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DESIGN AND TESTING CONSIDERATIONS FOR HARDENING A FRIGATE AGAINST EMP THREAT

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DEFENCE RESEARCH ESTABLISHMENT OTTAWA

REPORT N0. 1254

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Countermeasures Section
Electronic Warfare Division

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ABSTRACT

The new Canadian Patrol Frigates (CPF) integrate an extensive suite of electronic systems. If those systems were found to be vulnerable to the electromagnetic environment, the safety and mission of the ship would be jeopardized. One of the most severe threats is the EMP resulting from a nuclear detonation. Not only may this very intense field disrupt or permanently damage electronic systems, but its extensive coverage could also result in disruption of all unprotected platforms in a very wide area. It is a requirement that the CPF be adequately hardened against EMP. The hardening of the CPF against EMP was primarily based on analysis. Testing with a simulated EMP is the only means of verifying that the various protections incorporated into the design are indeed effective and that the contractor has delivered an EMP hardened system. In preparation for a possible EMP test of one of our frigates, DREO has investigated the potential use of the Dutch EMP test facility and has sent a team to participate in the testing of one of the Dutch new frigates. This research has been sponsored by DMCS 5-5-4.

This report discusses various aspects of electromagnetic compatibility in general and EMP in particular on-board modern ships. Guidelines for preparing a test plan and difficulties which may be encountered during the test are discussed in detail.

RÉSUMÉ

Les nouvelles frégates canadiennes dépendent considérablement des systèmes électroniques pour assurer la plupart des fonctions critiques, telles que les systèmes de communications, de navigation, de défense et d'armement. Cette dépendance accrue pourrait mettre en péril la mission, voire la survie, du navire si ces systèmes étaient vulnérable à l'environnement électromagnétique. L'une des menaces électromagnétique les plus sévère est l'impulsion électromagnétique (IEM) générée par une explosion nucléaire. Cette IEM est non seulement très intense, mais peut perturber simultanément toutes les plate-formes manoeuvrant dans une très vaste étendue. L'entrepreneur principal devait livrer les frégates adéquatement protégées contre les IEM.

La protection des frégates contre les IEM est basée principalement sur des analyses théoriques. Des tests utilisant une IEM simulée constitue le seul moyen disponible pour vérifier si les mesures de protection incorporées lors de la conception des systèmes sont en fait efficaces. Ces tests confirment que les méthodes d'analyses sont exactes et que l'entrepreneur a livré des systèmes adéquatement protégés. En préparation pour un test IEM possible de l'une de nos frégates, le CRDO a étudié la possibilité d'utiliser une installation hollandaise.

Ce rapport décrit plusieurs aspect de la compatibilité électromagnétique à bord des navires modernes en général, et plus particulièrement des effets des IEM. Des directives pour la préparation du plan de test sont présentées, de même qu'une description des difficultées qui peuvent être rencontrées lors du test. Cette recherche a été commanditée par DSCN 5-5-4.

EXECUTIVE SUMMARY

The new Canadian Patrol Frigates (CPF) integrate an extensive suite of electronic systems. Those highly sophisticated electronics systems considerably extend the communications, navigation, ship's defence and weapon's control capabilities. This greater dependance on electronics may jeopardize the ship safety and mission if those systems were found to be vulnerable to the electromagnetic environment. One of the most severe threats is the electromagnetic pulse (EMP) resulting from a nuclear detonation. Not only may this very intense field disrupt or permanently damage electronic systems, but its very wide coverage could also result in disruption of all unprotected platforms in a very wide area (up to 500 km radius). It is a requirement that the CPF be adequately hardened against EMP.

The hardening of the CPF against EMP was primarily based on analysis. Testing with a simulated EMP provides the only means of verifying that the various measures incorporated into the design for protection are indeed effective. It provides confirmation of the effectiveness of the EMP analysis and design and is the only guarantee that the contractor has delivered an EMP hardened system. In preparation for a possible EMP test of one of our frigates, DREO has investigated the potential use of the Dutch EMP test facility (EMIS-2) and has sent a team to participate in the testing of one of the Dutch new frigates.

This report discusses various aspect of electromagnetic compatibility in general and EMP in particular on-board modern ships. The various types of EMP simulators are presented and a description of EMIS-2 is given. Data acquisition instrumentation required for EMP test of large objects such as a ship is also described. Guidelines for preparing a proper test plan and difficulties which may be encountered during the test are discussed in detail. This research has been sponsored by DMCS 5-5-4.

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1. INTRODUCTION

The new Canadian Patrol Frigates (CPF) integrate an extensive suite of electronic systems. Not only do these systems considerably extend the communications, navigation, ship defence and weapon control capabilities, but in many cases they have been identified as critical to the success of the mission or to the survival of the ship. The electromagnetic environment on-board modern naval ships is one of the most severe that can be encountered, with dozens of powerful on-board transmitters, sensitive receivers and sensors, as well as intense emissions from friendly or unfriendly sources. One of the most severe threats is the electromagnetic pulse (EMP) resulting from a nuclear detonation. Not only may this very intense field disrupt or permanently damage electronic systems, but its very wide coverage could also result in disruption affecting all unprotected platforms in a very wide area (up to 500 km radius). EMP is well recognized as a very serious threat and DND has issued the NDHQ Instruction DCDS 3/83 on "*Electromagnetic Pulse Protection for CF Equipments, Systems and Installations*" which states that:

> ***EMP protection of strategic capabilities must be sufficient such that an effective level of strategic operational capability would survive an EMP from a nuclear blast.***

EMP hardening was a requirement for the new CPFs as stated in references [1] and [2]. Hardening was achieved by thorough analysis of electromagnetic coupling to all critical sub-systems [3]. Although EMP testing was not part of the contract, it provides the only means of verifying that the various measures incorporated into the design for protection are indeed effective. From that perspective, it is a unique tool for quality control. It provides confirmation of the effectiveness of the EMP analysis and design and is the only guarantee that the contractor has delivered an EMP hardened system.

In view of a possible EMP test of one of our frigates, DMCS 5-5-4 has tasked DREO to develop expertise the area of EMP testing of ships. DREO has considerable experience in EMP assessment, protection and verification, both analytically and experimentally. They have extensive numerical simulation capabilities that were used for predicting the electromagnetic interactions of several critical sub-systems on-board the frigates. They have also developed experimental facilities capable of testing objects as large as an helicopter with a simulated EMP at full-threat level. DREO has always maintained close contacts with other laboratories, particularly in the US, UK and Netherlands. A full-threat EMP simulator facility capable of illuminating a whole ship once existed but has been dismantled since (EMPRESS-II). Netherlands has one of the few sub-threat level EMP simulators suitable for testing ships that is still operational (EMIS-2). It was developed in-house by TNO Defence Research. They have a solid background in EMP hardening and testing. They are open to international collaboration and have offered us the use of their simulator for testing one of our frigates. To gather the expertise necessary in preparation for the testing of one of the Canadian

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"*TNO Physics and Electronics* Laboratory" is an independent laboratory doing most of their work for the defence department.

