ELECTROMAGNETIC PROTECTION ASSESSMENTS OF NAVAL VESSELS

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1. INTRODUCTION

Modern naval vessels are well equipped with a lot of weapon and sensor systems, all controlled by electronics. Mutual interference between all those electronic systems as well as illumination of a ship by an Electromagnetic Pulse (EMP) caused by lightning or by a nuclear detonation can potentially upset or damage electronic systems. Large (transient) electrical currents may flow in all exposed structures like metal surfaces, pipes, antennas and cables. These currents penetrate through the many entry points into the ship's interior where they can potentially cause damage. Computers, radar and communications systems, and weapon-control apparatus are sources of interference as well as likely victims. Unforeseen and unwanted consequences for the operational capabilities of a ship may result. In other words, the Electromagnetic Compatibility (EMC) of the electronic systems onboard a ship is an issue to look at.

Protecting a ship, or rather its electronics, against these electromagnetic interference effects is a complex issue. The conventional metal ship's hull will give adequate shielding effectiveness against electromagnetic fields from the outside like lightning and nuclear EMP. However, the penetration of pipes, the discontinuities in the construction and the necessary accesses degrade this shielding quite considerably. The use of Glass Reinforced Plastics in the ship's hull complicates the situation even more.

The technical approach to reach an electromagnetic compatibility between all systems on board is similar for all the various effects that occur. In some cases combined protections can be designed that work against several of these effects and are quite cost-efficient. Examples are described in the next paragraphs. For this reason, electromagnetic testing and verification of installation can be done in a similar way. In this paper electromagnetic protection assessments using EMP simulators will be highlighted.

2. ELECTROMAGNETIC FIELDS: THE PROBLEM

Electromagnetic fields are emitted in general by radars and by communications antennas, placed on the outside of the ship. In addition, unintended emissions result from data processing equipment and the like. These electromagnetic fields are either continuous or pulsed repetitively. An electromagnetic pulse (EMP) from a lightning strike or a nuclear detonation is a transient field; a fast-rising pulse is produced. In the case of a nuclear detonation this pulsed electromagnetic field covers a large area, depending on the altitude of the blast. An EMP covering an area as large as the entire North-American or European continent is very well possible as is illustrated in figure 1. Its field strength reaches values of tens of thousands of volts per meter, reaching its peak in a few thousandth millionth of a second. This sounds dramatic enough, but is clearer understood when it is realized that the energy collected by a communications system from this pulse can be one hundred million times the energy the system is designed to handle. Obviously, this may cause problems.

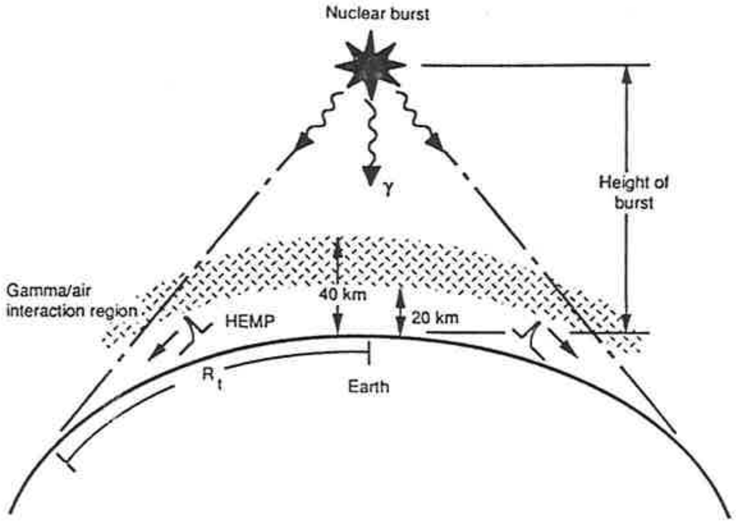

Figure 1: A nuclear burst generates a pulsed electromagnetic field through interaction of gamma rays (γ) and the atmosphere, covering a large area.

