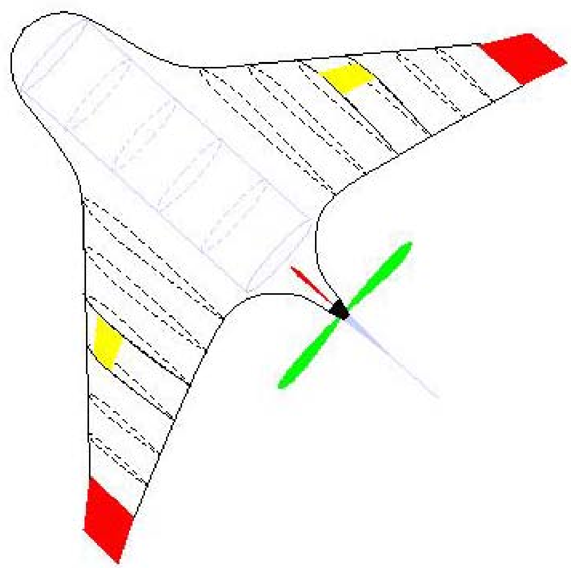

Figure 5-2: Conceptual design for the IOT development glider. The cylinder in the middle of the hull represents the buoyancy, pitch and roll module. It may by a hybrid vehicle, as indicated by the green propeller.

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APL University of Washington, Manufacturers of Seaglider: www.apl.washington.edu/projects/seaglider/summary.html

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Appendix A

Buoyancy Engine Budget

$US Conversion: 1.34 $CDN
Note: All units in inches

Components

Components		Quantity	Unit Cost	Total Cost
Digit Linear Actuator		1	1259.60	1,259.60
Applied Motion Stepper Controller		1	348.40	348.40
Dia-Com Diaphragms		10	15.41	154.10
Dia-Com Setup Charge		1	703.50	703.50
Absolute Pressure Sensor		1	477.04	477.04
Absolute Pressure Transducer		1	155.44	155.44
Nickel Plated Cord Grip		5	6.70	33.50
Stainless Steel Button Head #10-24 x1/4		1	8.99	8.99
O-Ring Buna N 240		1	15.87	15.87
Quick Disconnect Socket		5	11.32	56.62
Quick Disconnect Plug		5	10.89	54.47
	Components Total:			$3,267.52

Materials List

Stainless St. 304	ROUND BAR: 1/2 DIA x 15 1/2	1	-	21.00
Al 6061-T6	ROUND BAR: 3 DIA x 3 1/2	1	-	10.00
	ROUND BAR: 4 1/2 DIA x 2 5/8	1	-	40.00
PVC	PIPE: 4 1/2 OD, 4 ID x 38	1	-	15.00
	ROUND BAR: 4 1/2 DIA x 7 1/8	1	-	55.00
ABS	PIPE: 4 DIA SCH 40	1	-	15.00
Nylon	WASHER: 3 7/8 OD, 3 ID x 1/16	1	-	n/c
	Materials Total:			$156.00

Special Tools

Radial Face Grooving Turning Tool		1	250.00	250.00
	Special Tool Total:			$250.00

Sub-Total:	$3,673.52
Tax Rate:	15.00%
Total:	$4,224.55

Buoyancy Engine Part Masses

See Appendix Cover For Note

8/20/2004

Notes: Unless otherwise:
1) All masses in g
2) All volumes in cm^3

Material Densities

Aluminum 6061-T6	2.7	g/cm^3
St. Steel 304/303	8.0	g/cm^3
PVC	1.4	g/cm^3
ABS	1.04	g/cm^3
Nylon	1.1	g/cm^3

Engine Volume:	**MMC:**	**9.76E-03**	**m^3**
	LMC:	**9.71E-03**	**m^3**
Displaced Mass:	**MMC:**	**9.74**	**kg**
	LMC:	**9.69**	**kg**
Additional Ballast:	**MMC:**	**2.90**	**kg**
	LMC:	**2.85**	**kg**

Component Mass	Quantity	Volume Max	Volume Min	Calculated Mass Max	Calculated Mass Min	Measured Mass	Total Mass	Calculated Volume
Digit Linear Actuator	1	-	-	-	-	1593.8	1593.8	-
Applied Motion Stepper Controller	1	-	-	-	-	267.2	267.2	-
Dia-Com Diaphragm	1	-	-	-	-	NOT COMPLETED		-
Absolute Pressure Sensor	1	-	-	-	-	210.3	210.3	-
Absolute Pressure Transducer	1	-	-	-	-	8.1	8.1	-
Nickel Plated Cord Grip	1	-	-	-	-	31.6	31.6	-
Stainless Steel Button Head #10-24 x1/4	12	-	-	-	-	1.3	15.6	-
O-Ring Buna N 240	5	-	-	-	-	3.6	18	-
Quick Disconnect Socket	1	-	-	-	-	5.9	5.9	-
Alignment Piece (clamp included)	1							

Part Mass

Part Mass	Quantity	Volume Max	Volume Min	Calculated Mass Max	Calculated Mass Min	Measured Mass	Total Mass	Calculated Volume
Diaphragm Mount	1	394.7	376.9	552.6	527.7	540.3	540.3	385.9
Diaphragm Nut	1	120.1	110.4	168.1	154.6	157.7	157.7	112.6
Alignment Piece (clamp included)	1	NOT COMPLETED 8/20/2004				307.4	307.4	
Mid-Body Section	1	191.5	163.8	517.1	442.3	468.0	468	173.3
End Cap	1	235.2	220.1	329.3	308.1	317.3	317.3	226.6
Piston	1	183.8	172.0	496.3	464.4	473.4	473.4	175.3
Connecting Pipe - Diaphragm End	1	**Mean:**	1006.0	**Mean:**	1046.2	1056.2	1056.2	1015.6
Connecting Pipe - Electronics End	1	**Mean:**	947.0	**Mean:**	984.9	990.6	990.6	952.5
Washer	1	**Mean:**	5.0	**Mean:**	5.5	5.9	5.9	5.4
Actuator Hold-Down	4	-	-	-	-	29.0	116	-
Stainless Steel Straps Long	3	-	-	-	-	41.9	125.7	-
Stainless Steel Straps Short	3	-	-	-	-	44.2	132.6	-

Total Mass: 6.84 kg

Appendix B

Component Orders

Part Instructions

National Research Council Canada | Conseil national de recherches Canada
Institute for Ocean Technology | Institut des technologies océaniques

To be Assigned by Finance & Supply

Order Number: ____________________

IMPORTANT

This number must appear on invoices, B/L, packing lists, correspondence and outside containers.

IOT Purchase Requisition

Project Code or Name: 891

Start Date (If Services):

Completion or Date Req'd:

Supplier: Dia-Com Corporation

Address: 5 Howe Drive

Amherst, NH 03031

Telephone: 1-800-632-5681 Fax: 1-603-880-7616

Contact: Cathy Sirois

Ship To:

Kerwin Place	Place Kerwin
P.O. Box 12093	C.P. 12093
Postal Station A	Station postale A
St. John's Newfoundland	St-Jean, Terre-Neuve
A1B 3T5	A1B 3T5
Fax:(709) 772-2462	Telecopieur: (709) 772-2462

IMPORTANT

IOT is located on Memorial University's campus on Sandpits Rd. off Arctic Ave (between the Engineering Building and the smoke stack). Deliveries are only accepted at Door Number 3 between 8:30am - 1:00pm and 1:30pm - 4:30pm Monday to Friday.

Ship Via:

Item No.	Description	Unit of Issue	Quantity	Unit Cost	Total Cost
1	D-300-300 (NO REV) Diaphragm DC1115	1	10.00	11.50	115.00
2	Setup Charge for Diaphragm	1	1.00	525.00	525.00

Receiving Inspection Level:	A x	B	C	D	Service	**Sub-Total**	**640.00**
Confirmed Order:	Yes		No			**Freight**	
Taxes Included in Sub-Total:	Yes		No	x	N/A	**Tax Rate**	15.00%
Freight Included in Sub-Total:	Yes		No	x	N/A	**Taxes**	**96.00**
						Total	**736.00**

Special Instructions:

1. If a Level D inspection is identified above, this means that IOT and/or its client will be inspecting the goods at the vendor's site. If appropriate info is not included with this form, please contact the undersigned.
2. When specified, please provide certification, e.g. *Mill Certificate, Calibration Certificate* or *MSDS*.
3. IOT reserves the right to refuse all orders that do not contain packing slips/invoices and/or do not make reference to the Order Number specified above.
4. This document contains the following attachments or references, e.g. drawing numbers.

Notes/Remarks: Prices are in US currency, Materials: EPDM Elastomer and Polyester Fabric, Quoted utilizing an NSF grade, chloramine r
FDA grade ingredient 57 +/- 5 Durometer EPDM reinforced with a polyester fabric.

Requested by: ____________________ Date: ____________________

Approved by: ____________________ Date: ____________________ **B-1**

National Research Council Canada | Conseil national de recherches Canada

Institute for Ocean Technology | Institut des technologies océaniques

To be Assigned by Finance & Supply

Order Number: ____________________

IMPORTANT

This number must appear on invoices, B/L, packing lists, correspondence and outside containers.

IOT Purchase Requisition

Project Code or Name: 891-10

Start Date (If Services):

Completion or Date Req'd:

Supplier: McMaster-Carr Chicago

Address: 600 County Line Rd.
Elmhurst, IL 60126-2081

Telephone: (630) 833-0300   Fax: (630) 834-9427

Contact: www.mcmaster.com

Ship To:

Kerwin Place	Place Kerwin
P.O. Box 12093	C.P. 12093
Postal Station A	Station postale A
St. John's Newfoundland	St-Jean, Terre-Neuve
A1B 3T5	A1B 3T5
Fax:(709) 772-2462	Telecopieur: (709) 772-2462

IMPORTANT

IOT is located on Memorial University's campus on Sandpits Rd. off Arctic Ave (between the Engineering Building and the smoke stack). Deliveries are only accepted at Door Number 3 between 8:30am - 1:00pm and 1:30pm - 4:30pm Monday to Friday.

Ship Via:

Item No.	Description	Unit of Issue	Quantity	Unit Cost	Total Cost
6907K12	**Cord Grip:** Nickel-Plated Brass Trade Size 3/8" NPT	1	5.00	5.00	25.00
92949A238	**Screws:** Stainless S. Button Head #10-24 x1/4"	100	1.00	6.71	6.71
6138K35	**Bearing:** Type 440C R8 Stainless Steel Sealed	1	2.00	18.20	36.40
9452K191	**O-Ring:** Buna N 240	50	1.00	11.84	11.84
51545K23	**Quick Disconnect:** Polypropylene coupling socket	1	5.00	8.45	42.25
51545K79	**Quick Disconnect:** Polypropylene coupling plug	1	5.00	8.13	40.65

Receiving Inspection Level:	A ___	B ___	C ___	D ___ Service ___	**Sub-Total**	**162.85**
Confirmed Order:	Yes ___	No ___			**Freight**	
Taxes Included in Sub-Total:	Yes ___	No ___	N/A ___		**Tax Rate**	15.00%
Freight Included in Sub-Total:	Yes ___	No ___	N/A ___		**Taxes**	**24.43**
					Total	**187.28**

Special Instructions:

1. If a Level D inspection is identified above, this means that IOT and/or its client will be inspecting the goods at the vendor's site. If appropriate info is not included with this form, please contact the undersigned.
2. When specified, please provide certification, e.g. *Mill Certificate, Calibration Certificate* or *MSDS*.
3. IOT reserves the right to refuse all orders that do not contain packing slips/invoices and/or do not make reference to the Order Number specified above.
4. This document contains the following attachments or references, e.g. drawing numbers.

Notes/Remarks: Prices are in US Dollars
Parts for a Laboratory-scale Glider

Requested by: ____________________ Date: ____________

Approved by: ____________________ Date: ____________ **B-2**

National Research Council Canada | Conseil national de recherches Canada
Institute for Ocean Technology | Institut des technologies océaniques

To be Assigned by Finance & Supply
Order Number: ____________
IMPORTANT
This number must appear on invoices, B/L, packing lists, correspondence and outside containers.

IOT Purchase Requisition

Project Code or Name: 891
Start Date (If Services):
Completion or Date Req'd:
Supplier: Omega Canada Inc.
Address: 976 Bergar Street
Laval, Quebec
H7L 5A1
Telephone: 1-514-856-6928 Fax: 1-514-856-6886
Contact: Michael Grace (ext 227)

Ship To:

Kerwin Place	Place Kerwin
P.O. Box 12093	C.P. 12093
Postal Station A	Station postale A
St. John's Newfoundland	St-Jean, Terre-Neuve
A1B 3T5	A1B 3T5
Fax:(709) 772-2462	Telecopieur: (709) 772-2462

IMPORTANT
IOT is located on Memorial University's campus on Sandpits Rd. off Arctic Ave (between the Engineering Building and the smoke stack). Deliveries are only accepted at Door Number 3 between 8:30am - 1:00pm and 1:30pm - 4:30pm Monday to Friday.

Ship Via:

Item No.	Description	Unit of Issue	Quantity	Unit Cost	Total Cost
1	PX303-050A5V Absolute Pressure Sensor	1	1.00	356.00	356.00
2	PX138-015A5V Absolute Pressure Sensor	1	1.00	116.00	116.00

Receiving Inspection Level:	A x	B	C	D	Service		**Sub-Total**	**472.00**
Confirmed Order:	Yes		No				**Freight**	
Taxes Included in Sub-Total:	Yes		No	x	N/A		**Tax Rate**	15.00%
Freight Included in Sub-Total:	Yes		No	x	N/A		**Taxes**	**70.80**
							Total	**542.80**

Special Instructions:

1. If a Level D inspection is identified above, this means that IOT and/or its client will be inspecting the goods at the vendor's site. If appropriate info is not included with this form, please contact the undersigned.
2. When specified, please provide certification, e.g. *Mill Certificate, Calibration Certificate* or *MSDS*.
3. IOT reserves the right to refuse all orders that do not contain packing slips/invoices and/or do not make reference to the Order Number specified above.
4. This document contains the following attachments or references, e.g. drawing numbers.

Notes/Remarks:

Requested by: Date:

Approved by: Date:

B-3

National Research Council Canada | Conseil national de recherches Canada

Institute for Ocean Technology | Institut des technologies océaniques

To be Assigned by Finance & Supply

Order Number: ____________

IMPORTANT

This number must appear on invoices, B/L, packing lists, correspondence and outside containers.

IOT Purchase Requisition

Project Code or Name: 891

Start Date (If Services):

Completion or Date Req'd:

Supplier: Ultra Motion

Address: 225 East Side Avenue
Mattituck, NY 11952

Telephone: 1-631-298-9179 Fax: 1-631-298-6593

Contact: Sean Roger

Ship To:

Kerwin Place
P.O. Box 12093
Postal Station A
St. John's Newfoundland
A1B 3T5
Fax:(709) 772-2462

Place Kerwin
C.P. 12093
Station postale A
St-Jean, Terre-Neuve
A1B 3T5
Telecopieur: (709) 772-2462

IMPORTANT

IOT is located on Memorial University's campus on Sandpits Rd. off Arctic Ave (between the Engineering Building and the smoke stack). Deliveries are only accepted at Door Number 3 between 8:30am - 1:00pm and 1:30pm - 4:30pm Monday to Friday.

Ship Via:

Item No.	Description	Unit of Issue	Quantity	Unit Cost	Total Cost
1	Digit Actuator Model Number D-A.083-HT23-8-P-/4	1	1	940.00	940.00
2	3540M Applied Motion Stepper Controller	1	1	260.00	260.00

Receiving Inspection Level: A x B ___ C ___ D ___ Service ___

Confirmed Order: Yes ___ No ___

Taxes Included in Sub-Total: Yes ___ No x N/A ___

Freight Included in Sub-Total: Yes ___ No x N/A ___

Sub-Total	**1,200.00**
Freight	
Tax Rate	15.00%
Taxes	**180.00**
Total	**1,380.00**

Special Instructions:

1. If a Level D inspection is identified above, this means that IOT and/or its client will be inspecting the goods at the vendor's site. If appropriate info is not included with this form, please contact the undersigned.
2. When specified, please provide certification, e.g. *Mill Certificate, Calibration Certificate* or *MSDS*.
3. IOT reserves the right to refuse all orders that do not contain packing slips/invoices and/or do not make reference to the Order Number specified above.
4. This document contains the following attachments or references, e.g. drawing numbers.

Notes/Remarks: Prices listed are US currency

Requested by: ____________ Date: ____________

Approved by: ____________ Date: ____________

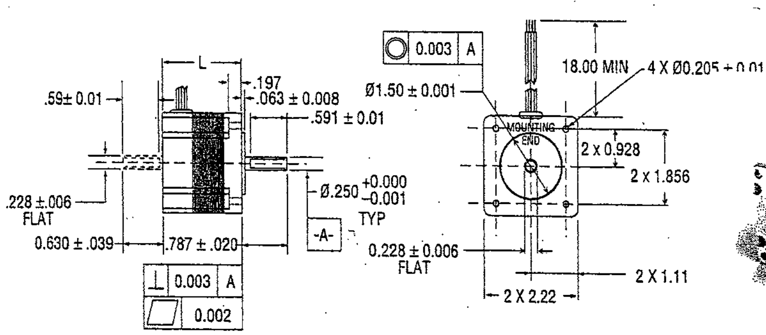
ACTUATOR

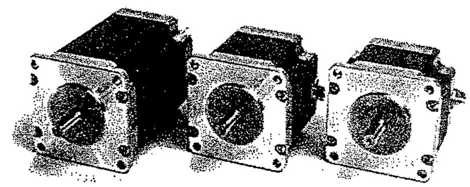
UltraMotion

225 East Side Ave. Mattituck, NY 11952
Phone: 631 298 9179 Fax: 631 298 6593
http://www.ultramotion.com

Hybrid Step Motors

SIZE HT 23





Part #	MOTOR CONNECTION 1 = series 2 = parallel 3 = unipolar	Motor Length (inches)	Minimum Holding Torque (oz-in)	Leads	Step Angle	Volts	Amps	Ohms	mH	Rotor Inertia (oz-in²/G-CM²)	Motor Weight (Lbs.)
HT23-398	1	2.13	177.0	8	1.8	3.3	2.12	1.5	4.8	1.64/300	1.54
	2	↓	177.0	↓	↓	1.6	4.24	0.4	1.2	↓	↓
	3	↓	125.0	↓	↓	2.3	3.00	0.8	1.2	↓	↓
HT23-399	1	2.99	264.0	↓	↓	11.6	0.71	16.4	56.0	2.62/480	2.20
	2	↓	264.0	↓	↓	5.8	1.41	4.1	14.0	↓	↓
	3	↓	187.0	↓	↓	8.2	1.00	8.2	14.0	↓	↓
HT23-400	1	↓	264.0	↓	↓	6.4	1.41	4.5	14.4	↓	↓
	2	↓	264.0	↓	↓	3.2	2.83	1.1	3.6	↓	↓
	3	↓	187.0	↓	↓	4.5	2.00	2.3	3.6	↓	↓
→ HT23-401	1	↓	264.0	↓	↓	4.2	2.12	2.0	6.4	↓	↓
	2	↓	264.0	↓	↓	2.1	4.24	0.5	1.6	↓	↓
	3	↓	187.0	↓	↓	3.0	3.00	1.0	1.6	↓	↓

OTHER LENGTHS AND WINDINGS AVAILABLE UPON REQUEST

- Part numbers listed are for single shaft. To order double shaft add 'D' to the end.
- All HT23 motors are optimized for microstepping.