Navy ships, a team from DREO joined them to participate in the EMP testing of one of their new frigates. This EMP test was conducted in Den Helder (Netherlands) in October 1994.

This report discusses various aspect of electromagnetic compatibility in general and EMP in particular on-board modern ships. It also discusses guidelines for preparing a proper test plan for conducting an EMP test on a frigate.

2. DESIGNING FOR ELECTROMAGNETIC COMPATIBILITY

The primary objective of conducting tests is to verify that the system has been designed properly to survived its electromagnetic environment. To understand how the test plan implements this objective, it is necessary to discuss the electromagnetic environment and the various protection techniques.

2.1 Electromagnetic Environment and Electromagnetic Compatibility

The electromagnetic environment (EME) above deck of modern naval ships have evolved over the past 50 years into what may be called an *electromagnetic nightmare*. Dozens of on-board transmitters covering the whole frequency spectrum contribute to the EME. These include HF, VHF, UHF and satellite communication transmitters, air search, surface surveillance, air control, weapons control and navigation radars, electronic warfare jammers, various transponders and beacons. Other friendly sources also include emissions from other ships and airborne platforms operating nearby. Natural RF interferences such as lightning also contribute to the EME. Finally, deliberate transmissions from unfriendly sources such as radars, jammers and also nuclear endo- or exo-atmospheric electromagnetic pulse (EMP) must also be considered.

Failure to control this very complex and intense EME may result in severe degradation of the electronic equipment or even have dramatic consequences, as in the case of the sinking of the British destroyer *HMS Sheffield*. It was hit during the battle of the Falklands in 1986 by an Exocet missile which came in undetected because the radar was turned off so it would not cause interference with radio communications to England. EMP is also an example of very serious threat because it could render inoperative many electronic systems (particularly the ship defence and communication systems) simultaneously on all ships operating in a rather wide area. To ensure effective performance of all electronic systems, a number of well accepted techniques may be used together to suppress or reduce the EME to acceptable levels. Those techniques include:

a) Decoupling — a reduction of RF energy received by sensitive electronic systems may be achieved by carefully positioning the antennas or sensors to obtain the widest separation between them and power transmitters.

b) Antenna reduction — the problems associated with very dense clutter of antennas may be lessen by reducing their numbers with the use of multicouplers.

c) Blanking — the effects of intense burst emission may in some cases be controlled by actively blocking their reception by sensitive systems.

d) Power reduction — operating transmitters at lower power levels will lessen electromagnetic interference (electromagnetic interference) problems.

e) Frequency management — selection of frequency bands should be chosen very carefully to minimize on-board EMI problems.

f) Shielding — essentially provides an effective barrier preventing the RF energy from entering the ship (and then interact with internal cables and sub-systems) or from entering individual sub-systems (and then interaction with printed circuit boards and electronic components).

g) Grounding and bonding — an effective method of diverting current induced on external cables into the bulkhead, preventing it from penetrating a shielded enclosure and propagating inside.

h) Filtering — reject some or all of an unwanted signal by blocking the reception of all out-of-band signals.

i) Arrestors — non-linear devices are effective for limiting transients to safe levels that would not permanently damage the electronic components.

The two principal interaction paths which the unwanted RF energy follow to cause degradation or failure of electronic equipment are through antennas and other collectors designed to receive RF signals (front door coupling) or through unintended penetration from poor shielding or through unsuspected ports (back door coupling). Front door coupling may be controlled relatively easily by hardening the receiver entrance circuitry and using a combination of the techniques listed above. Back door coupling is more difficult to control because of the thousands of cables linking the various sub-systems across the ship. More about electromagnetic interference and compatibility (EMI/EMC) on board ships is found in [5].

2.2 Design Philosophy for Electromagnetic Hardening of a Ship

The task of protecting all electronic equipment against this very complex EME is by no means simple and it is virtually impossible to look at all possible interactions between the hundreds systems on board. To effectively control the EME, a very simple and cost effective design philosophy can be applied systematically, which can be summarized as:

keep the electromagnetic energy outside.

The overall structure of the ship makes it inherently a good shielded enclosure but the shielding integrity may be violated whenever a cable penetrates the hull. If very good electrical bonding is used everywhere a cable penetrates the hull, the inside of the ship (with few exceptions) can then be considered as electromagnetically safe. Standard equipment meeting the MIL-STD-461C (including CS10 and CS11) specifications may then be used anywhere inside the ship without any special protection against the EME. This simplifies the system designer's task considerably: only electronic equipment located outside needs to be protected. This includes the bridge and helicopter hangar areas which are considered outside because the large number of windows on the bridge and the bay door of the hangar provide very little electromagnetic protection. With the exception of areas near the outside hatches, the fields inside are very small and may be neglected. Consequently, although all equipment inside must meet MIL-STD-461C, the radiated susceptibility tests may be relaxed by as much as 20 dB in some cases. Another advantage of a clean inside EM environment is that there is no need to have shielded rooms (with finger-stock doors on board). However, it is most important that all equipment pass the 10 A burst current tests of MIL-STD-461C (CS-10 & 11) as this criteria is the limit set for the current induced into external cables allowed to penetrate the hull.