Looking at a ship, five major areas are identified as critical victims of electromagnetic interference:

- The sonar room contains processing-, signal conditioning- and power equipment. Cables may carry microvolt signals as well as kilovolt signals. The system parts clearly need a solid EM-separation. The kilovolt equipment, used for sending pulses into the water, generates transients which may easily influence the processing units and its cabling.
- The radar room contains radar processing equipment. This is high-frequency equipment prone to radiation.
- The technical control room houses a lot of measurement equipment often combined with a computer. Here various systems throughout the ship are monitored. The equipment controls the safety onboard as well as the propulsion of the ship. The systems are connected to a lot of sensors which may be very sensitive to EM radiation on certain frequencies.
- The command room contains displays for radar, sonar, weapon systems, navigation and communication equipment. The automated equipment supports combat control, operates weapons systems and displays vital information to the commander. The fields radiated by the equipment itself are relatively low. Special attention needs to be given to magnetic fields in relation to the information displays.
- The radio room is the room where all antenna signals are collected. The antennas carry RF energy that can easily influence unprotected equipment, like computers.

The computer-like, automated control equipment for various systems tend to get faster; more high-speed microprocessors are being used that required wide-band transmission channels for their communications. Some ships already have wide-band local area networks (LAN's) running through the ship. These wide-band systems not only produce more interference themselves, they are also wide-open for electromagnetic fields from the outside if not properly protected.

3. PROTECTION METHODS

What follows is a precis of the protection guidance provided to ship builders and designers by the Royal Netherlands Navy. It is based on theoretical calculations, computer modelling, experimentation and trials, experience and common sense.

The ideal situation would be to create a Faraday shield using the ships metallic hull, inside which all the electronic equipment would be operating in a safe electromagnetic environment. Like all ideals it is impossible to achieve this in practice. The very nature of a ship means that it must have external electrical equipments such as radar and communications antennas, missile launchers, guns, lights and loudspeakers. It must have external mechanical equipments such as boats davits and hydraulically driven winches. It must have apertures such as bridge windows, access doors and hanger doors. These defects in the shield allow electromagnetic energy from the outside to penetrate the hull to some degree with the resulting possibility of interference or damage to susceptible electronic equipment.

In a structure as complex as a ship it is obvious that the number of methods of ingress will by many. The major contributors are:

3.1 Antennas

These are specifically designed to be good acceptors of electromagnetic energy and will also readily couple with the unwanted signals.

The antenna feeder cable must be treated in the same way as any other cable penetrating the ideal shield. The antenna itself is, however, connected directly to the electronic equipment and devices must be installed in the antenna system to limit the induced voltage reaching the electronics. Simple voltage protection devices such as spark gaps and gas tubes will give some degree of protection without affecting system performance to any great extent.

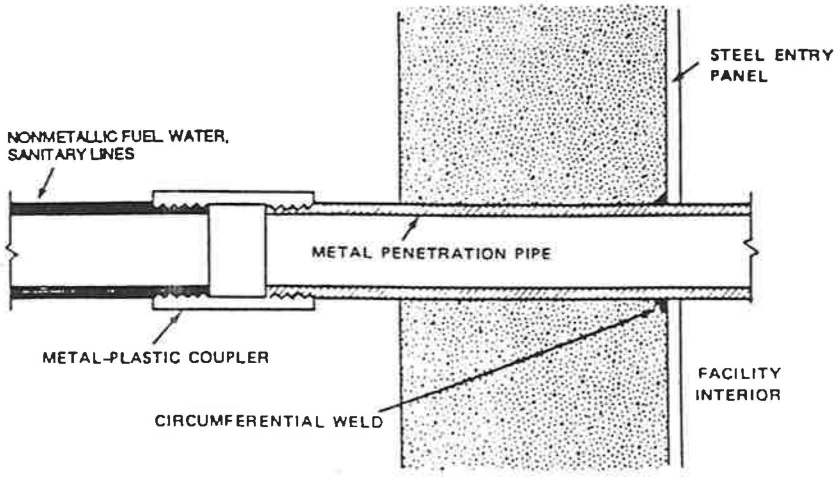

Figure 2: A non-conductive pipe carrying a conductive fluid, passing through the ships hull.

3.2 Pipework to Upper Deck Equipment

Many items of upper deck equipment, such as boats davits and winches are driven by hydraulics, resulting in mechanical pipe-work penetrating the ideal Faraday shield. Any currents induced in this pipework will be conducted into the ship where it can cross-couple with adjacent cabling.

The ingress of electromagnetic energy via mechanical pipework is easy to minimize. All that is required is that the pipework is bonded to the superstructure at the point of entry. This can be achieved in a number of ways. The actual technique chosen will depend on the fluid being transferred and also mechanical installation considerations. Plastic pipework carrying a conductive liquid such as sea water can also act as a method of ingress and measures need to be taken to ensure that the liquid is in contact with a short section of metallic pipe inserted in the pipe run as figure 2 shows.