Step Tables & Wiring Diagrams

UltraMotion

225 East Side Ave. Mattituck, NY 11952
Phone: 631 298 9179 Fax: 631 298 6593
http://www.ultramotion.com

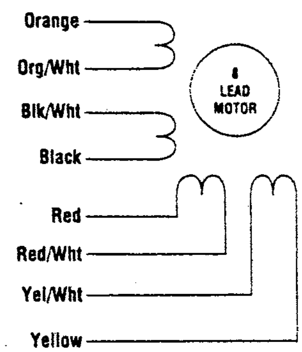
8 Lead Wire Configuration – Unipolar Drive

STEP TABLE

STEP	ORANGE	BLACK	RED	YELLOW
0	ON	OFF	ON	OFF
1	OFF	ON	ON	OFF
2	OFF	ON	OFF	ON
3	ON	OFF	OFF	ON
4	ON	OFF	ON	OFF

CW FACING MOUNTING END

WIRING DIAGRAM



Connect orange/white, black/white, red/white, and yellow/white to plus (+) voltage.
UNIPOLAR DRIVE ONLY!

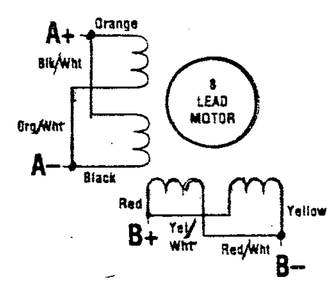
8 Lead Wire Configuration – Bipolar Drive/Parallel Connected

STEP TABLE

STEP	A+	A–	B+	B–
0	+	–	+	–
1	–	+	+	–
2	–	+	–	+
3	+	–	–	+
4	+	–	+	–

CW FACING MOUNTING END

WIRING DIAGRAM



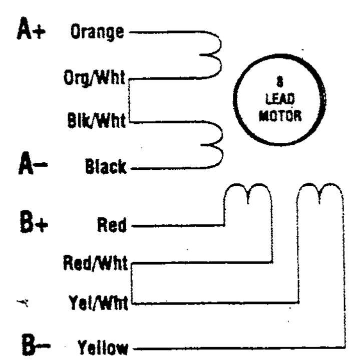
8 Lead Wire Configuration – Bipolar Drive/Series Connected

STEP TABLE

STEP	ORANGE	BLACK	RED	YELLOW
0	+	–	+	–
1	–	+	+	–
2	–	+	–	+
3	+	–	–	+
4	+	–	+	–

CW FACING MOUNTING END

WIRING DIAGRAM



UltraMotion

225 East Side Ave. Mattituck, NY 11952
Phone:631 298 9179 Fax: 631 298 6593 www.ultramotion.com

INSTRUCTIONS AND OPERATING LIMITATIONS

DIGIT SERIES

Reed Switches (optional on unit)

1. Contacts - S.P.S.T. Form A (normally open)
2. Contact Rating - 10 watts max.
3. Switching Voltage - 200 volts max. DC
4. Max. Current - 500 MA (resistive)
5. Initial Contact Resistance - .10 ohms max.
6. Breakdown Voltage - 400 volts min.
7. Actuating Time, Average - 1.0 milliseconds
8. **Reed switches should not be mounted in line with any flat head screws along the actuator barrel.**

Torque, Side Load and Impact Loads

Side loads should not exceed 3 lb. especially in the extended position. **Torque should never be applied directly to the polished stainless steel shaft**. When tightening a nut or fixture to the end plug, 2 wrenches should be used, one on the end plug, the other on the nut or fixture. Units with Nema 23 size motors should not be run at high speed into the end stops.

Stepper Motor Linear Resolution

2400 Full steps per inch (AT 200 FULL STEPS PER REVOLUTION) x2

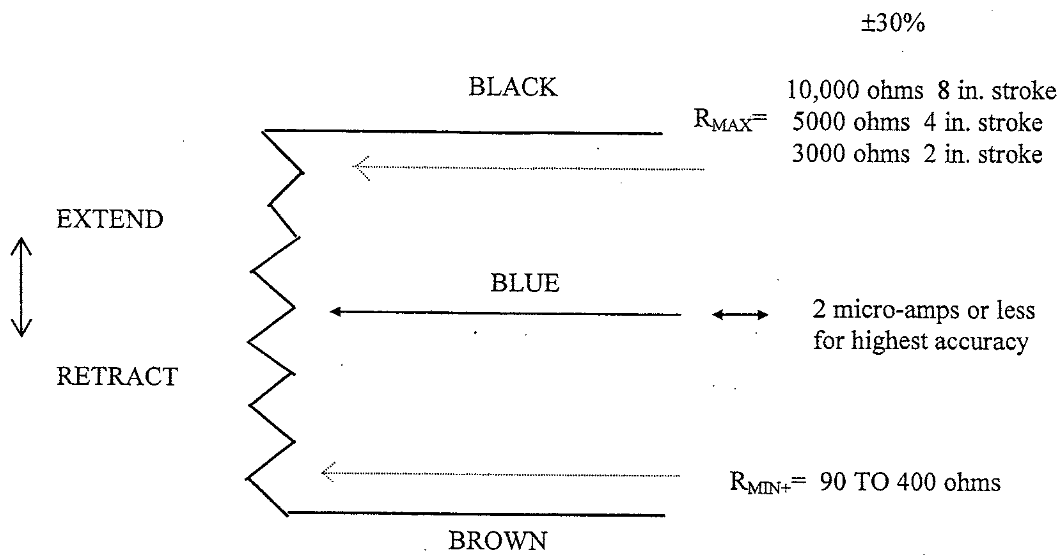
Optical Encoder Linear Resolution

_________Cycles per inch

_________Quad counts per inch

Ultra Motion's products are not intended for applications where a failure could result in a costly, dangerous, or life threatening situation. Ultra Motion will not be held responsible for damages or losses greater than the cost of the Ultra Motion replacement parts.

POTENTIOMETER WIRING



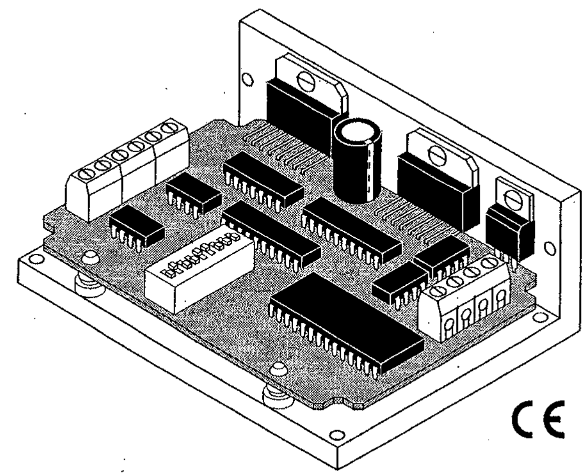
7/14/98

Applied Motion Products, Inc.
404 Westridge Drive • Watsonville, CA 95076
Tel (831) 761-6555   (800) 525-1609   Fax (831) 761-6544

User's Manual

3540 M

Step Motor Driver



CE

Applied Motion Products

motors • drives • controls

Introduction

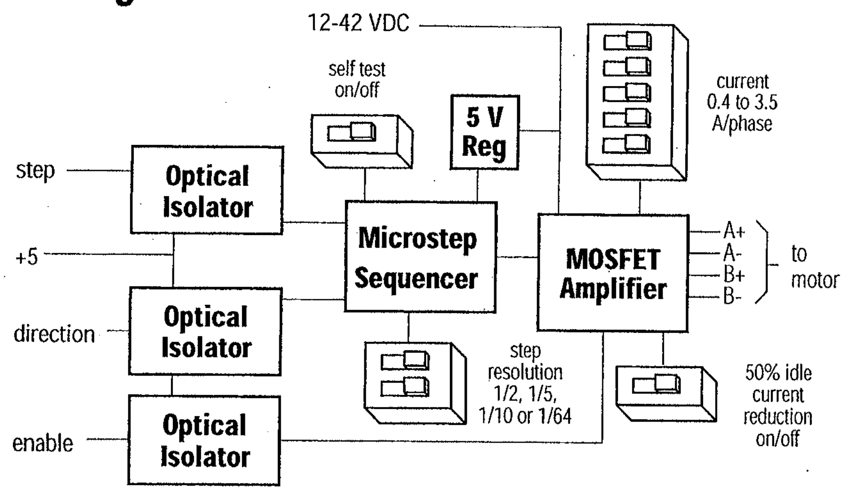
Thank you for selecting an Applied Motion Products motor control. We hope our dedication to performance, quality and economy will make your motion control project successful.

If there's anything we can do to improve our products or help you use them better, please call or fax. We'd like to hear from you. Our phone number is (800) 525-1609 or you can reach us by fax at (831) 761-6544.

Features

- Drives sizes 14 through 34 step motors
- Pulse width modulation, MOSFET 3 state switching amplifiers
- Phase current from 0.4 to 3.5 amps (switch selectable, 32 settings)
- Optically isolated step, direction and enable inputs
- Half, 1/5, 1/10, 1/64 step (switch selectable)
- Automatic 50% idle current reduction (can be switched off)

Block Diagram

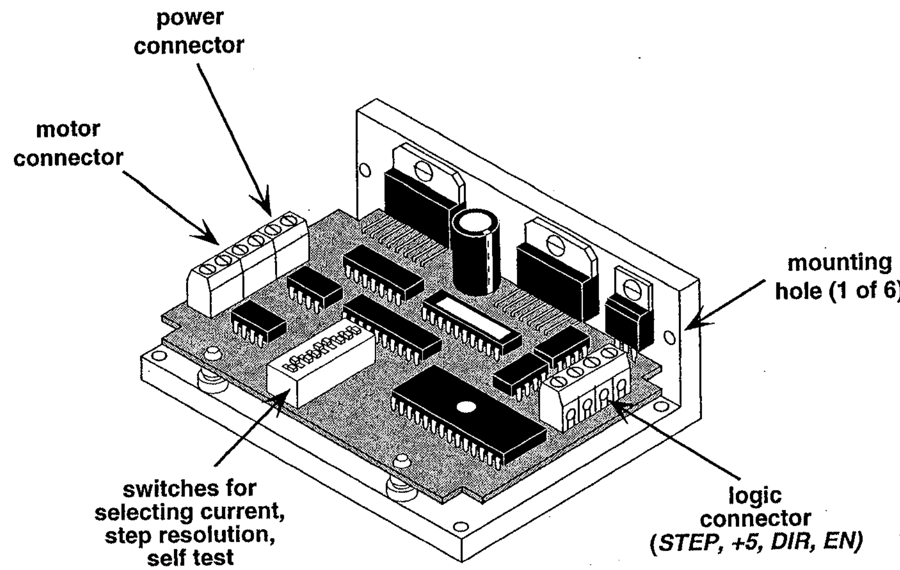


Getting Started

To use your Applied Motion Products motor control, you will need the following:

- a 12-42 volt DC power supply for the motor. Please read the section entitled *Choosing a Power Supply* for help in choosing the right power supply.
- +5 volts DC, 15mA to activate the optoisolation circuits (if you don't use 5 volt logic, see page 6.) This is provided by most indexers and PLCs.
- a source of step pulses capable of sinking at least 5 mA
- if your application calls for bidirectional rotation, you'll also need a direction signal, capable of sinking 5 mA
- a compatible step motor
- a small flat blade screwdriver for tightening the connectors

The sketch below shows where to find the important connection and adjustment points. Please examine it now.

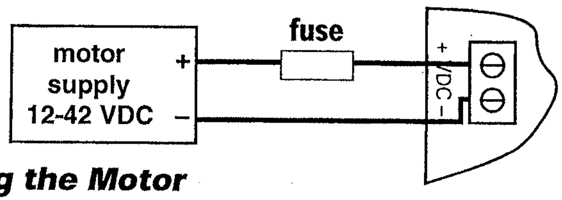


Connecting the Power Supply

If you need information about choosing a power supply, please read *Choosing a Power Supply* located on page 12 of this manual. The PS430 from Applied Motion Products is a good supply for this drive.

If your power supply does not have a fuse on the output or some kind of short circuit current limiting feature you need to put a 4 amp fast acting fuse between the drive and power supply. Install the fuse on the + power supply lead.

Connect the motor power supply + terminal to the driver terminal labeled "+ VDC". Connect power supply Ð to the drive terminal labeled "VDC Ð". Use no smaller than 20 gauge wire. **Be careful not to reverse the wires.** Reverse connection will destroy your driver, void your warranty and generally wreck your day.

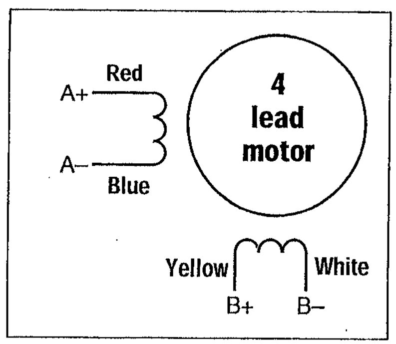


Connecting the Motor

Warning: When connecting the motor to the driver, be sure that the motor power supply is off. Secure any unused motor leads so that they can't short out to anything. Never disconnect the motor while the drive is powered up. Never connect motor leads to ground or to a power supply!

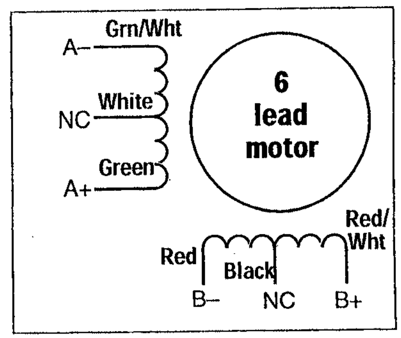
You must now decide how to connect your motor to the drive.

Four lead motors can only be connected one way. Please follow the sketch at the right.

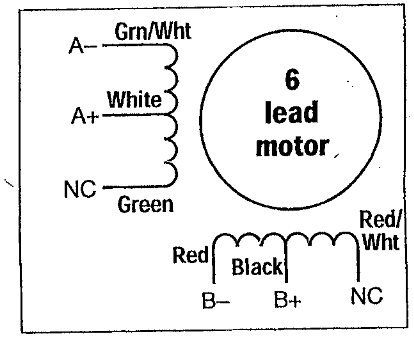


4 Leads

Six lead motors can be connected in series or center tap. In series mode, motors produce more torque at low speeds, but cannot run as fast as in the center tap configuration. In series operation, the motor should be operated at 30% less than rated current to prevent overheating. Wiring diagrams for both connection methods are shown on the next page. NC means not connected to anything.

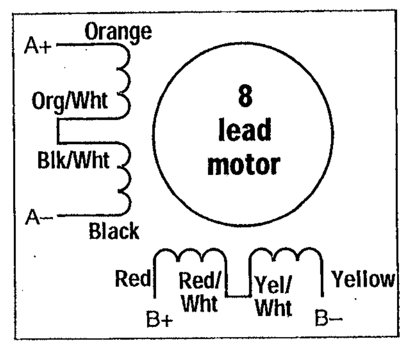


6 Leads Series Connected

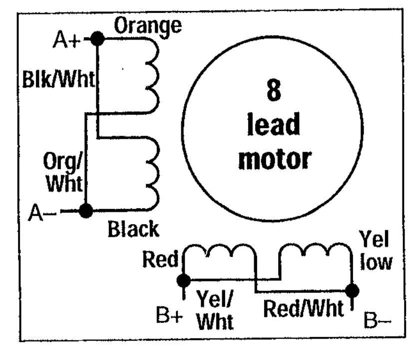


6 Leads Center Tap Connected

Eight lead motors can also be connected in two ways: series or parallel. As with six lead motors, series operation gives you more torque at low speeds and less torque at high speeds. In series operation, the motor should be operated at 30% less than the rated current to prevent over heating. The wiring diagrams for eight lead motors are shown below.



8 Leads Series Connected



8 Leads Parallel Connected

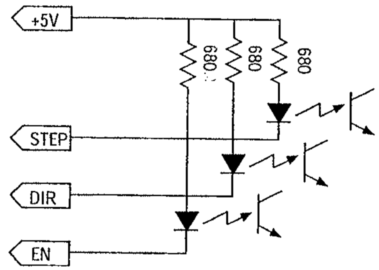
Connecting Logic

The 3540 M contains optical isolation circuitry to prevent the electrical noise inherent in switching amplifiers from interfering with your circuits. Optical isolation is accomplished by powering the motor driver from a different supply than your circuits. There is no electrical connection between the two: signal communication is achieved by infrared light. When your circuit is in the logic low state (near 0 volts), it is directing electrical current through an LED that is built into the drive. The LED, in turn, produces infrared light which turns on a phototransistor that is wired to the brains of the drive. When your circuit is in the logic high state, the LED and phototransistor turn off.

A schematic diagram of the input circuit is shown below.

You must supply 5 volts DC to supply current to the LEDs on the input side of the optoisolators. The maximum current draw is 15 mA total.

Your controlling logic must be capable of sinking at least 5 mA to control each drive input. Most CMOS and open collector TTL devices are directly compatible with this drive. Logic low, or 0, for a given input occurs when that input is pulled to less than 0.8 volts DC. In this state the LED is conducting current. Logic high, or 1, occurs when the input is greater than 4 volts or open.



Drive Input Circuit

STEP tells the driver when to move the motor one step. The drive steps on the falling edge of the pulse. The minimum pulse width is 0.5 microseconds.

DIRECTION signals which way the motor should turn. See the step table on page 8 for details. The *DIRECTION* signal should be changed at least 2 microseconds before a step pulse is sent. **If you change the state of the direction input and send a step pulse at the same instant the motor may take a step in the wrong direction.**

ENABLE allows the user to turn off the current to the motor by setting this signal to logic 0. The logic circuitry continues to operate, so the drive "remembers" the step position even when the amplifiers are disabled. However, the motor may move slightly when the current is removed depending on the exact motor and load characteristics. **If you have no need to disable the amplifiers, you don't need to connect anything to the *ENABLE* input.**

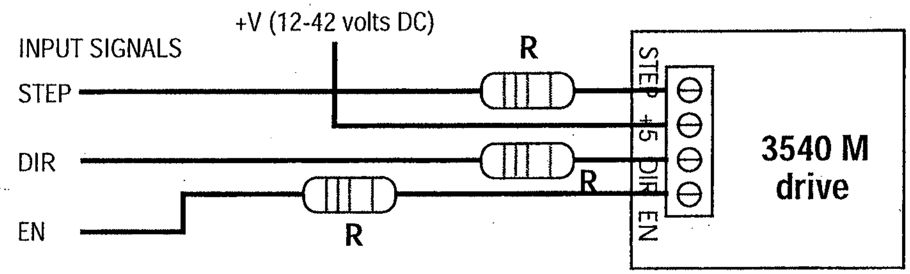
Using Logic Voltages other than 5 volts DC

The 3540 M was designed to be used with 5 volt CMOS and TTL logic signals. To prevent interference between the drive and the controlling logic, the input signals are optically isolated. That means that your signals are powering LEDs within the drive's optocoupler circuits. The LEDs require at least 5 milliamps of current to turn on, but cannot stand more than 20 mA. Since the LEDs themselves only drop about two volts, current limiting resistors must be used on each logic input.

We have included the proper resistor (680 ohms) within the drive for 5 volt operation. Therefore, if your logic voltage is 5 volts, you do not need to add resistors externally.

If your logic voltage is higher than five volts, you must add a resistor in series with each signal that you use (STEP, DIR and EN). The recommended wiring diagram is shown below. Table I lists the appropriate resistor value to use for a given power supply voltage. 1/4 watt or larger resistors should be used.

Please take care not to reverse the wiring, as damage to the LEDs will result rendering the drives inoperable. Check your wiring carefully before turning on the power supply!



Note: DIR signal is only required for bidirectional motion.
EN signal is only required to shut off motor current.
Both inputs can be left open if not needed.