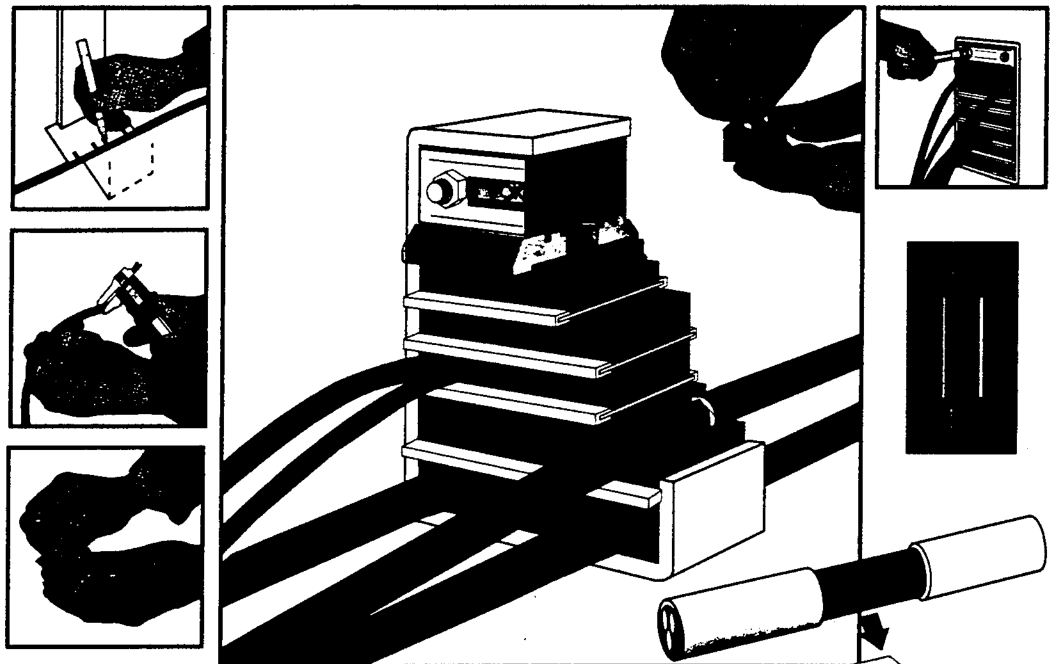
Every effort should be made to route the cables inside the ship to minimize the number of cables running outside, thus reducing the number of entry points to protect. In addition, these cables should be kept short in order to minimize the amplitude of the induced currents. If exterior cables are necessary, then only shielded cable with proper electrical bonding should be used. They should run preferably horizontally and not exceed 30 cm in length. Conduits with apertures are not very ineffective and only completely sealed conduits (with good bonding for all cables penetrating) should be used if longer exterior runs are nescessary.

Because the overall design philosophy relies on keeping the electromagnetic energy out, great care needs to be taken to bond the shield of all exterior cables where they penetrate the ship and also between rooms inside the ships in some cases. By diverting most of the induced current to the bulkhead, the bonding the shield is an effective method of protection which does not alter the signal which is normally carried by the cables. Although shielded rooms are not required on-board, all cables entering critical rooms should be shielded and bonded. Additionally, high power cables should also be bonded at several locations to reduce potential EMI.

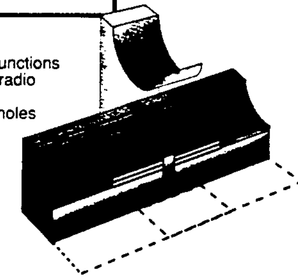
Two main types of assemblies are necessary to provide good electrical bonding of the cable shields to the bulkhead. One type is required when both electromagnetic and weather protections on individual cables are needed. Although it is preferred from an electromagnetic point of view to bond on the exterior, it is more practical to seal for weather protection on the exterior side and use a commercial back-shell connectors on the inside to provide a good electrical contact that will not degrade with time. When cable bundles running inside the ship need to be bonded, cable transit assemblies provide a cost-effective long term solution. Figure 1 shows a typical commercial product with some details (we have not evaluated that product neither do we formulate an opinion about its effectiveness). This assembly provides a good connection between the bulkhead and the shield of all the cables.

The 10 A criteria of MIL-STD-461C specify the survivability limit for electronic equipment. In many cases, particularly digital electronics, even upset cannot be tolerated. Upset may be induced by currents of the order of tens of mA. To filter the EMI without altering the digital signal is quite difficult and is not always practical when considering the number of signals involved. To overcome this problem, fiber optic cables should be used extensively for digital signals that can not tolerate upset. To further reduce potential EMI induced by cross-talk, cable separation into groups (eg. for power, control, data, etc.) should be done systematically across the ship.

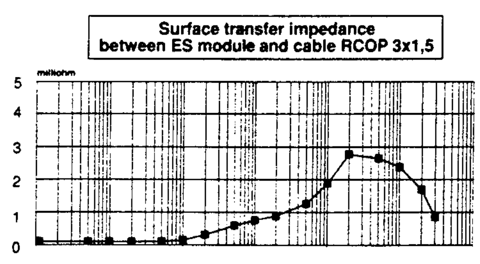
ES ROX SYSTEM
for electromagnetic protection



The ES ROX SYSTEM
Is used for sensitive areas containing computer and signal-processing functions and other electronic equipment to prevent malfunctions stemming from radio frequency interference (RFI), whether mains-borne along the screen of incoming cables, or air-borne as radio frequencies penetrating through holes and openings. RFI, EMI etc is effectively prevented from entering the construction. The measured general shielding properties (attenuation) in the 100 - 300MHz range is as high as 80 - 100 dB. And the surface transfer impedance less than 2.7 milliohm (5-300MHz range).



FLEXIBLE AND YET HIGHLY PROTECTIVE
Like the standard Rox System penetrations, the ES penetration is built up of adaptable insert modules utilizing the same cost-saving multi-diameter technique that simplifies assembly and minimizes stocks. However, each ES module also contains a vertical conductive screen and a conductive tape which attaches to the cable passing through. Once installed the penetration effectively stops and taps off energy to the ground from each cable screen passing through the frame.



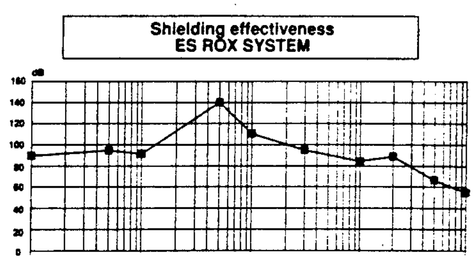


Figure 1. Commercial cable transit assembly from Roxtec. The cut-away view shows the details of the electrical bonding between the buldhead and cable shield.

2.3 Hardening against EMP

Hardening against EMP is part of the more general EMI/EMC hardening process. When all the proper precautions have been taken to protect against the on-board radars and power transmitters, then hardening against EMP has almost been achieved. Often, the only additional protection that is required is the inclusion of arrestors or other protection device at the antennas. This represents a very small cost.

Contrary to the various on-board EM threats, EMP is externally induced and broadband by nature. Thus, the only way to asses the vulnerability of the ship is to test the whole system with a simulated EMP. With the Dutch facility (EMIS-2) the overall EMP test can be done at sub-threat level of about 2 kV/m. Through carefully post-analysis, the results can be scaled to full threat level and assessment of the EMP vulnerability can be made. However, it is necessary to test some critical sub-systems at full threat levels, particularly if they include some type of non-linear protection device. Those sub-systems can be tested individually at other EMP simulator facilities such as the Defence Research Establishment Ottawa EMP Simulator (DREMPS). The EMP test can also provide valuable information about the effectiveness of most of the cable bonds used thorough the ship. A very good reference to EMP interactions is found in [6].

3. TEST PLAN

As previously mentioned, the design philosophy behind EMP and other electromagnetic threats hardening is to prevent current, which is induced on exterior cables, from penetrating into the hull. By achieving this, the interior of the ship can be declared as *electromagnetically clean*. With this goal in mind, most of the verification (about 80% of the measurements) will consist of interior and exterior current measurement. Electric and magnetic field measurements should also be performed in areas containing critical electronic equipment. Fields should also be measured on the bridge and the helicopter hangar, which are considered exterior zones.

