Evaluation of Emerging Non-Destructive Inspection Techniques to Characterize Damage Beneath Polymeric Tiles on VICTORIA Class Submarine Hulls

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Abstract

This report summarizes the basic study conducted by Owens Aerospace Inc on emerging non-destructive inspection (NDI) technologies for submarine hull inspections. The report identifies the various technologies that were considered. It also outlines the rationale for selecting or eliminating the various technologies from further evaluation. Pulsed Eddy Current was identified as the main technology to undergo a detailed evaluated under the present contract. This technology was formally tested at the DRDC Atlantic Dockyard Laboratory in Halifax Nova Scotia Canada.

Tests were conducted on simulated test panels (mock-ups) which were meant to represent the hull of an actual Victoria Class submarine. The samples were made of the same parent material and of a similar geometry to actual submarine hulls. Artificial simulated defects were embedded in the steel face of these panels. The defects were covered over with 30 mm thick solid rubber tiles which were bonded to the steel surface to represent actual submarine acoustic/anechoic tiles.

The test data collected consisted thickness readings which were as determined using the RTD Quality Services "INCO-Test" Pulsed Eddy Current Technology. The results of these tests are reported in Section 5 in the RTD test report and they are also discussed in detail and presented as contour plots in the main body of the report. An assessment of the RTD INCO-Test is included at the end of the report which outlines the applicability of the technology. In addition, an assessment of the possible additional work and cost required to further evaluate and develop the technology is provided.

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INTRODUCTION

Most modern submarine hulls are covered with anechoic acoustic rubber tiles. While these tiles are beneficial in providing enhanced stealth for submarines, they may conceal hull damage and active corrosion zones which may pose a threat to these vessels.

In an effort to assess the extent of damage which may be present beneath these polymeric tiles DRDC Atlantic has contracted Owens Aerospace Inc. to perform a study. This study was focused on evaluating emerging non-destructive inspection (NDI) technologies to facilitate the detection of damage beneath polymeric tiles [1]. The damage could consist of corrosion and cracking of the steel hull as well as dis-bonding of its polymeric tiles (see Table 1).

Table 1: List of Possible Defects That Could Be Present On The Test Panel [1]:

No	Defect Description	Minimum Defect Size
1	Dis-bond between Carbon steel and thin hard rubber layer. Dis-bond may have a gap filled with water or air or it is possible that no gap will be present.	Minimum surface area 100 cm^2 (16 in^2)
2	General corrosion on the steel plate at adhesive bond interface .	Minimum surface area 20 mm^2 (0.032 in^2) to a minimum depth of 3mm (0.12”).
3	Corrosion pitting on the steel plate at adhesive bond interface	Minimum pit diameter of 2 mm (0.080 “) to a minimum depth of 3 mm (0.120”)
4	Surface breaking cracks in steel plate at adhesive bond interface. Plane of cracks may be normal to surface	Minimum length of 6 mm (~0.24”) and a minimum depth of 3 mm (0.12”).

1.1 Significance of Potential Damage On Submarine Hulls

The corrosion and cracking listed in table 1 (No 2-4) is common to submarine steel hulls, and these types of damage can seriously degrade hull strength if allowed to propagate overtime. It is therefore imperative to be able to detect and quantify these degradations so that their effect on structural integrity can be assessed.

The other type of damage noted in Table 1 (No 1) is the dis-bonding of the polymeric tiles which can result in a complete loss of the tiles and/or a significant degradation in their performance. Based on Owens Aerospace’s experience, the polymeric tiles serve two main purposes. The first purpose is to absorb sonar pulses which are emitted by enemy vessels to detect the submarine’s presence. The second purpose is to absorb noise radiating from the submarines interior to prevent them from being transmitted outside the vessel where they can be detected by the enemy's passive acoustic sensors. It is therefore imperative to maintain the integrity of these tiles to help ensure the safety of the submarines when in a combat situation or during reconnaissance missions.

1.2 Reasons for Conducting the Proposed Study

Based on the past experience of the British Navy, the types of damage listed in Table 1 were a common and chronic problem that must now be addressed by the Canadian Navy. Therefore, to ensure the safe operation of any submarine, it is imperative that the types of damage listed in Table 1 be readily detected and quantified. It is for these reasons that the work tasks outlined in this document were carried out.

1.3 Material Properties

Three submarine pressure hull mockups were constructed by DDRDC Atlantic for this study. A Schematic of the test panels is shown in Figure 1.

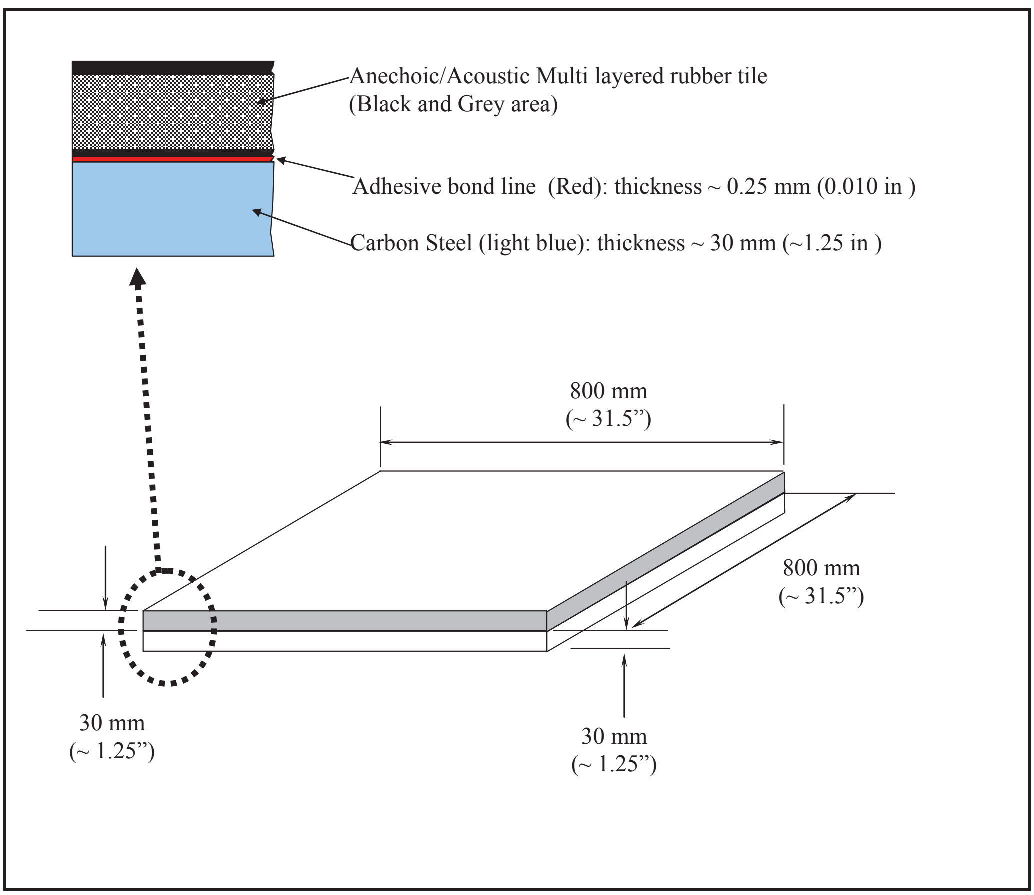

Figure 1: Test panel with material X-section

The material properties used in the submarine tile and hull and the adhesives used to bond them are described below.

- Steel Alloy of the submarine hulls: Q1N HY80.
- Adhesive for bonding acoustic tiles to hull : 3M Epoxy 2216 B/A Scotchweld
- Caulking material used between acoustic tiles: Sikaflex 221 by Sika
- Simulated acoustic tiles: Black neoprene from Associated Industrial Rubber.

1.4 Objectives of Proposed Work

There were four main objectives of the present project which were outlined in the Statement of Work (SOW) of the proposed project which are as follows [1,2]:

a) Experimentally ascertain the feasibility of an emerging NDI technology to detect damage limits listed in Table 1.

b) Define the limitations and expectations of the technology for detecting these damage limits.

c) Define further development activities required if (any) to refine the applicable technology to enable it to detect these damage limits.

d) Define the effort required to be enable the selected technology to be used in a real hull inspection. This would include a description of the training requirements for operators and the types of equipment that would be needed in the system. It would also include estimates of the development cost of a system.

1.5 Benefits Derived From The Study

There were several benefits derived from carrying out the present work. Foremost among these benefits was that insight was gained into various technologies that could be of great value to the Canadian Navy. In particular, technologies were identified that could help ensure the safe operation of the VICTORIA CLASS Submarines. Early detection of the types of damage listed in Table 1could help the Navy plan preventative maintenance for the submarine hulls. This could have a long term cost savings effect by reducing the cost and effort spent to repair submarine hulls subjected to long term corrosion damage.

Another benefit of the present work is that it could also provide insight into pre-existing damage present on the submarine hulls. Any such susceptibility to corrosion damage, cracking and tile de-lamination may not have been previously disclosed during contract negotiations with the British Government or the manufacturer BAE Systems. This information may be of great value to the Canadian government during subsequent contract negotiations pertaining to these submarines.

Another major benefit of the investigations into emerging NDI technologies is that they could foster the development of state of the art NDI systems in Canada. The development of high end nondestructive inspection/testing systems for the Victoria Class submarines could spin-off into a marketable product for other applications. The emerging NDI initiative could essentially act as an incubation mechanism to foster export development of this knowledge based technology. Export development offers direct tangible benefits to the Canadian tax base as it brings revenue into Canada and creates taxable employment income for highly skilled and educated Canadians.

1.6 Limitations on Inspection Techniques

The main requirement that DRDC had identified for the present work was to facilitate inspection of the pressure hulls of the VICTORIA CLASS submarines for damage limits listed in Table 1. Any emerging NDI technology used to meet this requirement must account for the following two critical limitations which have been imposed on the detection procedure [2]:

> *Limitation No. 1*
> Access for inspection of the steel plate test sample is available from the tiled side only. This is to reflect the fact that in the case of the actual submarine hull, the only side accessible is the exterior tiled surface.
>
> *Limitation No. 2*
> Removal or damage of tiles is not permitted. Access to the steel substrate may be considered at the corner points of the tiles, as long as the tiles remain undisturbed.