Table I: External Dropping Resistors

Supply Voltage	R Ohms	Supply Voltage	R Ohms	Supply Voltage	R Ohms
12	1200	21	3000	30	4700
15	1800	24	3600	33	5100
18	2400	27	4200	35	5600

Step Table
(half stepping)

DIR=1 CW (steps 0 → 8); DIR=0 CCW (steps 8 → 0)

Step	A+	A-	B+	B-
0	open	open	+	–
1	+	–	+	–
2	+	–	open	open
3	+	–	–	+
4	open	open	–	+
5	–	+	–	+
6	–	+	open	open
7	–	+	+	–
8	open	open	+	–

Step 0 is the Power Up State

Setting Phase Current

Before you turn on the power supply the first time, you need to set the driver for the proper motor phase current. The rated current is usually printed on the motor label. The 3540 M drive current is easy to set. If you wish, you can learn a simple formula for setting current and never need the manual again. Or you can skip to the table on the next page, find the current setting you want, and set the DIP switches according to the picture.

Current Setting Formula

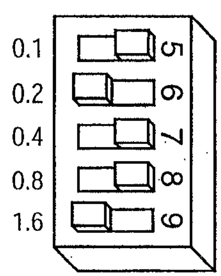
Locate the bank of tiny switches near the motor connector. Four of the switches have a value of current printed next to them, such as 0.4 and 0.8. Each switch controls the amount of current, in amperes (A), that its label indicates. There is always a base of current of 0.4 A. To add to that, slide the appropriate switches toward their labels on the PC board. You may need your small screwdriver for this.

Example

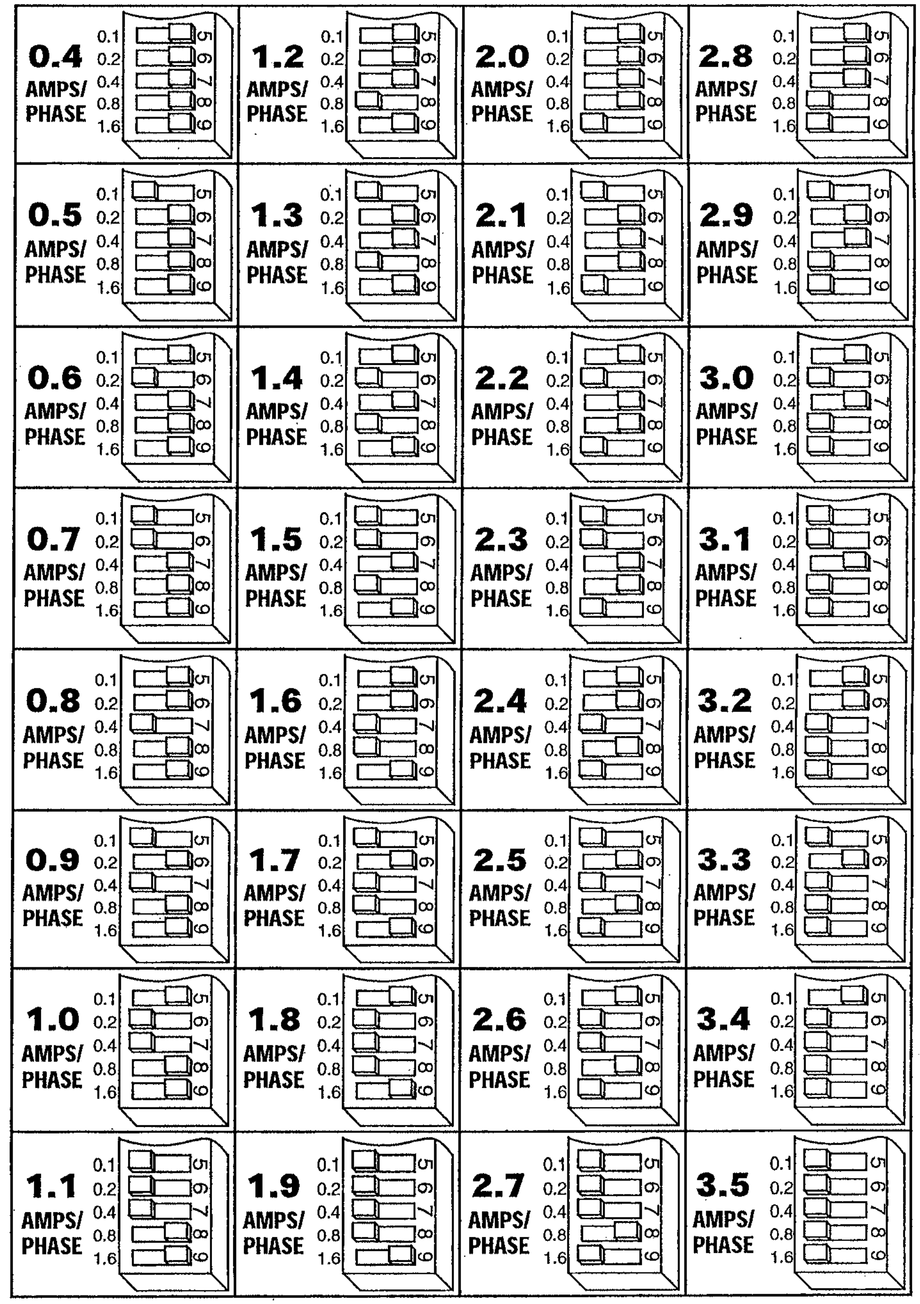
Suppose you want to set the driver for 2.2 amps per phase. You need the 0.4 A base current plus another 1.6 and 0.2 A.

2.2 = 0.4 + 1.6 + 0.2

Slide the 1.6 and 0.2 A switches toward the labels as shown in the figure.



Current Setting Table



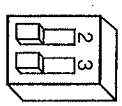
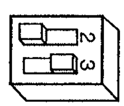
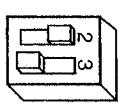
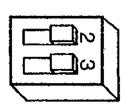
Microstepping

Most step motor drives offer a choice between full step and half step resolutions. In most full step drives, both motor phases are used all the time. Half stepping divides each step into two smaller steps by alternating between both phases on and one phase on. Microstepping drives like the 3540 M precisely control the amount of current in each phase at each step position as a means of electronically subdividing the steps even further. The 3540 M offers a choice of half step and 3 microstep resolutions. The highest setting divides each full step into 64 microsteps, providing 12,800 steps per revolution when using a 1.8° motor.

In addition to providing precise positioning and smooth motion, microstep drives can be used to provide motion in convenient units. When the drive is set to 2000 steps/rev (1/10 step) and used with a 5 pitch lead screw, you get .0001 inches/step.

Setting the step resolution is easy. Look at the dip switch on the 3540 M. Next to switches 2 and 3, there are labels on the printed circuit board. Each switch has two markings on each end. Switch 2 is marked 1/5, 1/10 at one end and 1/5, 1/64 at the other. Switch 3 is labeled 1/2, 1/5 and 1/10, 1/64. To set the drive for a resolution, push both switches toward the proper label. For example, if you want 1/10 step, push switch 2 toward the 1/10 label (to the left) and push switch 3 toward 1/10 (on the right).

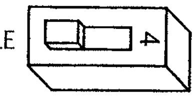
Please refer to the table below and set the switches for the resolution you want.

400 STEPS/REV (HALF) 1/2 1/10 1/5 1/2  1/5 1/64 1/10 1/64	**2000 STEPS/REV (1/10)** 1/2 1/10 1/5 1/2  1/5 1/64 1/10 1/64
1000 STEPS/REV (1/5) 1/2 1/10 1/5 1/2  1/5 1/64 1/10 1/64	**12800 STEPS/REV (1/64)** 1/2 1/10 1/5 1/2  1/5 1/64 1/10 1/64

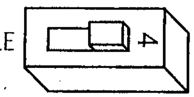
Idle Current Reduction

Your drive is equipped with a feature that automatically reduces the motor current by 50% anytime the motor is not moving. This reduces drive heating by about 50% and lowers motor heating by 75%. This feature can be disabled if desired so that full current is maintained at all times. This is useful when a high holding torque is required. To minimize motor and drive heating we highly recommend that you enable the idle current reduction feature unless your application strictly forbids it.

Idle current reduction is enabled by sliding switch #4 toward the *50% IDLE* label,as shown in the sketch below. Sliding the switch away from the *50% IDLE* label disables the reduction feature.

50% IDLE 

Idle Current Reduction Selected

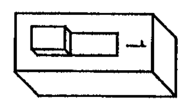
50% IDLE 

No Current Reduction

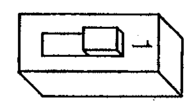
Self Test

The 3540 M includes a self test feature. This is used for trouble shooting. If you are unsure about the motor or signal connections to the drive, or if the 3540 M isn't responding to your step pulses, you can turn on the self test.

To activate the self test, slide switch #1 toward the *TEST* label. The drive will slowly rotate the motor, 1/2 revolution forward, then 1/2 rev backward. The pattern repeats until you slide the switch away from the *TEST* label. The 3540 M always uses half step mode during the self test, no matter how you set switches 2 and 3. The self test ignores the *STEP* and *DIRECTION* inputs while operating. The *ENABLE* input continues to function normally.

TEST 

Self Test ON

TEST 

Self Test OFF

Choosing a Power Supply

Voltage

Chopper drives work by switching the voltage to the motor terminals on and off while monitoring current to achieve a precise level of phase current. To do this efficiently and silently, you'll want to have a power supply with a voltage rating at least five times that of the motor. Depending on how fast you want to run the motor, you may need even more voltage. More is better, the only upper limit being the maximum voltage rating of the drive itself: 42 volts (including ripple).

If you choose an unregulated power supply, do not exceed 30 volts DC. This is because unregulated supplies are rated at full load current. At lesser loads, like when the motor is not moving, the actual voltage can be up to 1.4 times the voltage list on the power supply label.

Current

The maximum supply current you will need is the sum of the two phase currents. However, you will generally need a lot less than that, depending on the motor type, voltage, speed and load conditions. That's because the 3540 M uses switching amplifiers, converting a high voltage and low current into lower voltage and higher current. The more the power supply voltage exceeds the motor voltage, the less current you'll need from the power supply.

We recommend the following selection procedure:

1. If you plan to use only a few drives, get a power supply with at least twice the rated phase current of the motor.

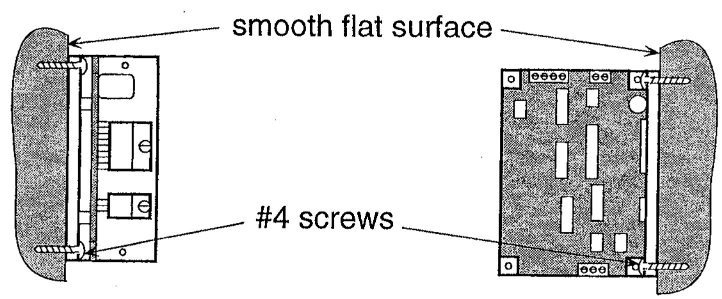
2. If you are designing for mass production and must minimize cost, get one power supply with more than twice the rated current of the motor. Install the motor in the application and monitor the current coming out of the power supply and into the drive at various motor loads. This will tell you how much current you really need so you can design in a lower cost power supply.

If you plan to use a regulated power supply you may encounter a problem with current foldback. When you first power up your drive, the full current of both motor phases will be drawn for a few milliseconds while the stator field is being established. After that the amplifiers start chopping and much less current is drawn from the power supply. If your power supply thinks this initial surge is a short circuit it may "foldback" to a lower voltage. With many foldback schemes the voltage returns to normal only after the first motor step and is fine thereafter. In that sense, unregulated power supplies are better. They are also less expensive.

The PS430 from Applied Motion Products is a good supply to use with the 3540 M.

Mounting the Drive

You can mount your drive on the wide or the narrow side of the chassis. If you mount the drive on the wide side, use #4 screws through the four corner holes. For narrow side mounting applications, you can use #4 screws in the two side holes.

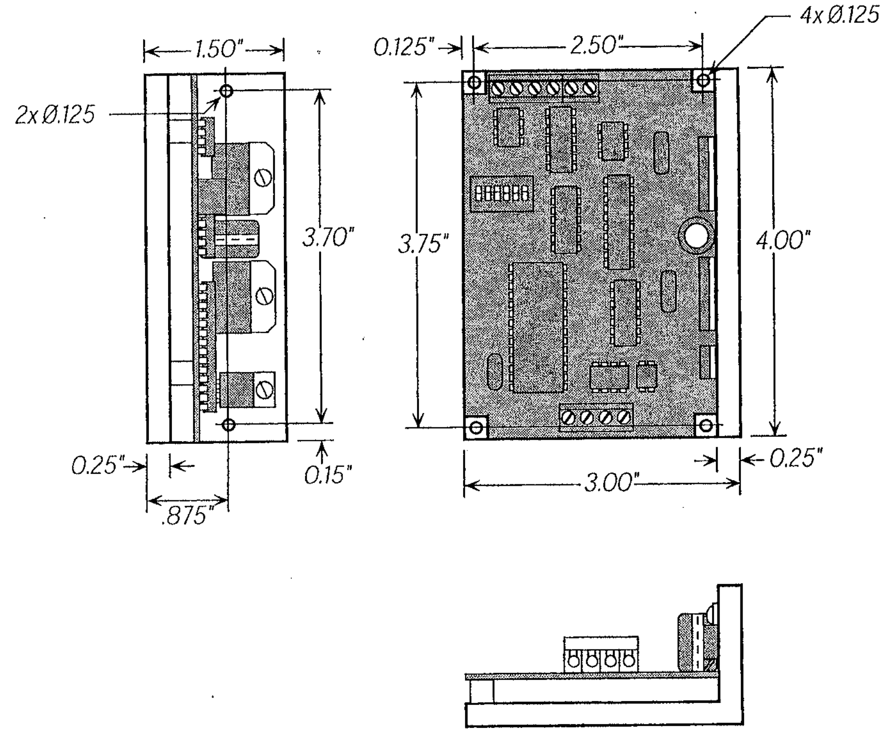


wide side mount | narrow side mount

The amplifiers in the drive generate heat. Unless you are running at 1 amp or below, you may need a heat sink. To operate the drive continuously at maximum power you must properly mount it on a heat sinking surface with a thermal constant of no more than 4°C/watt. Applied Motion Products can provide a compatible heat sink. Often, the metal enclosure of your system will make an effective heat sink.

Never use your drive in a space where there is no air flow or where other devices cause the surrounding air to be more than 70 °C. Never put the drive where it can get wet or where metal particles can get on it.

Mechanical Outline



Technical Specifications

Amplifiers Dual, bipolar MOSFET H-bridge, pulse width modulated three state switching at 20kHz. 12-42 VDC input. 0.4 - 3.5 amps/phase output current, switch selectable in 0.1 A increments. 122 watts maximum output power. Automatic idle current reduction (switch selectable), reduces current to 50% of setting after one second.

Inputs Step, direction and enable, optically isolated, 5V logic. 5mA/signal, sink requirement. Motor steps on rising edge of step input. 0.5 µsec minimum pulse width. 2 µsec minimum set up time for direction signal.

Physical Mounted on 1/4 inch thick black anodized aluminum heat transfer chassis. 1.5 x 3.0 x 4.0 inches overall. Power on red LED. See drawing on page 14 for more information. Maximum chassis temperature: 70° C.

Connectors European style screw terminal blocks. Max wire size: AWG 18.
Motor: 4 position (A+, A-, B+, B-)
Signal Input: 4 position (+5, STEP, DIR, EN)
DC Input: 2 position (V+, V-)

Self Test Switch selectable, rotates motor 1/2 revolution each direction at 100 steps/second, half step mode.

Microstepping Four switch selectable step resolutions. With 1.8¡ motor:
Half step (400 steps/rev)
1/5 step (1000 s/r)
1/10 step (2000 s/r)
1/64 step (12,800 s/r)
Other resolutions, up to 12,800, available to qualified OEMs upon request.

CE Mark Complies with EN55011A and EN50082-1(1992).
CE

OMEGA
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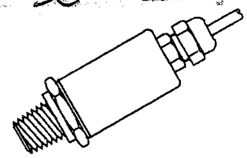
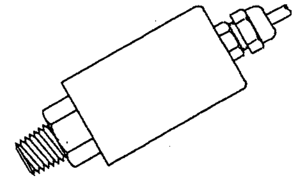
PX300, 302, 303 and 305 Series Pressure Transducers
M1306/0798



PX300, 302



PX303, 305

COMMON SPECIFICATIONS FOR ALL UNITS

ACCURACY: (Linearity, hysteresis, and Repeatabilty)	0.25% BFSL
ZERO BALANCE:	2%
OPERATING TEMP:	0° TO 160°F (-18° TO 71°C)
COMPENSATED TEMP:	30° TO 130°F (-1° TO 54°C)
THERMAL EFFECTS:	1% over entire comp. range
THERMAL HYSTERESIS:	0.25%
VIBRATION:	15g's @ 10-200Hz MIL-STD-202, M204, Cond. B)
SHOCK:	50 g,s @ 11ms (MIL-STD-202, M213, Cond. G)
PROOF PRESSURE:	200% or 13,000 psi (whichever is less)
STABILITY:	0.5% over one year
GAGE TYPE:	Corrugated stainless steel diaphragm fluid filled with diffused semiconductor sensor
ELECTRICAL CONNECTION:	36", 22AWG, pigtail unshield wire
WETTED PARTS:	17-4 PHSS
PRESSURE CAVITY:	0.075 cubic inches
PRESSURE CONNECTION:	1/4" NPT

MILLIVOLT OUTPUT FOR PX300 & 302

EXCITATION:	10VDC (12 VDC max)
OUTPUT:	
PX300:	30mV± 1mV (3mV/V)
PX302:	100mV± 1mV (10mV/V)
INPUT & OUTPUT RES.:	5000 ohms nominal
RESPONSE TIME:	1msec
WEIGHT:	4.6 oz (131 grams)
WIRING:	Red (+ EXC), Black (- EXC), Green (+ SIGNAL), White (- SIGNAL)

VOLTAGE OUTPUT FOR PX303-xxx5V, PX303-xxx10V

EXCITATION:	9-30VDC (5 VDC output) 14-30VDC (10 VDC output)
OUTPUT:	0.5 - 5.5VDC 1-11VDC
SPAN:	5VDC±1% 10VDC±1%
MIN.LOAD RESISTANCE:	2000 ohms
QUIESCENT DRAW:	16 mA
RESPONSE TIME:	1 msec
WEIGHT:	5.8 oz (166 grams)
WIRING:	Red (+EXC), Black (COMMON), White (+ OUTPUT)

CURRENT OUTPUT FOR PX305

EXCITATION:	6-30 VDC
OUTPUT:	4-20 mA
SPAN:	16 mA±1%
MAX LOOP RESISTANCE:	Max resistance = 50 (Voltage supply -12)
RESPONSE TIME:	1msec
WEIGHT:	5.9 oz (168 grams)
WIRING:	Red (+), Black (-), (Reverse polarity protected)

CALIBRATION

All models are tested to meet or exceed the published specifications. The calibration and testing were done using instrumentation and standards traceable to the National Institute of Standards and Technology (NIST) (also tested per MIL standard 45662A).

WARNING ! READ THIS BEFORE INSTALLATION

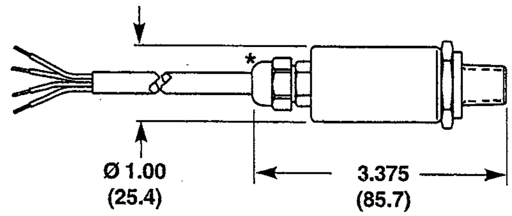
Fluid hammer and surges can destroy any pressure transducer and must always be avoided. A pressure snubber should be installed to eliminate the damaging hammer effects. Fluid hammer occurs when a pump is suddenly stopped, as with quick closing solenoid valves. Surges occur when flow is suddenly begun, as when a pump is turned on at full power or a valve is quickly opened.