3.3 Apertures

There are two main categories of apertures: the comparatively small access door or small bridge windows and the large access door such as that on the hanger. Because of their size in relation to the volume they serve, the two categories have different effects on the electromagnetic environment, see figure 3.

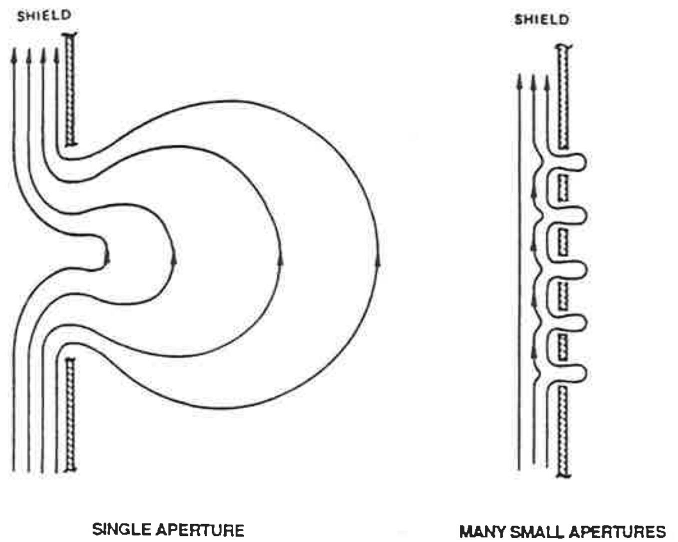

Figure 3: Field penetration through large and small apertures.

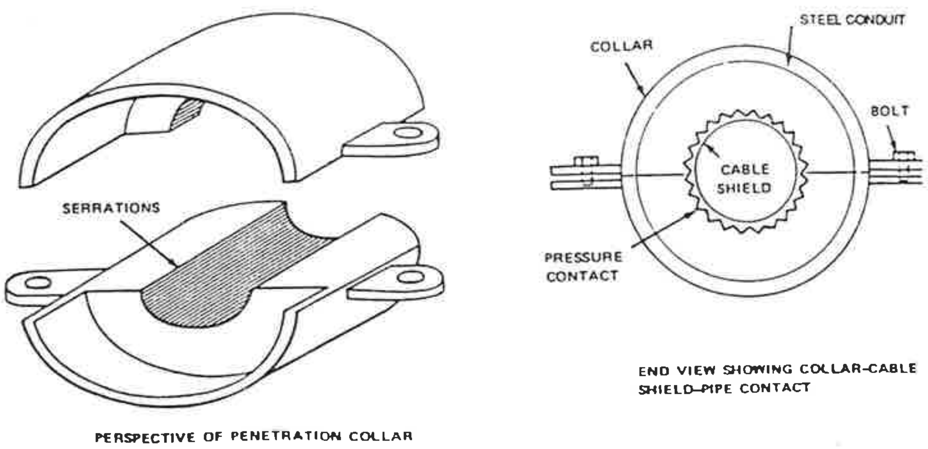

Figure 4: Cable gland designed to bond the cable shield to the ships hull.

The hardening techniques to be employed will depend on whether the aperture is small or large. A small aperture will act as a high pass filter removing much of the electromagnetic energy. It follows that some residual energy will enter the volume served, increasing the electromagnetic environment which may or may not be exacerbated by compartment resonances. This requires equipment and installations within the volume to be designed to withstand the increased threat. A compartment of particular concern is the bridge.

Regarding the hanger it has been assumed that the hanger door will have little, if any, screening effect. It follows, therefore, that the inside of the hanger must be treated as if it were upper deck and all equipment, mechanical installations, and cabling must be designed, installed and protected accordingly.

3.4 Cables to external equipment

Currents are induced in cables to external equipments by two mechanisms: direct spatial coupling to the electromagnetic field and cross-coupling from currents induced in the ships structure. Once these cables enter the ship the induced currents will cross-couple to other ships cabling, propagating the interference throughout the ship. There is a number of protective measures that can be employed:

a. Keep the resonant frequencies of masts etc. as high as possible to minimize the energy available for coupling to cables.
b. Keep cables away from known or anticipated hot spots such as the base of masts.
c. Clip cables close to the ships structure to reduce the loop effect.
d. Keep the length of exposed upper deck cable as short as possible.
e. Where it is imperative to run cables on the upper deck, the cables should be run in fully earthed, hard drawn conduit which is circumferentially welded to the ships structure at the point of entry. Where this is not possible the cable must be screened and the screen circumferentially bonded to the ships structure at the point of entry, using a cable gland especially designed for the purpose. A typical gland is shown in figure 4. A rather new technique is using pot's. These are already in use for waterproof and fireproof inlets, but combined with a conductive element these pot's are a cheap and relatively good replacement of the glands.