1.7 Inspection Environment

The inspection environment for NDI technologies used to inspect the Victoria Class submarine hulls would generally be in air. Some protection for the operator and equipment could be provided by large tarps under which the air might be heated during winter months. DRDC indicate that inspection while the submarine was submerged might present some additional benefits as it may reduce the time required in dry-dock or on the hydro-lift. This is an advantage as dry-dock and hydro-lift time is at a premium in the DND dockyards.

1.8 Challenges for Non-Destructively Inspecting Submarine Hulls

There are six main factors which make the inspection of the Victoria Class submarine hulls somewhat challenging. Each of these factors is listed in the subsections below along with a discussion of how they affect the ability of NDI techniques to meet the Canadian Navy and DRDC Atlantic's requirements.

1.8.1 Challenge No. 1- No Direct Access to Bare Steel Hull

One of the challenging factors for the application of various NDI technologies is the fact that it is not possible to have direct access to the bare metal surface. If access were possible, then it would be a trivial matter to detect general corrosion, pitting and surface cracks with visual inspection and/or Liquid Penetrant Inspection (LPI). Therefore this factor alone eliminates the most basic forms of NDI technology from consideration in this program. In fact most other standard systems such as eddy current and ultrasonics are also normally applied to bare surfaces, or at least to surfaces with very thin coatings.

1.8.2 Challenge No. 2- Thick Non Conductive Elastomeric Coating

A second challenging factor is that the surface is covered by thick, non-conductive polymeric tiles. It is assumed that the tiles are in the form of an elastomeric composite sandwich with a low density cellular foam rubber core sandwiched between two hard rubber layers (See Figure 1). The fact that the tiles are thick and non-conductive provides significant challenges to employing standard electro-magnetic based NDI technologies and procedures for any of the defects. Some of the tiles have an elastomeric honeycomb sandwich type construction as noted above and this presents great challenges to standard acoustic/sonic based systems. The reason for this is that elastomers are notoriously visco-elastic in nature and have a propensity to dampen sound waves rapidly.

1.8.3 Challenge No. 3 – Single Sided Access

A third major factor which presents a challenge to any NDI technology proposed for the submarine hull inspections is that it is only accessible from the tile side. Therefore, any NDI technology which requires dual sided access to the submarine hulls is immediately rendered inapplicable in the present application. This factor alone eliminates any system based on through-transmission ultrasonic or X-Ray radiography.

1.8.4 Challenge No. 4 – Orientation of Cracks

A fourth major factor which makes the inspection of the submarine hulls challenging is the orientation of potential cracks and the relatively small defect size that must be detected. The standard approach to most sonic probe based NDI systems is to direct a signal normal to the surface of interest. In the present project the SOW indicated that the technology must be capable of detecting surface breaking planar cracks. This implies that the plane of the cracks may therefore be normal to the surface. Therefore any sonic based technology must employ innovative techniques for detecting cracks of this orientation since a standard 90° sonic pulse will have difficulty detecting them.

1.8.5 Challenge No. 4 – Size of Defects in Metal Surface

As noted previously the defects limits outlined in the Statement of Work could be readily detected with visual inspection and/or with the aid of Liquid Penetrant Inspection on bare surfaces. They may also possible be detected with electro-magnetic based systems such as Magnetic Particle and Eddy Current. However, when these defects are concealed under a very thick non-conductive layer such as in the present case, the sizes of the pits and cracks may be somewhat challenging to detect. For example, it would be challenging to develop a technology capable of discerning a single pit of 2 mm diameter which is only 3mm deep, especially with all of the other imposed limitations.

1.8.6 Challenge No. 5 – Multiple Materials

A fifth major factor which makes the inspection of the Victoria Class submarine hulls challenging is that the hull and tiles have dramatically different material properties. Furthermore, it is desired to determine defects in both the tile (i.e dis-bonding) and also in the steel hull (i.e. corrosion and cracks). Many NDI systems rely on evaluating how the given material properties affect the signals being transmitted through the materials. For example, a signal which propagates well in one material may not propagate very well at all in another. Therefore it may be challenging to find a single NDI technology and procedure which is able to detect both tile dis-bonds as well as surface cracks and corrosion in a steel hull.

1.8.7 Challenge No. 6 – Multiple Layers and Interfaces

A sixth major challenging factor in inspecting submarine hulls is that there are numerous layers in the tile-hull x-section. Therefore an NDI system may have to be able to readily differentiate between the signal responses of the various material interfaces. Inspecting this multi-layered stack-up for tile dis-bonds on actual submarine hulls can be another challenging task. For example, it may be challenging to differentiate dis-bonds which could be of three possible interface gap configurations as follows: a) intimate contact i.e no gap, b) air/gas or vacuum gap, d) water filled interface gap. In addition, a disbond may in fact be due to corrosion. The presence of such a dis-bond may inhibit certain sonic technologies from detecting the underlying corrosion which caused it.

2 TASK 1- IDENTIFY MOST PROMISSING NDI TECHNOLOGY

Owens Aerospace conducted an in-depth literature search of possible emerging technologies which could possibly be used to meet the project requirement. This search consisted searching databases for technical articles and papers in trade publications and research journals. It also consisted of searching the internet for online industry trade journals which list suppliers.

2.1 Previous Work

During the preliminary literature study, Owens Aerospace identified two technologies which claim to be capable of detecting some or all of the types of damage listed in Table 1. The first technology is acoustic pulse-echo ultrasound which was reported to have been effective at inspecting polymeric tiles on hulls of British Submarines [3]. These tiles were quite similar to some of the tiles presently used on the Canadian VICTORIA Class submarines. The second technology was Pulsed Eddy Current which has reportedly been proven capable of detecting corrosion in thick steel walls very thick (> 30 mm) insulation. Both of these technologies have reportedly been shown to be capable of detecting some of the types of damage in Table 1 within the limitations imposed in the SOW.

Owens Aerospace has also identified various other technologies which may show some promise for detecting some or all of the defects identified in the Statement of Work (SOW) [1]. The results of this study are presented in this report and fulfill the requirements of Task 1 of the SOW.

2.2 Overview of Disqualified NDI Technologies:

The following technologies were identified as being unlikely candidates due to a lack of access to both sides of the ship hull and/or due to the thickness and material properties of the acoustic tiles: Visual Inspection, Liquid Penetrant Inspection, Magnetic Particle, Radiography, Through Transmission Ultrasound, standard intimate contact Eddy Current. This assessment was reviewed with the scientific authority at DRDC who concurred that these technologies should be eliminated for from further consideration in the context of the contract covered by this report. However, further consideration of these technologies was not ruled out in possible future projects.

2.3 Overview of Potential Candidate Technologies

Several technologies were identified by Owens Aerospace as being potential candidates for consideration in the present contract. Each of these technologies was discussed with the DRDC Atlantic Scientific authority and a brief summary of each is listed in the paragraphs which follow.

2.3.1 Ultrasound/Acoustics Directly Through The Tiles

During the initial 2 weeks of the project, the DRDC scientific authority was in meetings in the UK and unavailable to provide guidance to Owens Aerospace. During this period, effort was focused on NDI technologies with published claims of success for inspecting submarine hulls. In particular, the effort was focused on ultrasonic testing for which a technical paper had been published in the UK which claimed success at detecting dis-bonds [3].

This paper on Pulse-Echo ultrasound from the UK claimed success in detecting dis-bonds between the tiles and the hulls of British Submarines. It is believed that the tests in this paper were conducted on tiles with a solid rubber core as opposed to a honey comb core as in the case of the Victoria Class submarines. Owens Aerospace's previous experience with ultrasonics was that it is used extensively to inspect aircraft composite sandwich panels with honeycomb cores, Owens Aerospace also found that the Australian department of defence was supposed to have conducted studies using ultrasonic techniques. The Australian defence department was contacted via email, but they were unwilling to comment on the level of success achieved with ultrasonics or inspecting submarine hulls.

Owens Aerospace had arranged some preliminary testing by a company called QMI in southern California on solid rubber tiles. Their preliminary results indicated that they were able to detect defects on the underside of relative thick soft rubber tiles. Based on these preliminary results, the possibility of investigating this technology further was proposed to DRDC. DRDC expressed doubt of it's capability for submarine tile inspection. The main reason for the concern was the attenuative nature of the rubber acoustic tiles. This technology was abandoned therefore disqualified from further consideration in the present project.

2.3.2 Ultrasonics/Acoustics Sent Through The Bare Hull At Tile Edges

Another ultrasonic/acoustic procedure identified by Owens Aerospace was a pitch-catch and echo reflection method. This technique would require direct access to relatively small bare areas of the submarine hulls. It was identified as a potential technique which could be used at the edges of the tiles where the caulking could be removed. This technique showed great promise for obtaining very good indications of hull corrosion, cracks and pitting. However, it would require the removal of the grouting in discrete areas and possibly along the entire length of several tile columns to allow 100% inspection.

An interesting aspect of this technique is that is supposed to be able to inspect over a significant length between the transmitter and receiver. It is uncertain what maximum length could be inspected but published literature claims that several meters of length at a time in piping systems can be inspected. The length of inspections possible would depend in part on the extent and size of defects to be inspected. It is believed that this technology and procedure could possibly be used to detect corrosion, pitting, cracks and weld lines in the steel hull. It is also believed that it may have potential to detect dis-bonds between tile layers and between the tiles and the hull. It is suspected that the tile delaminations and dis-bonds could require a different procedure than would be used for the inspection of the metal hull defects.

One challenge to applying this technology and procedure to the submarines would be in automating the inspection technique. It would require some clever designing to make it automated and efficient when compared to a surface scanning mechanism which can generate C-scan contour plots. It is uncertain if probes which are sufficiently small enough to be inserted between the tiles are commercially available. It is thought that a water squirting mechanism may also be required for ultrasonic coupling to help automate this technology for submarine hull inspection. DRDC indicated that it was definitely an interesting technology but that that perhaps a more automated and less intrusive procedure would be more beneficial if available. Therefore DRDC decided to eliminate this technology and procedure from further consideration in the present contract.

2.3.3 Guided Wave Technology and Report by SMRC:

Another technology which had been previously investigated for submarine hull inspections is guided wave technology. This technology was investigated by a company called SMRC in the U.S. for the US Navy [4]. Their preliminary results suggested the technology was feasible for detecting welded seams and damage to these areas. The technology used a hammer and/or pneumatic piston to generate impact energy and used EMATs (Electro Magnetic Acoustic Transducers) to pick up the response. DRDC had in its possession a copy of the study which was summarized in a report [4].

