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RESTRICTED

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SUPERCONDUCTING ELECTRIC POWER SYSTEMS

A. W. Lamport
Ministry of Defence

Introduction

For some years now the Ministry of Defence has taken an active interest in the application of superconductivity to electric generators and motors, the principal interest being in the possible application to ship propulsion systems. The initial work sponsored by the Ministry of Defence, starting in the early '60s, was discussed in a previous article in the Journal(1). The purpose of this present article is to bring the picture up-to-date, with particular reference to the Ministry of Defence developments.

Basic Principles

Superconductivity is the property of certain materials, under appropriate conditions, to offer zero resistance to the flow of electric current through them. The most important requirement, for the superconductors available at present, is that the temperature must be very low, in fact the highest temperature at which any known material exhibits the phenomenon is about 23°K (minus 250°C). Current density and magnetic field strength also pose limitations, and indeed it was only with the discovery in the 1950s of alloys able to accept worthwhile values of these that exploitation of superconductivity really began in earnest. Much work has been done in industry on the development of superconductors and on their fabrication into the required forms of wire for coil-winding and the position now is that superconductors with satisfactory performance are available in wire form. The preferred construction is that in which the conductors are composed of many fine filaments of superconductor in a copper matrix; this provides strong resistance to the tendency to " quench " back to normal resistive conditions when the system is electrically or physically disturbed. Wires of this form, with filaments as small as five microns diameter, are now available.

Superconductors are at present still very expensive: the alloys of niobium are the principal class of superconductor finding use, with niobium-titanium most widely used at present because it offers a generally adequate performance at reasonable cost. The cost of the wire and the need for very low temperature are the two principal drawbacks to the commercial use of superconductivity for power systems. The required low temperature is commonly achieved by immersing the superconductor in liquid helium (about 4°K).

Superconductivity opens up a number of possibilities in power electric systems. The high current capacity (upwards of 2×10^5 amps/cm^2 for niobium-titanium and about three times this figure for niobium-tin) makes it appear attractive for high current power supply lines and considerable work has in fact been done in this field, but the need to maintain the entire length of the transmission line at very low temperature results in a very costly system. The most likely application is for special links in locations where overhead grid systems are socially unacceptable, but no operational installation of this kind had so far been commissioned.

Application to electro-magnets is also attractive. It is possible to dispense with iron cores, the usefulness of these being severely limited by magnetic saturation, and to produce electromagnets of very high field strength (10 Tesla or more) which have virtually zero power requirement for continuous operation. Such electro-magnets have a variety of potential applications:

Their use in particle accelerators in nuclear physics is attractive and has been exploited. Their use in levitation systems for high speed trains etc has been the subject of much research and experiment in a number of countries, though as yet no advanced train system using other than normal wheeled support has been commissioned for service.

Their use in electro-magnetic machines has also been explored to a considerable degree. It is this application which forms the subject matter of the rest of this article.

Superconducting Electro-Magnetic Machines

For electro-magnetic machines — generators and motors — superconductivity offers the possibility of much more intense magnetic fields than are possible with conventional iron cored magnets, with low power consumption for the maintenance of that field. For DC machines this has led to a radically new design approach — though in a sense not new in that it is a return to the concept of the Faraday disc. The high field strength available means that designs on this basis — homopolar designs — can now achieve substantial armature EMFs.

Reference 1 described such a homopolar motor, with a superconducting field, which had been built and tested by Messrs International Research and Development Ltd under Ministry of Defence contract. The design concept is shown in Fig. 1, which also shows the original Faraday disc arrangement. One advantage of the homopolar motor is that the field coil experiences no torque reaction and is virtually unaware of the rotating system within it. The torque reaction is in fact carried by the fixed part of the armature circuit. Furthermore, in steady-state conditions there is no fluctuation of armature current or EMF. Such a device can equally well be operated as a DC generator and by use of generator and motor together one has a very simple form of DC electric transmission.