Liquid surges are particularly damaging to pressure transducers if the pipe is originally empty. To avoid damaging surges, fluid lines should remain full (if possible), pumps should be brought up to power slowly, and valves opened slowly. To avoid damage from both fluid hammer and surges, a surge chamber should be installed, and a pressure snubber should be installed on every transducer.

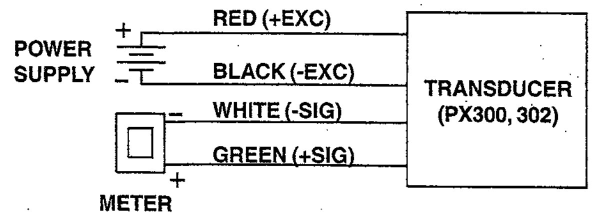
Symptoms of fluid hammer and surge's damaging effects:

1. Pressure transducer exhibits an output at zero pressure (large zero offset). If zero offset is less than 10% FS, user can usually re-zero meter, install proper snubber and continue monitoring pressures.
2. Pressure transducer output remains constant regardless of pressure.
3. In severe cases, there will be no output.

MILLIVOLT TRANSDUCERS - PX300, 302

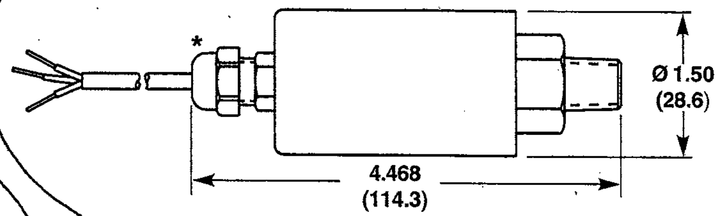


WIRING

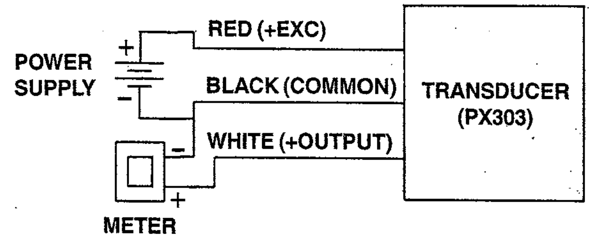


* THE WIRES CAN NOT BE UNPLUGGED FROM THE SENSOR!

VOLTAGE OUTPUT TRANSDUCER - PX303

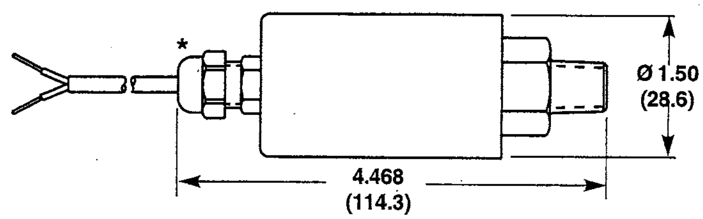


WIRING

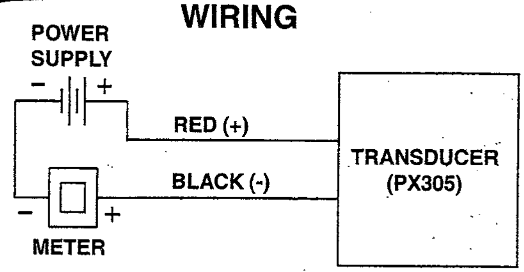


* THE WIRES CAN NOT BE UNPLUGGED FROM THE SENSOR!

CURRENT OUTPUT TRANSDUCER - PX305



WIRING



* THE WIRES CAN NOT BE UNPLUGGED FROM THE SENSOR!

DIMENSIONS IN INCHES (mm)

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For immediate technical or application assistance:

USA and Canada: Sales Service: 1-800-826-6342 / 1-800-TC-OMEGA℠
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United Kingdom: ISO 9002 Certified — 25 Swannington Road, Broughton Astley, Leicestershire, LE9 6TU, England, Tel: 44 (1455) 285520, FAX: 44 (1455) 283912, Toll Free in England: 0800-488-488

It is the policy of OMEGA to comply with all worldwide safety and EMC/EMI regulations that apply. OMEGA is constantly pursuing certification of its products to the European New Approach Directives. OMEGA will add the CE mark to every appropriate device upon certification.

WARRANTY/DISCLAIMER

MADE IN USA

OMEGA warrants this unit to be free of defects in materials and workmanship and to give satisfactory service for a period of **13 months** from date of purchase. OMEGA Warranty adds an additional one (1) month grace period to the normal **one (1) year product warranty** to cover handling and shipping time. This ensures that OMEGA's customers receive maximum coverage on each product. If the unit should malfunction, it must be returned to the factory for evaluation. OMEGA's Customer Service Department will issue an Authorized Return (AR) number immediately upon phone or written request. Upon examination by OMEGA, if the unit is found to be defective it will be repaired or replaced at no charge. However, this WARRANTY is VOID, if the unit shows evidence of having been tampered with or shows evidence of being damaged as a result of excessive corrosion; or current, heat, moisture or vibration; improper specification; misapplication; misuse or other operating conditions outside of OMEGA's control. Components which wear or which are damaged by misuse are not warranted. These include contact points, fuses, and triacs.

OMEGA is pleased to offer suggestions on the use of its various products. Nevertheless, OMEGA only warrants that the parts manufactured by it will be as specified and free of defects.

OMEGA MAKES NO OTHER WARRANTIES OR REPRESENTATIONS OF ANY KIND WHATSOEVER, EXPRESSED OR IMPLIED, EXCEPT THAT OF TITLE AND ALL IMPLIED WARRANTIES INCLUDING ANY WARRANTY OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE ARE HEREBY DISCLAIMED.

LIMITATION OF LIABILITY: The remedies of purchaser set forth herein are exclusive and the total liability of OMEGA with respect to this order, whether based on contract, warranty, negligence, indemnification, strict liability or otherwise, shall not exceed the purchase price of the component upon which liability is based. In no event shall OMEGA be liable for consequential, incidental or special damages.

CONDITIONS: Equipment sold by OMEGA is not intended to be used, nor shall it be used: (1) as a "Basic Component" under 10 CFR 21 (NRC), used in or with any nuclear installation or activity; or (2) in medical applications or used on humans. Should any Product(s) be used in or with any nuclear installation or activity, medical application, used on humans, or misused in any way, OMEGA assumes no responsibility as set forth in our basic WARRANTY / DISCLAIMER language, and additionally, purchaser will indemnify OMEGA and hold OMEGA harmless from any liability or damage whatsoever arising out of the use of the Product(s) in such a manner.

RETURN REQUESTS / INQUIRIES

Direct all warranty and repair requests/inquiries to the OMEGA ENGINEERING Customer Service Department. BEFORE RETURNING ANY PRODUCT(S) TO OMEGA, PURCHASER MUST OBTAIN AN AUTHORIZED RETURN (AR) NUMBER FROM OMEGA'S CUSTOMER SERVICE DEPARTMENT (IN ORDER TO AVOID PROCESSING DELAYS). The assigned AR number should then be marked on the outside of the return package and on any correspondence.

FOR **WARRANTY** RETURNS, please have the following information available BEFORE contacting OMEGA:

1. P.O. number under which the product was PURCHASED,
2. Model and serial number of the product under warranty, and
3. Repair instructions and/or specific problems relative to the product.

FOR **NON-WARRANTY** REPAIRS OR **CALIBRATION**, consult OMEGA for current repair/calibration charges. Have the following information available BEFORE contacting OMEGA:

1. P.O. number to cover the COST of the repair/calibration,
2. Model and serial number of the product, and
3. Repair instructions and/or specific problems relative to the product.

OMEGA's policy is to make running changes, not model changes, whenever an improvement is possible. This affords our customers the latest in technology and engineering.

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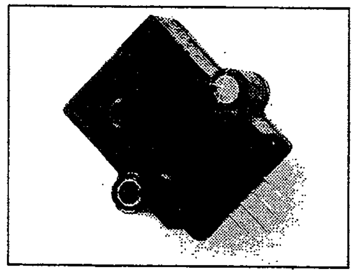
PRESSURE TRANSDUCER

OMEGA®
An OMEGA Technologies Company

PX138 Series Pressure Sensors

Instruction Manual

M2002/0598



General Description

The OMEGA® PX138 Series Pressure Transducer uses state-of the-art micromachined silicon pressure sensors in conjunction with stress-free packaging techniques to provide highly accurate, temperature-compensated pressure transducers for the most demanding applications. When operated from an 8 Vdc regulated power source, it provides a 1 to 6 Vdc output. Other regulated voltages from 7 to 16 volts can be used but the output will change in proportion to the excitation.

PX138 pressure transducers are available in absolute and differential models. Differential models can also be used to measure gage pressure or vacuum by simply varying the pressure connections. To measure gage pressure, make the pressure connection to port B and leave port A open to the atmosphere. For vacuum measurement, connect to port A and leave port B open. When using absolute models connect to part A.

Available Models

Differential Pressure Ranges	Model
±0 to 0.3 PSI	PX138-0.3D5V
±0 to 1 PSI	PX138-001D5V
±0 to 5 PSI	PX138-005D5V
±0 to 15 PSI	PX138-015D5V
±0 to 30 PSI	PX138-030D5V
±0 to 100 PSI	PX138-100D5V

Absolute Pressure Ranges	Model
0 to 15 PSIA	PX138-015A5V
0 to 30 PSIA	PX138-030A5V
0 to 100 PSIA	PX138-100A5V

PX138 Pinouts

1 = + Excitation
2 = Common
3 = + Signal
4 = No Connection

Unpacking

Remove the Packing List and verify that you have received all equipment, including the following:

PX138 Series Pressure Sensor
Operator's Manual

If you have any questions about the shipment, please call the OMEGA Customer Service Department.

When you receive the shipment, inspect the container and equipment for any signs of damage. Note any evidence of rough handling in transit. Immediately report any damage to the shipping agent.

NOTE

The carrier will not honor any damage claims unless all shipping material is saved for inspection. After examining and removing contents, save packing material and carton in the event reshipment is necessary.

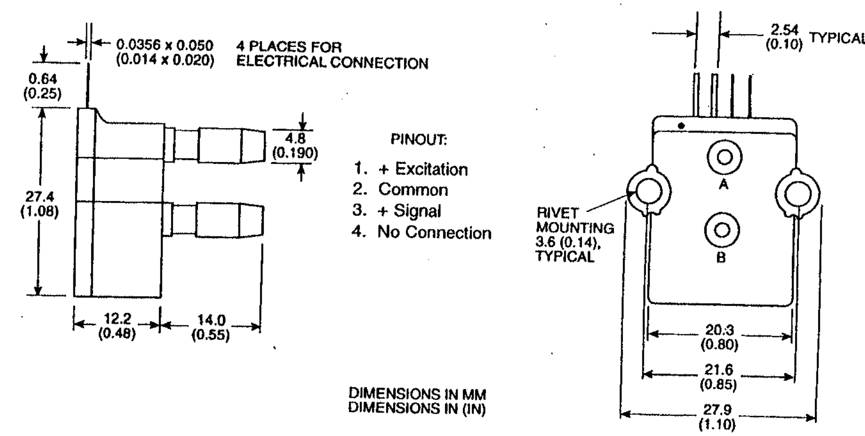
WARNING

Read Before Installation

Fluid hammer and surges can destroy any pressure transducer and must always be avoided. A pressure snubber should be installed to eliminate the damaging hammer effects. Fluid hammer occurs when a liquid flow is suddenly stopped, as with quick closing solenoid valves. Surges occur when flow is suddenly begun, as when a pump is turned on at full power or a valve is quickly opened.
Liquid surges are particularly damaging to pressure transducers if the pipe is originally empty. To avoid damaging surges, fluid lines should remain full (if possible), pumps should be brought up to power slowly, and valves opened slowly. To avoid damage from both fluid hammer and surges, a surge chamber should be installed, and a pressure snubber should be installed on every transducer.
Symptoms of fluid hammer and surge's damaging effects:

1. Pressure transducer exhibits an output at zero pressure (large zero offset). If zero offset is less than 10% FS, user can usually re-zero meter, install proper snubber and continue monitoring pressures.
2. Pressure transducer output remains constant regardless of pressure.
3. In severe cases, there will be no output.

Dimensions



Specifications

Excitation Voltage:	8 Vdc (7 to 16 limits)
Output:	1 to 6 volts (@ 8 volt excitation)
Linearity and Hysteresis:	±0.1% FS typical, 0.5% max. (0.5% typ., 1% max. for 0.3 PSI range)
Repeatability:	±0.1% FS typical, 0.3% max.
Zero Balance:	1 Vdc ±0.05 Vdc
Storage Temperature:	-40 to 125°C (-40 to 257°F)
Compensated Temp. Range:	0 to 50 °C (32 to 122°F)
Zero Temp. Effects:	±0.5% FS (±1% FS for 0.3 PSI)
Span Temp. Effects:	±0.5% FS (±1% FS for 0.3 PSI)
Proof Pressure:	> 3X FS pressure
Burst Pressure:	> 5X FS pressure
Common Mode Pressure:	50 PSI
Media Compatibility:	For use with gases compatible with silicon, glass-filled nylon, and alumina ceramic

WARRANTY/DISCLAIMER

OMEGA ENGINEERING, INC. warrants this unit to be free of defects in materials and workmanship for a period of **13 months** from date of purchase. OMEGA Warranty adds an additional one (1) month grace period to the normal **one (1) year product warranty** to cover handling and shipping time. This ensures that OMEGA's customers receive maximum coverage on each product.

If the unit should malfunction, it must be returned to the factory for evaluation. OMEGA's Customer Service Department will issue an Authorized Return (AR) number immediately upon phone or written request. Upon examination by OMEGA, if the unit is found to be defective it will be repaired or replaced at no charge. OMEGA's WARRANTY does not apply to defects resulting from any action of the purchaser, including but not limited to mishandling, improper interfacing, operation outside of design limits, improper repair, or unauthorized modification. This WARRANTY is VOID if the unit shows evidence of having been tampered with or shows evidence of being damaged as a result of excessive corrosion; or current, heat, moisture or vibration; improper specification; misapplication; misuse or other operating conditions outside of OMEGA's control. Components which wear are not warranted, including but not limited to contact points, fuses, and triacs.

OMEGA is pleased to offer suggestions on the use of its various products. However, OMEGA neither assumes responsibility for any omissions or errors nor assumes liability for any damages that result from the use of its products in accordance with information provided by OMEGA, either verbal or written. OMEGA warrants only that the parts manufactured by it will be as specified and free of defects. OMEGA MAKES NO OTHER WARRANTIES OR REPRESENTATIONS OF ANY KIND WHATSOEVER, EXPRESSED OR IMPLIED, EXCEPT THAT OF TITLE, AND ALL IMPLIED WARRANTIES INCLUDING ANY WARRANTY OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE ARE HEREBY DISCLAIMED. LIMITATION OF LIABILITY: The remedies of purchaser set forth herein are exclusive and the total liability of OMEGA with respect to this order, whether based on contract, warranty, negligence, indemnification, strict liability or otherwise, shall not exceed the purchase price of the component upon which liability is based. In no event shall OMEGA be liable for consequential, incidental or special damages.

CONDITIONS: Equipment sold by OMEGA is not intended to be used, nor shall it be used: (1) as a "Basic Component" under 10 CFR 21 (NRC), used in or with any nuclear installation or activity; or (2) in medical applications or used on humans. Should any Product(s) be used in or with any nuclear installation or activity, medical application, used on humans, or misused in any way, OMEGA assumes no responsibility as set forth in our basic WARRANTY/DISCLAIMER language, and additionally, purchaser will indemnify OMEGA and hold OMEGA harmless from any liability or damage whatsoever arising out of the use of the Product(s) in such a manner.

RETURN REQUESTS / INQUIRIES

Direct all warranty and repair requests/inquiries to the OMEGA Customer Service Department. BEFORE RETURNING ANY PRODUCT(S) TO OMEGA, PURCHASER MUST OBTAIN AN AUTHORIZED RETURN (AR) NUMBER FROM OMEGA'S CUSTOMER SERVICE DEPARTMENT (IN ORDER TO AVOID PROCESSING DELAYS). The assigned AR number should then be marked on the outside of the return package and on any correspondence.

The purchaser is responsible for shipping charges, freight, insurance and proper packaging to prevent breakage in transit.

FOR **WARRANTY** RETURNS, please have the following information available BEFORE contacting OMEGA:

1. P.O. number under which the product was PURCHASED,
2. Model and serial number of the product under warranty, and
3. Repair instructions and/or specific problems relative to the product.

FOR **NON-WARRANTY** REPAIRS, consult OMEGA for current repair charges. Have the following information available BEFORE contacting OMEGA:

1. P.O. number to cover the COST of the repair,
2. Model and serial number of product, and
3. Repair instructions and/or specific problems relative to the product.

OMEGA's policy is to make running changes, not model changes, whenever an improvement is possible. This affords our customers the latest in technology and engineering.

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USA and Canada:
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It is the policy of OMEGA to comply with all worldwide safety and EMC/EMI regulations that apply. OMEGA is constantly pursuing certification of its products to the European New Approach Directives. OMEGA will add the CE mark to every appropriate device upon certification.

The information contained in this document is believed to be correct but OMEGA Engineering, Inc. accepts no liability for any errors it contains, and reserves the right to alter specifications without notice.

WARNING: These products are not designed for use in, and should not be used for, patient connected applications.