The report noted above only addressed a 1st phase of research and it indicated that follow up phases would be investigated. Inquiries were made with SMRC to determine if any follow up studies had been conducted and whether they were successful. No response was received from this company and the DRDC technical authority (TA) had not heard of any follow up studies through its counterparts in the US Navy.

In the report, it was noted that the steel submarine hulls and rubber acoustic tiles are coupled and give a unique signature. Owens Aerospace indicated to DRDC that since the Canadian subs had a lot of variation in dis-bond area sizes and locations that it may be difficult to discern rust from dis-bonding or cracking. The DRDC Technical authority indicated that the technology might have some potential but that it should be eliminated from further consideration in the present study.

2.3.4 Vibration Based Technology (SIDER)

An interesting vibration based technology that may have some potential is the broadband vibration-based Structural Irregularity and Damage Evaluation Routine (SIDER) [5]. It uses features in complex curvature structures to locate damage and other areas with structural stiffness variations. SIDER was developed for the inspection of large-scale composite structures which weren't amenable to more conventional inspection methods. In the present case, cracks and corrosion can certainly affect the natural frequency and stiffness response of the hull on a localized level. However there may be challenges in applying this technology to the Victoria Class submarines. This is due to the fact that they are covered with thick anechoic rubber tiles which may have a high damping capability for high frequency mechanical waves.

2.3.5 Microwave Technology

The Australian department of defence completed a study [6] on the use of microwave technology to identify dis-bonds between the acoustic/anechoic tiles and the submarine hulls. This study identified serious limitations with microwave technology due to the variation in tile and bond-line thickness and also due to vibration of the sensors when moving along the surface of an actual submarine. Slight variations in distance between the sensor and the tile/bond area were reported to have a major effect on the noise generated in the signal response and make it difficult to discern dis-bonds. It was decided by DRDC that this technology would be eliminated from further consideration in the present project.

2.3.6 Laser Shearography:

There had been a study reportedly conducted in the US on laser shearography on acoustic submarine tiles to detect variations in surface strain associated with dis-bonds and defects [7]. Owens Aerospace was unable to obtain a copy of this paper during the course of the present project. DRDC indicated that they had serious doubts about the shearography's ability to detect the tiny strain variations associated with steel hull defects through thick rubber tiles.

This technology faces tough challenges in the present application considering the low modulus of the rubber relative to the steel hull. Owens aerospace indicated that the technology is commonly used to inspect polymeric composites. This technology has also been reportedly successful at inspecting elastomeric products such as tires. DRDC suggested that the small strain variations in the submarine tiles would most likely drop asymptotically to nearly undetectable level through 30 mm of complaint rubber tiles. DRDC indicated that this technology should be eliminated from further consideration in the present study.

2.3.7 Thermography

Thermography has been successfully used in the inspection of aircraft composite materials (Fiberglass/epoxy with nomex core) to detect damage associated with moisture ingression into the honey comb core cells. In these applications, a heat source such as heat lamps is used to raise the temperature of the inspected area above ambient conditions. The area is then inspected using infra-red cameras to detect differences in heat retention/radiation. In the present application, this may not be as likely to work since all tiles are subject to moisture continuously. In addition, the rubber tiles are thought to be very good insulators against heat.

It was though that there may be some possibility of detecting water trapped behind or within the tiles. It was not determined if dis-bonds or corrosion on a surface would be detectable using thermography under the thick tiles. This technology did not show any obvious potential for success in the present application. Therefore, DRDC indicated that this technology should be eliminated from further consideration in the present study.

2.3.8 Magnetic Flux Leakage (MFL)

Magnetic Flux Leakage (MFL) was identified as a possible method for detecting pitting and corrosion under the tiles [8]. The basic concept is to saturate ferromagnetic materials with a magnetic field and then detect bends in the magnetic flux lines where leakage occurs near discontinuities.

Several suppliers of MFL equipment indicated that it had good potential for detecting general corrosion in thick steel walls underneath thick insulation. They indicated however that this technology had little potential for detecting tight stress cracks or discrete corrosion pits. DRDC indicated that MFL technology should be set aside as possible technology to consider further in the present study.

After further investigation, there were no commercial vendors of MFL equipment or services found that claimed they could detect corrosion in the present submarine hull application. Several of these vendors indicated that they thought that MFL could be used for this application but that it would require additional development work on hardware and/or software. In the interest of time and cost control, DRDC decided that this technology should be eliminated from further consideration in the present study.

2.3.9 Pulsed Eddy Current

A paper was identified which claimed that “pulsed eddy current” technology could be readily used to inspect corrosion under thick layers of insulation [9,10,11]. These papers were written by employees of a company called RTD Quality in the Netherlands. These papers indicated that the footprint of the sensor would have a diameter roughly equal to the thickness of the insulation layer. For example, in the present case this could be taken to infer that the footprint would be about equal to 30 mm. Upon further investigation, it was found that for the present case a probe of approximately 6” x 6” square was recommended by RTD.

Based on conversations with representatives of RTD, their Pulsed Eddy Current technology uses a proprietary patented software algorithm to process the signals. RTD was the only company employing electro-magnetic techniques which Owens Aerospace had found which claimed to be able to detect corrosion in the present application. Their patented technology is referred to as the INCO test, which stands for the “Insulated Component” test. Based on RTD’s claims and the tight time restrictions for the present project, INCO-test was chosen by DRDC as the second potential technology for further evaluation in the present study.

2.3.10 Saturated Low Frequency Eddy Current (SLOFEC) and Large Coils

Another emerging form of eddy current technology is referred to as saturated low frequency eddy current (SLOFEC) [12]. The basic principle as it was explained is to saturate the metal with a magnetic field from powerful magnets. Once this is achieved standard eddy current is super imposed the metal using an eddy current probe. The basic idea is to reduce the permeability of the steel plate to that of air so that the eddy currents can penetrate deeper into the steel.

A company in Germany (Kontroll Technik) was identified as an expert source of this technology and they were contacted for further discussions. They indicated that their present equipment could not be used effectively with the thickness of rubber and steel plates that were typical of the VIctotria Class submarines. They did however express that they believed that their technology could most likely be modified to detect such defects. They also proposed that perhaps standard Eddy current could also hold some promise if a large enough probe were used with low frequency eddy currents.

This concept was discussed with Dr. Catalin Mandache of the National Research Council in Ottawa. He indicated that this saturation technique could have advantages over other techniques. He stated that using larger diameter eddy current probes at lower frequencies could improve penetration of the eddy currents into ferromagnetic steel. The concepts were also discussed with Dr. Dubois of the Canadian Royal Military College in Kingston. He indicated that it may be possible to detect corrosion using these techniques but that it would have to be very significant and furthermore that cracks would be difficult to detect.

Mr. Tommy Bourgelas of Olympus Corp. was also consulted on these concepts. He indicated that with a large diameter eddy current probe of 1-3” in diameter that it might be possible to detect general corrosion and to a lesser extent corrosion pitting and cracks. He indicated that it might be possible to use large diameter eddy current probes to detect these defects even without a super imposed saturated magnetic field.

Mr. Ahmad Chahbaz, also of R/D Tech - Olympus corp. was also contacted to discuss the use of standard Eddy Current technology for detecting corrosion and cracks on the submarine hulls. He indicated that he had spent considerable effort examining the problem. He stated that he was confident that his company could develop a procedure using standard Eddy current equipment. In particular, he indicated that Olympus’ RD/Tech Omni scan system could most likely be used for this purpose. The DRDC TA considered these findings and indicated that this might well be a path to explore at a future date. However, he indicated that in the present contract it should be eliminated from further consideration.

2.4 Emerging NDI Technologies To Focused On In Present Contract

After initial discussions with DRDC, they had decided to focus only on metal defects in the surface of the submarine hulls at the bond interface. These types of defects were chosen since they represented the most significant problem for submarine structural integrity and safety. DRDC decided that dis-bond defects and other damage to the tiles would not be a focus of the remaining portion of the project. DRDC indicated that the dis-bonds might be the subject of a later study which would possibly focus on using an impedance hammer to evaluate its ability to detect dis-bonds.

As noted in the preceding sections above, DRDC had decided to focus on two technologies for detecting defects in the metal hull: magnetic flux leakage (MFL) and pulsed eddy current (PEC). Due to the lack of commercially available MFL equipment for the Victoria Class submarine configuration, this technology was eliminated from further consideration by DRDC. Therefore the only technology which was selected by DRDC for formal evaluation testing at its lab in Halifax was the RTD INCO-test Pulsed Eddy Current technology. This technology was evaluated for its basic ability to detect metal defects under the submarine tiles as well as its feasibility for performing full scale inspections of actual submarine hulls. These evaluations are outlined in the sections below.

3 TASK 2 –BASIC FEASIBILITY EVALUATION OF RTD INCO-TEST

After DRDC selected RTD INCO Test Pulsed Eddy Current, Owens Aerospace proceeded with a basic evaluation of this technology for inspecting submarine hulls. In evaluating this technology, consideration was given to the size, orientation and location of the defects as well as to the influence of the properties of the materials in question. In addition, careful consideration was given to the two limitations imposed on the inspection procedure and to potential unseen or hidden discontinuities. Consideration was given to discontinuities such as tile and adhesive thickness variations, underlying hull ribs, welded seems and other discontinuities which may inadvertently affect the NDI results.

It was explained to DRDC by Owens Aerospace that the RTD INCO-Test would not likely be able to provide a high resolution of defects. This was mainly due to the large size of the probe. (6” x6”). In addition, it was pointed out that small defects such as pits would be much more difficult to detect than general corrosion. This is due to the fact that the technique is sensitive to the total wall volume loss under the foot print of the probe. Therefore small pits represent very little volume loss, the INCO-Test was not expected to be very effective at identifying small pits.

It was also explained that the RTD INCO-Test has little or no ability to detect cracks in the steel hulls. Another limitation of the technology that was pointed out prior to testing was that the technology has not had a great success with discerning machined defects. The reason provided by RTD for this limitation was that machining processes dramatically affect the magnetic permeability of the surface. This in turn is reported by RTD to have a tremendous affect on the sensitivity and accuracy of the INCO-Test pulsed eddy current technology.