Given the large number of bulkhead penetrations, exposed cables, specialized sub-systems etc. on a frigate, the preparation of an EMP test plan requires the assistance of one or two experts very familiar with the mechanical design of the ship and ideally also with EMC/EMP. This task requires about 6 months to identify all the points of entry on ship schematics, physically checking all of them for accessibility and then preparing a test plan.

One suggestion worth emphasizing is to incorporate the manufacturers of various equipment into the EMP test by inviting manufacturers to evaluate their own equipment during the EMP trial. It should be done on a cooperation basis (ie. no fee should be charged or payed). The manufacturers would be given free access to their equipment while on the ship and allowed to monitor it in any way they deemed necessary. In exchange, they would share their results and provide a test report of their evaluation. This practice takes advantage of the fact that the manufacturer is by far the most familiar with their own equipment and will know what to expect and what to measure. Lessons learnt from the test can (in principle) result in improvements to be incorporated into future developments, benefitting both manufacturer and buyer.

3.1 Cable Selection

Energy can couple into a ship via two mechanisms; either directly through hatches, ports, etc. or indirectly via cable networks which are partially exposed to the exterior of the ship or which can couple to other cables which are exposed. Since direct coupling should be very small (especially in the lower decks and interior of the ship), indirect coupling is the most prominent source of EM interference as it allows the EM energy to follow the cables and penetrate deep inside the ship. The key factor of the EMP/EMC protection of a ship is to minimize the amount of externally exposed cables and to prevent the induced currents from penetrating the ship's bulkhead, thereby eliminating any EM problems.

As mentioned before, the use of shielded cables and proper electrical bonding is the best strategy for preventing the induced current from propagating inside the ship. The quality of the electrical bond determines the degree to which unwanted current is rejected. Best performances are obtained by sealing all seams circumferentially and using the shortest possible connection to ground. This can be done by using a connector with a back shell to bond the cable shield directly to the bulkhead. Putting the conventional environmental gasket on the outside and the back shell connector on the inside is more practical because the electromagnetic properties of the connectors degrade rapidly in salt-spray environment.

At locations inside where several cables penetrated the bulkhead, cable transit assemblies can be used to reduce cost (Figure 1).

Since a great deal of effort has been made to limit the amount of current entering the ship, it is not to surprising that a large portion of the EMP test is devoted to appraising these measures. Approximately 80% of the test typically involve the measurement of current induced on cables at the bulkhead penetration point, both on the inside and outside. Measurements should be planned for virtually every cables running outside, provided they are accessible. This should amount to approximately 400 point of entries, resulting in a total of about 800 measurement points.

Measurements of the currents propagating inside should be given the highest priority since it is those values which are used to compare against the 10 A limit sets by MIL-STD-461C. Measurements on the exterior side are useful in establishing the transfer function of the point of entry, thus providing a direct measurement of the performance of the bonds. However, if the EMP test is to run behind schedule, the number of those measurements should be curtailed. A transfer function could still be established, but with respect to the ambient field levels instead, making the assessment of the performance of the bond more difficult.

Since there is a great deal of symmetry in the structure of the ship, the number of measurements can be reduced significantly by considering only the illuminated side of the ship (the EMP pulse generator was located off the port). The only exception to this rule is the mast where measurements on both sides should be done. Since it is a tall, slender and well exposed, it is not unreasonable to expect significant currents on the shadow side as well.

3.2 Field Selection

Assuming that the current induced in external cables allowed to penetrate into the ship has effectively been limited to the specifications of MIL-STD-461C, a detailed field mapping inside is not considered to be necessary because those residual currents would not generate any significant fields. However, some field measurements (electric and magnetic) should be done in rooms containing equipment which is either mission critical or vulnerable, or because of the large number of cables penetrating the room. Critical rooms include for instance the bridge, the command room, the weapon control room, the ship control room, etc. Measurements of the magnetic field should always be performed for all three orientations, while only the vertical component of the electric field is necessary.

Although the bridge and the hangar are considered to be exterior of the ship, a detailed field mapping should be planned for both of these areas. DREO has done extensive modelling of both these areas and comparison between theory and measurement is of interest.

3.3 Critical Components

Electronic equipment connected to antennas are particularly vulnerable to EMP. The antennas, which by definition are designed to collect EM energy, provide a very efficient coupling mechanism for the EMP to reach the front-end electronics. In some cases, such as for HF communications, the spectrum of both the EMP and the signal of interest coincide and it is not always possible to filter out the interference completely without hampering the normal operation of the unit. Special protection using non-linear devices such as like Zener diodes, spark gaps, varistors, etc. (or some combination of the above with passive filters) is then used. Typically, the only EM protection devices specific to EMP are the surge arrestors installed at antennas. All other EM protection are intended to increase the electromagnetic hardening against electromagnetic threats in general.

The non-linear protection devices can only be tested at full threat level. Since the pulser and its vertical dipole antenna (described in Section 4.) can only generate a small fraction of the threat level, several critical sub-systems need to be tested separately at full threat. Full threat level tests may need to be performed prior to the ship trial in the 10 m parallel plate EMP simulator at DREO (DREMPS).

3.4 Preparation

An EMP test involves making a considerable number of measurements in a very short period of time. This can only be accomplished if most of the problems which might be encountered are anticipated and eliminated prior to the start of the test. A few suggestions are as follows;

- All ordnances and munitions must be removed from the ship

- About 12 to 24 people are required for the test. Appropriate people should be selected and subdivided into smaller groups with each group responsible for pre-established series of measurements. The ship will also have to be prepared to receive several visitors. For example, manufacturers of various equipment may be present to evaluate their own products.

- The location of each cable should be identified prior to the start of the test. Each cable should be clearly marked with either a cable number or with a temporary tag. At least one person from each team should be aware of these locations and should be present during the EMP test. In some cases, it may be necessary to include a drawing to help locate specific cables.

- Each team should have one person familiar with EMP (or perhaps EMC) measurements. It would also be wise to include a member of the ships maintenance crew in each team to provide access to various parts of the ship, to assist with the location of cables, etc.

- The measurements made by the various sensors are transmitted to the measurement room (on the helicopter deck) through fiber optic cables. The point of entry for these cables and the route they have to follow through the various decks should be planned in advance for each room. In addition, the sequence of measurements should be arranged so as to minimize the cable displacement and travel time between locations

- Charts to guide each of the measurement teams should be prepared. They should clearly identify every cables to measure (description, location, tag number, etc.). They should also provide space for the teams to record various information such as the pulse generator shot number, etc. This information is required to correlate the individual recordings with specific cable. An example of such a chart is located in Figure 2.

