Design of pitch and roll control for IOT glider

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SUMMARY

This report outlines modifications that have been designed for the IOT glider during my term at IOT. This includes investigation of an alternative hull for the glider and design of a pitch and roll control mechanism. The glider body is currently constructed of ABS pipe. Changing the body to aluminium was investigated. It was concluded that due to mass constraints, the inside diameter will need to be modified. As this is a detailed procedure, the switch to aluminium pipe has been postponed.

The IOT glider moves using changes in the glider's volume, and therefore buoyancy. This change carries with it a change in pitch as well. However, fine-tuning of pitch angle is not currently possible. The mechanism outlined in this report uses internal actuation to change the location of the vehicle's center of gravity (CG) to finely adjust the pitch and roll attitude of the vehicle. This system slides the vehicle's battery pack forward and aft to adjust trim and offsets the battery pack to the left or right of centerline to adjust roll. In this manner the CG of the vessel is manipulated causing the orientation of the vehicle to change. This report describes the process involved in designing this mechanism and outlines the way forward for manufacturing and installing it in the IOT glider.

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DESIGN OF PITCH AND ROLL CONTROL FOR THE IOT GLIDER

SR-2005-28

Gerald Hewitt

December 2005

Summary

The goal of the IOT glider project is to design and construct an autonomous underwater glider. Gliders move through the water using changes in buoyancy to generate upward or downward forces. Through the use of wings, these vertical forces are translated into horizontal movement in the water.

This report outlines modifications that have been designed for the IOT glider during my term at IOT. This includes investigation of an alternative hull for the glider and design of a pitch and roll control mechanism.

The glider body is currently constructed of ABS pipe. This pipe is readily available and inexpensive. However, it is prone to bending and not durable enough for a vehicle that is assembled and disassembled on a regular basis. Changing the body to aluminium was investigated. This would involve purchasing an aluminium pipe and, since the aluminium pipe is quite heavy, machining it to reduce its volume. It was concluded that machining the outside of the pipe was not a viable option because it would reduce the buoyant force of the glider. Therefore, the inside diameter will need to be modified. As this is a more detailed procedure, the switch to aluminium pipe has been postponed.

The IOT glider moves using changes in the glider's volume, and therefore buoyancy. This change carries with it a change in pitch as well. However, fine-tuning of pitch angle is not currently possible. The mechanism outlined in this report uses internal actuation to change the location of the vehicle's center of gravity (CG) to finely adjust the pitch and roll attitude of the vehicle. This system slides the vehicle's battery pack forward and aft to adjust trim and offsets the battery pack to the left or right of centerline to adjust roll. In this manner the CG of the vessel is manipulated causing the orientation of the vehicle to change. This report describes the process involved in designing this mechanism and outlines the way forward for manufacturing and installing it in the IOT glider.

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1.0 Aluminium Body for Buoyancy Engine Portion

Currently the IOT glider is constructed in two distinct pieces, one housing the electronics and one housing the buoyancy engine (BE). Each of these sections is constructed using ABS Drainway for an outer body and machined PVC end caps. In his examination of the BE section Ben Skillings discovered that the body was not straight. His findings are documented in NRC LM-2004-21. This condition means that as the piston moves it is not centered in the body of the buoyancy engine. In order to rectify this situation, an aluminium alignment piece was installed. This piece acts to guide the piston ensuring that it is centered inside the BE.

Aside from adding critical weight to the glider, this alignment piece also over constrains the BE linear actuator. This over-constraint caused high stress concentrations to build up at the base of the BE actuator. This caused the shaft to separate from the motor body. While the problem was corrected using a simple clamp collar, elimination of the alignment piece was considered to be the best way forward.

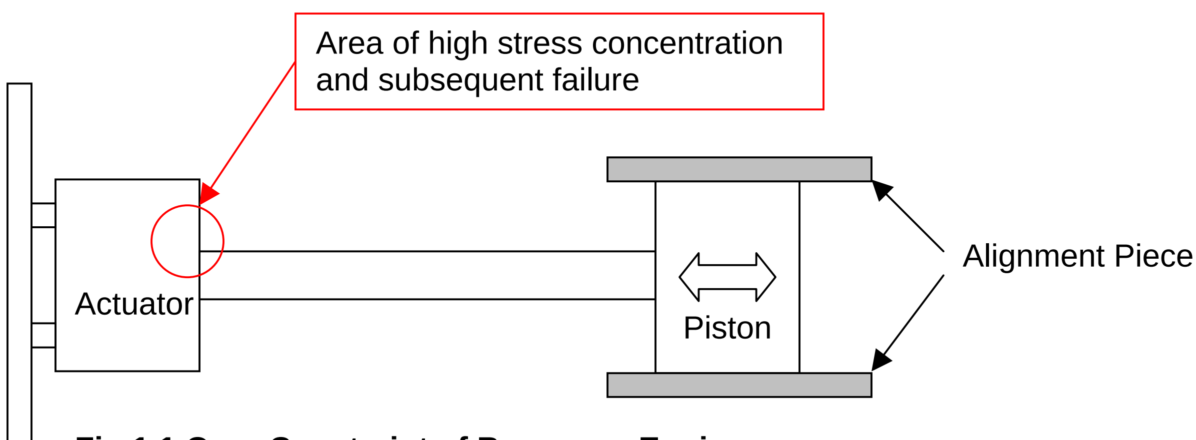


Fig 1.1 Over-Constraint of Buoyancy Engine.

One solution to eliminate the alignment piece would be to install a straight, machined aluminium body for the BE portion of the glider. In order to mate with the existing parts the new body would require an ID of 4.026”, but the OD was not closely restricted except that it needed to provide sufficient structural support for the glider. The closest, commercially available product was schedule 40 aluminium pipe. The properties of this pipe are listed in the table below.

ASTM Specification	ASTM B241
Shape	Pipe
Pipe Type	Unthreaded
Pipe Size	4"
Pipe to Pipe Connection	Unthreaded (pipe)
Schedule	40
Length	36"
Inside Diameter	4.026"
Outside Diameter	4.5"
Wall Thickness	.237"
Specifications Met	American Society for Testing and Materials (ASTM)

Table 1.1 Properties of SCH 40 Aluminium Pipe

Because of the wall thickness this pipe is much heavier then the ABS. Two methods of reducing the weight of the pipe were considered; reducing the OD, boring the ID. Reducing the OD of the pipe was considered the easier of the two options and was looked into in some detail. As is outlined in Fig 1.2. The aluminium pipe, before machining, would be 2.6 kilograms, approximately 1.6 kilograms heavier then the ABS.