4. VERIFICATION TESTS

Verification of the measures taken is a necessity. It is not obvious that installation instructions have been carried out correctly, nor can a visual inspection alone reveal all possible discrepancies. Minor deviations may have a devastating effect on the interference levels experienced during operations; even damage may occur.

Electromagnetic hardness verification is carried out in two phases: a visual inspection by one or two experienced EMC engineers and an actual illumination of the whole ship with an electromagnetic field. First we present some experiences from visual inspections, partly taken from [2], as an illustration, not in any order of importance:

a. The most common fault with glands is the failure to remove the sheath from the cable. It was suspected that the bonding spring may have been omitted from some glands too. It was also found that a normal watertight gland was fitted in lieu of an EMP type. It is interesting to note that it is impossible to tell if the correct type of gland is fitted by visual inspection alone.
b. Poor corrosion resistance of the trunking material. The trunking as designed for its EM protection properties on good metal to metal contacts between the two halfs of the trunking and the EM gasket which was inserted between them.
c. Voltage Protection Devices not fitted in antenna systems. This was found to be due to a conflict in the information supplied to the shipbuilder. On the one hand he was told in the EMP Hardening guidance to fit protection devices and on the other hand he was told to install the equipment strictly in accordance with the installation

instructions for the equipment which made no mention of the protection devices.

d. Lack of adequate cable protection in the hanger. If the interior of the hanger is to be treated as upper deck then all cables must be treated as exposed cables.

e. Pipework generally entered the ship by way of a normal watertight gland and any bonding was purely accidental. The mechanical engineering departments seem to be of the opinion that EMP is "electrical" and therefore has nothing to do with them. This illustrates the need for "cross the board" EM education.

5. EMP SIMULATION.

An EMP simulator can be used to carry out an actual measurement of the level of protection against an electromagnetic field. Such a simulator generates a fast, pulsed electromagnetic field to which the ship is exposed in its entirety. Measurements can be taken at several points of cable entry that have been identified as important. The main advantages are that by measuring with such a pulsed electromagnetic field in the time-domain the entire spectrum of interest is covered and indeed non-linear effects can be studied. EMP simulators have been used quite extensively to study hardening against nuclear electromagnetic pulse and lightning effects.

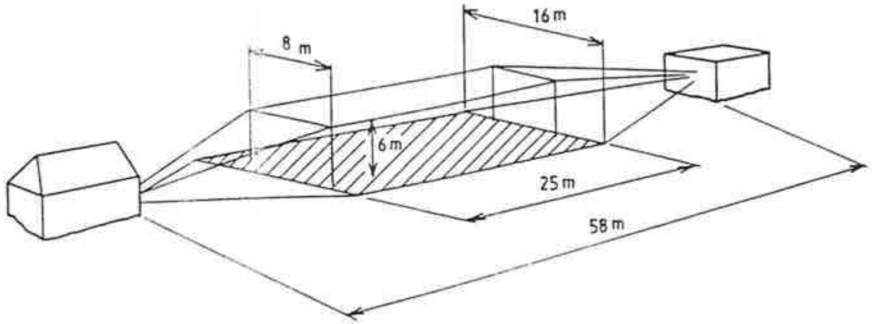

Figure 5: Layout of the parallel-plate EMP simulator EMIS-2 of FEL-TNO.