3.5 Implementation

The most important aspect of the implementation of the test plan is the coordination of the various teams. It is critical that each team positioning the probes be able to communicate their location and status to the team in the measurement room so that the data obtained is labeled properly for future processing and analysis. Conversely, they must be able to be informed that a measurement has been successfully obtained and that they may move on to their next location. It is also necessary for communication to be maintained with the crew running the pulse generator on the simulator.

It is important to remember that the initial test plan should be considered a guide. The scheduling should be arranged so that if unexplainable phenomena are observed during the test, then time can be allocated for further investigation. Practically speaking, this is the only way reduce the amount of speculation in the post-test analysis and produce a meaningful test report. Alternatively, if measurements are found to be redundant due to excessive shielding, symmetry etc., it should be possible to remove portions of the test plan and, thus, shorten the test time required.

Page 1

G -DEK / BERGPLAATS SCHIPPER (FRONT) ZIE TEK. 8

1 RMT	2 LABEL	3 KABEL NR	4 VAN/NAAR	5 OPMERKING	6 PROBE	7 VERZW	8 KAN-PULS
734	094	1625 x 42	wcd illuminatie E2				
	096	1631 x142	wcd tel E170				
	098	1671 x 4	MOB alarmknop E35				
	100	1671 x 18	wcd provoost E14				
	102	2325 x487	plot wcd E479				
	104	2325 x489	plot wcd E480				
	107	1621 x	dekverl E1415 SB front (alleen binnen)				

1 ROOM (SEE DRAWING)
2 ID NUMBER
3 LABEL NUMBER
4 DESCRIPTION
5 REMARK
6 PROBE
7 ATTENUATION
8 CHANNEL / PULS NUMBER

Figure 2. Sample test plan chart. Columns 1 to 4 represent the test plan. Columns 5 to 8 are filled during measurements by the teams moving the sensors. A drawing is sometime attached to help locating the cables.

4. EMP TEST SET-UP

Even when adequate analysis tools are available for predicting the vulnerability to the electromagnetic environment of a complete system such as a ship, and when proper EMC rules are followed to harden the system against this environment, testing in a simulated EMP environment still constitutes the only reliable means of verifying the actual system hardness. Ideally, the whole system should be exposed to a plane electromagnetic wave whose characteristics match the EMP as close as possible, ie. with a peak field of 50 kV/m, a rise time of less than 5 ns and a pulse width of about 200 ns, as described in AEP-4 and MIL-STD-461C. However, it is not always possible to generate the full-threat EMP, particularly when illumination of a wide area is required for large structures as in this case. Testing at sub-threat level and/or with different rise time or duration characteristics may still be extremely useful, but the results must be analyzed very carefully.

To support the Dutch EMP test program, TNO has developed a very versatile EMP simulator (EMIS-2) which can be used in a variety of configurations. It consists of a 500 kV Marx generator (designed to be transportable) which can be connected to different antennas. One type is a fixed 6 meter high, parallel plates type antenna which produces a bounded wave pulse, ie. a field that is mostly confined in between the two sets of wires. This design is very similar to our EMP simulator at DREO (DREMPS, [4]). With this type of simulator, it is possible to produce very accurate and repeatable fields at threat level with very short rise time and appropriate duration. However, bounded wave simulators offer a limited working volume and thus are inadequate to test very large objects. For instance, DREMPS has a working volume of 20x30x10 meters. EMIS-2 may also be used with one of two radiating antennas: for horizontal and vertical polarization respectively. These antennas and the generator are transportable and can be assembled in about one week. A vertical dipole antenna provides a suitable field for testing ships. This assembly is shown on Figure 3. This configuration can be installed in Den Helder Naval Harbour (Netherlands). The generator is installed close to the shore and the ship can be anchored close to it for the duration of the tests. It produces a field of about 2-3 kV/m at the ship location, with a rise time of about 3.5 ns, which is excellent.

Most of the instrumentation used during EMP tests of a ship is very similar to those used during tests at fixed sites such as DREMPS. One of the noticable differences is the use of a transportable shielded shelter to house the electronic instrumentation. This shelter needs to be hauled onto the helicopter landing deck. All the cables penetrating the shelter (usually only few cables, including main power for the shelter) needto be appropriately filtered at their point of entry.

4.1 Computers

All the data acquisition and data processing tasks are under the control of computers. At least one computer needs to be dedicated to the data acquisition and storage. The use of a mini-LAN (local-area network) provides a convenient way of sharing data on-line among different computers. Enough free disk space or a backup device should be planned to accommodate the large number of data generated by the test.