Direct comparison of ABS - Aluminum pipe

ID	4.026	(in)
OD	4.5	(in)
WT	0.237	(in)

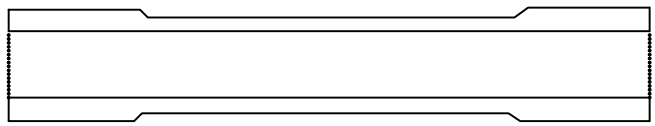
	Area (cm2)	Length (cm)	Vol (cm3)	Density (g/cm2)	Mass (g)
Aluminum	20.478	47.6	974.7	2.7	**2631.8**
ABS	20.478	47.6	974.7	1.04	**1013.7**

Displaced volume	4884.2

Fig 1.2 Aluminium vs. ABS body.

This highlighted the importance of reducing the mass of the pipe. The option that was considered to be most favourable was to reduce the OD of the pipe, only in the center portion. In this way the OD could be changed gradually and the full wall thickness would be available to mate with the existing end cap and divider. The figure below shows the results of this analysis. As can be seen the combination of removing the alignment piece, and machining the OD of the pipe to 4.25” balance the increased mass of the aluminium to within 10 grams. However, since reducing the outside of the pipe also reduces its displaced volume, the net effect is a significant reduction in buoyant force. At an OD of 4.25”, the wall thickness would only be 1/8”, and it was decided that any further reduction would jeopardize the structural integrity of the vehicle. The conclusion was made that if the ID of the pipe could be bored (center portion only) to 4.25”, the aluminium body would be a feasible option. However, due to the current lead times associated with this machining the project was deferred until a later date.

Reduction of Mass by Machining the Center Portion of the Pipe OD



ID (in)	4.026	4.026	4.026
OD (in)	4.5	4.25	4.5
WT(in)	0.237	0.112	0.237
L (cm)	4	39.6	4

Area (cm2)	20.478	9.393	20.478	
Vol (cm3)	81.91	371.98	81.91	
Mass (g)	221.2	1004.3	221.2	1446.7
Displaced volume	410.4	3624.4	410.4	4445.2

ABS - Aluminum mass difference (g)	432.9
Mass of alignment piece (g)	316.7
Mass of counterweight on actuator shaft (g)	100.2
Additional weight due to aluminum body (g)	**16.0**
Reduction in Displaced volume due to machining (cc)	438.9
Total Effect (g)	**455.0**

Fig 1.3 Proposed Design of Aluminium Body for BE Portion of the IOT Glider

2.0 Pitch and Roll Control Design

2.1 Background

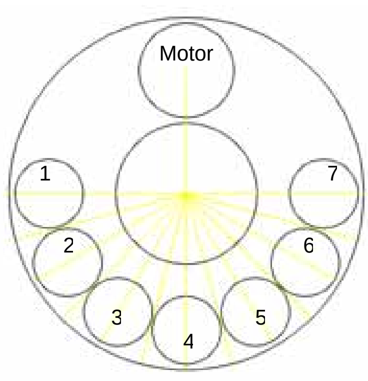
Pitch and roll control of underwater gliders is normally provided by internal actuation. Internal actuation refers to the manipulation of the vehicle's center of buoyancy and/or center of gravity to control movement. The control system normally employed involves moving the vehicle's battery pack(s) to change the center of mass. By sliding the battery pack forward or aft the vehicle's center of mass moves horizontally, controlling pitch. By rotating the battery pack about the longitudinal axis of the vehicle, the center of mass can be shifted to one side. This causes the vehicle to roll, instigating a change in yaw.

2.2 System Design

The first step in the system design was to decide what mass would be moved in order to manipulate the center of gravity. In this case the decision was made to design the system based on movement of a single battery pack, containing seven lithium ion batteries. These batteries would be mounted on a sleeve bearing that would ride on the shaft of the BE actuator. This would allow the batteries to translate for pitch control, and rotate around the shaft for roll control.

Fig 2.1 BE Actuator with Battery Pack Sleeve Bearing.

Each of these batteries has a mass of 47 g (329 g total), a diameter of 18 mm and length of 65 mm. It was important to situate the batteries around the shaft so that the CG of the battery pack was as low as possible. This would allow for the maximum vehicle roll for minimum motor actuation. The arrangement of the batteries is shown below along with the calculation for their center of mass.



Battery #	Mass	X-Coord	Y-Coord	Mass x X	Mass x Y
	(g)	(cm)	(cm)	(g cm)	(g cm)
1	47	-2.858	0.000	-134.30	0.00
2	47	-3.188	-1.842	-149.82	-86.55
3	47	-1.429	-3.189	-67.15	-149.91
4	47	0.000	-3.683	0.00	-173.10
5	47	1.429	-3.189	67.15	-149.91
6	47	3.188	-1.842	149.82	-86.55
7	47	2.858	0.000	134.30	0.00
	329	4.44E-16	-12.4325	-2.84E-14	-646.013
			Center of Mass:	0.000	-1.964
			Moment of Batteries:		-6.337

Fig 2.2 Battery Arrangement and Center of Gravity.

Having clearly defined the mass that would be moved, the next step was to determine how to move it. It was apparent that two independent drives would be required, one for pitch and one for roll. This would permit infinite combinations of pitch and roll.

The initial design of the system is shown in Fig 2.3. It involved sliding an outer carriage along the BE actuator shaft, and rotating the battery pack inside this carriage. In this way, a linear actuator could slide the carriage, and a motor and gear arrangement mounted on the carriage could rotate the battery pack. However, it became apparent during the design process that, as the battery pack rolled a significant torque would be placed on the actuator. While this could be rectified using guide rods and/or a keyway milled in the main actuator shaft, this would complicate the matter further. Instead a different, less complicated design was developed.