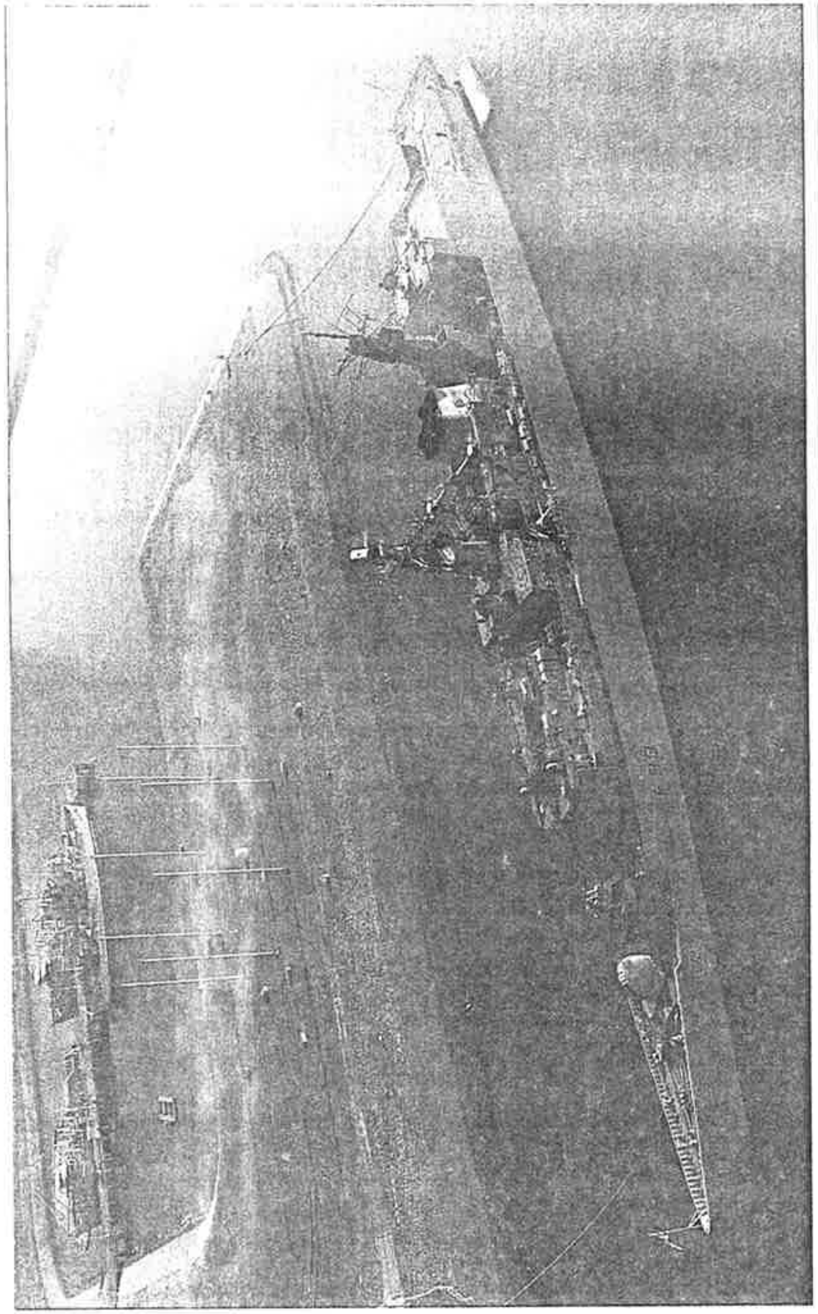

Figure 6: The radiating EMP simulator EMIS-3 of FEL-TNO illuminating a Navy frigate during a test.

In general there are two methods to simulate an EMP. A commonly used and well-known method to test an object is to position it in the test volume of a parallel-plate or transmission-line simulator, as illustrated in figure 5. This technique makes it relatively easy to simulate at the required high amplitude level of the EMP, which is called the threat-level. The advantage of testing at threat-level is that one can measure all effects of the EMP including all non-linear effects such as spark-overs and the operation of overvoltage protections. It is possible that damage occurs if shielding and protective measures are not sufficient. Disadvantage of the method, particularly for ships, is the limited test volume of the current simulators of this type.

If the dimensions of the test object are too large, it is possible to illuminate the object with a radiating EMP simulator, as shown in figure 6. The Physics and Electronics Laboratory FEL-TNO in the Netherlands is using this type of EMP simulator to test vessels and other large objects. Naval vessels are tested in co-operation with the Royal Netherlands Navy at the naval base Den Helder with the EMIS-3 Vertically Polarized Dipole simulator. The advantage of testing with a simulator like this is that there are no limitations to the dimensions of the object under test. It is however, rather expensive to construct a simulator of this type that radiates the required threat-level. A pulse generator with a very high voltage is needed, since the energy is radiated over a large area. This in contrast to the transmission-line simulator, where the energy is practically contained entirely between two conductors. Because the threat-level electromagnetic field is not only limited to a certain test volume in the case of the radiating simulator, there could be environmental problems. Therefore a sub-threat level to generate a radiated EMP is chosen. The obvious disadvantage being that a number of non-linear effects will not be visible. Damage as a result of the test will not occur, however.