Appendix C

Matlab Code

Centre of Gravity/Mass Specifications for Components

```
%--------------------------------------------------------------------------
% Name:     CBCGPlot.m
% Author:   Ben Skillings
% Date:     July 19, 2004
% NRC-IOT
% Notes:    1) Computes Centre of Buoyancy for the Mechanical Components.
%           2) All units in g, cm, s
%           3) Datum is the CG of the Mid-Body Section.
%              Positive x-axis is towards the diaphragm side.
%           4) Plots have switched signs for clear direction of motion.
%==========================================================================
% CONSTANTS AS DEFINED IN APPENDIX *X,Y,Z*
%==========================================================================

%--------------------------------------------------------------------------
% Maximum material condition:
%--------------------------------------------------------------------------

% Lengths as defined in Appendix ***XYZ***
L1_m = 3.416;        % 1)  Diaphragm Mount       [cm]
L2_m = 1.321;        % 2)  Diaphragm Nut         [cm]
L3_m = 1.333;        % 3)  Mid-Body Section      [cm]
L4_m = 1.780;        % 4)  End Cap               [cm]
L5_m = 47.841;       % 6)  Diaphragm Side Pipe   [cm]
L6_m = 44.641;       % 6)  Elec. Side Pipe       [cm]

% Masses as defined in Appendix ***XYZ***
M1_m = 552.9;        % 1)  Diaphragm Mount       [g]
M2_m = 168.14;       % 2)  Diaphragm Nut         [g]
M3_m = 517.1;        % 3)  Mid-Body Section      [g]
M4_m = 329.3;        % 4)  End Cap               [g]
M5_m = 496.26;       % 5)  Piston                [g]

% Actuator extention:
% Note: Does not start from zero due to tolerance calibration.
ExtensionMax = [1.846: 0.01: 14.046];

%--------------------------------------------------------------------------
% Minimum material conditions:
%--------------------------------------------------------------------------

% Lengths as defined in Appendix ***XYZ***
L1_l = 3.404;        % 1)  Diaphragm Mount       [cm]
L2_l = 1.219;        % 2)  Diaphragm Nut         [cm]
L3_l = 1.207;        % 3)  Mid-Body Section      [cm]
L4_l = 1.220;        % 4)  End Cap               [cm]
L5_l = 47.765;       % 6)  Diaphragm Side Pipe   [cm]
L6_l = 44.564;       % 6)  Elec. Side Pipe       [cm]

% Masses as defined in Appendix ***XYZ***
M1_l = 527.7;        % 1)  Diaphragm Mount       [g]
M2_l = 154.6;        % 2)  Diaphragm Nut         [g]
M3_l = 442.3;        % 3)  Mid-Body Section      [g]
M4_l = 308.1;        % 4)  End Cap               [g]
M5_l = 464.4;        % 5)  Piston                [g]

% Actuator extention:
% Note: Does not start from zero due to tolerance calibration.
ExtensionMin = [1.928: 0.01: 14.13];

%--------------------------------------------------------------------------
% Untoleranced measured masses and lengths:
%--------------------------------------------------------------------------

% As defined in Appendix XYZ
MP_dia = 1056.2;     % mass of Diaphragm End Pipe     [g]
MP_elec = 990.6;     % mass of Electronics End Pipe   [g]
Ld = 6.223;          % Piston depression              [cm]
```

```
%-------------------------------------------------------------------------------
% Actuator Assembly Components:
%-------------------------------------------------------------------------------

m1 = 1134.0;        % mass of actuator static base *                    [g]
L1 = 8.204;         % length of actuator base (motor and flange)        [cm]
m2 = 340.0;         % mass of the actuator static tube *                [g]
L2 = 26.298;        % length of the actuator static tube (cylinder)     [cm]
m5 = 116.000;       % mass of actuator hold-downs *                     [g]
l6 = 3.543;         % length of actuator hold-downs                     [g]

m3 = 227.0;         % mass of the moving rod in the actuator *          [g]
L3 = 21.209;        % length of the moving rod in the actuator *        [cm]
m4 = 473.4;         % mass of the *measured* piston                     [g]
L4 = 1.845;         % CG of piston mean with respect to Appendix XYZ    [cm]

% *Do not have data confirmation.

%===============================================================================
% ESTIMATE OF ACTUATOR ASSEMBLY (INCLUDING PISTON) OVER STROKE LENGTH:
%===============================================================================

% Assumtions:  1) ALL masses are homogeneous
%              2) Assembly is axysymmetric

CGEngineDynamicMass = m1+m2+m3+m4;

% CG of actuator static part measured from the motor end:
CGActStatic = ( 0.5*m1*L1 + m2*(L1 + 0.5*L2) + (0.5*l6*m5) )/(m1 + m2 + m5);


% CG of actuator dynamic part measured from the dynamic end:
CGActDynamic = (0.5*m3*L3 + (L3 + L4)*m4)/(m3 + m4);

% CG of actuator measured from motor end as a function of actuator extension:
% CGActDynamic shifts reference point to L1 + ( L2 - L3 ) - approximation

% MAXIMUM MATERIAL CONDITION:
[i,j] = size(ExtensionMax);
for i = 1:j
    CGActTOTALmax(1,i) = (CGActStatic*(m1+m2) + (L1+(L2-L3)+CGActDynamic+ExtensionMax(1,i))
...
                    *(m3 + m4))/(CGEngineDynamicMass);
end

% MINIMUM MATERIAL CONDITION:
[i,j] = size(ExtensionMin);
for i = 1:j
    CGActTOTALmin(1,i) = (CGActStatic*(m1+m2) + (L1+(L2-L3)+CGActDynamic+ExtensionMin(1,i))
...
                    *(m3 + m4))/(CGEngineDynamicMass);
end

%-------------------------------------------------------------------------------
% Actuator Assembly CG Plot - Datum: Motor Surface:
%-------------------------------------------------------------------------------

figure(1);
hold on;
plot (ExtensionMax,-CGActTOTALmax,'r');
title('CG Shift vs. Actuator Assembly Displacement - Datum: Motor Surface ');
xlabel('Actuator Axial Position [cm]');
ylabel('Actuator Assembly CG [cm]');
plot (ExtensionMin,-CGActTOTALmin,'b-.');
legend('MMC Extension', 'LMC Extension',0);
set(1,'Name','CG Shift of Actuator Assembly');
set(1,'FileName', '1) CG Shift of Actuator Assembly');
```

```
hold off;
grid;

%---------------------------------------------------------------------------
% Mass estimate check and print to screen:
%---------------------------------------------------------------------------

M_act = m1 + m2+ m3;
fprintf('\n\nMass of Measured Actuator: 1593.8 g\nMass as summed for CG Calculations: %6.1f ↙
 g',M_act)
fprintf('\n**Clearly there is an error in these numbers**\n\n')
M_totalMAX = M1_m + M2_m + M3_m + M4_m + M5_m + MP_dia + MP_elec + m1 + m2 + m5 + m3 + m4
M_totalMin = M1_l + M2_l + M3_l + M4_l + M5_l + MP_dia + MP_elec + m1 + m2 + m5 + m3 + m4

%===========================================================================
% Buoyancy Engine CG over stroke length:
%===========================================================================

% Assumtions:  1) ALL masses are homogeneous
%              2) Assembly is axysymmetric

CGEngineStaticMassMAX = M1_m + M2_m + M3_m + M4_m + MP_dia + MP_elec;
CGEngineStaticMassMIN = M1_l + M2_l + M3_l + M4_l + MP_dia + MP_elec;

% MAXIMUM MATERIAL CONDITION:
CGEngineMAXstatic = (  -(0.5*L3_m+L6_m+L4_m)*(M4_m)-(0.5*L3_m+0.5*L6_m)*(MP_elec)...
                       +(0.5*L3_m+0.5*L5_m+0.190)*(MP_dia)+(0.5*L3_m+L5_m-L1_m)*(M1_m)...
                       +(0.5*L3_m+L5_m+2.09+L2_m)*(M2_m) ) / (CGEngineStaticMassMAX);

[i,j] = size(ExtensionMax);
for i = 1:j
     CGEngineMAXtotal(1,i) = ( CGEngineMAXstatic*CGEngineStaticMassMAX + (CGActTOTALmax(1, ↙
i)+0.279)*CGEngineDynamicMass )...
                            / (CGEngineStaticMassMAX+CGEngineDynamicMass);
end

% MINIMUM MATERIAL CONDITION:
CGEngineMINstatic = (  -(0.5*L3_l+L6_l+L4_l)*(M4_l)-(0.5*L3_l+0.5*L6_l)*(MP_elec)...
                       +(0.5*L3_l+0.5*L5_l+0.190)*(MP_dia)+(0.5*L3_l+L5_l-L1_l)*(M1_l)...
                       +(0.5*L3_l+L5_l+2.09+L2_l)*(M2_l) ) / (CGEngineStaticMassMIN);

[i,j] = size(ExtensionMin);
for i = 1:j
     CGEngineMINtotal(1,i) = ( CGEngineMINstatic*CGEngineStaticMassMIN + (CGActTOTALmin(1, ↙
i)+0.330)*CGEngineDynamicMass )...
                            / (CGEngineStaticMassMIN+CGEngineDynamicMass);
end

%---------------------------------------------------------------------------
% Buoyancy Engine CG Plot - Datum: Motor Surface:
%---------------------------------------------------------------------------

figure(2);
hold on;
plot (ExtensionMax,-CGEngineMAXtotal,'r');
title('CG Shift vs. Actuator Assembly Displacement for Buoyancy Engine - Datum: Mid-Body Se ↙
ction ');
xlabel('Actuator Axial Position [cm]');
ylabel('Buoyancy Engine CG [cm]');
plot (ExtensionMin,-CGEngineMINtotal,'b');
legend('MMC Extension', 'LMC Extension',0);
set(2,'Name','CG Shift of Buoyancy Engine');
set(2,'FileName', '2) CG Shift of Buoyancy Engine');
hold off;
grid;

%===========================================================================
% Estimate CB over stroke length:
```

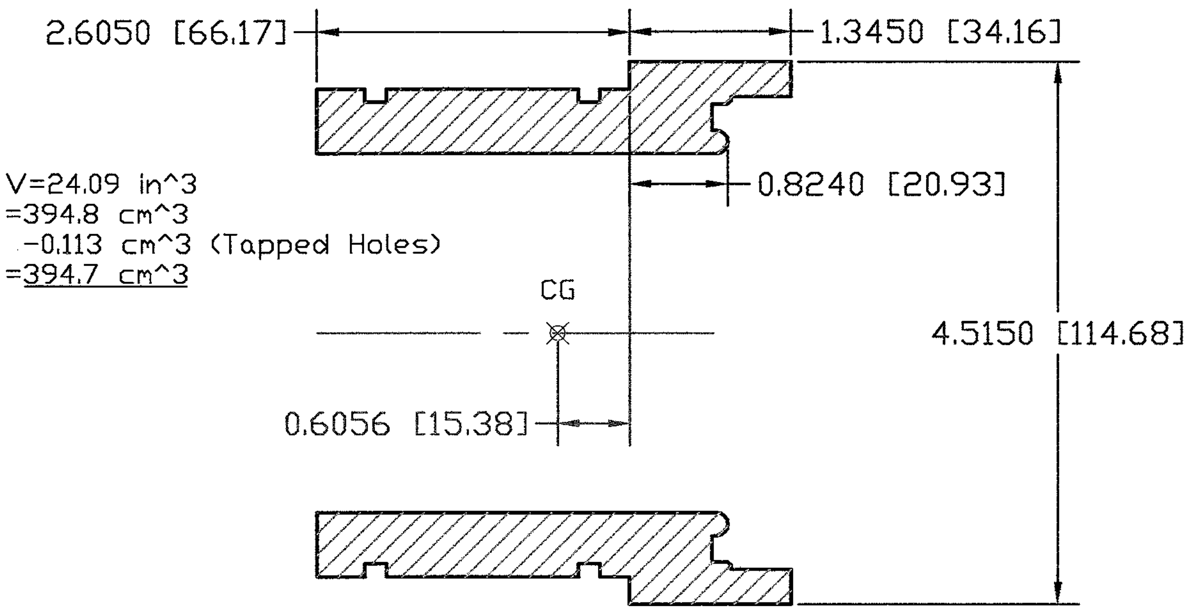
```
%==========================================================================

CBExtention = [0.00: 0.01: 12.2];     % No datum offset because of relative movement.
                                      % Length taken into account in calculations.

% MAXIMUM MATERIAL CONDITION:

% STATIC:
VolumeTotalMAX= VolumeCyl(11.468,1.626) + VolumeCyl(11.43,L6_m) + VolumeCyl(11.43,L5_m)...
                + VolumeCyl(11.468,1.333)+ VolumeCyl(11.468,3.416) + VolumeCyl(11.468,1.321 ↙
)...
                - VolumeCyl(7.658,Ld) - VolumeCyl(7.658,2.578)

NEUTRALVolumeTotalMAX = VolumeTotalMAX - VolumeCyl(7.658,2.578)

CBstaticMAX = ( -(0.5*L3_m+L6_m+0.5*1.626)*VolumeCyl(11.468,1.626)...
              -(0.5*L3_m+0.5*L6_m)*VolumeCyl(11.43,L6_m)...
              +(0.5*L3_m+0.5*L5_m)*VolumeCyl(11.43,L5_m)...
              +(0.5*L3_m+L5_m+0.5*3.416)*VolumeCyl(11.468,3.416)...
              +(0.5*L3_m+L5_m+3.416+0.5*1.321)*VolumeCyl(11.468,1.321)...
              -(0.5*L3_m-0.279+42.113+0.5*Ld)*VolumeCyl(7.62,Ld) )...
              / (VolumeTotalMAX);

% DYAMIC
[i,j] = size(CBExtention);
for i = 1:j
    CBEngineMAXtotal(1,i) = ( CBstaticMAX*VolumeTotalMAX + (0.5*CBExtention(1,i)-0.279+42 ↙
.113)...
                           *VolumeCyl(7.62,CBExtention(1,i)) )...
                         / (VolumeTotalMAX+VolumeCyl(7.62,CBExtention(1,i)));
end


% MINIMUM MATERIAL CONDITION:

% STATIC:
VolumeTotalMIN= VolumeCyl(11.392,1.524) + VolumeCyl(11.43,L6_l) + VolumeCyl(11.392,1.207).. ↙
.
                + VolumeCyl(11.43,L5_l)+ VolumeCyl(11.392,3.404) + VolumeCyl(11.392,1.219). ↙
..
                - VolumeCyl(7.582,Ld) - VolumeCyl(7.582,2.502)

NEUTRALVolumeTotalMIN = VolumeTotalMIN - VolumeCyl(7.658,2.502)

CBstaticMIN = ( -(0.5*L3_l+L6_l+0.5*1.524)*VolumeCyl(11.392,1.524)...
              -(0.5*L3_l+0.5*L6_l)*VolumeCyl(11.43,L6_l)...
              +(0.5*L3_l+0.5*L5_l)*VolumeCyl(11.43,L5_l)...
              +(0.5*L3_l+L5_l+0.5*3.404)*VolumeCyl(11.392,3.404)...
              +(0.5*L3_l+L5_l+3.416+0.5*1.219)*VolumeCyl(11.392,1.219)...
              -(0.5*L3_l-0.330+41.986+0.5*Ld)*VolumeCyl(7.62,Ld) )...
              / (VolumeTotalMIN);

% DYAMIC
[i,j] = size(CBExtention);
for i = 1:j
    CBEngineMINtotal(1,i) = ( CBstaticMIN*VolumeTotalMIN + (0.5*CBExtention(1,i)-0.330+41 ↙
.986)...
                           *VolumeCyl(7.62,CBExtention(1,i)) )...
                         / (VolumeTotalMIN+VolumeCyl(7.62,CBExtention(1,i)));
end

CBExtensionMAX = CBExtention +1.846;    % +1.846 Datum offset
CBExtensionMIN = CBExtention +1.928;    % +1.928 Datum offset

%--------------------------------------------------------------------------
% Buoyancy Engine CB Plot - Datum: Mid-Body Section:
%--------------------------------------------------------------------------
```

```
figure(3);
hold on;
plot (CBExtensionMAX,-CBEngineMAXtotal,'r-');
title('CB Shift vs. Actuator Assembly Displacement for Buoyancy Engine - Datum: Mid-Body Se ↙
ction ');
xlabel('Actuator Axial Position [cm]');
ylabel('Actuator Assembly CB [cm]');
plot (CBExtensionMIN,-CBEngineMINtotal,'b-');
legend('MMC Extension', 'LMC Extension',0);
set(3,'Name','CB Shift of Buoyancy Engine');
set(3,'FileName', '3) CB Shift of Buoyancy Engine');
hold off;
grid;

%---------------------------------------------------------------------------
% Buoyancy Engine CG and CB Plot - Datum: Mid-Body Section:
%---------------------------------------------------------------------------

figure(4);
hold on;
title('CB and CG Shift vs. Actuator Assembly Displacement for Buoyancy Engine - Datum: Mid- ↙
Body Section ');
xlabel('Actuator Axial Position [cm]');
ylabel('Buoyancy Engine CG and CB Positions [cm]');
set(4,'Name','CG and CB Shift of Buoyancy Engine');
set(4,'FileName', '4) CB and CG Shift of Buoyancy Engine');
plot (CBExtensionMAX,-CBEngineMAXtotal,'r-.');
plot (CBExtensionMIN,-CBEngineMINtotal,'b-.');
plot (ExtensionMax,-CGEngineMAXtotal,'r');
plot (ExtensionMin,-CGEngineMINtotal,'b');
legend('CB MMC Extension','CB LMC Extension','CG MMC Extension','CG LMC Extension',0);
hold off;
grid;

%---------------------------------------------------------------------------
% CG and CB Separation Distance - Datum: Mid-Body Section:
%---------------------------------------------------------------------------

% MAXIMUM MATERIAL CONDITION:
distanceMAX = CGEngineMAXtotal-CBEngineMAXtotal;

% MINIMUM MATERIAL CONDITION:
distanceMIN = CGEngineMINtotal-CBEngineMINtotal;

figure(5);
hold on;
plot (ExtensionMax,distanceMAX,'r-');
title('CG CB Separation Distance vs. Actuator Assembly Displacement' );
xlabel('Actuator Axial Position [cm]');
ylabel('CG CB Separation Distance [cm]');
plot (ExtensionMin,distanceMIN,'b-');
legend('MMC Extension', 'LMC Extension',0);
set(5,'Name','CG CB Separation Distance');
set(5,'FileName', '5) CG CB Separation Distance');
hold off;
grid;
```

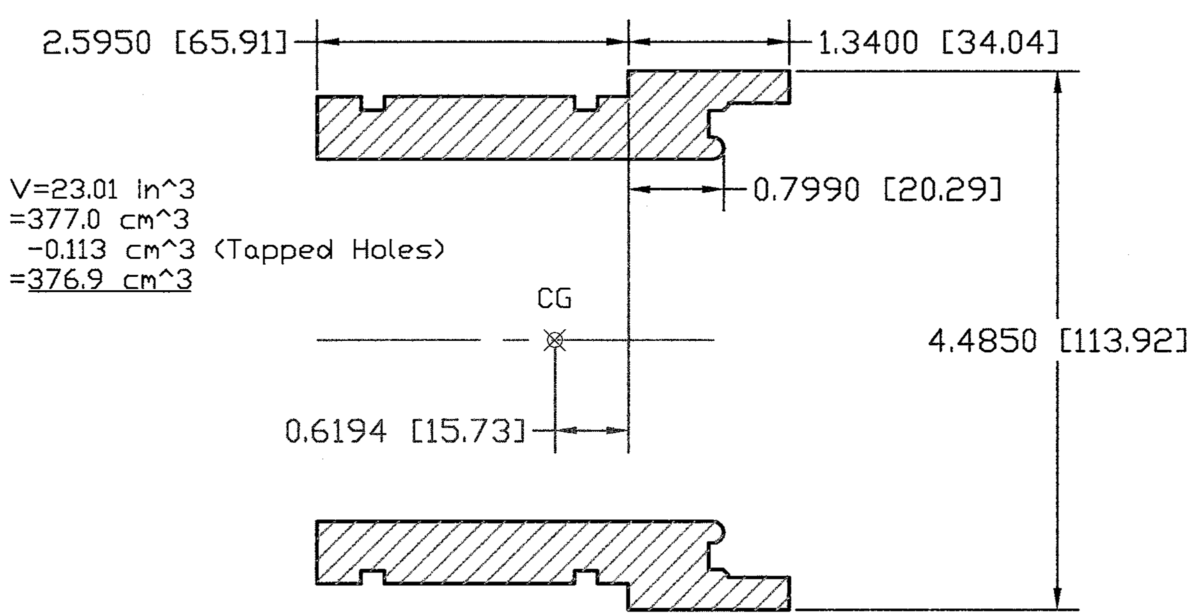
CG Calculations: Diaphragm Mount

inch [mm]