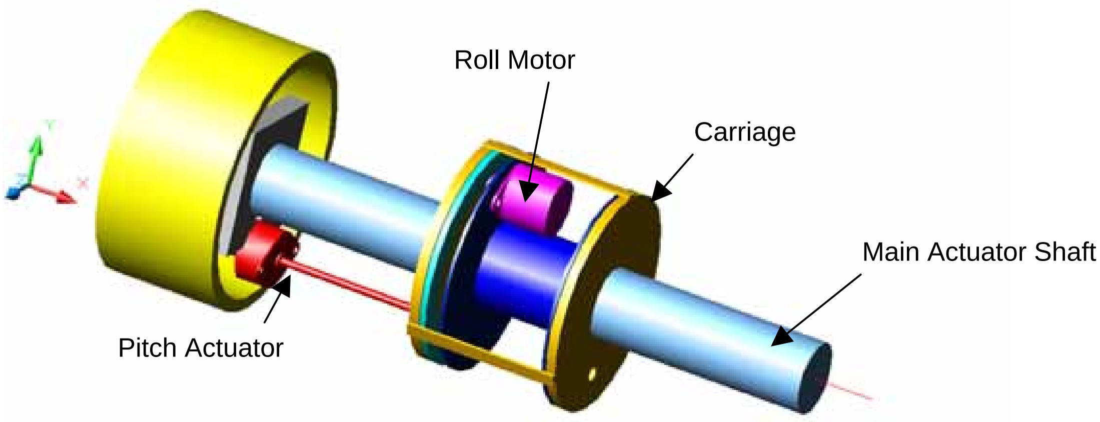


Fig 2.3 Initial Design of Pitch and Roll Mechanism.

The second design involved rotating the carriage, and sliding the battery pack inside this cage. The outer carriage is 8 inches long and allows the battery pack 4” of travel. The carriage has an outside diameter of 3.75” and can rotate through 360°. This simplified the design because the larger carriage is now only rotating, not sliding.

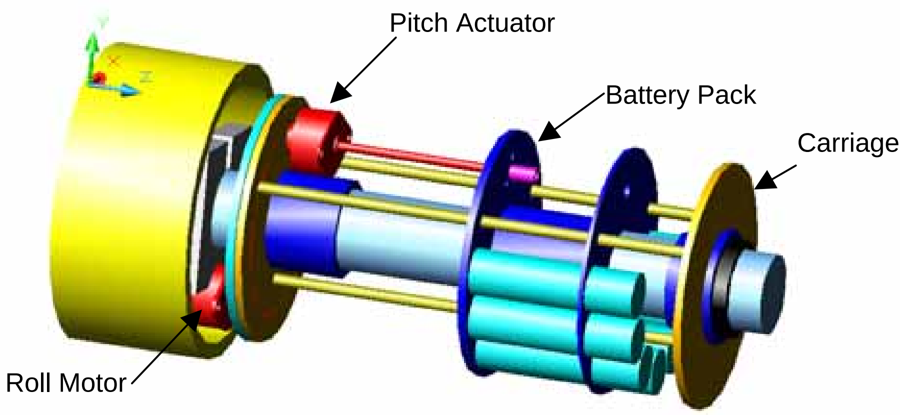


Fig 2.4 Final Design of Pitch and Roll Mechanism.

The linear actuator (for pitch control) is mounted inside the carriage. It rolls with the carriage, which means it is fixed relative to the battery pack that it is controlling. Guide rods run through the carriage and battery pack. These rods support the torque associated with offsetting the CG of the battery pack. This relieves lateral stress from the pitch actuator, which was the major problem with the initial design.

The carriage is rolled using a stepper motor attached to the motor body of the BE actuator. There is a small spur gear attached to the motor, which meshes with a larger internal ring gear attached to the carriage. In this manner the motor can be controlled to roll the carriage when required, independently of any pitch control movements taking place within the carriage.

2.3 Component Sizing

The first step in sizing the components was to locate a suitable internal ring gear. This gear needed to be less then 4” OD and required a pitch diameter that would allow the spur gear to be mounted in the manner described above. The ring gear selected was a 48 pitch, 3” pitch diameter with a 3.75” OD. The spur gear to mesh with it is a 48 pitch; 0.375” pitch diameter with a 0.125” bore. This combination provides a gear ratio of 8.

$$G.R. = \frac{PitchDiameter_{RingGear}}{PitchDiameter_{SpurGear}} = \frac{3.0}{0.375} = 8$$

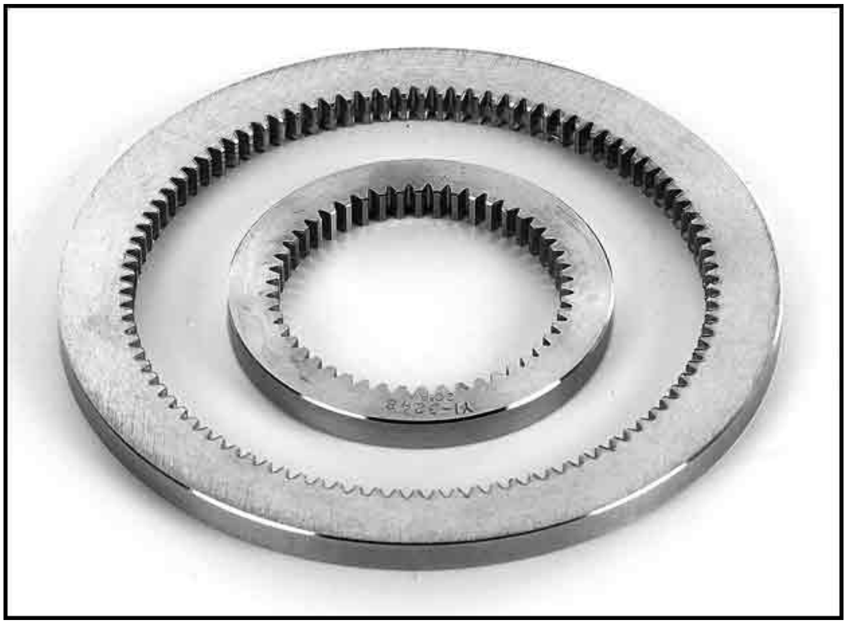


Fig 2.5 Internal Ring Gear.

Secondly, the pitch actuator was sized. The pitch actuator needs to move the battery pack along 4” of travel within the carriage, and provide enough thrust to slide the pack when the glider is pitching at 45°. The design mass used for the battery pack was 500 g (329 g for batteries, 171 g for the sleeve and mounting)

This meant the required thrust is:

$$Force = mg\cos 45° = 0.5kg \cdot 9.81m/s^2 \cdot \cos 45° = 3.5N$$

Based on this criterion a Haydon Switch and Instruments, Z26 linear actuator was selected. This actuator will deliver greater than 5 N of thrust.