Measurements are made primarily on cables, outside and inside the ship that are connected to vital equipment.

Measurements can be divided into:

- bulk current on cables,
- current on single wires,
- voltages on connector pins.

In addition, magnetic and electric fields are measured in the ship's technical centre, the command centre, the hangar and at the bridge, as well as in a number of other places that are identified as important.

The signals from measurement sensors and probes are transported from the point of interest to the measurement system via fibre optic cables, thus avoiding that the measuring system itself is affected by the simulated EMP.

6. LESSONS LEARNED

Four sub-threat whole ship EMP trials were carried out on frigates and one on a submarine to quantify the degree of hardening resulting from the techniques given in the guidance provided to the shipbuilders. The aim was to consolidate the guidance or to amend it to give the most cost effective techniques for ship electromagnetic hardening. The results of the trials showed that, in general, the techniques, if properly applied, were effective in producing an electromagnetically hardened ship.

The predominant frequencies that were found in measured signals are due to resonances in cables and structures. They are associated with the energy coupling on re-induced currents in external cables.

It is accepted that the requirement to treat all cables and equipment in the hanger as upper deck imposes severe constraints on the design of the hangar installations but the results showed that these constraints are necessary if the aim of a fully hardened ship is to be achieved.

Based on the test results, three area's on a ship can be distinguished: outerdeck area's, innerdeck area's and EM-outerdeck area's.

- Innerdeck area's are area's in the ship, completely enclosed by the metal hull. Windows are not allowed and doors are made of metal also.
- Outerdeck area's are area's that are not enclosed by metal, outside the hull and on deck of the ship.
- EM-outerdeck area's are area's that are not completely enclosed by metal, such as the bridge, which have windows and where the doors are most of the time opened. Also the hanger is considered an EM-outerdeck area because it appeared that the door of a hangar offers little protection against EM-influences.

The tests proved that the glands, used for the inlet of cables, gave such a mechanical strength on the cables that the cable shield started to flow. This effect was clearly visible in the measurements: the attenuation near the glands was less then usual. To solve this problem, it was necessary to use other glands. Waterproof bonding glands are expensive. A much cheaper solution was to put a waterproof gland on the outside and a grounding gland on the inside of the ships hull.

Another thing noticed, was that when cables, pipes and the like, running outerdeck and kept as short as possible, are correctly bonded to the ships hull, there is a good electromagnetic separation between outerdeck and innerdeck. Every cable that penetrates the metal enclosure uses a bonding gland that connects the cable shield 360 degrees to the metal enclosure.

Bonding in more than one place is good for EM protection. It is also good practice to keep the cable close to the ships structure.

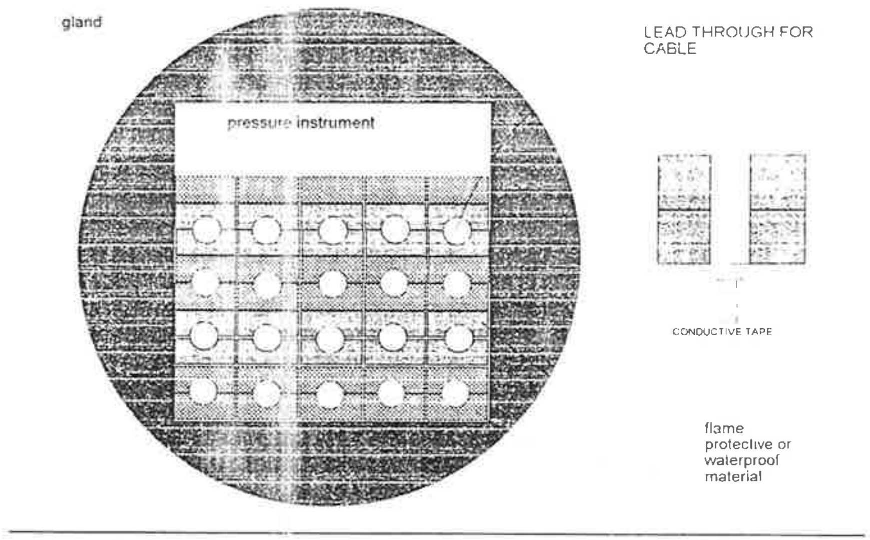

Figure 7: Multi-cable gland, providing a waterproof, fireresistant and an EM-protected feed-through.