Much of the work which has been done, both in this country and abroad, since the Ministry of Defence machine ran in 1966, has been on variants of this basic type. A particular attraction is the possibility of a compact low-speed high-power motor, and this was exploited further in the " Fawley motor " described in(1). This was designed to develop 3200 HP at 200 RPM. AC superconducting systems have also been explored; the great prize here would be in the exploitation of superconducting machines for large alternators for national grid purposes. Much yet remains to be done before these are technically proved; development is proceeding in a number of countries.

Considering further the Ministry of Defence projects in this field, the operation of the Fawley motor had confirmed that such machines had potential for ship propulsion, where low speed motors would permit direct drive of the propeller. Marine propulsion does however pose requirements for reversing and manoeuvring, while naval requirements impose further problems in respect of such matters as ability to withstand shock and limitations on ship magnetic field. As a further stage of development it was therefore decided to commission the design and construction of a 1 MW system suitable for marine propulsion drive and comprising a diesel-driven direct coupled superconducting DC generator powering a superconducting DC motor connected directly to the propeller shaft. The whole system to be sized and schemed to be suitable for trials at sea in a minesweeper-type hull.

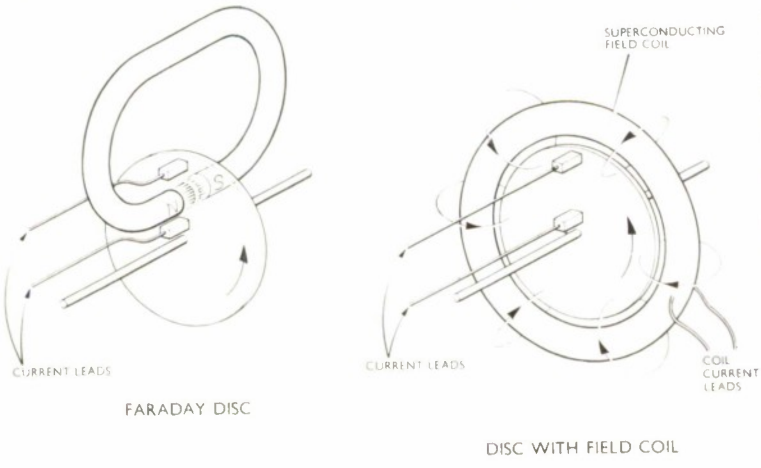

FIG. 1. The Faraday Disc. Design concept of first superconducting motor.

The 1 MW Superconducting Transmission System

Work on this project was started in 1970. Messrs International Research and Development Ltd were the main contractors, as for the previous projects. The design concept was that both the generator and the motor would be of basic homopolar design, each with a superconducting field coil. The armatures, as in the earlier machines, are not superconducting; they are of a segmented design so as to put a number of conductor bars in series giving increased machine voltage and hence keeping required armature current levels down. The field systems of the generator and motor are very similar and the speed reduction ratio of transmission (about 4:1) is achieved by choice of numbers of armature conductor bars in the two machines. The armature of the motor is shown in Fig. 2. The two ends of the armature are electrically quite distinct; this also applies in the case of the generator armature so that the transmission can be operated as two electrically separate parallel systems. Each armature conductor is water-cooled and inter-connects between a segment on one of the two large-diameter internal slip-rings near the centre of the rotor and a segment on one of the small-diameter slip-rings at the rotor ends. Variation in speed ratio, to give the desired manoeuvring capability, is achieved by variation in field strength of the generator unit. The requirement for rapid variation of this field (full reversal in 15 seconds) posed a major design problem in the generator field cryostat, because of the need to minimise eddy current heating in the components at liquid helium temperature so as to avoid excessive liquid helium boil-off and risk of return to resistive conditions when manoeuvring. Rapid field changing also necessitated a large exciter and field charging system able to provide the substantial short-duration power to raise the field when required.