Sizing the motor for roll control was more detailed. The critical parameter for this sizing was hold torque. The design value of hold torque was obtained by considering the worst-case scenario for roll. When the carriage is rolled to 90° left or right, the CG of the batteries is furthest offset from the centerline. In this case the moment created by the batteries is partially offset by the moment created by the pitch actuator mounted on the top half of the carriage.

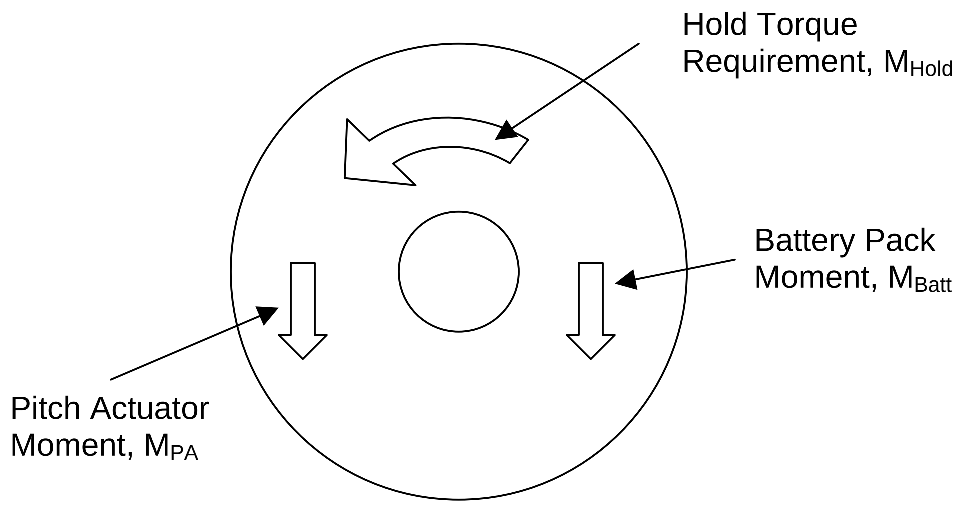


Fig 2.6 Free body Diagram of Carriage

$$M_{PA} = m_{PA} \cdot g \cdot r_{PA} = 34g \cdot 9.81m/s^2 \cdot 3.3cm = 1.10Ncm$$

$$M_{Batt} = m_{Batt} \cdot g \cdot r_{Batt} = 329g \cdot 9.81m/s^2 \cdot 1.96cm = 6.34Ncm$$

$$M_{Hold} = M_{Batt} - M_{PA} = 6.34Ncm - 1.10Ncm = 5.24Ncm$$

$$M_{Motor} = \frac{M_{Hold}}{GR} = \frac{5.24Ncm}{8} = 0.655Ncm$$

The stepper motor selected for this application was a HSI, Z26 motor with an output hold torque of 1.0 N·cm. This motor also has a 0.125” shaft diameter, which matches the bore of the spur gear without any further machining.

2.4 Construction

The construction schedule for this project depends largely on the availability of machines and personnel in the IOT machine shop. Each of the pieces that require machining will be manufactured here. A list of those pieces is presented below and detailed drawings are attached in Appendix A. These pieces are similar in that they are all made form 1/8” aluminium, each has an OD of 3.75” and ID of 1.5”. However, since each serves a different purpose, each will have to be machined individually.

Table 1: Description of Components to be Machined

Item	Qty	Description
1	1	Aft Carriage plate – Made from 1/8” aluminium and drilled to accommodate guide rods on one side and attachment of the internal ring gear on the other.
2	1	Pitch Actuator Mount – Made form 1/8” aluminium, drilled to allow guide rods to pass through and drilled and tapped for motor mounting screws.
3	1	Aft Battery Plate – 1/8” aluminium, drilled to accept guide rod bearings and allow attachment of the flanged nut of the actuator shaft
4	1	Fwd Battery Plate – 1/8” aluminium, drilled to accept guide rod bearings, and to hold the battery pack
5	1	Fwd Carriage Plate – 1/8” aluminium drilled for attachment of the guide rods
6	1	Stepper Motor Mount – 1/8” aluminium drilled for motor attachment and mounted to the BE actuator

Aside from the pieces manufactured here, a number of piece need to be purchased as well. A list of these pieces is presented in Table 2 below

Table 2: Description of Components to be purchased

Item	Qty	Description	Supplier Product #
1	1	Stepper Motor	Haydon Switch and Instrument Z26440
2	1	Linear Actuator	Haydon Switch and Instrument Z26 External
3	2	1.25” Flanged Delrin Sleeve Bearing	McMaster-Carr 2705T45
4	10	3/16” Flanged Delrin Sleeve Bearing	McMaster-Carr 2705T11
5	4	3/16” PEEK Sleeve Bearing	McMaster-Carr 6627K11
6	1	3” , 48 pitch Internal Gear	Small Parts Inc. GBI-48144
7	1	0.375” , 48 pitch Spur Gear	Small Parts Inc. GBS-48018

3.0 Conclusion and Recommendations

At present the IOT glider body is sufficiently strong, and the piston centered so as to allow construction of the pitch and roll mechanism. It would be recommended to pursue the change in body from ABS to aluminium after the pitch and roll mechanism is installed. This would involve machining the ID of the pipe so that the wall thickness is reduced to 0.125”.

The way forward for the pitch and roll controller is to order the appropriate parts as outlined above. The lead-time for some of these components, gears and motors, will likely be 2 to 3 weeks.

The machining of parts for the pitch and roll controller will also need to be initiated. Drawings for these components are attached in Appendix A.