The latest frigate built, electronic enclosures were used to achieve electromagnetic compatibility (EMC) between electronic systems at the same location. This consisted of a metal structure in which the equipment is placed. Every piece of equipment inside such an enclosure is EMC. Therefore no additional countermeasures against radiation or susceptibility are needed inside such an enclosure.

If a good EM-separation between inner and outerdeck area's is achieved, a possibility to cut costs on innerdeck EMP-protection exists. For waterproof and fireresistant penetrations in innerdeck area's often a 'MCT' (multiple cable transit) is used. This is a gland consisting of many pieces with holes, through which the cables are fed, as figure 7 illustrates. Pushed together they provide a waterproof and fireresistant penetration. If each piece is made of conductive material or each piece is wrapped in conductive foil, this offers a waterproof, a fireresistant and an EM-protected feed-through. The attenuation of such a gland is less then that of a normal bonding gland, but is enough for these areas. Portable radio's on board often cause a lot of problems, because of their proximity to equipment. It has occurred that a diesel engine could be started just by pushing the push-to-talk button on a portable radio. Therefore it is advisable to use portable radio's with a low output power only.

Fire detection equipment is sensitive to emitting devices, and causes a lot of stress in case one doesn't know what causes the alarm. Fire dectection systems on board of ships are tested on EMC, to get to know the weak spots. These are several examples where problems with EM radiation existed.

7. The EMPSIS Project

EMP assessments on large ships have been carried out with the low-level simulator EMIS-3 in the Netherlands for many years. Since 1987, the possibility of a full threat-level simulator for naval vessels has been discussed within the joint study group ANLNCP I.22 of the United Kingdom, the Netherlands and Norway. From the onset, the envisaged simulator EMPSIS (EMP Simulator for Ships) is to be located in a suitable Norwegian fjord, that will provide a natural suspension for the simulator. This situation implies a transmission-line simulator. Radiating simulators have never been considered, mainly because of cost considerations and environmental impact.

The Defence Research laboratories of the mentioned countries, AWE, NDRE and FEL-TNO, initiated a feasibility study in 1989. This study was concluded with a small-scale experiment (the Lukksund trial, see [4]) with a transmission-line simulator suspended under a bridge over sea water in a Norwegian fjord. The experiments with a simulator height of 10 m, produc-

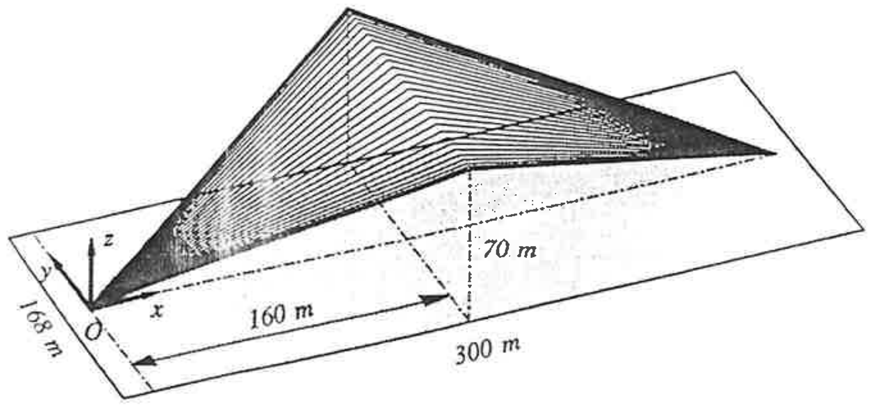

Figure 8: Layout of the EMPSIS simulator that can accommodate an entire ship for a full threat-level EMP test.

ing full threat-level, were carried out in 1990, and showed that with proper care the sea water can be used as part of the transmission-line structure of the simulator. During this trial, the MS Ravn of the Royal Norwegian Navy is probably the first ship in the world that underwent a full threat-level EMP assessment.

Encouraged by the promising results of the initial feasibility study, the navies of the participating countries ordered a feasibility study into a full threat-level simulator that can accommodate large naval vessels. The proposed EMPSIS simulator is of the triangular-plate type as shown in figure 8. It consists of a wave launcher, which is connected to a 3.6 MV pulser, and terminating taper. This taper is terminated with a resistor network that absorbs most of the incident energy. The terminating impedance matches the simulator's characteristic impedance, thereby effectively suppressing reflection. The simulator consists of 75 wires, and is suspended over sea water. EMPSIS is designed to accommodate ships with maximum dimensions of 200m x 35m x 47m (l x w x h) and to generate the latest NATO EMP waveform specification.