Even with a high field strength the voltages which can be generated in homopolar machines tend to be somewhat limited, resulting in armature currents which are rather high to achieve acceptable power outputs. As a result the problem of current transfer to and from the rotating systems has been of critical importance. The use of liquid metals for current transfer has obvious attractions for this purpose, particularly when related to the high relative speeds, and this approach has been favoured in the USA(2). We did not follow this course, deciding instead to explore the capabilities of solid brushes. This led to the development of brushes composed of stacks of metal-plated carbon fibres, each fibre being free to establish its own contact on the slip-ring. The research has proved highly successful, leading to brush/slip-ring systems with high current carrying capacity (100 amps/cm^2 compared with 12 amps/cm^2 for conventional brushes), low voltage drop and acceptable wear rates of brush and slip-ring. Rubbing speeds of up to 120 metres/sec are allowable. Brushes of this kind are utilised in the 1 MW generator — the segmented rotor design, which necessitates segmented slip-rings, would in any case preclude use of liquid brushes.

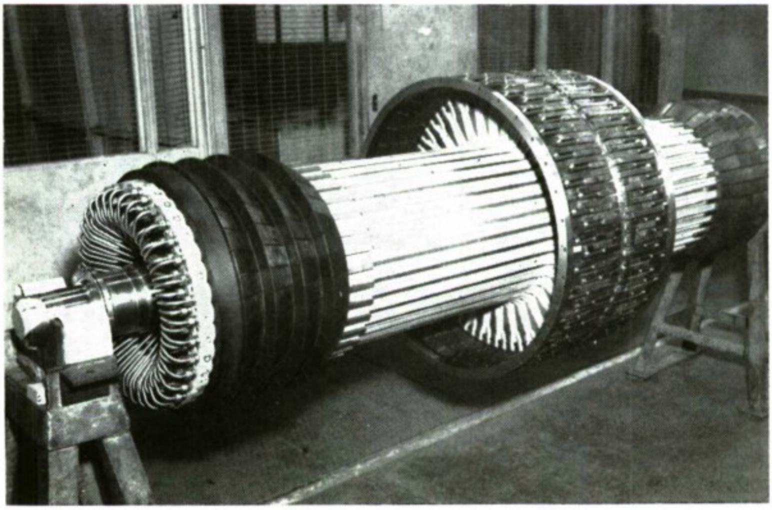

FIG. 2. The Armature of the 1 MW Motor.

Fig. 3 shows the 1 MW system set up for shore testing. It will be seen that the field cryostat systems of the generator and motor units are of identical frame size. They are also closely similar in design concept. The arrangement of the units for shore trials was designed to match that of the intended ship installation. The single refrigerator unit provides liquid helium for both cryostats. It can be seen in Fig. 3 coupled to the motor, with a connecting branch across to the generator for transport of helium. It is a Claude cycle machine, operating on a helium input flow at approximately eight bar and incorporating high-speed turbo-expanders. The refrigerator will be seen to be quite large in relation to the motor; this arises partly from the relatively low transmitted power for which the whole system is designed, but does show one of the basic problems of superconducting systems of the kind, *i.e.* the appreciable size of the ancillary equipment. The requirement for low external magnetic field was met by providing additional opposed superconducting field coils in the cryostats, of larger diameter than the main coils and sited to achieve the best compromise between reduction of external field and reduction of the internal effective field intersecting the armature.

Shore trials of the 1 MW system are now under way, following a long period of delay arising from a series of technical problems, compounded from time to time by industrial disputes. The machines are now fully cooled down and superconducting. Satisfactory running of both rotor systems has been shown but only low powers have been transmitted, until such time as the generator carbon-fibre brushes are fully bedded-in and adjusted. The field coils have been taken to " quench " and confirmation obtained that the quench is safely contained with no ill-effect.

The shore-testing will be carried on to further exploration of the performance and behaviour of the system, subject to the limitations of a shore-test installation, but because of the delays which have occurred and the high cost of ship installation there is now little probability of the system undergoing trials at sea, as originally planned. Technical uncertainties also influences the situation — in particular the reliability of helium compression plant and the leak-tightness of the generator helium containment vessel are matters of some uncertainty. Furthermore the system is now not representative of the latest design concepts for superconducting machines.