MAXIMUM MATERIAL CONDITION



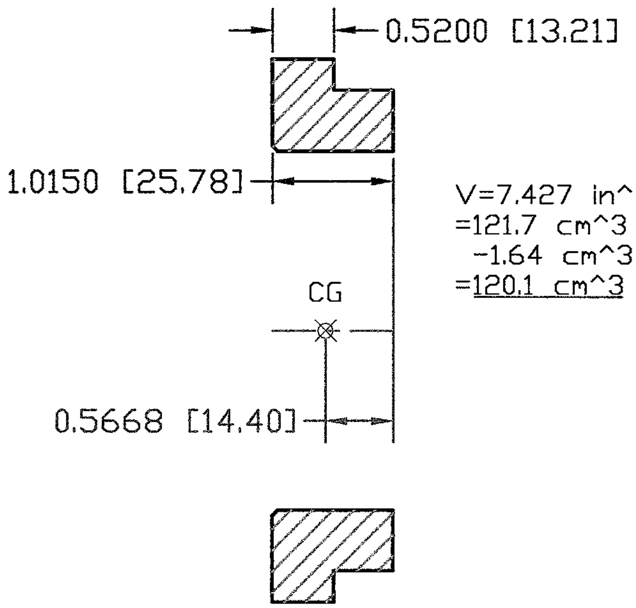
LEAST MATERIAL CONDITION



CG Calculations: Diaphragm Nut

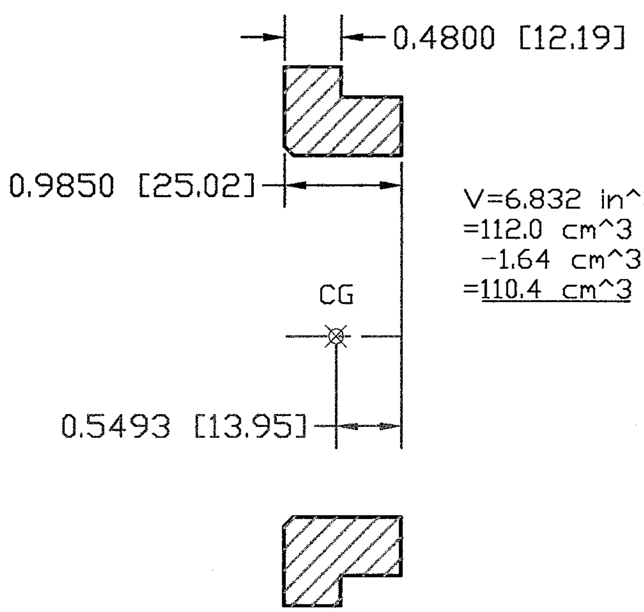
inch [mm]

MAXIMUM MATERIAL CONDITION



V=7.427 in^3
=121.7 cm^3
-1.64 cm^3 (Drilled Holes)
=<u>120.1 cm^3</u>

LEAST MATERIAL CONDITION

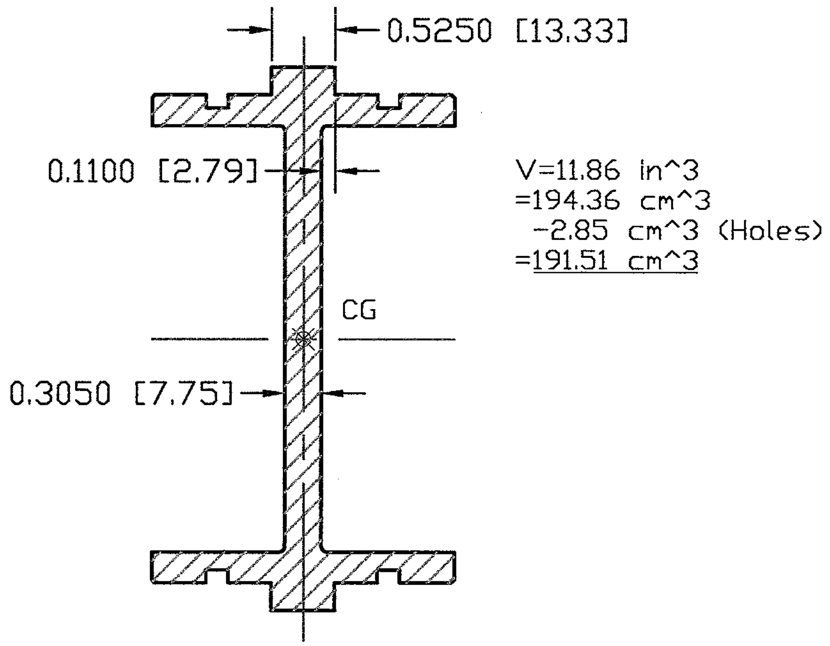


V=6.832 in^3
=112.0 cm^3
-1.64 cm^3 (Drilled Holes)
=<u>110.4 cm^3</u>

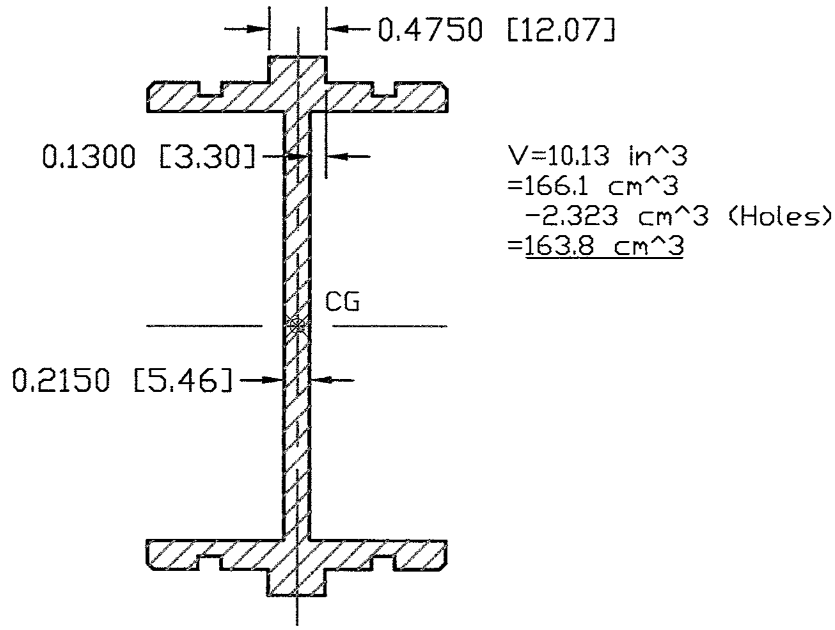
CG Calculations: Mid-Body Section

inch [mm]

MAXIMUM MATERIAL CONDITION

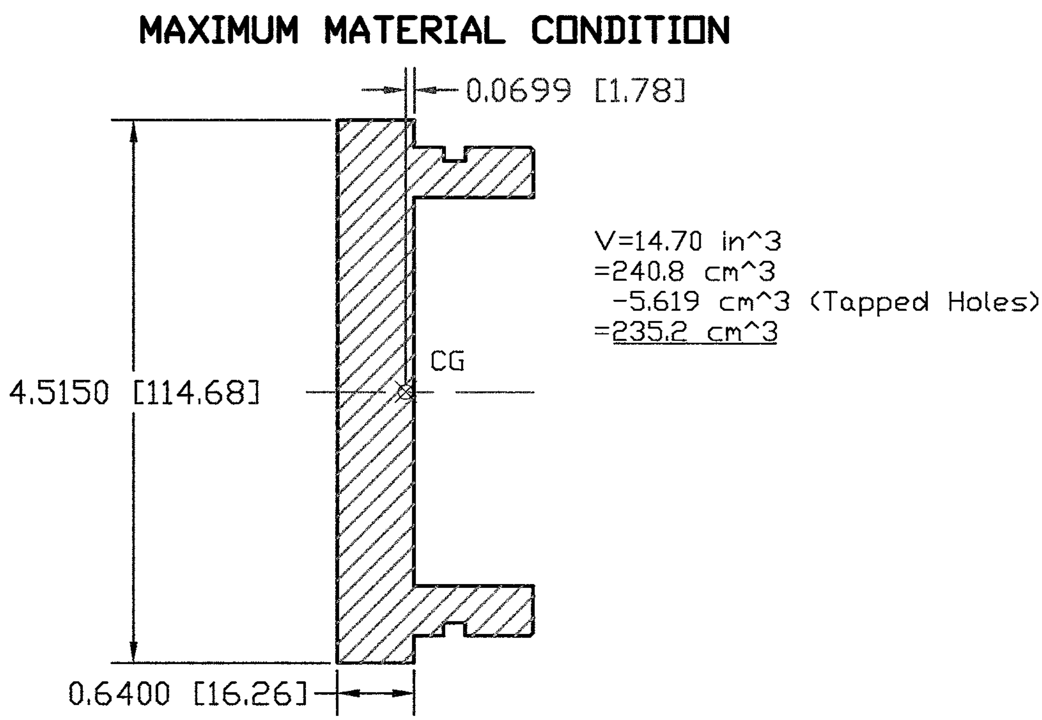


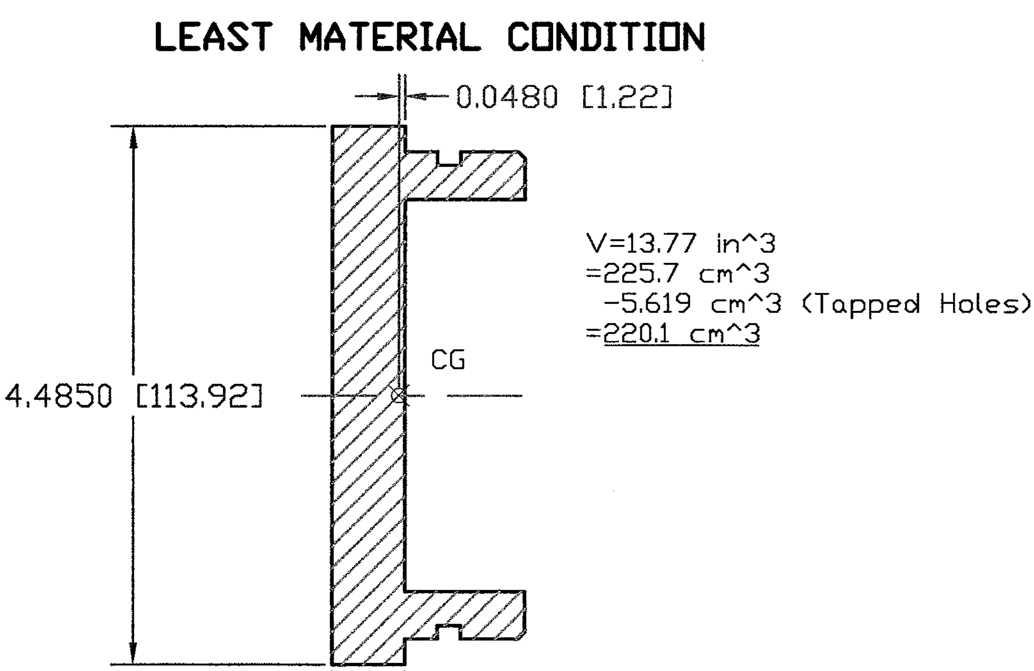
LEAST MATERIAL CONDITION



CG Calculations:
End Cap

inch [mm]

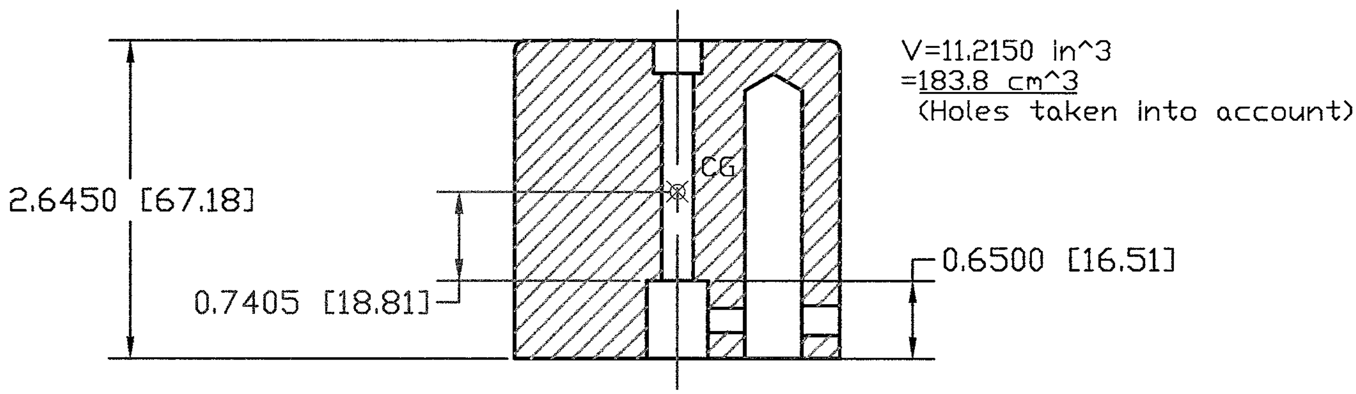




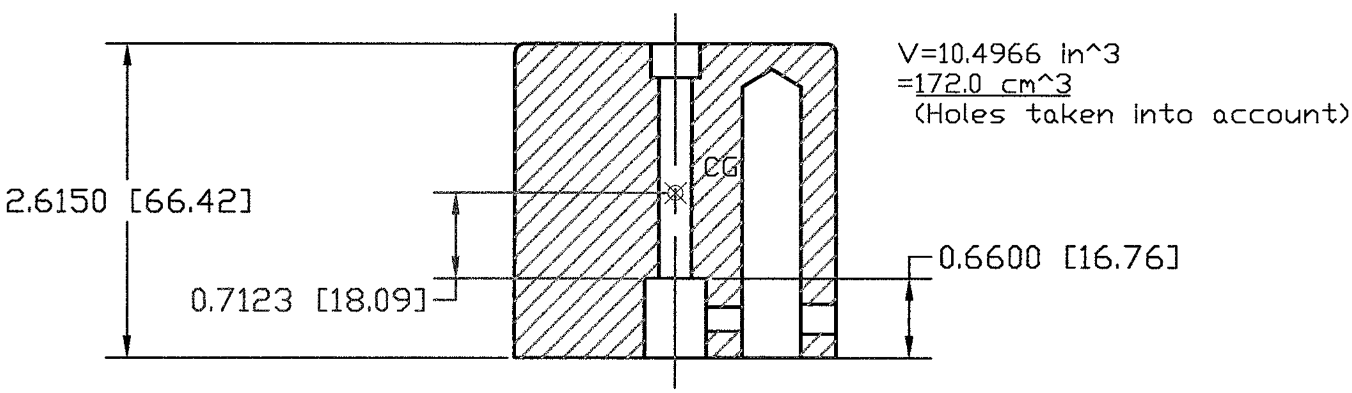
CG Calculations:
Piston

inch [mm]

MAXIMUM MATERIAL CONDITION



LEAST MATERIAL CONDITION

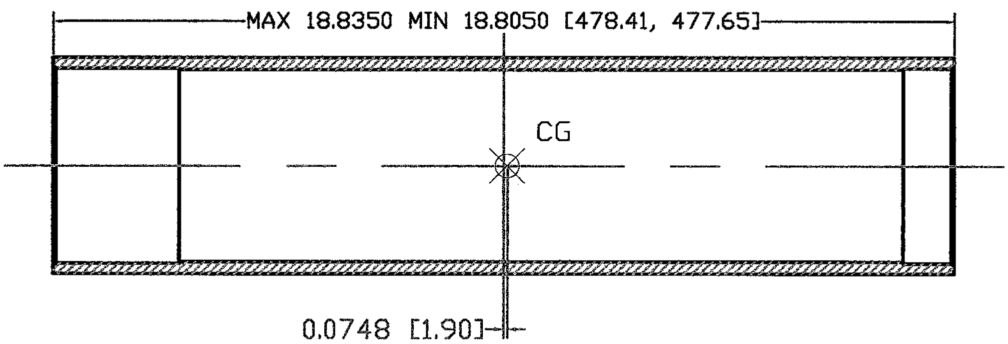


CG Calculations: Connecting Pipes

inch [mm]

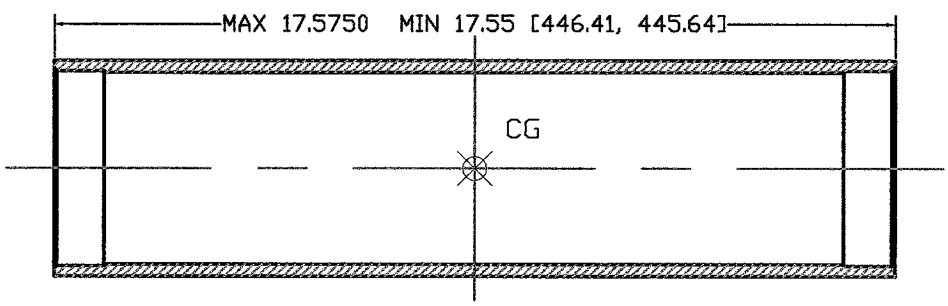
***Note: Change in volume due to tolerance variation is insignificant.**