After having considered, these limitations, DRDC indicated that it could still make use of qualitative technique like the RTD-INCO test even with the limitations noted above. DRDC further explained that the general corrosion was the main damage of concern since it represented the greatest amount of wall net section loss. This, it was pointed out was the principal concern since wall loss reduces the submarine's skin buckling stability when under dive pressure. After careful consideration, DRDC decided to proceed with a full formal test evaluation of the RTD INCO-Test at the DRDC Atlantic emerging materials test lab.

3.1 Pre-Test Evaluations and Preparations

Prior to performing the evaluation tasks outlined in Task no. 3 below, Owens Aerospace had intended to perform preliminary Pulsed Eddy Current testing on sample panels. The intent was to fabricate sample panels of similar materials to those used in the proposed formal tests listed in the SOW.

These preliminary test panels were to have hidden defects in the metal surface similar to those proposed for the formal test panels. It was hoped that these practice panels would facilitate the optimization and evaluation process by allowing sub-contractors to spend more time on testing at their own facilities and less time and money on travel costs. These preliminary tests panels were to be sent to potential NDI subcontractors to have them demonstrate their capabilities prior to engaging them for full tests.

Unfortunately, there was a delay in the contract award date and also subsequent delays in being able to meet with key personnel at DRDC. In addition there were other delays in being able to obtain segments of actual test plate which was made of a relatively rare alloy which is difficult to source in a short period of time. Due to these delays and in the interest of meeting the main target goal of formally evaluating a technology, the preliminary sample testing effort was abandoned

4 TASK 3: DEMONSTRATE FEASIBILITY of NDI TECHNOLOGY

As noted above, Pulsed Eddy Current was selected by the DRDC Atlantic Technical Authority as the technology which would be evaluated with formal tests. One of the world's most prominent users of this technology (RTD) was engaged. Three separate sample panels were tested using the RTD INCO Test as outlined in the test matrix in Table 2 below.

Table 2 : NDI Test Matrix

Panel No.	Design Type	Damage Description Provided Prior to NDI Test?
1	Design 1	Yes
2	Design 2	Yes
3	Design 3	No

Each of these 3 panels was provided by DRDC Atlantic for testing in their laboratory in Halifax. The panels conformed to the following description:

Panel Description:

800 x 800 mm Q1N HY80 steel panel, 30 mm thick
30 mm thick solid rubber tile bonded to 1 face

These test specimens were similar in construction to that which is depicted schematically in Figure 1. The tiles used on the test panels were simply solid neoprene black rubber and were not the actual tiles used on the hulls of the Victoria Class submarines. The test panels consisted of three different designs, which was slightly different from the panels outlined in the SOW (See Table 2).

A description of the damage in panel no.'s 1 and 2 was provided prior to testing. This was done so that the equipment could be calibrated to a zero defect area. It was also done to help provide insight into whether or not the test equipment was detecting the defects. No description of the damage in Panel No. 3 was provide prior to testing or prior to submission of the test reports. A description of the damage in panel No. 3 was provided after the test reports were submitted and this information has been used to evaluate the Pulsed Eddy Current technology of RTD. The test reports and their results are outlined and discussed in detail in the section which follows.

5 TASK 4: INSPECTION REPORTS

After the testing was completed, the sub-contractor RTD technologies, prepared a summary report of the test results. This is discussed in this Section of this report. Owens Aerospace reviewed these reports and concluded that additional information could be gleaned from the results by plotting them as contour plots. In addition Owens Aerospace also studied these plots and attempted provided a basic assessment of the RTD INCO Test results. Specifically, an attempt was made to determine from the contour plots if a correlation could be made between the anomalies observed and the known damage present. Also an attempt was made to identify anomalies in the contour plots which could indicate possible wall material reductions in the unknown defects panel. The inspection & interpretation reports were forwarded to DRDC Atlantic for review and discussion. The main content of the interpretation report written by Owens Aerospace has been inserted into this Final Report in the sections below.

5.1 Pulsed Eddy Current Test Results and Discussion

This section of the report addresses the results of Pulsed Eddy Current Testing which was performed by RTD Quality Systems of Hamilton Ontario . It is intended only as a commentary on the results with a view to identifying areas of potential defects. An interpretation of the test results has been provided by RTD quality services in their test report [8].

5.1.1 Description of Testing Performed:

The RTD INCO (Insulated Component) test was performed on three separate steel plates which were each covered by four separate solid rubber tiles (See Figure 2 - Figure 3). The steel plate was meant to represent the hull of the HMCS Victoria class submarines. The rubber tile represented the acoustic/anechoic tiles which cover the submarine hulls. The steel plates were made of Q1N HY80 pressure vessel steel. The plates were machined down to thickness of 30 mm by rough machining with a milling machine. The metal surface defects were made with basic hand tools such as drills and grinders.

The results of the 3 plates were plotted as contours to attempt to provide additional insight into the locations where anomalies were observed in the plates. These contour plots along with their tabulated data and pictures of the defect areas are presented and discussed in the sections below. All data presented and discussed below is from the RTD INCO Test pulsed eddy current tests performed at DRDC.

5.1.2 Plate 1: Known Defects

Two sets of Pulsed Eddy Current RTD INCO Test data were taken for plate no. 1 and normalized with respect to plate thickness (Figures 4 and 5). Each of these data sets has been plotted as contours in Figures 6 and 7. The INCO Test was conducted on a relatively coarse grid of 3 inch spacing in both the x and y locations as shown in Figure 2. This coarse grid was chosen as it was recommended by the RTD technician as a good optimized size for the large 6" probe being used. In fact, this 3 inch grid was estimated to be just slightly smaller than the foot print of the probe itself. It was reasoned that a finer grid would not likely provide dramatically improved resolution of defects and hence would not make the best use of testing time for the known defect plates.

The damage locations in plate 1 have been superimposed on Figures 6 and 7 to help determine whether an actual indication was detected during the tests. In these two figures, it can be seen that there are three areas which display significant anomalies. The largest of these areas is centered in the upper left corner of Quadrant C. The next most significant anomaly is located in the center area of quadrant B and the third most significant anomaly is located in the middle right area of quadrant C. It can be observed that the results were quite repeatable between test 1 and test two of plate 1. Another significant observation that can be made is that maximum indicated wall loss is approximately 10% of the nominal thickness which appears to compare very well with the actual depth of the defects.

In quadrant D it appears that there could be an indication of wall loss due to the two slots cut into the plate since there is a dramatic shift in the contour lines in their immediate vicinity. If in fact there is an indication, it is very gradual and not qualitatively comparable to those shown near the other defects. If in fact the tests are providing an indication for the slots and the drill-pits, they are not readily discernable on the plots. This may be due in part to the coarseness of the grid, but it is more likely due to the relatively large footprint of the probe which tends to provide an average indication of damage.

While there are significant defects close to the areas where the anomalies are observed, the anomalies appear to be somewhat offset from the actual damage areas. In addition the shape of the anomalies appears to be significantly different from those of the actual damage geometry. One observation which is somewhat odd is that the main anomaly region overlaps into quadrant A which is supposed to be defect free. In both of the contour plots for plate 1, there appears to be a significant drop in the contour lines as the edge of the plate is approached. It is suspected that this edge effect is due to either a shortened eddy current path due to the edge, or that there is significant heat damage due to a flame cutting or machining of the plate edge.

Figure 2: Plate 1 (known defects) – With acoustic tiles and INCO Test Probe

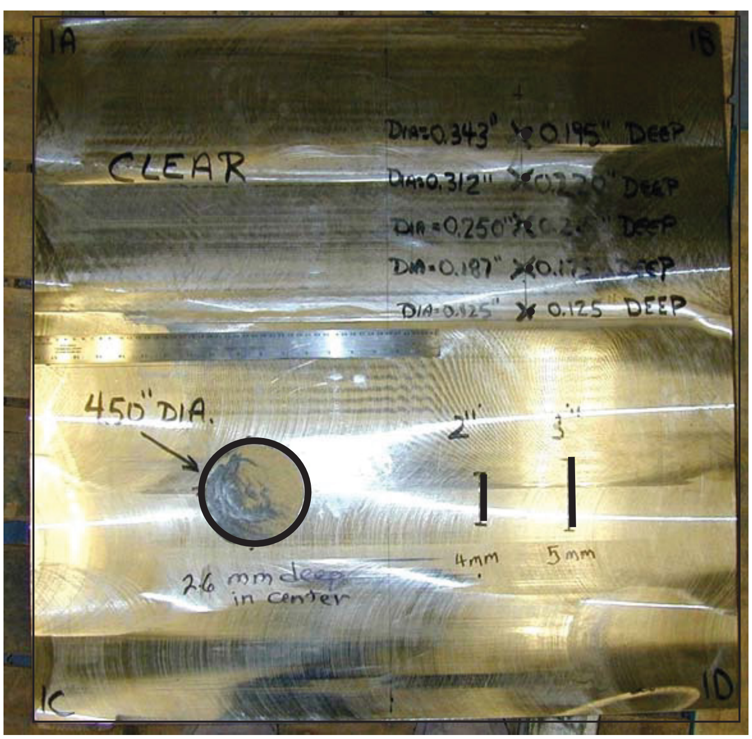

Figure 3: Plate 1 (known defects) – Bare plate and defects (i.e without acoustic tiles)

A B

X/Y	0	3	6	9	12	15	18	21	24
24	93.3	94.2	97.1	99.0	98.1	97.1	97.1	98.1	96.2
21	95.2	95.2	96.2	99.0	100.0	95.2	96.2	98.1	98.1
18	97.1	92.3	91.3	94.2	96.2	90.4	90.4	95.2	98.1
15	96.2	89.4	90.4	93.3	95.2	93.3	92.3	95.2	96.2
12	95.2	88.5	92.3	94.2	94.2	96.2	97.1	97.1	93.3
9	96.2	89.4	94.2	93.3	94.2	98.0	97.0	96.0	96.0
6	96.2	91.3	94.2	93.3	94.2	99.0	97.0	98.0	97.0
3	96.2	92.3	95.2	95.2	94.2	99.0	99.0	99.0	97.0
0	95.2	93.3	97.1	98.1	97.1	99.0	97.0	96.0	96.0

C D

Figure 4: Plate 1 – Tabular listing of % of Normalized plate thickness- Data set 1

A B

X/Y	0	3	6	9	12	15	18	21	24
24	94.2	94.2	97.1	100.0	99.0	97.1	97.1	98.1	96.2
21	96.2	95.2	96.2	98.1	100.0	95.2	96.2	98.1	98.1
18	96.2	91.3	91.3	94.2	97.1	90.4	90.4	95.2	98.1
15	96.2	88.5	90.4	94.2	94.2	93.3	92.3	95.2	96.2
12	96.2	88.5	91.3	94.2	94.2	96.2	97.1	97.1	93.3
9	96.2	89.4	94.2	94.2	94.2	99.0	97.0	96.0	97.0
6	97.1	91.3	95.2	93.3	94.2	99.0	97.0	97.0	98.0
3	96.2	93.3	95.2	94.2	95.2	100.0	99.0	99.0	98.0
0	95.2	93.3	97.1	97.1	97.1	99.0	98.0	96.0	96.0

C D

Figure 5: Plate 1 – Tabular listing of % of Normalized plate thickness- Data set 2

Note: lower Right Hand quadrant (D) was measured and normalized against a different reference value.