Concept Development and Ship Applications

In parallel with the work on the 1 MW unit there has been substantial effort on design studies and on experimental work to provide a reliable basis for the design concepts which have been devised. Warship installation studies have also been carried out, aimed at assessment of the potential of the concept in naval ship designs. It is perhaps as well to examine, at this point, what advantages superconducting systems can offer for naval ship propulsion. Being electric transmissions they can offer the advantages of such systems:

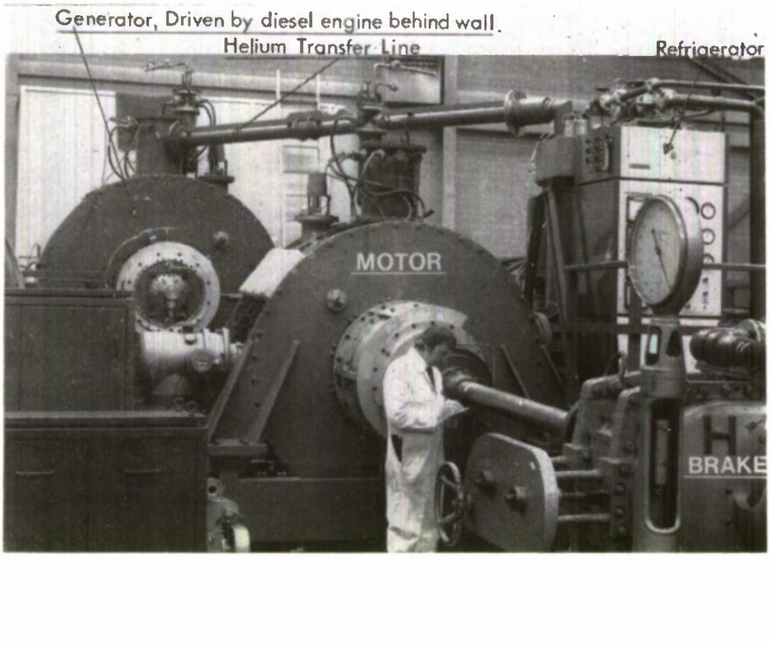

FIG. 3. The 1 MW System on Shore Test.

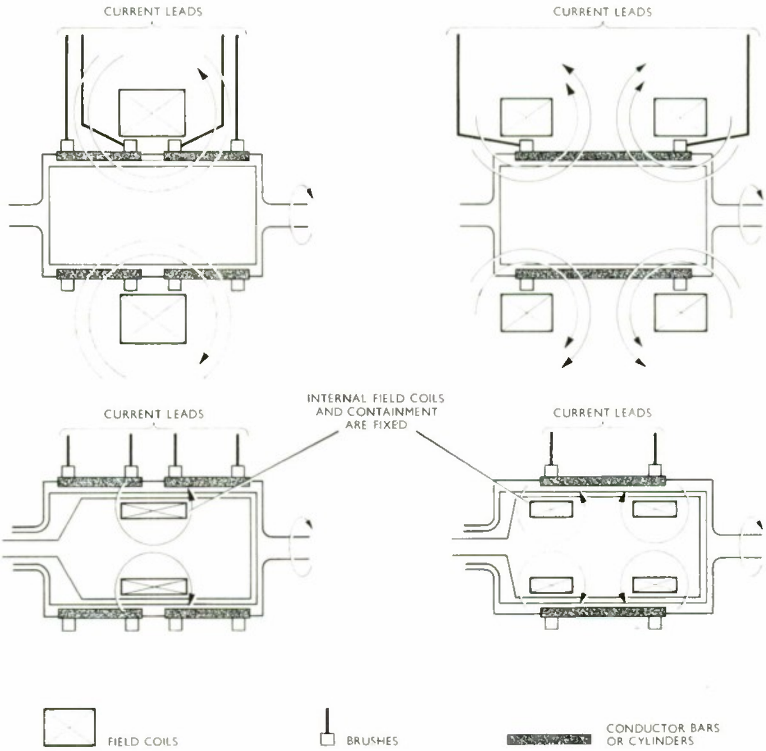

FIG. 4. Arrangements of Cylindrical Armatures.

1. Flexibility of location of the prime mover/generator unit — not tied to the propeller shaft line.
2. Ready inter-connection of multiple inputs with multiple output drives, for flexible use of prime movers.
3. Good manoeuvring capabilities.
4. Low noise.
5. Offers scope for utilising auxiliary sources of electric power or for delivering power for other services.