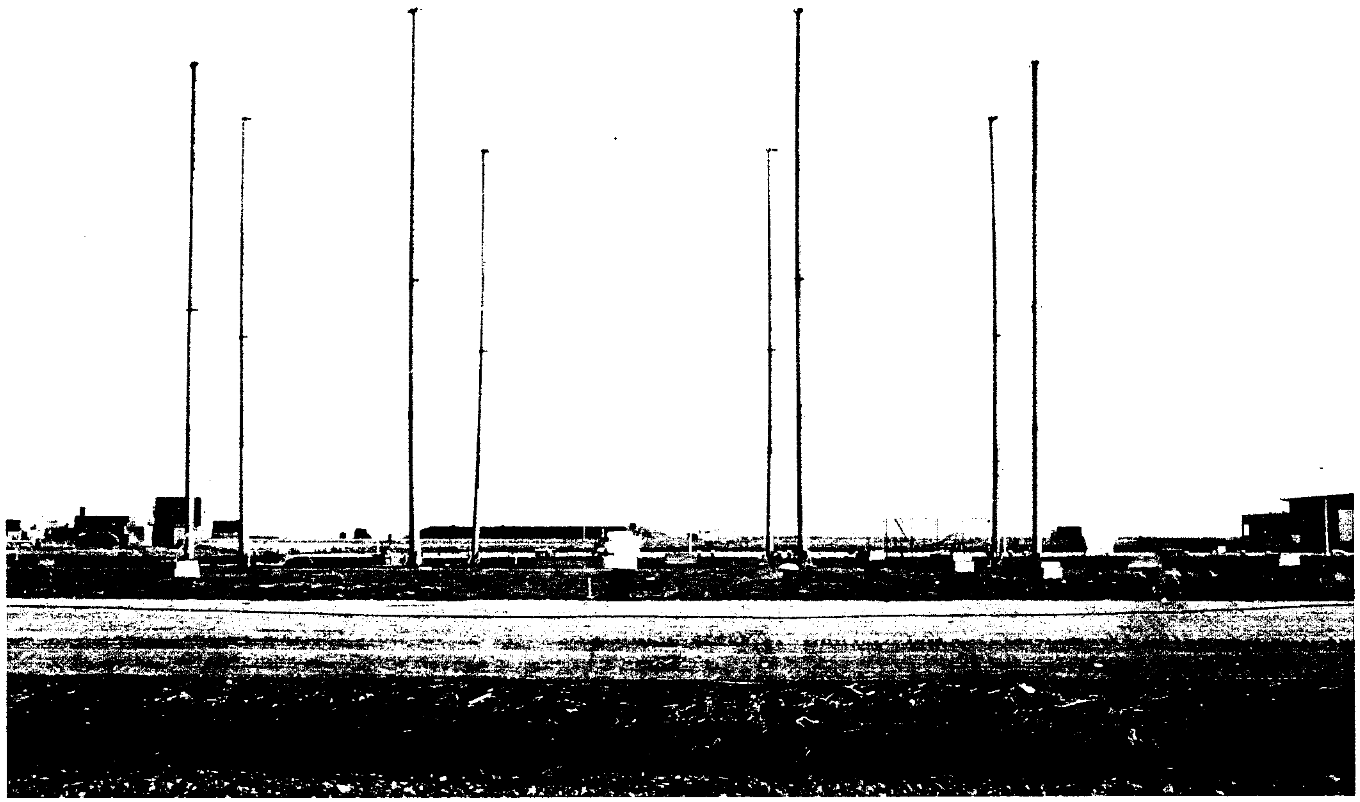


Figure 3. EMP pulser and its vertical dipole antenna (EMIS-2).

The computer dedicated to data acquisition needs to be equipped with one or two GPIB (IEEE-488) interface cards to control the digitizers and fiber-optic links. Windows-based commercial packages such as HP-Vee or Labview provide a nice environment for developping user-friendly data acquisition and analysis applications. They provide a nice Windows-like interface to control the most commonly used functions of the instruments; therefore, the instrument front panels are rarely used. The application running on this computer needs to read the data from the digitizers and collects complementary information which is stored in binary files. All measurements (ie. all channels) with their complementary information need to be stored in one file or in separated files, using the shot number to make unique file names.

Other computers can be devoted to other functions such as data analysis and printing. The data processing accounts for the various scaling (attenuation, sensor gain, etc.) and also for compensation for the frequency response of the various elements (fiber-optic links, sensors, etc.). The data processing algorithms may be implemented using either digital filters (FIR or IIR) or the FFT algorythm. Processing using FFT is more straighforward (although the FFT side effects are not always obvious) but has proved to be very inefficient to process long sequences. For this reason, processing should use FIR and IIR filters. By using efficient use for digital filtering, there is no need to store on disk the processed data, resulting in considerable savings in terms of disk space. Windows Dynamic Data Exchange (DDE) mechanism provides an alternative for passing binary or ASCII data to other applications such as Microsoft Excel or Matlab.

The capability to recall raw or processed data and plot them on the screen or obtain hard-copies is essential to assess the validity of particular measurements during the test. For instance, data can be recalled to check for sensor saturation, thus avoiding a day's worth of useless data. During the test, a fast monochrome printer (possibly with HPGL emulation) is preferable to a better quality color printer.

4.2 Digitizers

High-speed transient (ie. single shot) digitizers are required for the data acquisition. They should have full GPIB (IEEE-488) capability in that they can be fully controlled by a computer and transfer data to it. A minimum of 4-5 channels is required to record about 1000 measurements in 4-5 days. Channels need to have at least 250 MHz bandwidth at 1 GSa/s sampling rate with few channels exceeding 1 GHz bandwidth channel at 4 GSa/s sampling rate. All digitizers must have an external trigger input.

To understand the importance of this feature, one needs to remember how difficult it is to adjust digitizers to capture single event transient signals and how quickly the operator of the data acquisition system has to make the adjustments for all channels. During testing, up to 5 channels may be acquired every 90 seconds and the operator must quickly make a decision about which measurements to keep and which adjustments to make. As the various teams across the ship move the sensors according to the test plan, signals of widely different characteristics may be appear at various points, particularly the amplitude which may vary by many orders of magnitude, but also the signal duration and delay which may vary considerably. Using a long time window and a fixed trigger point simplifies the data acquisition task considerably; the operator needs only to concentrate on adjusting the amplitude of the signals and it is even possible to automate this task. Consistent and repeatable triggering is achieved by using a dedicated derivative E-field sensor connected directly to the external trigger input. A fiber-optic link is not used in this case, but the signal is appropriately filtered where it penetrates the shelter to maintain the shielding integrity. A relatively long time window (20 μs) and a large number of samples (>16384) should be used for all the measurements. Although the signal of interest whould then represent about only 10% of the samples, the time resolution of 1.2 ns would be adequate when considering the bandwidth of the sensors of the fiber-optic links. An additional advantage of an independent trigger is that the relative delays for the various signals are preserved. This can be a relevant piece of information during the analysis.

4.3 Fiber-optic links

Signals measured by the various sensors across the ship must be transmitted to the digitizers inside the shelter for acquisition and storage. Fiber-optic analog data communication links are commonly used in EMP testing to connect the output of the sensors to the digitizers. Shielded cables are not suitable, firstly because they may perturb the field in the vicinity of the measurement or may provide a coupling path to the field inside an area otherwise shielded, and secondly, because of the significant current the EMP field may induced into them, thus corrupting the measurements. For those reasons, fiber-optic analog data links have been traditionally used in EMP tests.

Fiber-optic links should be used in conjunction with all sensors except for the external trigger for which good reproduction is not required. Their analog bandwidth should match the bandwidth of the sensor and digitizer. Each link consists of a battery powered self-contained transmitter (which can be seen on Figures 4 and 5) and lab-bench receiver with all the front panel controls. Each receiver/transmitter pair is connected with two fibers (one for control and one for data). All units may be operated fully from their front panel and/or be controlled remotely through a GBIP bus. The links have an overall gain which helps measure weak signals. The transmitters also have a programmable set of attenuators to prevent saturation of the unit. These attenuators can be effectively used to make adjustment for signal amplitude; the vertical gain of the digitizers are then kept constant.

A spool with two fibers of 100 m each is required for each data link. Ideally, one would try to pull the fibers through existing access holes, thus avoiding having to go through door hatches and running on the floors. Unfortunately, this is not always possible and as a consequence, the fibers will be abused by people walking on them or closing hatches on them. It should be expected that some will be damaged and put out of service during the tests; therefore enough spools to maintain a minimum of 4 or 5 active channels is necessary. Remember also that some parts of the ship are not easily accessible and may require much longer length of fiber cables to reach.