DIAPHRAGM END PIPE



V=61.3881 in^3
=1006 cm^3

ELECTRONICS END PIPE



V=57.79 in^3
=947.0 cm^3

Appendix D - Drawings

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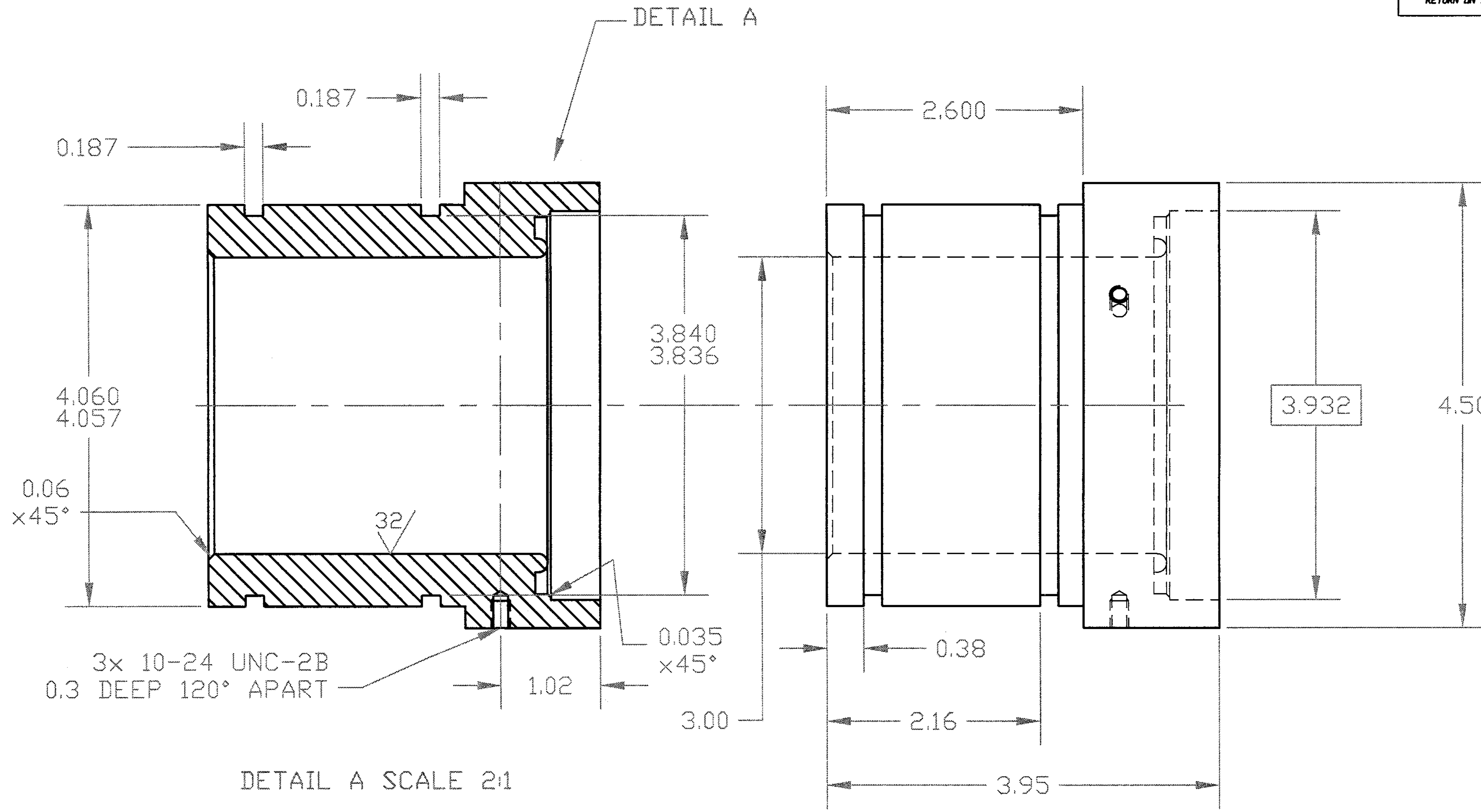
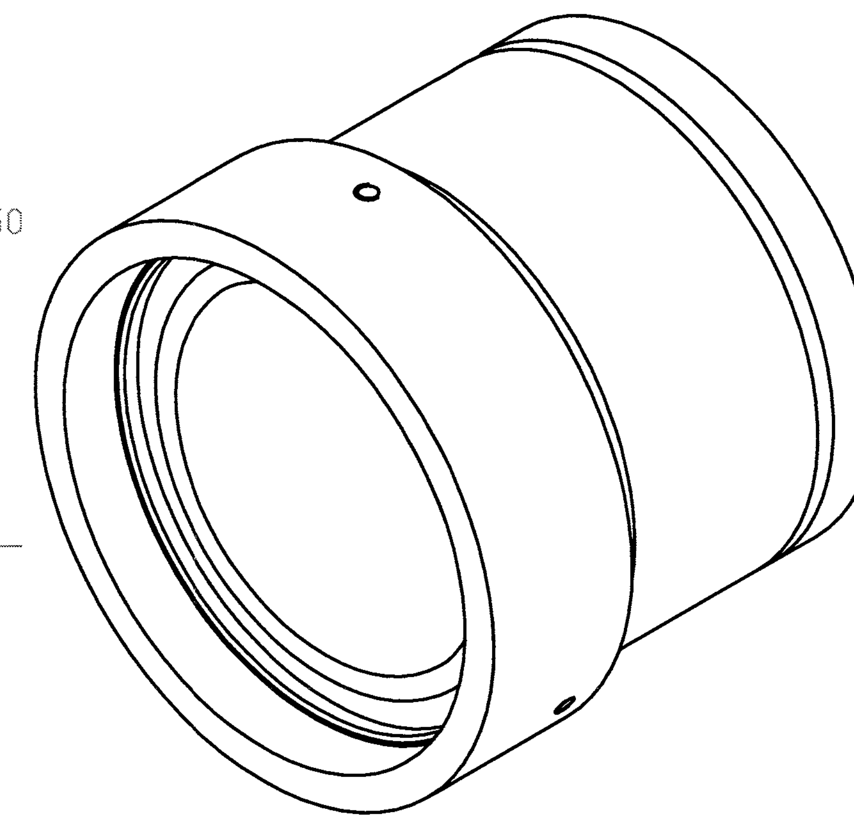
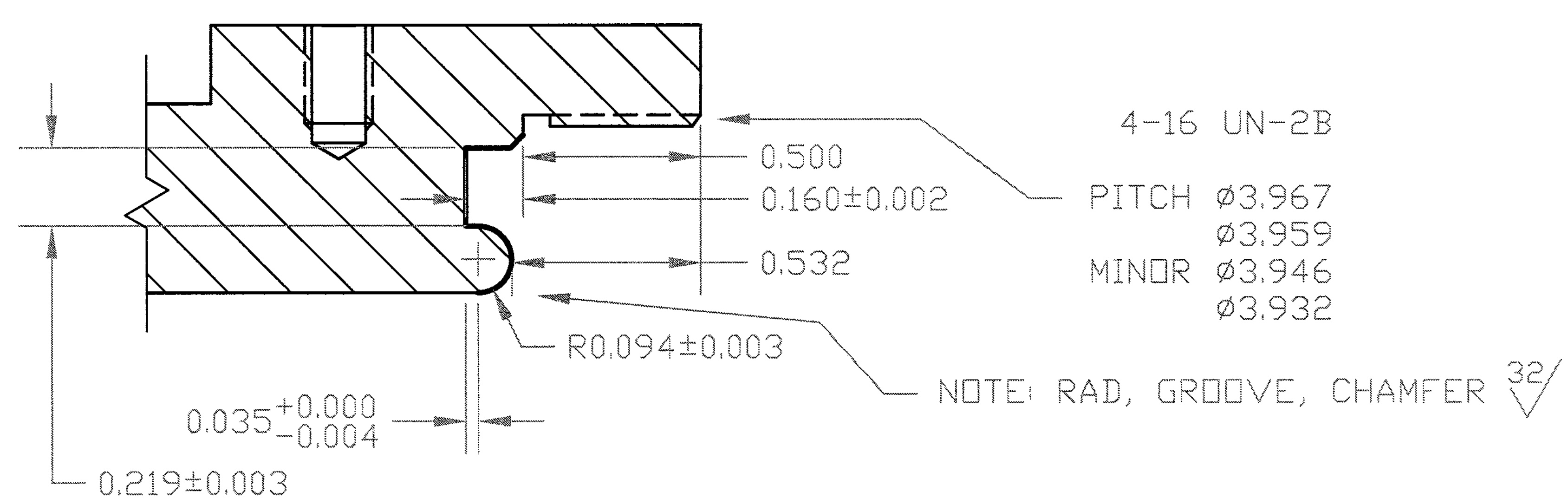
REVISIONS				
NO.	ZONE	DESCRIPTION	DATE	APPROVED
1	—	Issued For Comments	5.26.2004	BJS
2	B4	Overall Length Change	6.28.2004	BJS
3	A6	Added Dimension	6.28.2004	BJS

Note: Base has to be revised for $\frac{1}{4}$ dowel holes. See Drawing 891_10BS07 (No. 7)







Notes:
Deburr - Remove All Sharp Edges

NUMBER 891_10BS01

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St. John's NL A1B 3T5

TOLERANCES (unless specified)	
0. X	± 0.03
0. XX	± 0.015
0. XXX	± 0.005
Angle	± 0.5 deg.
Fabrication	± 0.04
Fraction < 6 Inch	± 1/64
> 6 Inch	± 1/32

Material: PVC
Heat Treatment: — — —
FINISH: 125 u-inch rms
DIMENSIONS IN: INCHES ☒ MILLIMETERS ☐
THIRD ANGLE

TRAX
DRAWN: B.Skillings
APPROVED
Quantity: 1

TITLE: **Diaphragm Mount Buoyancy Engine**

SCALE: 3:4 | NUMBER: 891_10BS01 | REV: 1
A2 | DATE: May 25, 2004 | SHEET 1 OF 1

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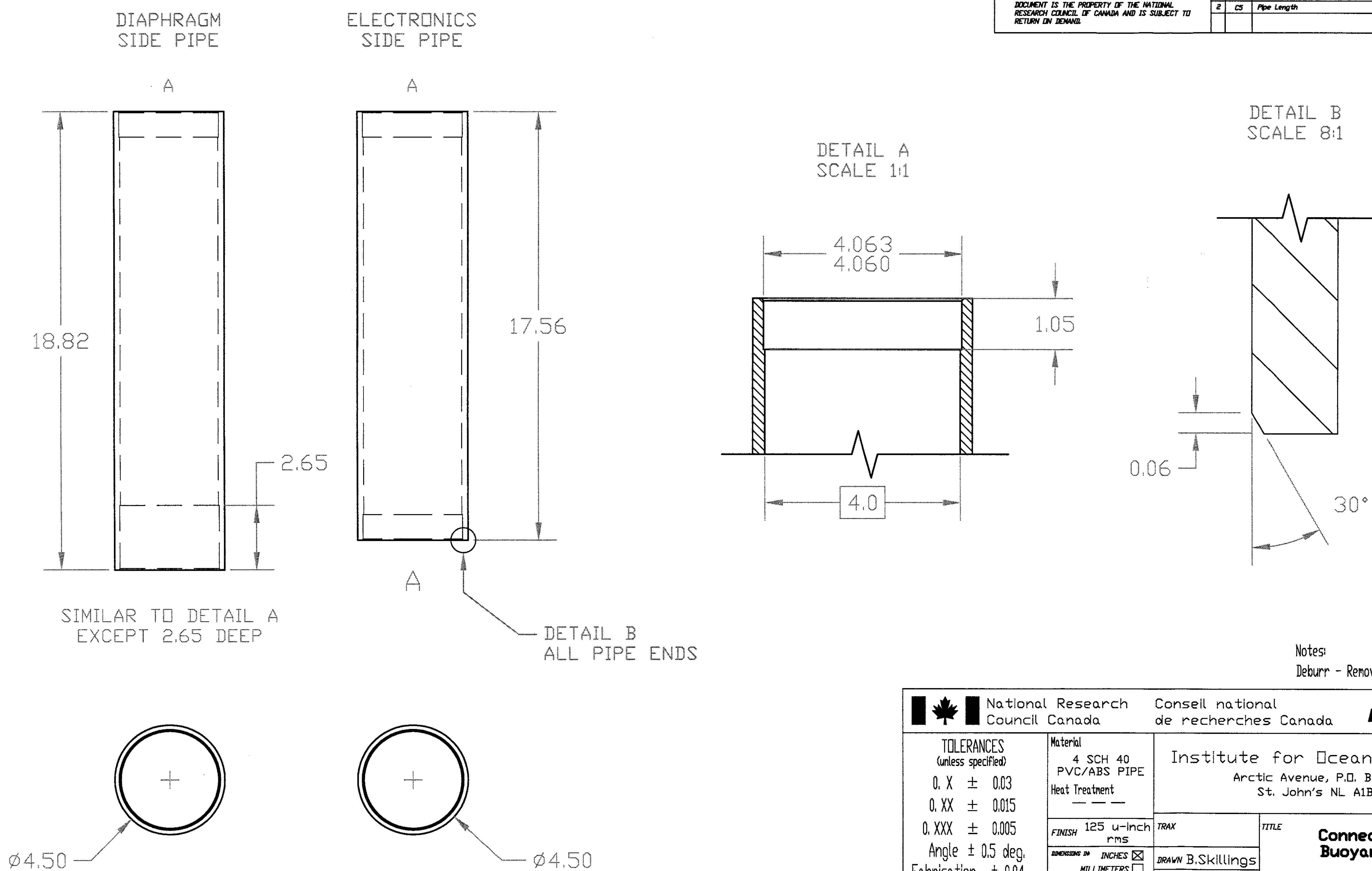
REVISIONS				
NO.	ZONE	DESCRIPTION	DATE	APPROVED
A0	--	Issued For Comments	5.26.2004	BJS
2	C8	Pipe Length	6.28.2004	BJS
2	C5	Pipe Length	6.28.2004	BJS



NUMBER 891_10BS06

Notes:
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St. John's NL A1B 3T5

TOLERANCES (unless specified)
0.X ± 0.03
0.XX ± 0.015
0.XXX ± 0.005
Angle ± 0.5 deg.
Fabrication ± 0.04
Fraction < 6 inch ± 1/64
> 6 inch ± 1/32

Material: 4 SCH 40 PVC/ABS PIPE
Heat Treatment: — — —
FINISH: 125 u-inch rms
DIMENSIONS IN: INCHES ☒ MILLIMETERS ☐
THIRD ANGLE

TRAX
DRAWN B.Skillings
APPROVED
Quantity 1

TITLE: **Connecting Pipes Buoyancy Engine**
SCALE 4:1
NUMBER 891_10BS06
REV 1
A2
DATE May 31, 2004
SHEET 1 OF 1

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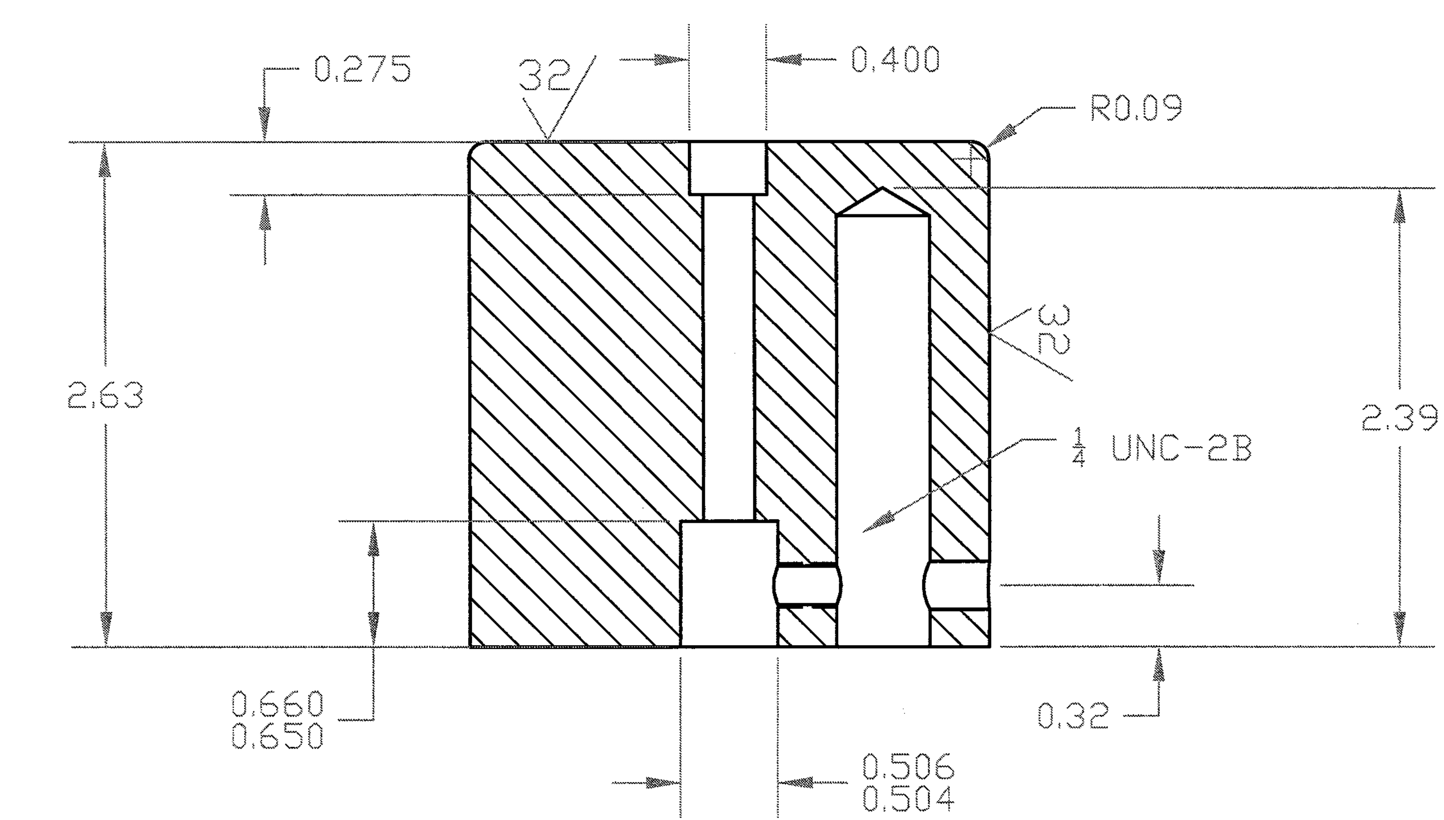
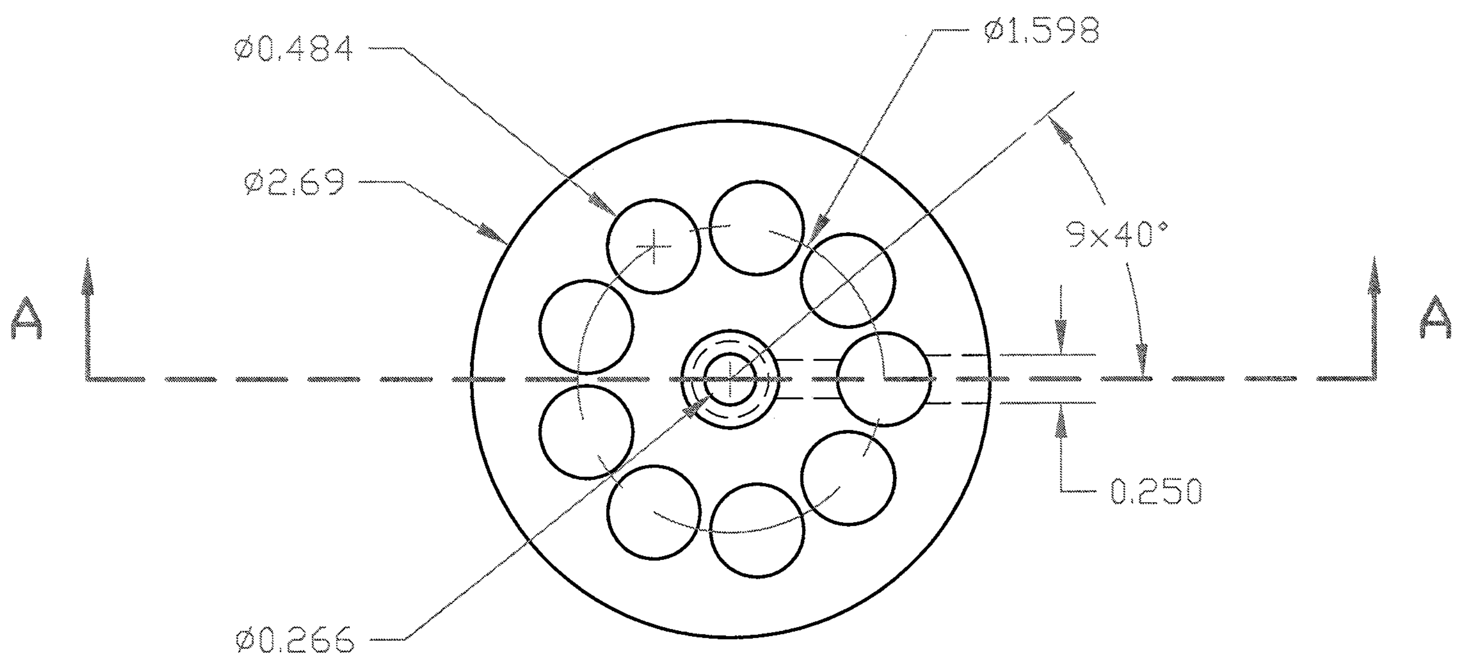
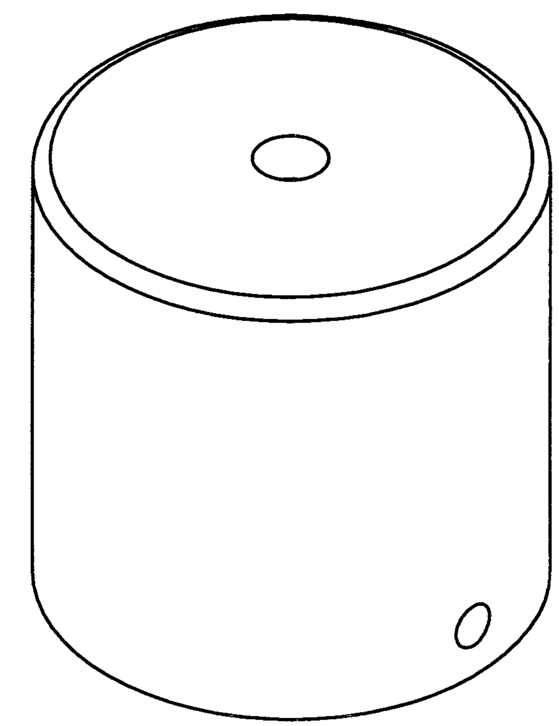
REVISIONS				
NO.	ZONE	DESCRIPTION	DATE	APPROVED
1	—	Issued For Comments	5.26.2004	BJS
2	C6	Lightening holes Instead of Slot	6.28.2004	BJS