4.0 References

Haydon Switch and Instruments. Supplier of Stepper Motor and Linear Actuator.
http://www.hsi-inc.com/

International Aluminium Institute
http://www.world-aluminium.org/

McMaster-Carr. Supplier of Aluminium pipe and sleeve bearings.
http://www.mcmaster.com/

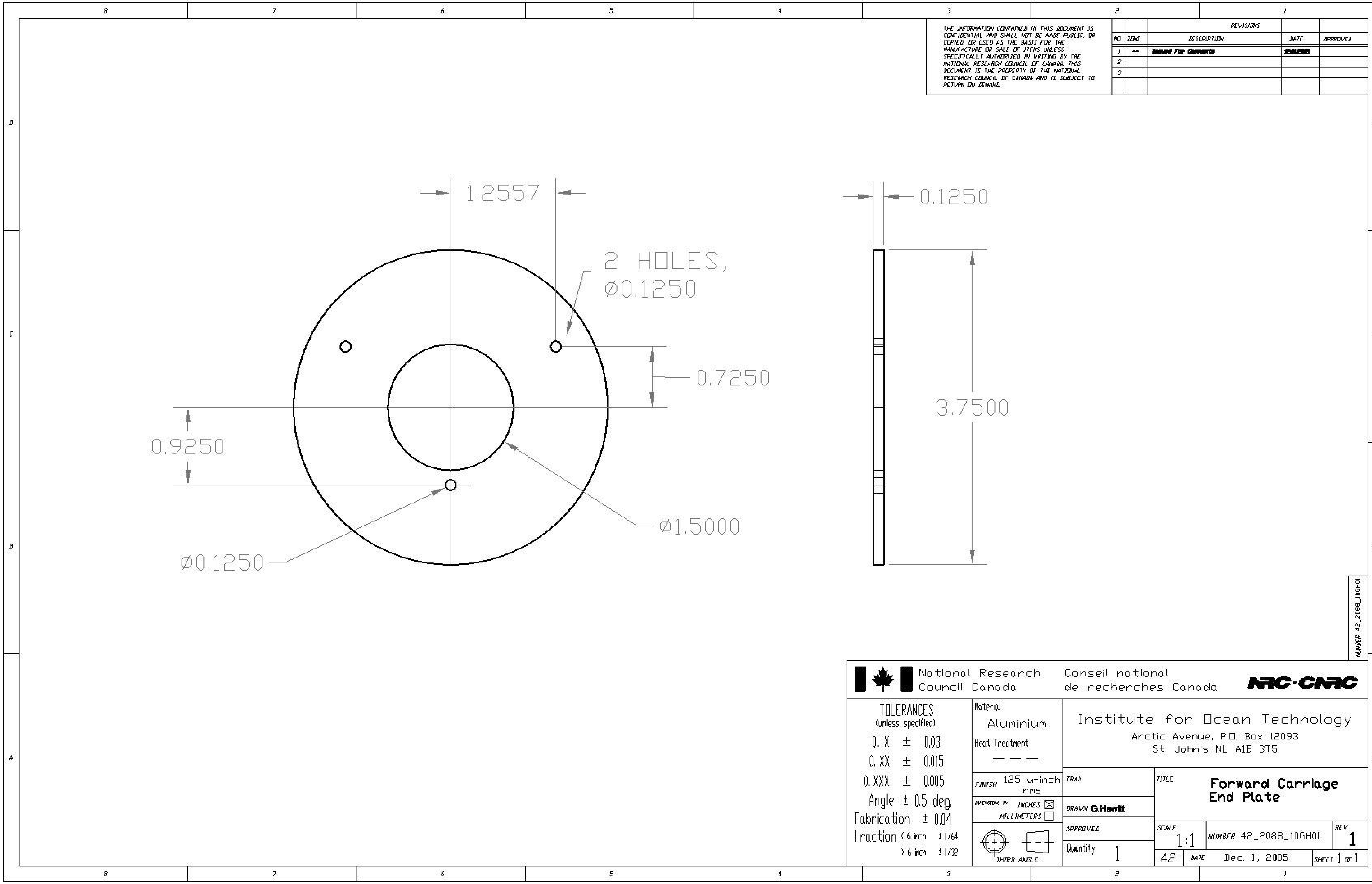
Skillings,B. Buoyancy Engine Construction and Design for an Underwater Vehicle. CISTI-IOT VM1 L121 LM-2004-21

Small Parts, Inc. Supplier of Spur and Ring Gears.
http://www.smallparts.com/

Webb Research Corporation, East Falmouth, Massachusetts.
http:www.webbresearch.com