The ship under test is moored transversely with respect to the simulator. The working volume starts at 125 m from the wave-launcher's apex so that the field strength at each side of a 35 m wide ship deviates no more than 14% from the value at the ship's centre. At the start of the working volume, the simulator is 55 m high. A quay covered with a wire mesh is provided up to the ship under test to reduce high-frequency attenuation by the lossy sea water. This quay offers yet another important feature: it enables land-based equipment to be placed easily within the simulator, thereby making the installation suited for multi-purpose use. In addition, the simulator can be used for EMC measurements with Continuous Waves (CW) by disconnecting the high-voltage pulser and connecting the appropriate equipment.

The size of the EMPSIS simulator prohibited the use of well-known performance analysis methods. Therefore a new analysis method was developed by FEL-TNO which is very efficient and enables one to analyze even the largest transmission-line simulators on a personal computer. The new analysis method has been implemented in a computer program called WS (Wire Simulator). An extensive description of this method was presented in [1]. The field within the working volume of EMPSIS is not homogeneous, especially close to the upper wire netting and its edges. Therefore, we analyzed the field distribution within the working volume. We considered the peak field distribution at the working-volume centre as a function of the height to study the field enhancements in the proximity of the wire netting. The analysis shows that the peck field strength at ground level underneath the outer edge of the wire netting reduces to 75% of the peak field strength at the working-volume centre. At the far end of the working volume the peak field strength reduces to 60% of the peak field strength at the working-volume centre. The first reflection occurs at different points in time (the so-called clear time) depending on the height of the observation point. This is due to the terminating-taper wire nearest to the point of observation. The clear time for EMPSIS is always larger than 142 ns within the working volume. The performance analysis demonstrated that the proposed design lives up to its expectances.

The report of the feasibility study, containing the technical and economical details has been published recently [3].

8. CONCLUSIONS.

1) Bad installation practices and poor quality control could prevent the achievement of a fully hardened ship.
2) Adequate cost-efficient solutions can be applied to offer protection against a variety of electromagnetic phenomena.
3) Further work needs to be undertaken on the apertures to enable adequate techniques proposed for hardening such volumes as the bridge and hanger.
4) The electromagnetic protection level of a naval vessel can be assessed using an EMP simulator.
5) The proposed EMPSIS simulator can accommodate in its working volume ships with maximum dimensions of 200m x 35m x 47m (l x w x h) as well as land-based equipment.
6) Because a ground plane is provided upto the ship under test and the early-time fields equal the current waveform generated by the pulser, EMPSIS is able to generate the new NATO EMP waveform. This waveform is applicable to assess a large number of other EMC effects.

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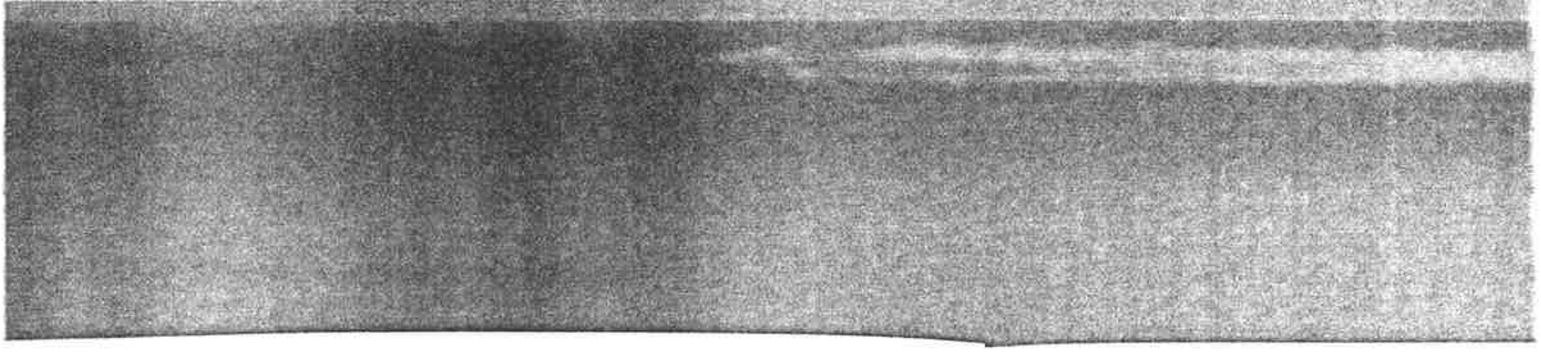

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