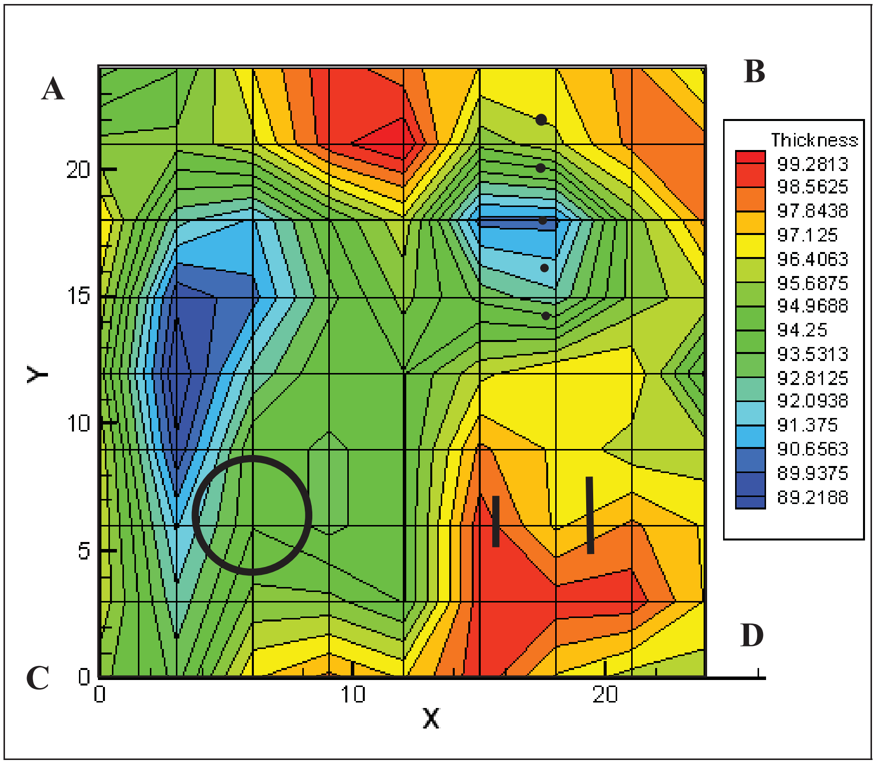

Figure 6: Plate 1 – Contour plot of % of Normalized plate thickness- Data set 1

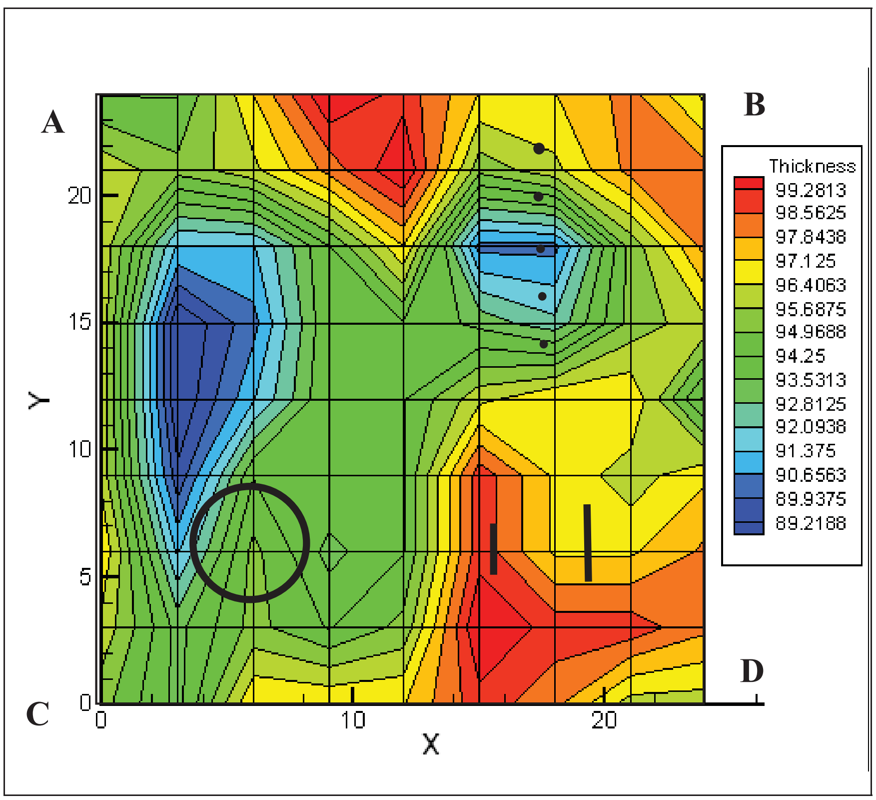

Figure 7: Plate 1 – Contour plot of % Normalized plate thickness- Data set 2

5.1.3 Plate 2: Known Defects

Two sets of Pulsed Eddy Current RTD INCO Test data were taken for plate no. 2 (Figure 8) and normalized with respect to plate thickness (Figures 9 and 10). Each of these data sets has been plotted as contours in Figures 11 and 12. Only the lower two quadrants, C and D were tested since these were the only ones with metal defects (See
Figure 4). As in the case of Plate 1, Plate 2 was also tested using a 3” grid spacing to provide an efficient inspection pattern for the probe used to maximize the amount of testing that could be accomplished. It should be noted that during these two tests, the probe was set to non-focused mode. According to the technician, the unfocused mode has a much larger foot print (4.5→ 5”) than when it is in focused mode (3.5”→ 4”).

The damage location in Plate 2 has been superimposed on Figures 11 and 12 to help determine if an actual damage location was detected. In these two figures, it can be seen that there are no sharp anomalies in the thickness contour plots. This may be due to the fact that the footprint is much larger in the unfocused mode which was used in these tests. Again it is interesting to note that the average wall loss indication in the area of the defects is approximately 10% which correlates well with the actual defect sizes.

Figure 4: Plate 2 – Bare plate and defects (i.e without acoustic tiles)

A B

X/Y	0	3	6	9	12	15	18	21	24
12	91.6	98.1	99.1	100.0	100.0	100.0	98.1	94.4	88.8
9	92.5	97.2	98.1	98.1	98.1	98.1	98.1	95.3	89.7
6	91.6	95.3	95.3	97.2	97.2	96.3	95.3	94.4	89.7
3	87.9	90.7	90.7	92.5	93.5	94.4	94.4	93.5	87.9
0	86.9	88.8	90.7	90.7	91.6	91.6	90.7	89.7	86.9

C D

Figure 9: Plate 2 – Tabular listing of % of Normalized plate thickness-Data set 1

A B

X/Y	0	3	6	9	12	15	18	21	24
12	91.6	98.1	99.1	99.1	100.0	100.0	98.1	94.4	87.9
9	90.7	96.3	98.1	98.1	98.1	98.1	98.1	95.3	89.7
6	90.7	95.3	96.3	97.2	97.2	96.3	95.3	93.5	88.8
3	86.9	90.7	91.6	92.5	93.5	94.4	94.4	92.5	87.9
0	86.0	89.7	90.7	91.6	91.6	91.6	89.7	89.7	85.0

C D

Figure 10: Plate 2 – Tabular listing of % of Normalized plate thickness-Data set 2