Coupled with these are the particular features of the super conducting system:

1. It offers the possibility of direct drive on the propeller shaft with a reasonable motor size and motor cost. For instance a 16·5 MW 200 RPM motor might be about 3 metres wide, 2·5 metres high, 4 metres long.
2. The motors are very suitable for accepting power from sources of high current DC, such as batteries, MHD, thermionics, and fuel cells.

Against these advantages must of course be ranged the problems of maintaining field coils at liquid helium temperatures and the problems of plant control and protection.

A wide range of types of homopolar machine has been studied, both for the generators, which ideally should run at relatively high speed to match the prime movers, and for motors, which should preferably run at low speed for direct drive to the propeller. The trend in design has been away from the disc form of armature as shown in Fig. 1 and towards the cylindrical form (Fig. 4). Some designs have the field coil and cryostat surrounding the armature, while others have them inside the armature. It is also possible to vary the machine design to best match the design requirements while also endeavouring to economise on use of the expensive superconducting wire. Maintenance accessibility must also be adequate and the design must be such as to offer high reliability.

The benefits to be gained in practice by use of the superconducting system will depend very much on the type of installation required, which again depends on the particular type of ship envisaged. In large ships the prime movers and generators could be put high in the ship, thus reducing the space taken up by uptakes and downtakes, with only the direct drive motors down at the shaft line. In hydrofoils, or SWATH type vessels, (small water-plane area twin hull — in essence a large platform supported above the surface by two submerged submarine-like hulls, with the vertical supports having small waterplane cross-section), an electric transmission is a possible means of dealing with the difficult problem of transmitting power down a long strut, while the relatively small superconducting direct drive motor is well suited to installation in the underwater pods or hulls.

In ship designs where a multiplicity of gas turbines is used for main propulsion it is desirable to run as few engines as are necessary to provide the power for the required ship speed, because this gives improved fuel economy and minimises expenditure of engine hours. With electric drives there is complete freedom of choice of engines. Any engine can drive any shaft and under cruising conditions it will often be best to have a single engine providing all the power to the shafts.

Reversing has always posed problems for gas turbine driven ships, since these engines are not usually themselves reversible. Reversing is generally achieved at present by use of controllable pitch propellers or by a system of reversing gears and clutches in the gearbox. There are undesirable features in both these approaches. Reversing in an electric DC transmission can be achieved by field reversal or by change-over of connections in the main transmission lines. For the superconducting drives the latter approach is now preferred, because of the problems of cryostat design which arise from rapid field changing. By proper control system design it can be arranged that the line current is reduced to a very low figure before the circuit is broken and the connections changed over.

Low noise level is of particular importance in some installations and there are evident advantages in having a quiet direct-drive electric motor driving a fixed-pitch propeller.

The suitability of superconducting systems for use with various sources of high-current DC power may prove increasingly significant with further advances in the novel concepts which are receiving attention. Advances in batteries continue to be made; progress on MHD, thermionics and fuel cells appears to be slow at present but the technical possibilities are apparent.

These potential advantages account for little, of course, unless accompanied by a high standard of reliability, and this has yet to be demonstrated. Our experience to date indicates — not surprisingly — that the cryogenic system is an area where further attention is needed.

The main elements of the cryogenic system are:

1 The helium compressor.
2 The refrigerator itself, consisting primarily of a series of heat exchangers, expansion engines and valves.
3 The cryostat surrounding each superconducting coil, consisting mainly of: low heat conduction suspension for the coil, a surrounding containing vessel for the liquid helium, surrounding insulation composed of a vacuum chamber, radiation shield and multiple layers of superinsulant.

Our experience with helium compressors has not been particularly good. It is essential that the helium delivered to the refrigerator has a very low level of contaminants, because these all separate out in the refrigerator system resulting in reduced performance and risk of failure of the expansion units. It has proved very difficult to maintain the required quality and this has led us to study various alternative approaches and to embark upon a project to develop a sealed aerodynamic helium compressor. Given good purity of the helium supply the refrigerator itself should be very reliable. The type used for the 1 MW system incorporates two turbo-expanders, each with a tiny rotor running on gas bearings, at extremely high speed. These rotors are the only moving parts in the system and are of proven reliability.