Appendix A: Component Drawings

	Description	**Drawing Number**
1	Forward Carriage Plate	42_2088_10GH01
2	Stepper Motor Mount	42_2088_10GH02
3	Forward Battery Plate	42_2088_10GH03
4	Aft Battery Plate	42_2088_10GH04
5	Aft Carriage Plate	42_2088_10GH05
6	Pitch Actuator Mount	42_2088_10GH06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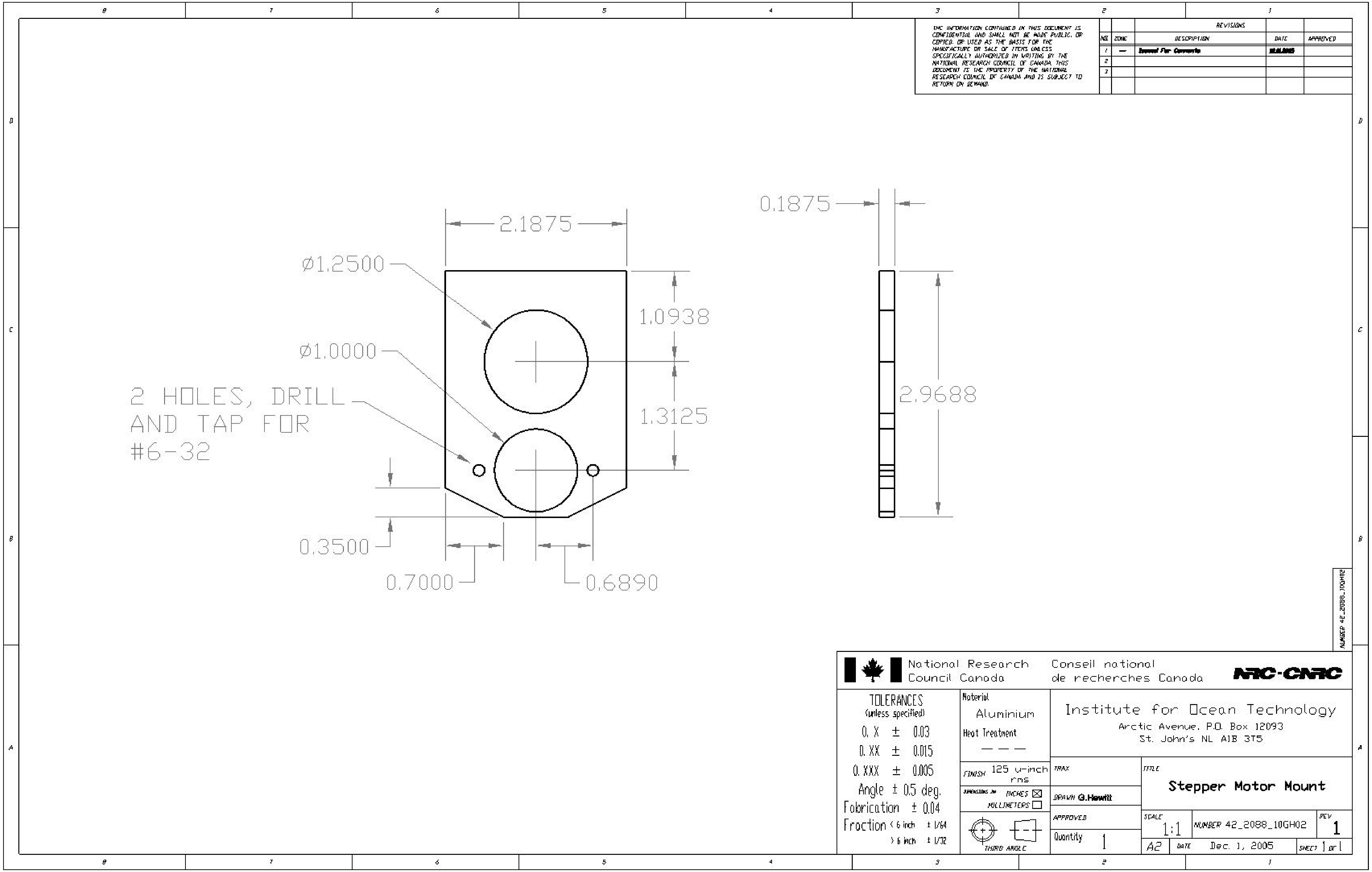