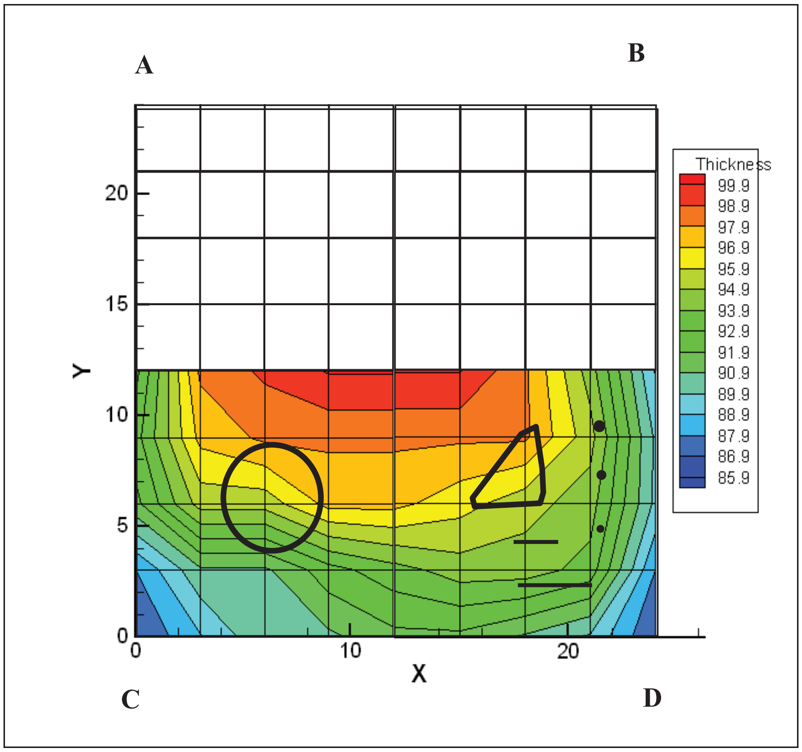

Figure 11: Plate 2 – Contour Plot % of Normalized plate thickness-Data set 1

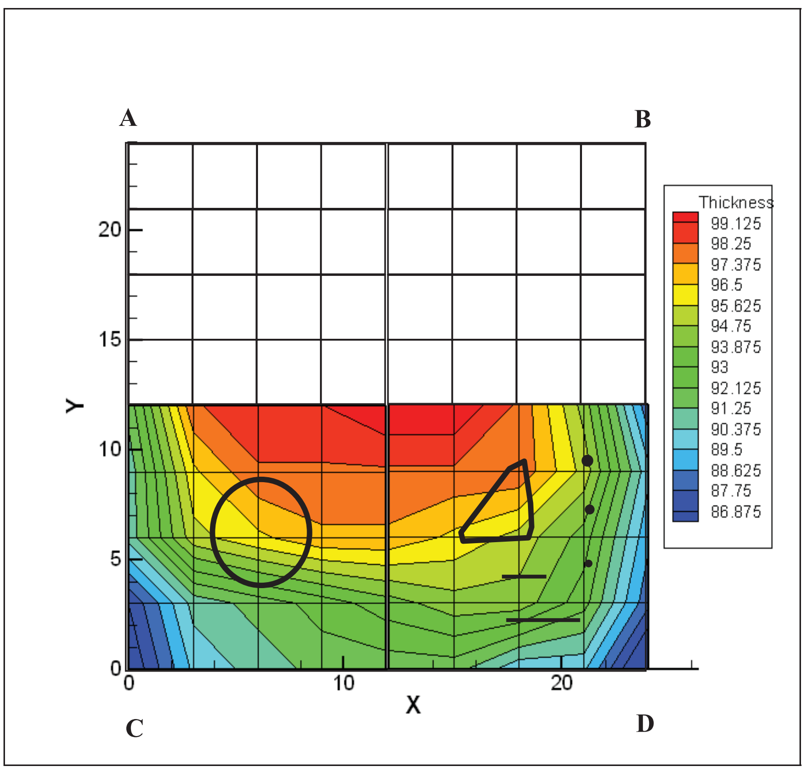

Figure 12: Plate 2 – Contour Plot % of Normalized plate thickness-Data set 2

It can be observed, that there is a more dramatic sharper drop off in the reported plate thickness in the lower left corner of quadrant C than in quadrant D. This is evidenced by the tight spacing between the contour lines in quadrant C as compared to the large spacing between those of quadrant D. This may indicate a correlation between the actual loss in plate volume which is more concentrated in quadrant C than in quadrant D. It can also be observed that like the contours for Plate 1, there is a pronounced edge effect indicated which may be due to material edge or heat effects due to torch cutting

It can be concluded that the unfocused mode does not enhance the detectability of defects. In fact, it appears that the unfocused mode may actually be smoothing-out the damage indications in the plate to the extent that they are no longer discernable.

5.1.4 Plate 3: Unknown Defects

The damage and tile configuration for test panel No. 3 are shown in **Figure 5** and Figure 6. Two sets of Pulsed Eddy Current RTD INCO Test data were taken for Plate No. 3 and normalized with respect to plate thickness (Figures 15 and 16). Each of these data sets has been plotted as contours in Figures 17 and 18. The INCO Test was conducted in focused mode on a refined grid of 2 inch spacing in both the x and y locations. This refined grid was chosen in an attempt to help maximize detectability of the unknown defects in this plate. This 2 inch grid helped ensure that there would be significant probe footprint overlap between sequential readings.

In the two contour plots (Figures 17 and 18), it can be seen that there are three areas which display significant anomalies. The largest of these areas is centered in the middle of the plate. There are also numerous other areas which are characterized by rapid changes in the contours and indicate anomalies in the thickness of the plate.

As observed for Plate No.'s 1 and 2, there appears to be a significant drop in the contour lines as the edge of the plate is approached. Again, it is suspected that this edge effect is due to either a shortened eddy current path near the edges, and/or that it is due to significant heat damage caused by flame cutting or machining of the plate edges.

In Figures 17 and 18, the areas with black circles and ellipses are the areas identified as anomalies in the contour plots. The white circles and ellipses are the outlines of the actual simulated damage in the test plates. Two or three of the anomalies seem to coincide very closely with the actual damage locations. However, there are also 7 or 8 other areas of anomalies identified on the plates at locations where there isn't any damage on the plates.

Figure 5: Plate 3 – Bare plate with defects shown

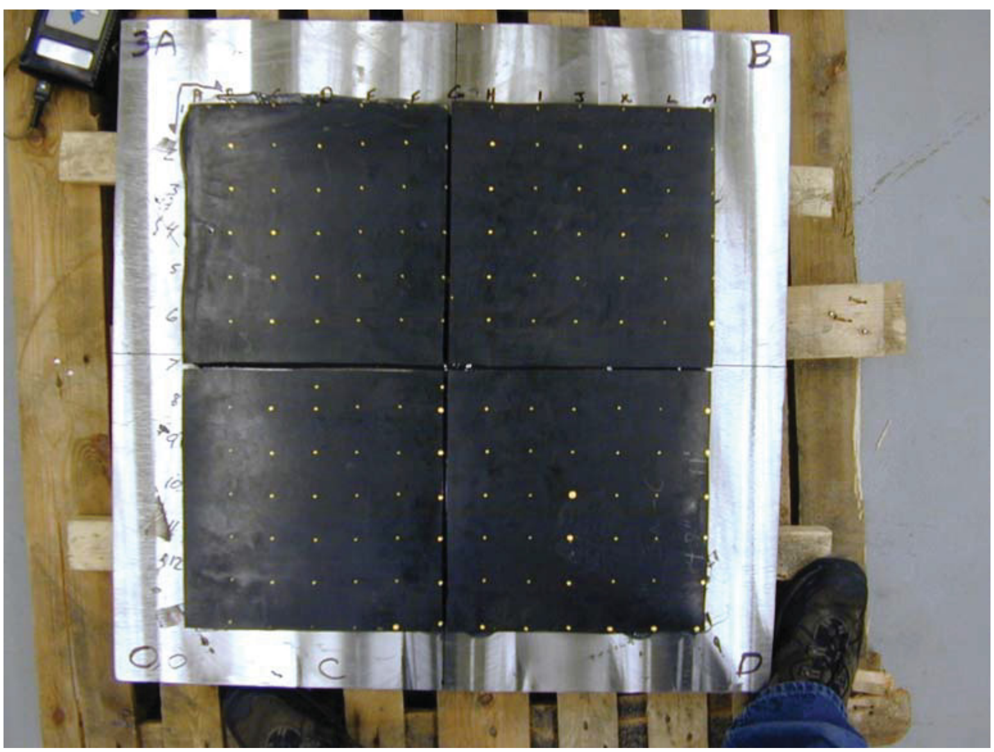

Figure 6: Plate 3 – Covered with solid rubber tiles and grid points

A B

X/Y	0	2	4	6	8	10	12	14	16	18	20	22	24
24	94.3	93.4	93.4	92.5	93.4	89.6	93.4	91.5	91.5	92.5	93.4	89.6	88.7
22	96.2	97.2	94.3	96.2	95.3	92.5	97.2	93.4	94.3	92.5	92.5	96.2	93.4
20	96.2	98.1	95.3	95.3	96.2	93.4	97.2	96.2	96.2	94.3	95.3	95.3	92.5
18	95.3	97.2	97.2	97.2	97.2	97.2	98.1	98.1	98.1	97.2	97.2	95.3	94.3
16	93.4	93.4	98.1	99.1	97.2	98.1	99.1	99.1	99.1	99.1	97.2	94.3	93.4
14	93.4	92.5	96.2	98.1	98.1	99.1	98.1	100.0	98.1	99.1	97.2	97.2	95.3
12	93.4	93.4	97.2	97.2	97.2	97.2	98.1	97.2	99.1	99.1	99.1	98.1	96.2
10	94.3	97.2	96.2	96.2	96.2	96.2	97.2	98.1	99.1	100.0	99.1	98.1	95.3
8	92.5	90.6	97.2	99.1	97.2	98.1	98.1	97.2	99.1	100.0	99.1	97.2	94.3
6	93.4	93.4	98.1	99.1	98.1	98.1	99.1	99.1	100.0	100.0	100.0	97.2	95.3
4	93.4	92.5	99.1	99.1	99.1	99.1	100.0	98.1	99.1	99.1	99.1	96.2	94.3
2	94.3	96.2	98.1	98.1	98.1	97.2	96.2	95.3	96.2	98.1	96.2	97.2	95.3
0	91.5	91.5	95.3	93.4	95.3	95.3	93.4	92.5	93.4	93.4	94.3	94.3	92.5

C D

Figure 15: Plate 3 – Tabular listing of % of normalized plate thickness- Data set 1

A B

X/Y	0	2	4	6	8	10	12	14	16	18	20	22	24
24	94.3	94.3	93.4	93.4	93.4	90.6	94.3	91.5	90.6	91.5	92.5	84.9	87.7
22	95.3	97.2	94.3	94.3	94.3	92.5	95.3	93.4	93.4	92.5	92.5	96.2	93.4
20	95.3	98.1	94.3	94.3	97.2	93.4	97.2	95.3	95.3	94.3	95.3	96.2	92.5
18	93.4	96.2	95.3	94.3	97.2	97.2	98.1	98.1	98.1	97.2	96.2	95.3	94.3
16	92.5	95.3	99.1	99.1	98.1	99.1	99.1	99.1	100.0	99.1	98.1	95.3	94.3
14	92.5	93.4	96.2	99.1	98.1	98.1	98.1	99.1	99.1	99.1	97.2	98.1	96.2
12	92.5	92.5	100.0	98.1	98.1	97.2	97.2	97.2	96.2	99.1	99.1	98.1	96.2
10	93.4	93.4	93.4	96.2	96.2	96.2	95.3	97.2	99.1	100.9	99.1	98.1	96.2
8	92.5	91.5	98.1	98.1	100.9	99.1	96.2	98.1	100.0	100.0	98.1	98.1	95.3
6	92.5	93.4	98.1	98.1	99.1	99.1	98.1	99.1	99.1	100.0	99.1	97.2	95.3
4	91.5	93.4	100.0	100.0	100.0	99.1	99.1	99.1	98.1	99.1	98.1	97.2	94.3
2	93.4	95.3	97.2	98.1	92.5	97.2	96.2	95.3	96.2	97.2	98.1	91.5	90.6
0	91.5	92.5	95.3	95.3	97.2	94.3	94.3	92.5	93.4	94.3	94.3	93.4	91.5