SECTION A-A







Notes:
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NUMBER 891_10BS05

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St. John's NL A1B 3T5

TOLERANCES (unless specified)
0. X ± 0.03
0. XX ± 0.015
0. XXX ± 0.005
Angle ± 0.5 deg.
Fabrication ± 0.04
Fraction < 6 inch ± 1/64
> 6 inch ± 1/32

Material: Al 6061-T6
Heat Treatment: — — —
FINISH: 125 u-inch rms
DIMENSIONS IN: INCHES ☒ MILLIMETERS ☐
THIRD ANGLE

TRAX
DRAWN B.Skillings
APPROVED
Quantity 1

TITLE: **Piston Buoyancy Engine**
SCALE 1:1
NUMBER 891_10BS05
REV 1
A2 DATE May 21, 2004
SHEET 1 OF 1

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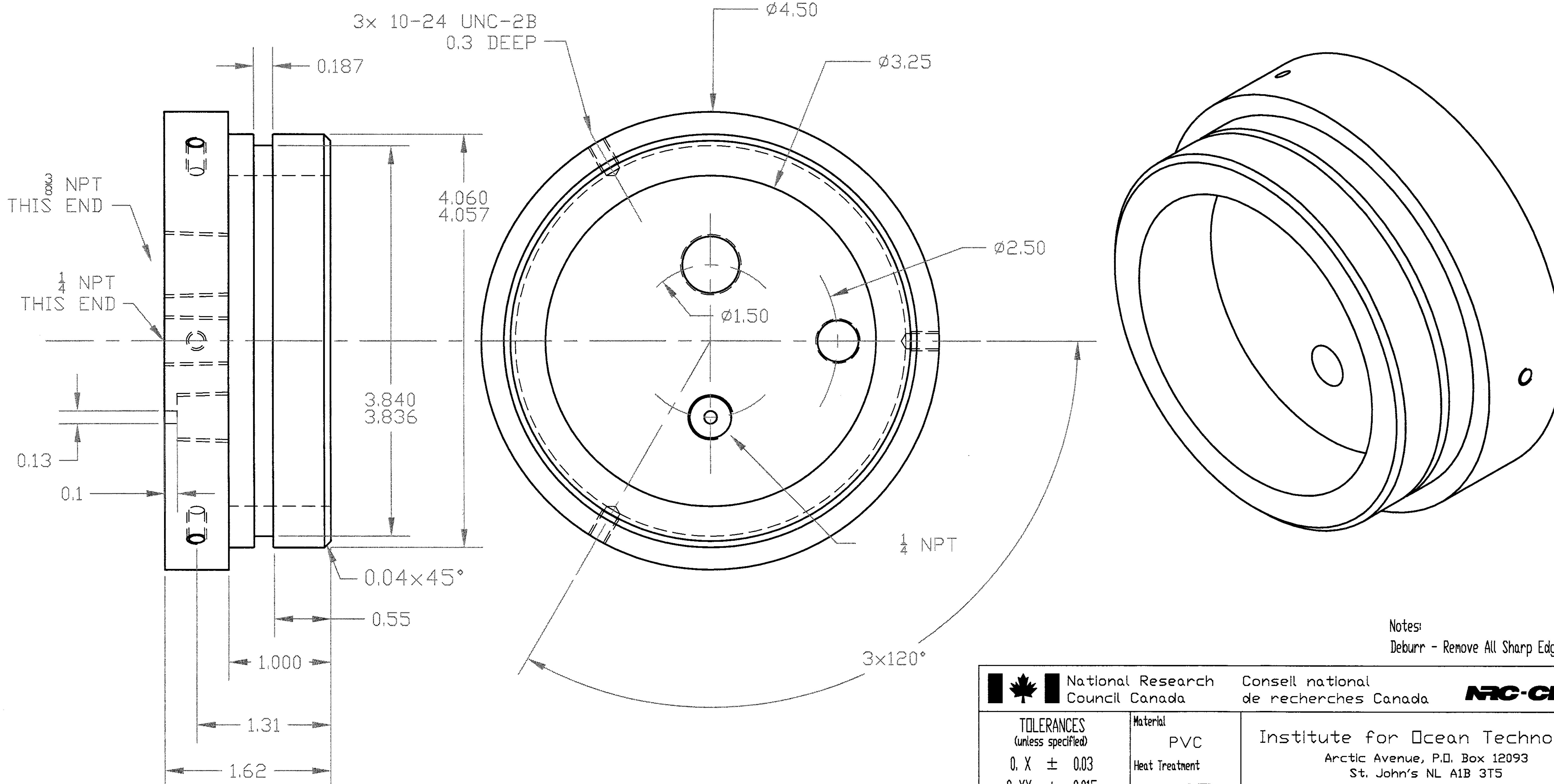
REVISIONS				
NO.	ZONE	DESCRIPTION	DATE	APPROVED
1	--	Issued For Comments	5.26.2004	BJS
2	C4	1/4 NPT Fitting Added	6.28.2004	BJS
3	A7	Overall Length Change	6.28.2004	BJS
4	B7	Chamfer Width Change	6.28.2004	BJS



Notes:

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NUMBER 891_10BS04

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TOLERANCES (unless specified)	Material: PVC	Institute for Ocean Technology, Arctic Avenue, P.O. Box 12093, St. John's NL A1B 3T5	
0. X ± 0.03	Heat Treatment: — — —		
0. XX ± 0.015	FINISH 125 u-inch rms	TRAX	TITLE: **End Cap Buoyancy Engine**
0. XXX ± 0.005	DIMENSIONS IN: INCHES ☒ MILLIMETERS ☐	DRAWN B.Skillings	
Angle ± 0.5 deg.	THIRD ANGLE	APPROVED	SCALE 1:1 — NUMBER 891_10BS04 — REV 1
Fabrication ± 0.04		Quantity 1	A2 — DATE May 25, 2004 — SHEET 1 OF 1
Fraction < 6 inch ± 1/64; > 6 inch ± 1/32			

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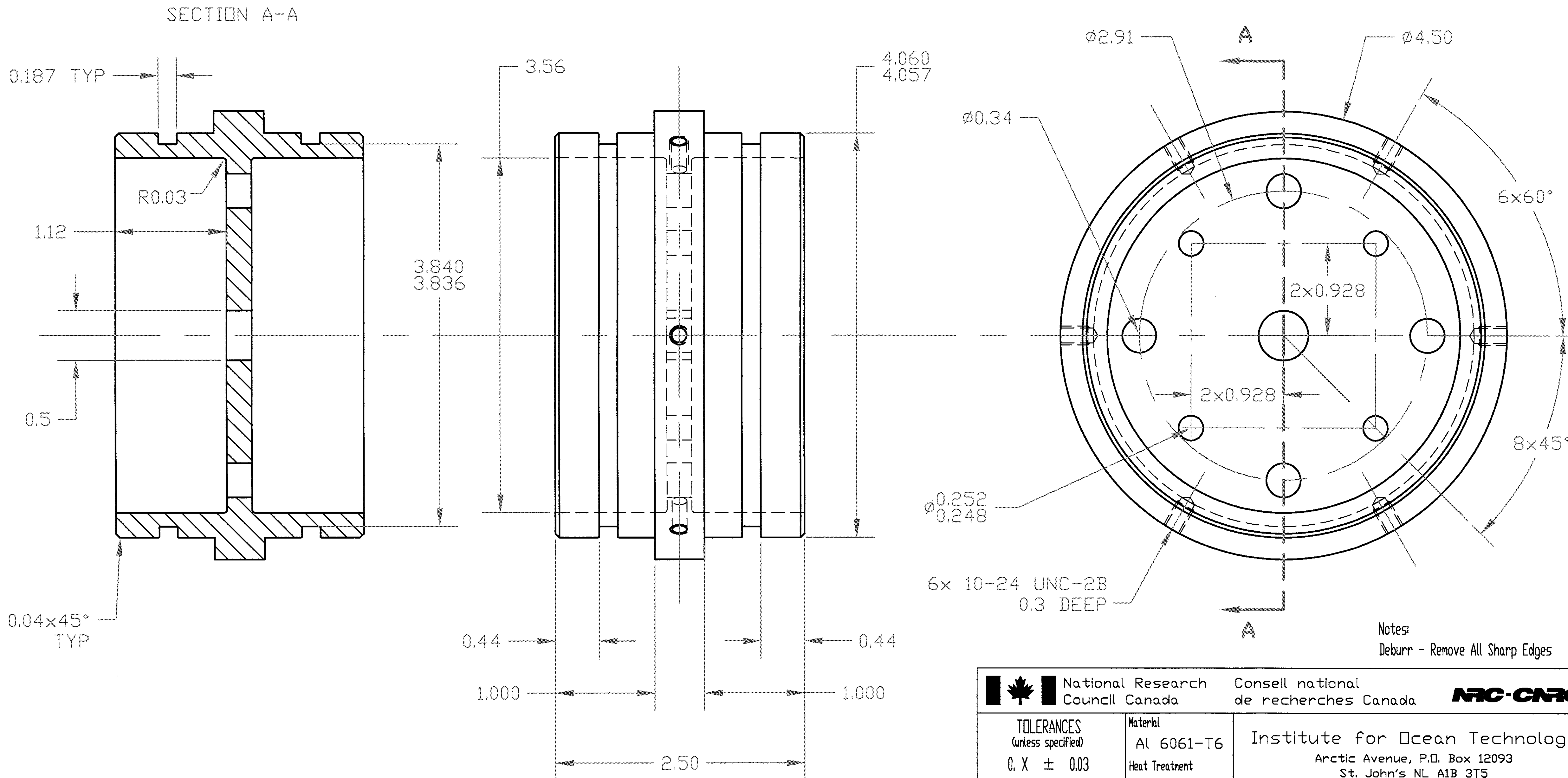
REVISIONS				
NO.	ZONE	DESCRIPTION	DATE	APPROVED
1	--	Issued For Comments	5.26.2004	BJS
2	C2	Alignment, Cord Holes	6.28.2004	BJS
3	C7	Inside Radius Change	6.28.2004	BJS
4	A8	Chamfer Width Change	6.28.2004	BJS



NUMBER 891_10BS03

National Research Council Canada / Conseil national de recherches Canada — NRC-CNRC

TOLERANCES (unless specified) 0. X ± 0.03 0. XX ± 0.015 0. XXX ± 0.005 Angle ± 0.5 deg. Fabrication ± 0.04 Fraction < 6 inch ± 1/64 > 6 inch ± 1/32	Material: Al 6061-T6 Heat Treatment: — — — FINISH 125 u-inch rms DIMENSIONS IN: INCHES ☒ MILLIMETERS ☐ THIRD ANGLE	Institute for Ocean Technology Arctic Avenue, P.O. Box 12093 St. John's NL A1B 3T5

TRAX	TITLE: Mid-Body Section Buoyancy Engine		
DRAWN B.Skillings			
APPROVED	SCALE 1:1	NUMBER 891_10BS03	REV 1
Quantity 1	A2	DATE May 21, 2004	SHEET 1 OF 1

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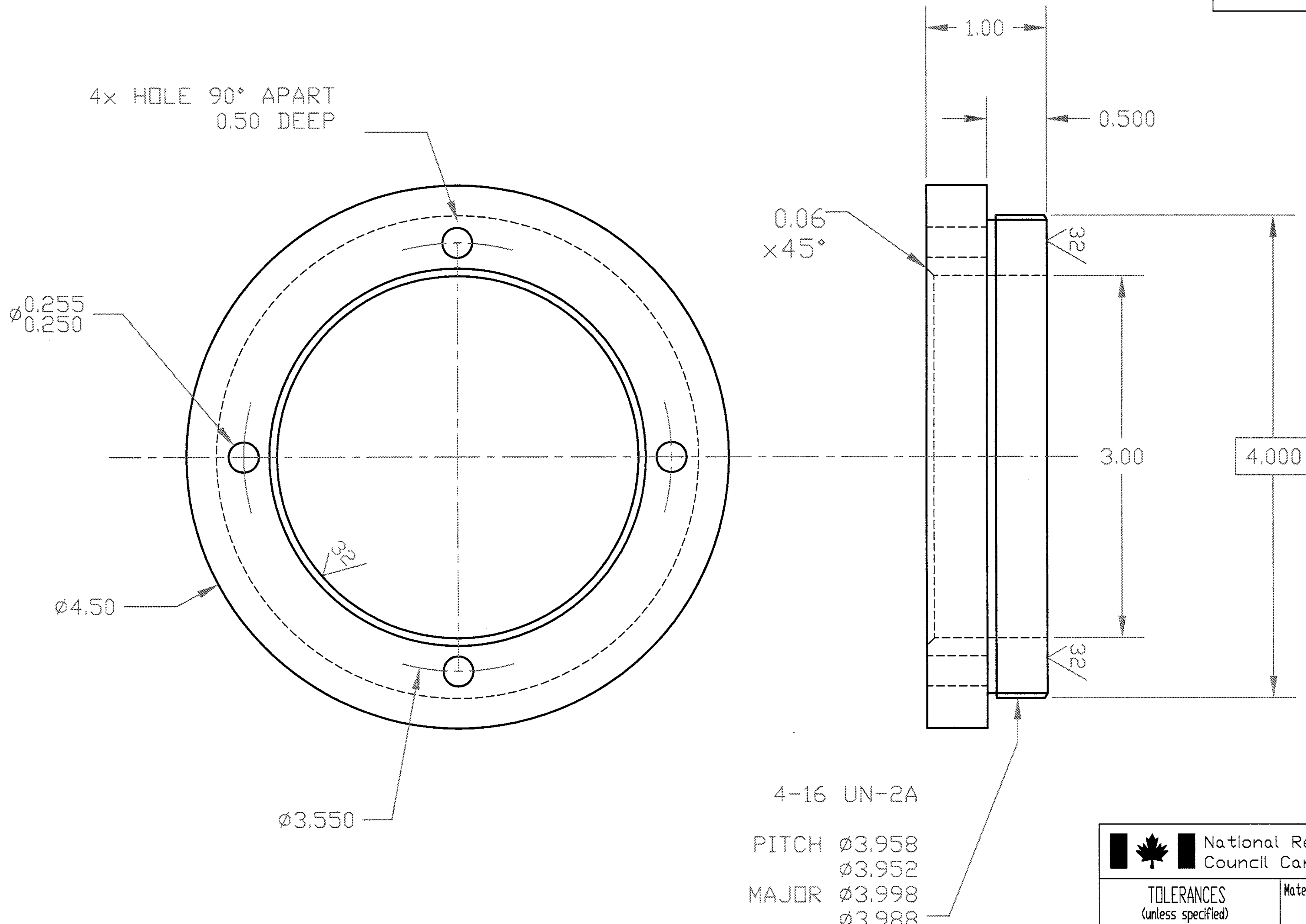
REVISIONS

NO.	ZONE	DESCRIPTION	DATE	APPROVED
A0		Issued For Comments		



Notes:
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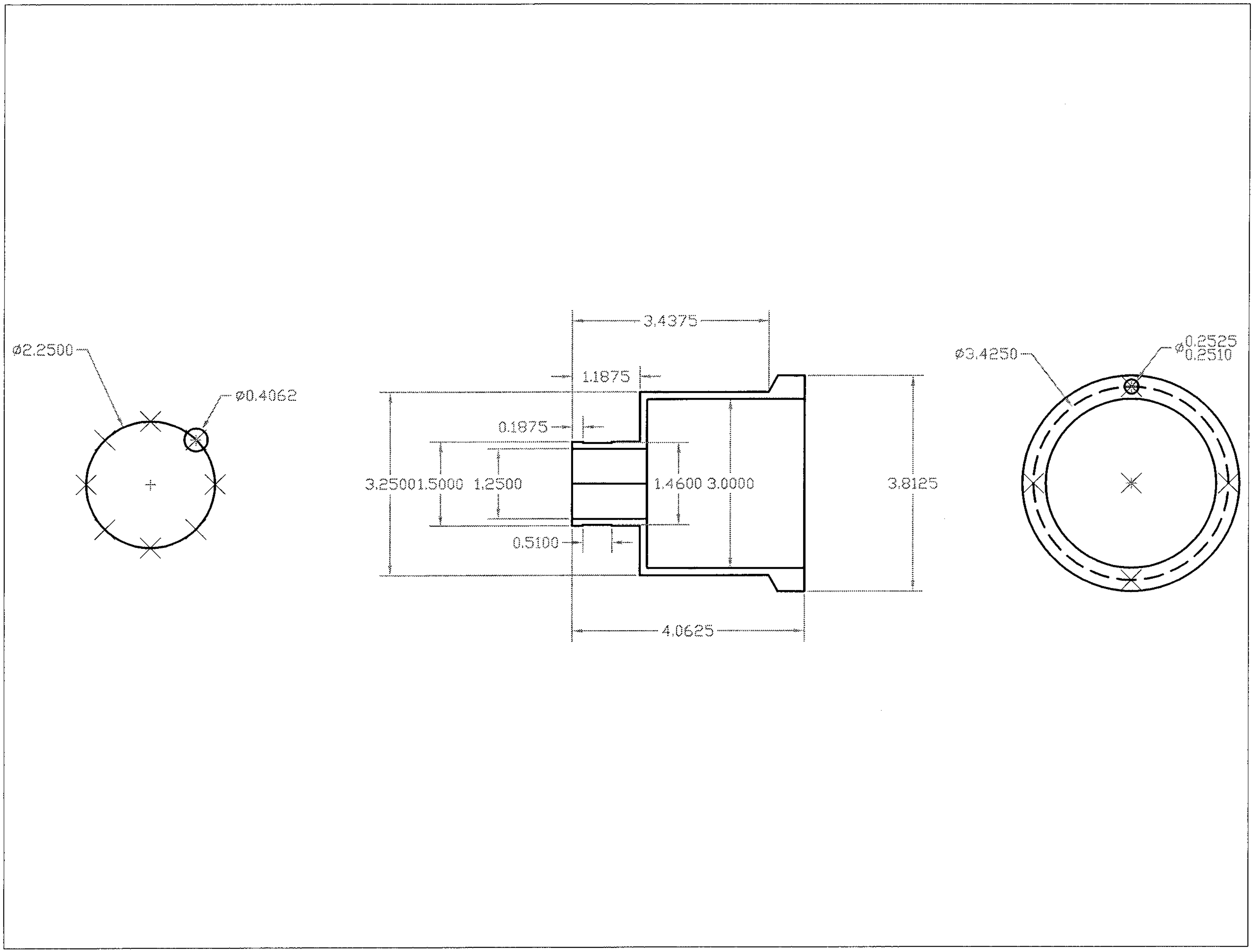
TOLERANCES (unless specified)
0. X ± 0.03
0. XX ± 0.015
0. XXX ± 0.005
Angle ± 0.5 deg.
Fabrication ± 0.04
Fraction < 6 inch ± 1/64
> 6 inch ± 1/32

Material: PVC
Heat Treatment: — — —
FINISH: 125 u-inch rms
DIMENSIONS IN: INCHES ☒ MILLIMETERS ☐
THIRD ANGLE

TRAX
DRAWN B.Skillings
APPROVED
Quantity 1

TITLE: **Diaphragm Nut Buoyancy Engine**

SCALE 1:1 | NUMBER 891_10BS02 | REV
A2 | DATE May 21, 2004 | SHEET 1 OF 1



Ø2.2500
Ø0.4062
3.4375
1.1875
0.1875
3.2500
1.5000
1.2500
1.4600
3.0000
0.5100
4.0625
3.8125
Ø3.4250
Ø0.2525
0.2510

Actuator Hold-Down