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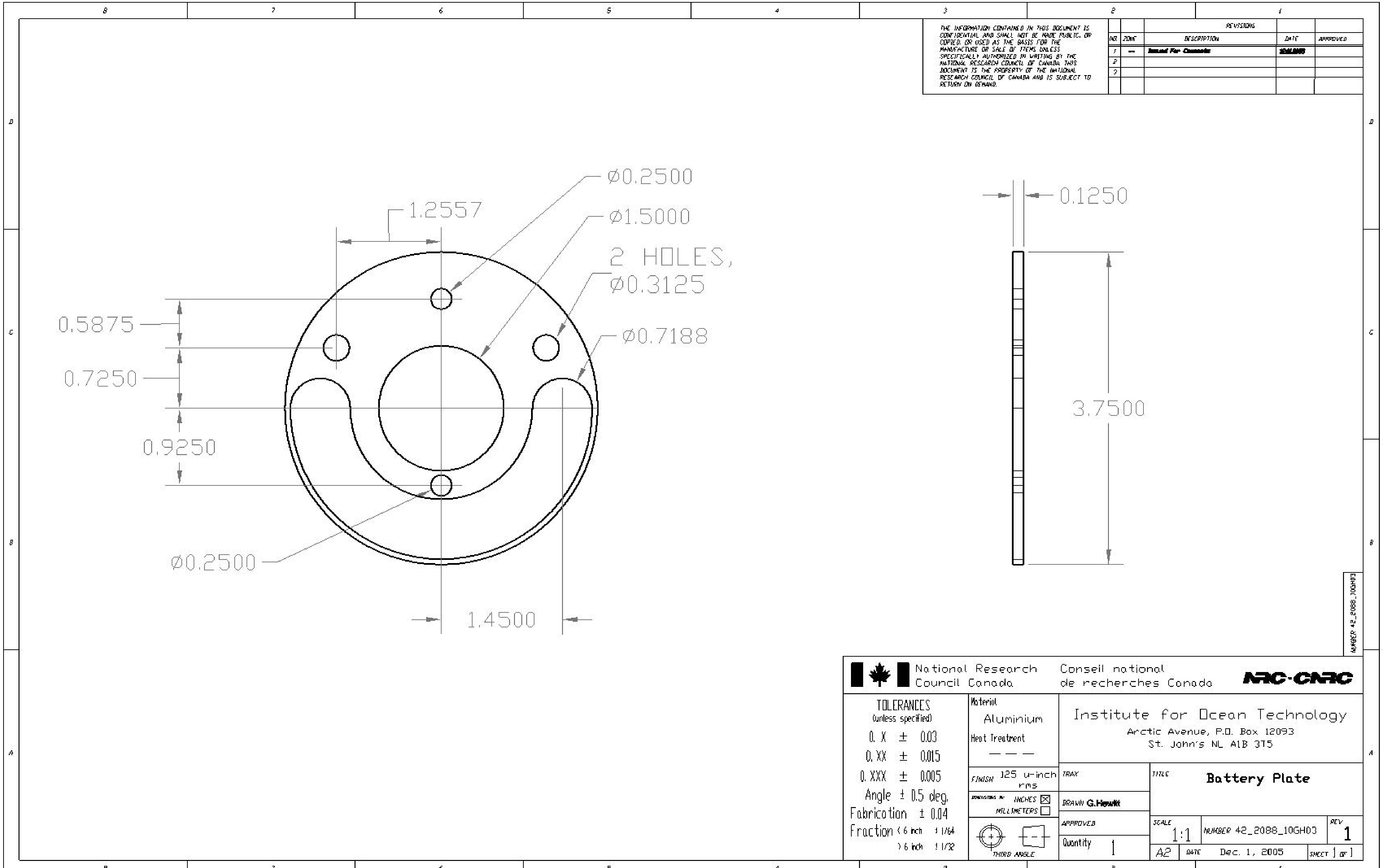
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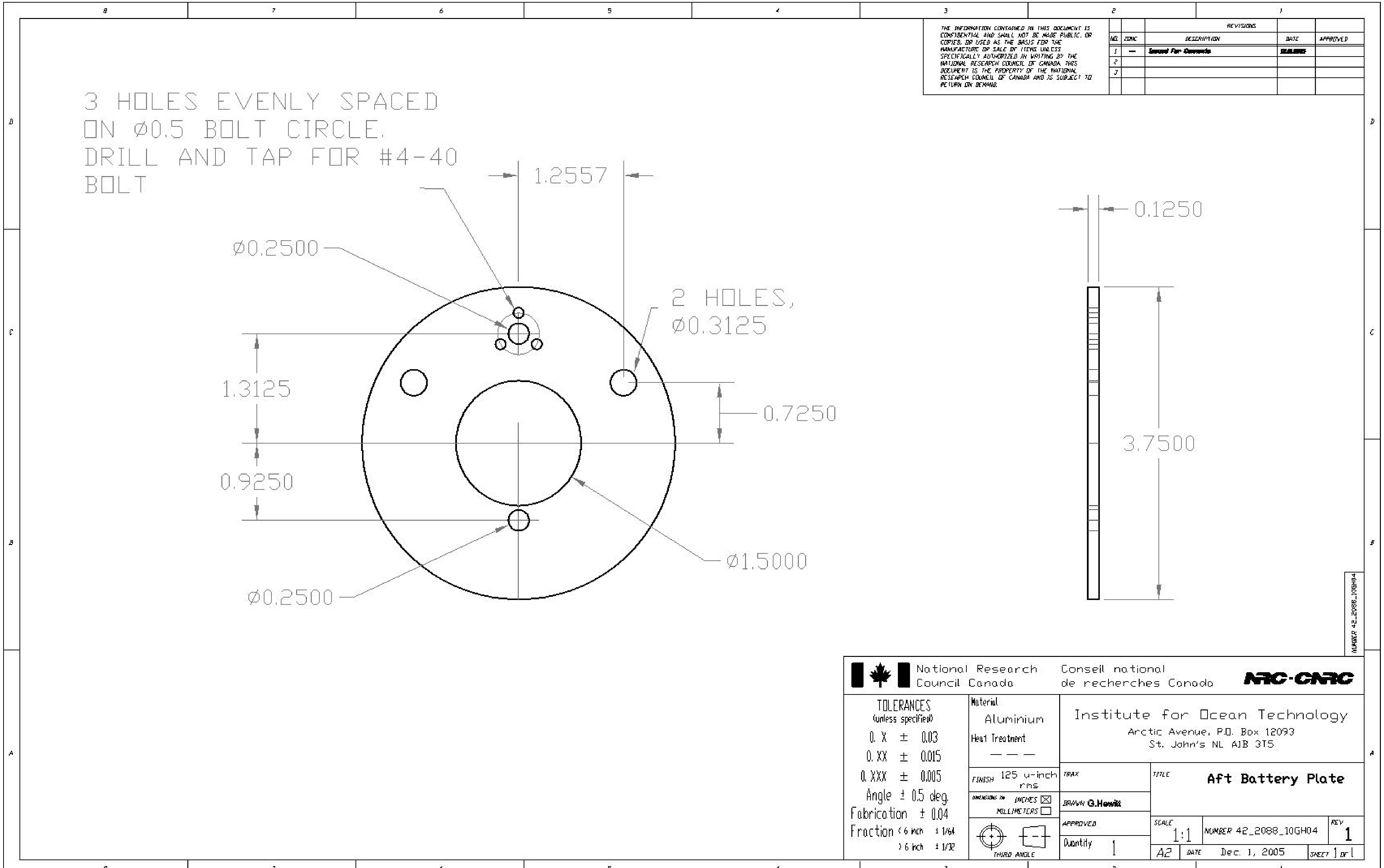
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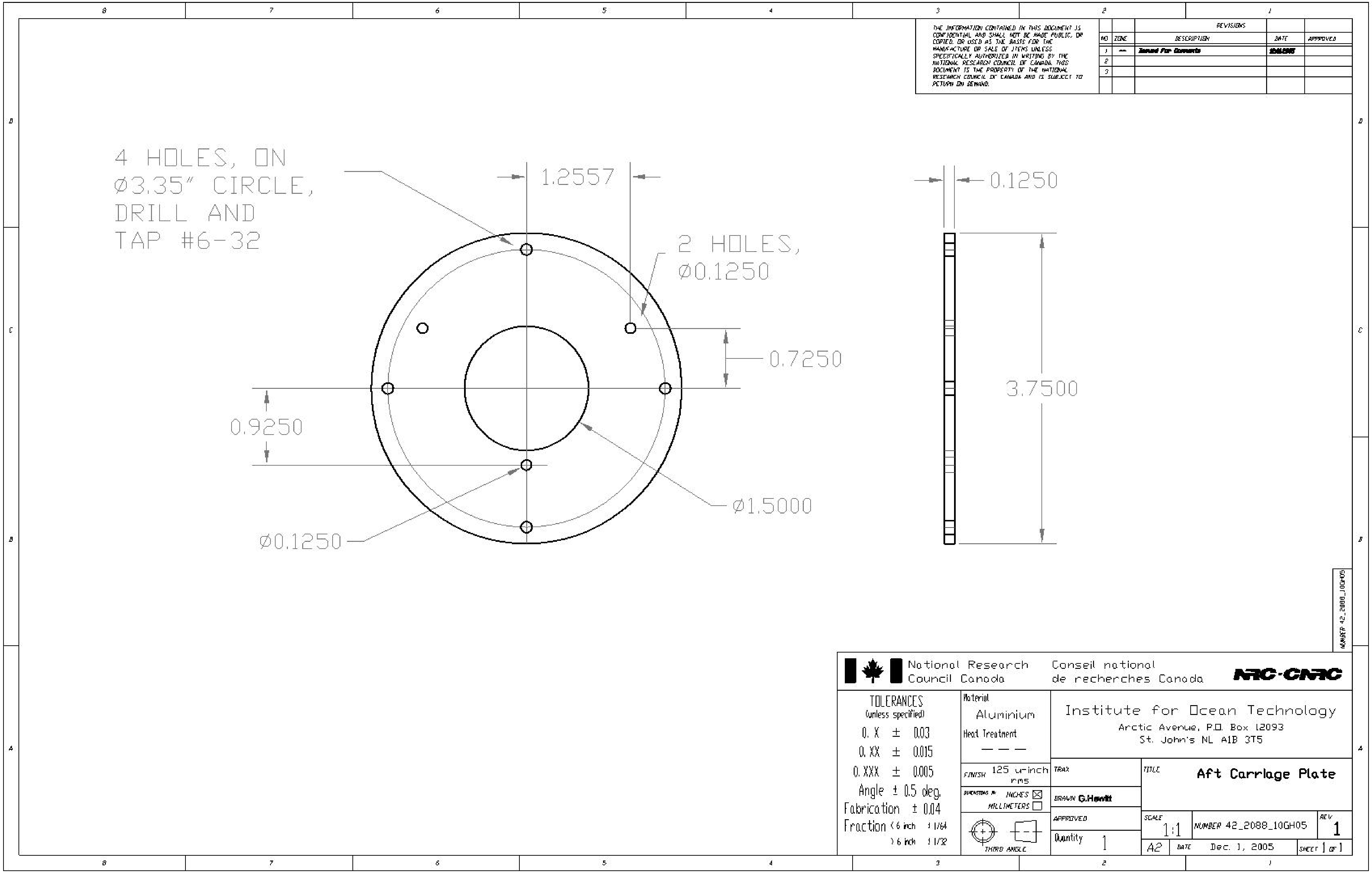
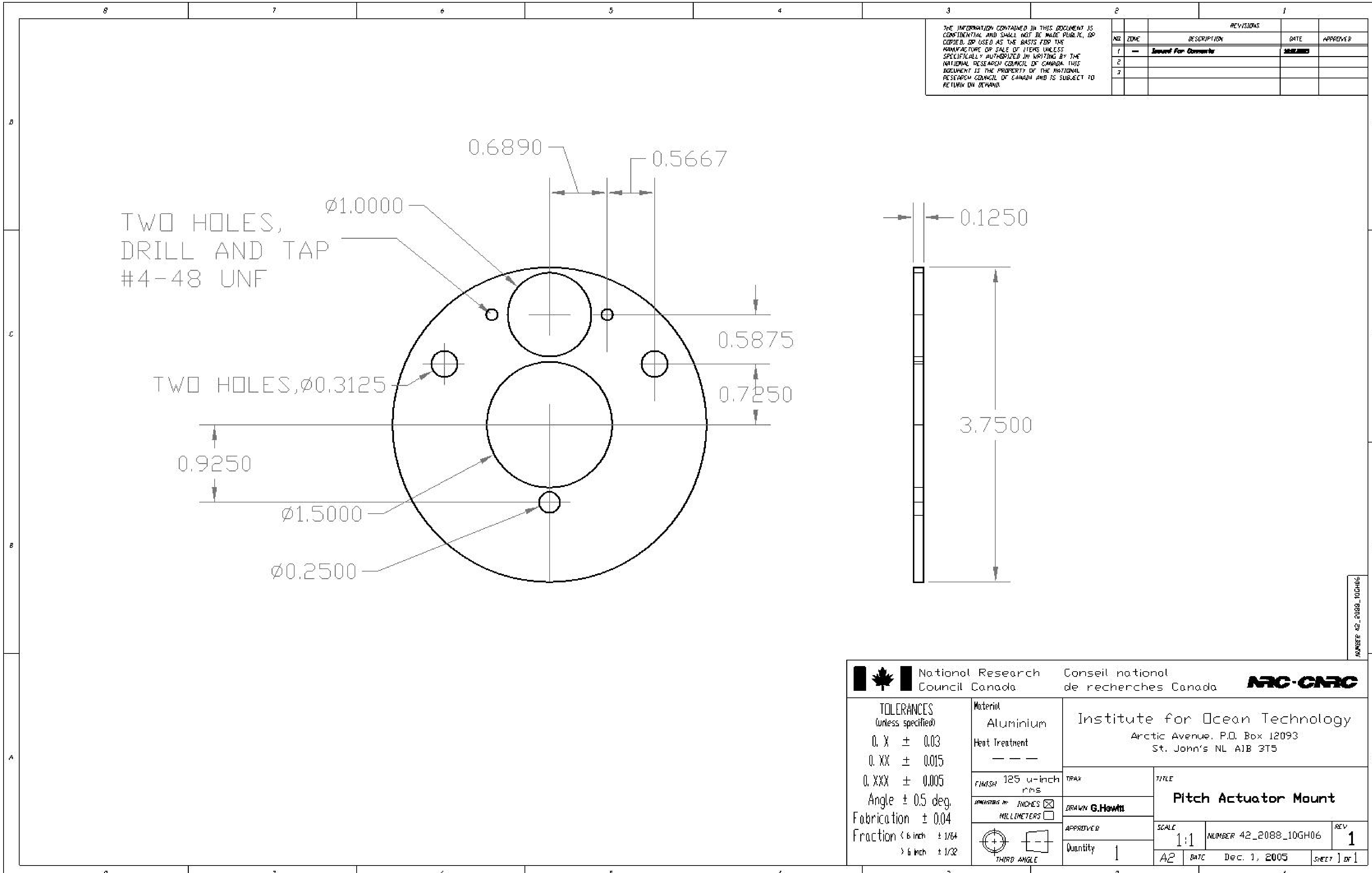
DATE Dec. 1, 2005
SHEET 1 OF 1