C D

Figure 16: Plate 3 – Tabular listing of % of Normalized plate thickness-Data set 2

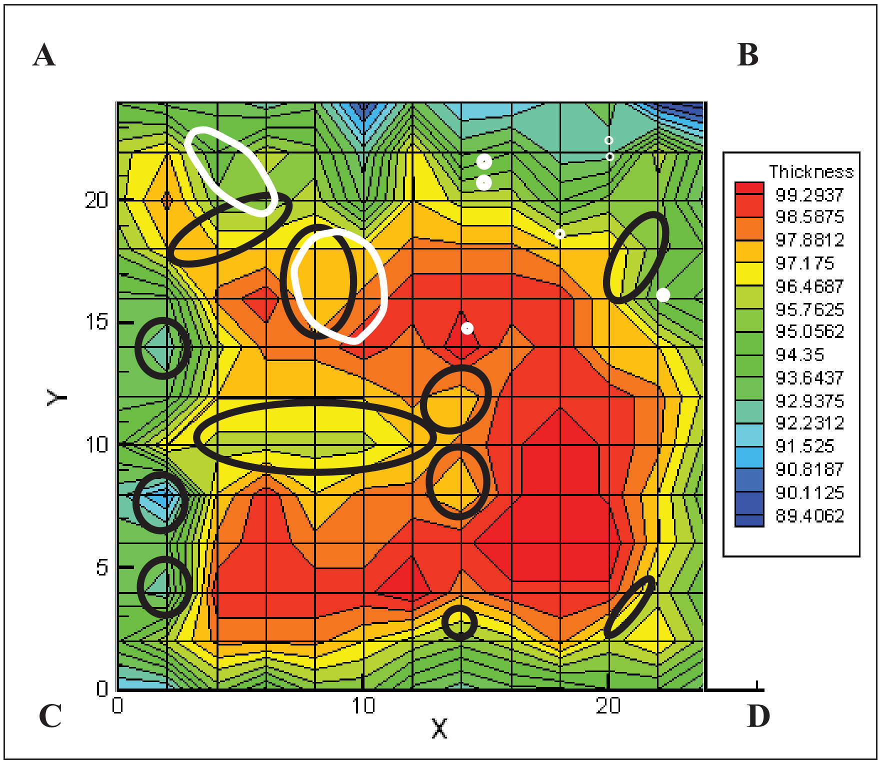

Figure 17: Plate 3 – Contour plot of % of Normalized plate thickness- Data set 1

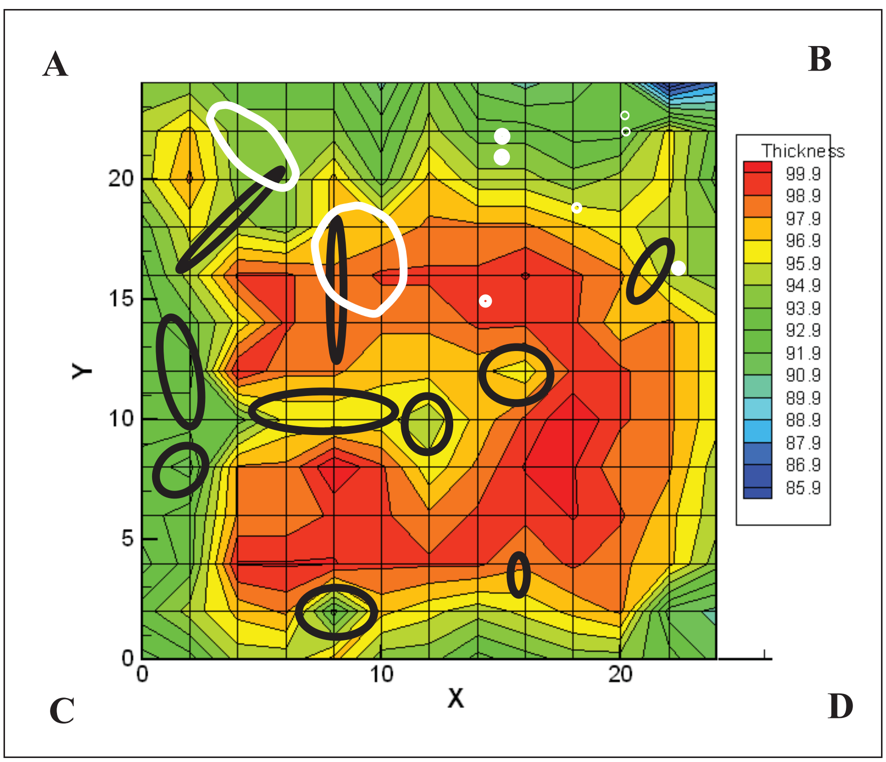

Figure 18: Plate 3 – Contour plot of % of Normalized plate thickness- Data set 2

There are therefore significant discrepancies between the anomalous areas in the contour plots generated with the INCO-Test data and the actual damage. These discrepancies may be an indication that the INCO test is very sensitive to something in the test panels other than basic wall thinning. According to the RTD Level 3 NDI specialist, the presence of machining in the surfaces can severely affect the magnetic permeability of the metal. This change in permeability is allegedly the reason why there are anomalies in the thickness readings.

Based on the level of variation in the data, it is not clear if in fact any of the wall thickness defects have been successfully detected. Furthermore, it brings into question whether the RTD INCO-Test is capable is capable of detecting the defects in the submarine hulls which are of interest to DRDC and DND.

6 TASK 5: FINAL ASSESSMENT OF NDI TECHNOLOGY FEASIBILITY

After Owens Aerospace received the description of the damage on Panel No. 3, a final assessment of the INCO Test feasibility was performed. This was accomplished by comparing the actual test results with the descriptions of the damage provided by DRDC. A detailed assessment of the feasibility of the technology for meeting the DRDC submarine inspection objectives was also conducted.

These assessments attempted to address the following issues identified in the SOW and/or in discussions with DRDC's TA:

a) A description of the applicability and limitations of the evaluated technology
b) Possible research activities required (if any) to overcome limitations in task a
c) Time and Cost estimates required (if any) to implement activities in task b
d) Risk associated with the research activities proposed in task b
e) Hardware/procedure development effort to overcome difficulties (if any) in a
f) Time and cost estimates for development effort (if any) in task e
g) Risks associated with development activities (if any) proposed in task e
h) Cost estimates and operator training requirements for NDI development in e

6.1 (A) Defect Detection Capability and Limitations

As noted in the test results and discussion section of this report, the INCO-Test detected several anomalies in the data. However the results were not conclusive since the location and shape of the defects did not coincide with the location of the anomalies in the data. While the locations of the anomalies were in the general vicinity of the defects, there is some doubt as to whether the defects were in fact captured. Based on the test results, there is also doubt as to whether the INCO test equipment used in the formal testing at DRDC is able to detect the smaller sized pits and crack/slots in the test panels.

RTD indicated in their test report that they believe that the machined surfaces of the specimens have affected the magnetic permeability of the steel. RTD has indicated that their study of the data has indicated a signal disturbance due to this machining. It can be surmised then that the current INCO test technology which was used in the testing will be inhibited from providing accurate and /or reliable test results when machined surfaces or defects are present. This is an important consideration, since it is presumed that welded seams and repairs are often subjected to surface grinding for fairing the surfaces. It must be carefully considered that this could well mean that post-ground weld repair areas may not be accurately inspected with this technique. In addition, any mechanically machined areas of the submarine hull might also generate erroneous defect anomaly indications using the RTD INCO-Test.

In addition to these signal disturbances noted by RTD, Owens Aerospace has clearly observed in the INCO Test data an edge effect around the test panels. As noted previously, it is suspected that there may be at least two reasons for this edge effect observed in the data. One of these is the presence of a physical edge which reduces the eddy current paths in the steel and thus appears as a reduction in wall thickness. The second would be that there may be a heat affected zone near the plate edge due to torch cutting and or high temperatures during machining. If the RTD technology is sensitive to heat affected zones, it may well have great difficulty in discerning defects coincident with welded seams or welded repair areas.

According to the RTD technician that performed the tests at DRDC, the INCO Test is much better at detecting wall losses above the 30%. He indicated that wall loss in the range of 10% of the thickness may be challenging and is near the threshold of detectability due to signal variation. DRDC is looking for defects roughly 3 mm deep in a wall of steel which is 30 mm thick, i.e 10% of the wall thickness. Hence the INCO-Test in its present form may not able to provide the desired detectability according to the RTD technician which performed the test.

6.1.1 INCO-Test Inspection Environment

According to RTD personnel, the INCO-Test is capable of working in a variety of environments including off shore inspection of oil rig structures. It has allegedly been used to inspect these structures even when they are coated with thick layers of barnacles and other sea matter. The technology has also allegedly been modified to enable underwater inspection of steel structures. If these claims can be verified and the technology could be proven effective for inspecting the Victoria Class subs, then RTD could prove to be a flexible tool. In particular, it could possibly be used to inspect the submarine hulls while these vessels are submerged. This would reduce or eliminate the amount of time required in dry-dock for inspection and also reduce the amount of time required on the Hydro-Lift at the DND Halifax ship yard.

6.1.2 Quality of INCO-Test Output Data Post Processing

If Owens Aerospace has understood correctly, the INCO-Test output data is presently limited to a tabular display of thickness values. These values can be presented as a % of a reference thickness or an actual thickness based on this reference value. According to the RTD technicians and managers, INCO-Test is not equipped with a real time display contour plotting capability similar to a C-Scan type of out-put. If this capability is deemed desirable and or required by DRDC, then it should be noted that this capability is not presently available. To develop this capability would require some software and/or hardware additions to the present INCO-Test system which was demonstrated at DRDC Atlantic. In this regard, the INCO-Test system is somewhat behind other NDI technologies on the market which provide this capability as a standard option.

6.1.3 INCO-Test Inspection Speed

The overall inspection speed of any NDI technology proposed for use on the Victoria Class submarines should be an important consideration. According to the RTD technicians and their literature, the average cycle time between readings can vary between 10 seconds and 30 seconds. Owens Aerospace performed some basic time studies on the RTD INCO-Test and found that at its peak performance the minimum cycle time was ~10 seconds. This was observed for the panels tested at DRDC in a controlled environment after the GRID pattern had been laid out on the panels.