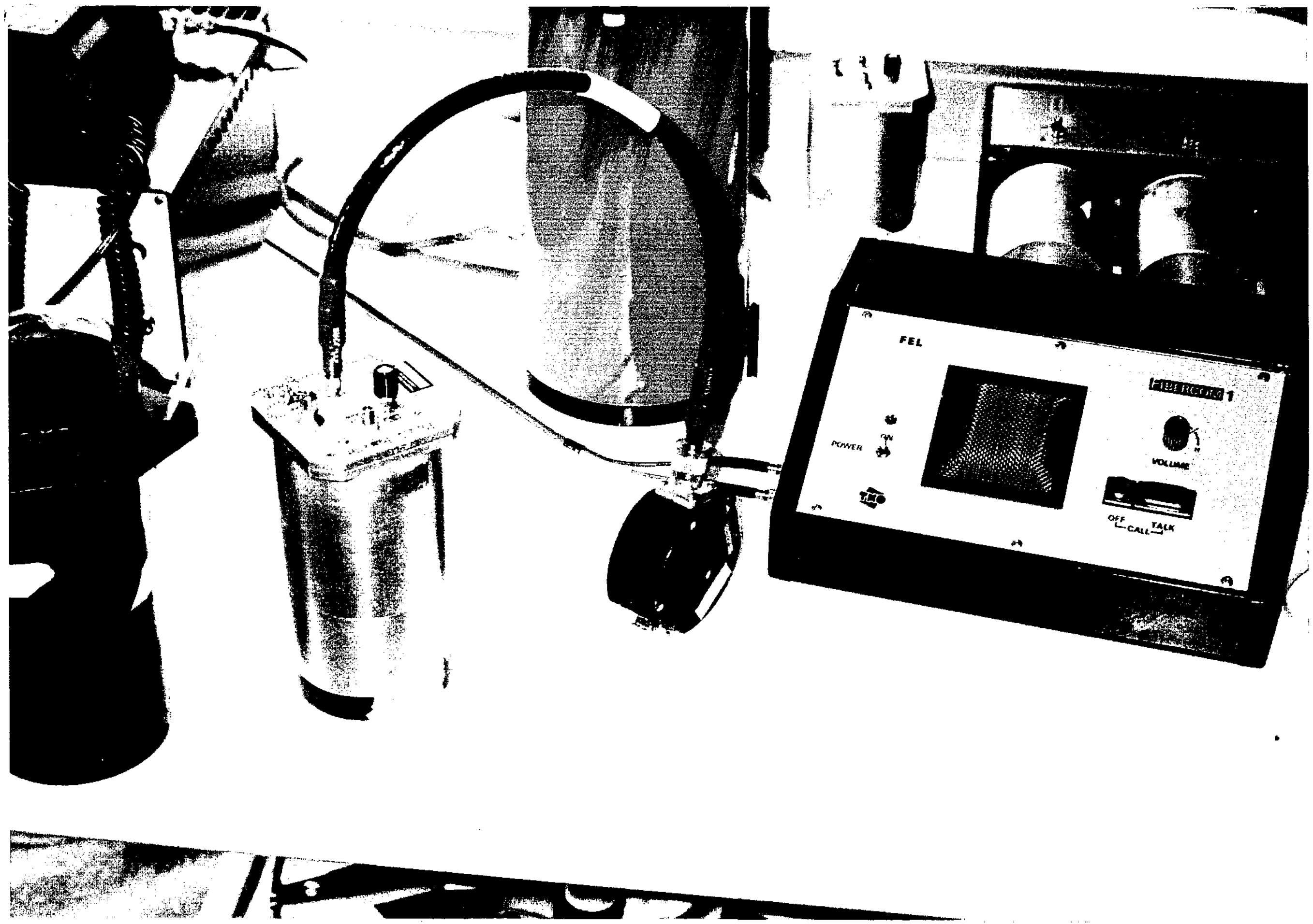


Figure 4. Current probe and its fiber-optic data link transmitter used for all current measurements across the ship.

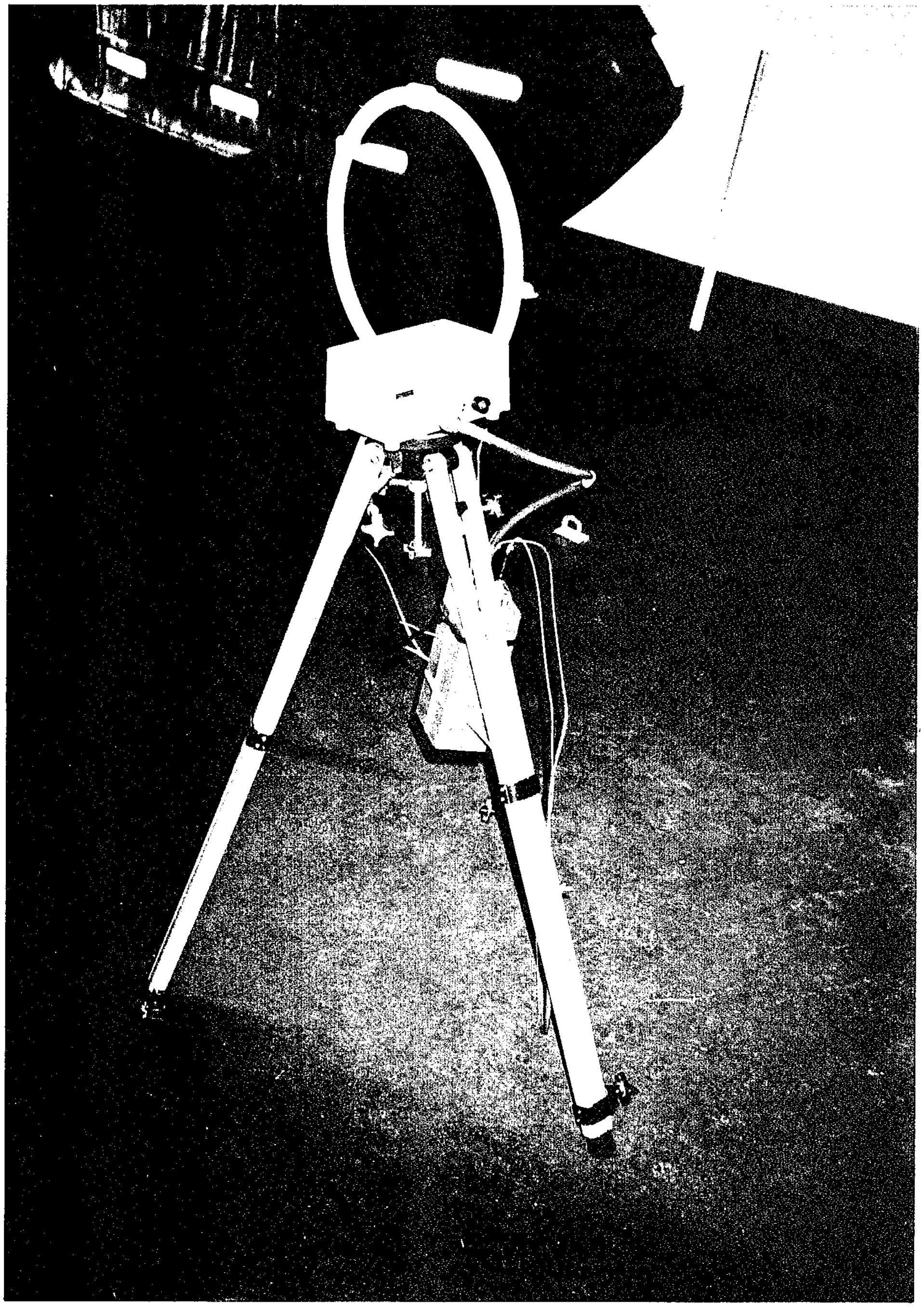


Figure 5. Setup for measurements with an active H-field sensor. Similar setup is used for passive H-field probe or active disk-cone antenna (not shown).