Cryostats have no moving parts but helium is particularly good at finding its way through the most minute leakage paths and this can result in loss of vacuum in the vacuum chamber with consequent excessive heat flow. The design of the cryostat must therefore be simple and easy to fabricate, and a high standard of manufacture, particularly in welding, is essential. The superconducting coils themselves, which are of potted construction, have proved to be trouble free, despite the considerable mechanical stresses arising when energised and the thermal shock from the heat release of a " quench " to non-superconducting conditions.

In the armature system the main uncertainty lies in the current transfer system. Tests have been conducted on carbon fibre brushes over long periods to demonstrate their reliability and acceptable rates of wear, but it is recognised that the ultimate tests for these must be that of service operation at sea.

Armature system fault protection poses problems because currents are large, ranging to 10,000 amps and above, while system inductance is low, with consequent high rates of current rise in the event of a fault. Nevertheless breakers are available which have the capacity and speed of response to handle short-circuit faults of such a system.

Consequently, although system reliability has yet to be demonstrated it is anticipated that by attention to these problems a standard of reliability meeting service requirements will be achieved.

Future Application

Whether or not superconducting machines will ultimately be selected for use in RN vessels will depend on their being able to show overall advantage over the alternatives available. As discussed above, this will depend not only on the technical advances made in superconducting systems and in other competing systems but also on the types of craft which will be required in the future to meet the Navy's needs. The object of the present programme is to establish the potential of superconducting machines for naval application and to carry the concept along to the stage of offering a viable propulsion transmission with a sound engineering basis.

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(1) The development of superconducting field electrical machines by Ministry of Defence. S. Bolshaw, *J.R.N.S.S.*, Vol. 26, No. 5.

(2) Journal of Naval Science Vol. 1, No. 1. Item on USN superconducting work, in Overseas Notes and News (p. 87).

OPERATIONAL ANALYSIS IN UNDERWATER WARFARE ASSESSMENT STUDIES

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Introduction

Within the Ministry of Defence the organisation for operational analysis reflects both the single Service and Central Staff functions. The Defence Operational Analysis Organisation consists of some 170 professional scientists working either in support of Central Staff activity or support of single Service Headquarters and operational commands. Of the total strength almost one half are based at the Defence Operational Analysis Establishment together with some 40 military officers. Of the remaining scientists about 6% are based with each of the Headquarters staff the remainder being in field commands.

The single Service OA teams are professionally responsible to their respective Chief Scientists and their work is aimed at management of planning decisions, logistic and support functions and in particular equipment procurement. The work is integrated with or supported by analytical studies in R&D establishments. The Naval Analytical Studies committee under the chairmanship of Deputy Chief Scientist Navy coordinates the Naval orientated study activity.

This article concerns itself with the use of operational analysis in underwater warfare studies as typified by the work of DAUWE's assessment division.

This article is based on a lecture given to the RN Staff Course at Greenwich in September 1975 and contains extracts from an unreferenced paper by Mr. D. H. O. Hider, formerly Head of DAUWE's Assessment division.

Types of Assessment

Terminology varies throughout the analytical studies community. The term assessment studies has been used in the R&D establishments to denote those in which due consideration and weight is given to the realities of equipment and environmental limitations. However there is a distinction between those which seek to establish the feasibility of a material solution and those which seek to establish whether such approaches will meet the requirements of the user.

Typical questions which each type of study may seek to answer are listed below.

Material Assessment Study

What is it?
What can it do?
How does it do it — defining a capability?
How is it deployed at sea — examination of ship engineering problems?
How much does it cost (including spares etc.)?
What are its upkeep limitations?

Operational Assessment Study

What it is up against?
What do we want it to do?
How do we use it?
How effective will it be?
or later
What results do we get with it?
Is it worthwhile? Are deployment costs commensurate with the effectiveness?

In many cases material and operational studies overlap.