If a very coarse grid point spacing of 3" is assumed, then this would constitute a 4 x 4 grid for every 1ft x 1ft square tile area which is ~ 16 points. At 10 seconds/point, this would mean that a 1 ft^2 area are could be inspected in 160 seconds.

Assuming the Victoria class submarines have 75% of their hull covered with tiles on the cylindrical portion of their hull, an inspection time estimate can be made. Based on a hull beam (diameter) of 25 m and a length of 110 m- 2 x 25 m, the total area of the cylindrical portion of the hull would be as follows:

- Assume a cylindrical shaped hull
- Assume tiles are only on the cylinder and not on the end semi-spheres
- Assume only 75% of this cylindrical area is covered with the tiles
- Assume a 100% inspection of this acoustic tiled area
- Ignore all set up time for scaffolding, grid point layout etc.

- Submarine Length: 70.26 metres
- Submarine Beam: 7.6 metres
- Area of Hull = $2\pi R \times L = 2 \times 3.1416 \times 7.6 \text{ m} \times 70.26 \text{ m} \times (3.28 \text{ m/ft})^2 = 36{,}095 \text{ ft}^2$
- 75% of area = $36{,}095 \times 0.75 = 27{,}071 \text{ft}^2$

- Inspect Time = Inspected Area x Inspect Time/ft^2 = 27,071 ft2 x 160 sec/ft^2
- Inspection hrs = 4,331,422 secs x 1 hour/ 3600 secs = 1,203 hrs
- Inspection days = 1,203 hrs/ 8 hrs/day = 150 days
- Inspection Weeks = 150 days/5days/week = 30 weeks
- Inspection months = 30 weeks/ 4.25 weeks/month = 7 months

It should be noted that this estimate may not be conservative and the actual inspection time may be substantially longer. The inspection schedule or calendar time could likely be reduced by employing several machines and technicians and by working overtime, weekends and 24 hour shifts. In any case, the net amount of man-hours required for 100 % hull inspection is very significant.

6.1.4 Projected Cost for INCO-Test Inspection of Complete Submarine

There would also be a very significant cost required for the RTD INCO Test inspections when one considers the labour rates and machine rates for the INCO Test. These numbers could grow substantially depending upon the difficulty of access to the structure, the set-up time, the weather conditions and other unforeseen conditions. The numbers might also be reduced somewhat based on bulk inspection discount rates. They might also be reduced if the INCO Test equipment and procedures are further developed to improve its efficiency. These numbers should not be relied upon for any business decisions and are for reference only.

6.2 (B) Further Research of RTD INCO-Test for Submarine Inspections

It has not has not been conclusively demonstrated that the RTD INCO-Test is capable of accurately detecting the submarine hull defects of interest to DRDC. To determine if this technology does have the capability, some further testing would definitely be required. Based on the commentary, by RTD in their test report for this project, new test specimens would likely be required for further evaluations. In particular specimens with natural corrosion defects and with no machining present on their surfaces or in the defect areas. Another possibility is to make the defects with chemical milling with acid, but again this has not been verified as a method which would improve test results.

In addition, the new specimen might have to be cut with a water-jet or other low temperature, method which minimizes heat and surface hardening at the plate edges. If DRDC believes that such samples would be an accurate representation of the actual submarine hull, then perhaps further testing with new specimens would be warranted.

However, if DRDC believes that the actual hulls, could have significant machining on their surfaces, then the merits of further testing must be questioned. This is due to the fact that RTD has indicated that they believe that the signal they rely on in the RTD INCO-Test are dramatically affected by machining. The tests noted above may possibly help determine if machining and/or heat affected areas on Victoria Class submarine hulls render the RTD INCO-Test ineffective.

6.3 (C) Cost and Time Estimate of Further Research/Testing

To conduct the basic additional research and testing noted in the preceding section, additional work and specimen fabrication would be required. It is estimated that an additional 3-4 weeks of research activities would be required to ascertain a more solid understanding of the limitations/capabilities of RTD INCO-Test. The effort for this basic activity would be 3-4 weeks of effort by the Owens Aerospace project engineer plus several days additional testing by RTD with their INCO-Test.

The cost would include the labour rate for Owens Aerospace at standard consultant fees plus travel expenses as well as the RTD testing and travel fees and the cost of the new test specimens. It should be noted that special care would have to be taken in the design and fabrication of the specimens to produce the controlled conditions required. It is likely that standard un-machined steel plate of nominal thickness would be used and it might not exactly match the 30 mm thickness used in the present specimens. It is uncertain how long it would take to generate natural corrosion defects on these plates to the size and depth required. It may be possible to chem.-mill the defects without altering the surface permeability. This approach is un-founded and it is recommended that it be tested on simple bare plate before it would ever be used for actual formal test specimens. Otherwise, the same permeability issues and questions could creep into the interpretation of the test results.

6.4 (D) Risks Associated With Further Research/Testing

The main risk in proceeding with further testing is that it may prove that the RTD INCO-Test is inherently incapable of effectively inspecting submarine hulls. If this were the case, then whatever further effort is expended is at risk of not producing DRDC advancing any closer toward an effective solution. It is hoped that at the end of this preliminary effort that an assessment of technology could be obtained which would definitively indicate if it could be used. There is no guarantee that this could be achieved in the 3-4 week time frame proposed.

6.5 (E) Further Development of INCO-Test for Submarine Inspections

Owens Aerospace has inquired with RTD about the possibility of further developing their equipment to make it more efficient for inspecting submarine hulls. In particular, Owens Aerospace has inquired if RTD would be interested in partnering with Owens Aerospace or DRDC Atlantic to work closely at modifying their technology. RTD indicated that their equipment was a closely guarded trade secret and that they would be very reluctant to work with outside companies on development.

They did indicate however that they would consider development to better suit the submarine hull inspections. However, they stated that such a development would likely be done in the Netherlands at their parent office where their development engineers are located. They also indicated that they are primarily an NDI service provider and not an NDI equipment developer and that any development would have to be supported by a substantial business case.

The effort to develop RTD INCO Test to the point where it could be used for inspecting general corrosion on the submarines is uncertain. In fact it is uncertain if the technology in its present state is a capable of providing accurate detection of general corrosion of the Victoria Class submarine hulls.

A deeper study of how the INCO-Test technology and its software are used to inspect steel is required. Only then could it be determined if such things as machined areas and heat affected zones could be accounted for using this technology. Some basic additional testing of the existing equipment could also be performed to help quantify the possible influence of machining and/or heat affected areas. This testing is discussed in the preceding sub-section.

At present, RTD does not appear to be willing to share this information with outside sources. Therefore, only RTD is in a position to establish whether the technology can be rendered effective and what development effort is required to do so. To obtain this information, further discussions and negotiations with RTD's development office in the Netherlands would likely be required.

In addition to developing the basic detection capabilities of the system, additional development of the output data processing and display could also be of value. Another significant area of improvement for the RTD INCO-Test could be in automating the inspection. This could possibly be accomplished by adapting the basic technology to a gantry system which would eliminate the need of an operator to manually take readings. This could help reduce human error, reduce the need of marking out a physical grid and speed up the cycle time between readings. Again, this idea was suggested to RTD and an interest on the part of Owens Aerospace in being involved with this development was expressed. However, RTD re-iterated that they would not likely be interested in having outside parties involved with developing their equipment.

6.6 (F) Time and Cost Estimates for Further Development of INCO-Test

Owens Aerospace inquired with RTD about the time frame for a development program similar to the one described above. RTD indicated that they weren't about the time frame but that it might not be able to begin until approximately 1 year or more due to other commitments. They indicated that in order to estimate the time and cost of such a development effort would require the involvement of their parent office in the Netherlands. It would require an in depth study of the basic results and possibly the results from additional test as noted above, before RTD could provide these estimates.

6.7 (F) Risk Associated With Further Development of INCO-Test

The risk is likely something that could be negotiated for a further development of the RTD INCO-Test as noted in the sections above. It is possible that a development cost could be made payable on the basis of demonstrated success and reliability of the technology. Such an arrangement would place the onus on RTD to ensure that it delivers a reliable product which will meet specified expectations of DRDC Atlantic. Unless such a conditional arrangement were made, and DRDC were to pay development cost up front, they may wind up with no valid technology for the moneys expended.

6.8 (G) Cost Estimates and Operator Training Requirements

According to RTD, it takes upwards of 6 months to train their INCO-Test technicians. They indicated that there is no formal national certification that they require for their technicians. However, they indicated that RTD has its own internal training and certification program.

6.8.1 Potential for Licensing INCO-Test

Owens Aerospace inquired if it would be possible to license the INCO-Test technology and obtain equipment specifically for the submarine inspections. It was explained to RTD that Owens Aerospace and/or DRDC might possibly consider performing the inspections themselves if possible. RTD indicated that their technology was proprietary and that they would not likely be interested in leasing and/or selling equipment for this purpose. They iterated that they would prefer to do the inspections themselves and only in rare cases have they ever licensed the technology to others. Owens Aerospace inquired if a franchise opportunity were available. RTD indicated franchise opportunities do not presently exist and that they would most likely not be interested in this arrangement.

7 FURTHER STUDY OF OTHER NDI TECHNOLOGIES

As noted in this report, there are other NDI technologies which could potentially be used to detect the defects of interest on the Victoria Class submarines. The most promising ones include: Saturated Low Frequency Eddy Current, Magnetic Flux Leakage, Standard Eddy current with large diameter coils and catch-pitch ultrasonic at the tile edges. With further investigation some of the other technologies identified in this report might also show promise and others may be identified as well.

Disclaimer

All facts, figures and opinions expressed in this report are for reference only. Owens Aerospace accepts no responsibility for any damages resulting from any decisions relying on the information provided in this report or in any other communication. It should be carefully noted that Owens Aerospace does not discount RTD INCO-Test from being able to detect the size and nature of the defects in the Victoria Class submarines which are of interest to DRDC. However, based on the test data collected at DRDC alone, it can not be concluded whether the RTD INCO-Test can effectively detect these defects on Victoria Class submarine hulls. To conclusively assess the RTD INCO-Test technology, further testing and/or research is required.

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