4 HOLES, ON
Ø3.35" CIRCLE,
DRILL AND
TAP #6-32
1.2557
2 HOLES,
Ø0.1250
0.7250
0.9250
Ø1.5000
Ø0.1250
0.1250
3.7500
REVISIONS
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
Material
Aluminium
Heat Treatment
FINISH 125 u-inch rms
INCHES
MILLIMETERS
THIRD ANGLE
Institute for Ocean Technology
Arctic Avenue, P.O. Box 12093
St. John's NL A1B 3T5
TITLE Aft Carriage Plate
DRAWN G.Hewitt
APPROVED
Quantity 1
SCALE 1:1
NUMBER 42_2088_10GH05
REV 1
A2
DATE Dec. 1, 2005
SHEET 1 OF 1


0.6890
0.5667
Ø1.0000
TWO HOLES,
DRILL AND TAP
#4-48 UNF
0.1250
0.5875
TWO HOLES,Ø0.3125
0.7250
3.7500
0.9250
Ø1.5000
Ø0.2500
REVISIONS
NO ZONE DESCRIPTION DATE APPROVED
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
Aluminium
Heat Treatment
FINISH 125 u-inch rms
INCHES
MILLIMETERS
THIRD ANGLE
Institute for Ocean Technology
Arctic Avenue, P.O. Box 12093
St. John's NL A1B 3T5
DRAWN G.Hewitt
APPROVED
Quantity 1
TITLE
Pitch Actuator Mount
SCALE 1:1
NUMBER 42_2088_10GH06
REV 1
A2
DATE Dec. 1, 2005
SHEET 1 OF 1