4.4 Sensors

As described in a previous section, the design philosophy behind the hardening of the frigates against EMP and other electromagnetic threats is to prevent the current induced into exterior cables from penetrating inside the hull. By achieving this, the interior of the ship can be declared as *electromagnetically clean*. With this goal in mind, most of the verification (about 80% of the measurements) will consist of measuring the current induced into exterior cables, both on the interior and exterior sides. Some field measurements (both electric and magnetic fields) should also be performed across the ship in various rooms containing critical electronic equipment. Fields should also be measured on the bridge and in the helicopter hangar, which are considered exterior zones.

To compare against the 10 A minimum criteria of MIL-STD-461C (CS10 and CS11) which corresponds to 400 mA for the sub-threat level used for the tests, the ability to measured currents as small as 1 mA and as large as more than 50 A is required. This can be achieved with a standard clamped-on passive current probe, such as the Eaton current probe (model 91550.7, shown on Figure 4).

Fields in open areas such as the helicopter hangar may be as high as the incident field while MIL-STD-461C (RS03) specifies that all electronic equipment must tolerate a 10 V/m ambient field. Those figures when scaled from threat level to the actual level used in the test set the limits to which field sensors must operate. Field sensors should be able to output a signal suitable for the fiber-optic links for fields ranging from 40 mV/m to 2 kV/m, or 0.1 mA/m to 50 A/m. Both active and a passive sensors can be used for magnetic field measurements. They can be oriented to record all three polarisation of the magnetic field. An active disk-cone antenna can be used for all electric field measurements, but it only allows measurement of the vertical polarization. A typical configuration is shown on Figure 5.

The bandwidth of the field sensors should also match the frequency content of the incident EMP field. In this case, the 1-200 MHz frequency band is of particular interest and the sensors should have a relatively flat response across this band. Active sensors should be monitored carefully to avoid saturation. In particualr, fields inside are expected to be much below 1 V/m, whie fields in the bridge and hangard areas are expected to be almost as high as the incident field.

4.5 Communication

One of the main differences between the EMP testing of large objects such as this ship and testing of smaller objects is the size of the team involved in the tests. About 12 to 24 people are directly involved in this type of test at any given time. They are organized into small teams of 2 or 3 people which are dispersed across the ship and the shore. Very good communication and very well defined protocol are essential to synchronize the work of all the teams to ensure a smooth testing routine.

The team controlling the data acquisition system makes the decisions about which measurements to keep and which ones to repeat. Other teams are formed (identified by keywords *Alpha, Bravo, Charlie, Echo, etc.* for unambiguous reference) to place sensors at various locations on the ship according to the test plan. They also maintain a log sheet to later correlate the recorded measurements with given locations. When the measurements are valid, the corresponding teams are told the shot # to record on their log sheet and they can proceed to the next location and must acknowledge when they are ready. Although the data acquisition shelter is the logical choice to dispatch the orders, it is not very practical. It is more effective to dispatch the orders to the bridge which would relay them. The various means of communication available are:

- A dedicated fiber-optic intercom link to allow direct communication between the data acquisition shelter and the bridge.
- The ship internal communication system to contact teams working inside the ship and who could not be reached by other means.
- Hand-held walkie-talkies are still the preferred way of communicating with the various teams.
- Portable cellular phone could also be used when necessary.
- The ship's intercom system to announce the firing of the pulse generator.

5. CONCLUSIONS

It has been shown that the EME on-board modern ships is a very serious threat if proper hardening is not included in the design of all critical electronic sub-systems. One of the most serious EM threats is the EMP generated by nuclear detonation which may affect all platforms in a very wide area. Although generally good EMI/EMC practices to protect against other high-intensity EM sources present are *almost* adequate to harden against EMP, it needs to be addressed separately. The fact that it is not normally present makes it more difficult to asses the effectiveness of the protective measures adopted during the design. Full-threat level illuminating the whole ship with a simulated EMP is a reliable means of hardness verification. However, testing of an object as big as a ship can only be done at sub-threat level as there is no full-threat level facility suitable for this type of test in operation today. Sub-threat level testing still provides valuable information which can be complemented with full-threat level tests of particularly critical sub-systems.

Conducting an EMP test on one of our frigates is encouraged as it provides the only means of verifying the effectiveness of the various measures incorporated into the design for EMP protection and is the only guarantee that the contractor has delivered an EMP hardened system.

Although the EMP testing of a ship only takes 4-5 days, the preparation of the test takes considerably longer. One or two individuals familiar with both EMP/EMC and ship's design will need to spend 6-8 months to prepare the test plan. Considering that a number of national and foreign directorates and laboratories, the prime contractor (and possible several sub-contractors), will be involved in this test, it is not unrealistic to estimate that a minimum of 12 months would be required for the preparation.

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(U) The new Canadian Patrol Frigates (CPF) integrate an extensive suite of electronic systems. If those systems were found to be vulnerable to the electromagnetic environment, the safety and mission of the ship would be jeopardized. One of the most severe threat is the EMP resulting from a nuclear detonation. Not only may this very intense field disrupt or permanently damage electronic systems, but its extensive coverage could also result in disruption of all unprotected platforms in a very wide area. It is a requirement that the CPF be adequately hardened against EMP. The hardening of the CPF against EMP was primarily based on analysis. Testing with a simulated EMP is the only means of verifying that the various protections incorporated into the design are indeed effective and that the contractor has delivered an EMP hardened system. In preparation of a possible EMP test of one of our frigates, DREO has investigated the potential use of the Dutch EMP test facility and has sent a team to participate in the testing of one of the Dutch new frigates.

(U) This report discusses various aspects of electromagnetic compatibility in general and EMP in particular on-board modern ships. Guidelines for preparing a test plan and difficulties which may be encountered during the test are discussed in detail.

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