At AUWE the assessment division conducts studies of the operational type but of course these rely heavily on inputs from associated material research activities. The operational analysis approach is similar but less academic than in more classically orientated OR organisations. More emphasis is given to the practical aspects of study problems and for this reason the majority of the staff engaged on studies not only have had previous experience in R&D divisions but also have spent many long days and nights at sea. In the main they are mathematicians, physicists or engineers. Few have any formal qualifications in OR techniques but are selected for their breadth of intellect which enables them to assimilate and apply OR principles — and of course for their 'wet feet'.

Types of Study

Fig. 1 shows a breakdown of the major sub-fields of underwater warfare, the various systems having applications to those sub-fields and associated material requirements. The characteristics of the material solutions needed for the systems to make an effective contribution to particular sub-fields of warfare are critically dependent on the threat and the importance of its continued assessment cannot be overstressed.

The variety of systems needed to undertake the operational tasks have to be matched to a mix of vehicles which often have conflicting tasks in other fields of warfare. A wide range of studies is undertaken at AUWE in response to requests from the Naval Staff, MOD(PE) R&D management and the Fleet. The emphasis is on the operational value of systems taking into account the life cycle interrelationships with the threat and the evolving mix of systems both ours and potential enemies.

The work undertaken falls into four categories.

a. *Forward Look Studies.* Assistance in the formulation of research programme objectives.
b. *Project Support Studies.* Support for specific feasibility, project definition and subsequent project development activities.
c. *Fleet Support Studies.* Assessment of overall underwater warfare system performance from Fleet evaluations or exercises to give guidance on the tactical use of such systems and to aid force level studies.
d. *Study Support.* Improvement of methodology, provision of data banks and advice.

Approaches and Limitations

The techniques used depend on the skills at the command of the individuals conducting the studies and the timescale of the studies. Much of the time the methods used are simple and the short study timescale invariably required proves helpful in that individuals are not tempted to use over-sophisticated methods for the quantifiable parts of the study. However when justified more elaborate approaches are made often with the aid of specialist OR activities under contract. Interrelationships with other authorities are many and varied and cooperation with other nations has been beneficial.

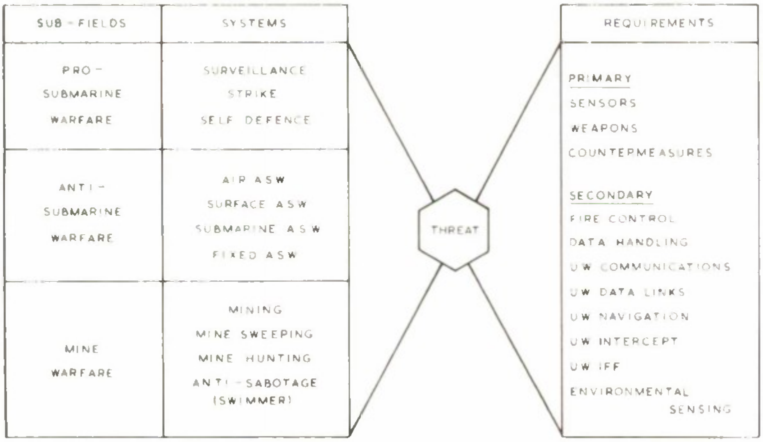

FIG. 1.

It is often of concern as to whether the many customers for studies are alive to the value of studies, or of the OR principles which apply to their choice of terms of reference, the need for validation of assumptions and models and whether the studies will in fact contribute to a rational decision making process or merely serve as part of a ritual to be followed.

Above all the operational analytical work must be seen to be credible and the validation of models is considered to be of major importance. The more complex the model the more difficult this becomes: invariably there is a lack of real data on how well systems perform at sea. The investment in exercises is considerable: there is a paramount need for them to generate performance data, which is possibly of comparable importance to the training benefits which they are designed to achieve.

Specific Types of Model

So much for generalities now to specific applications of operational analysis techniques to the decision making process. Examples have been chosen to illustrate modelling work which can be broadly categorised under the headings

a. *Operational* — aimed at determining vehicle/platform effectiveness in the total system sense.

b. *Tactical* — aimed at estimating specific engagement outcomes.

c. *Strategic* — aimed at formulating policy.

[Note these definitions are those in "local use". They are not generally accepted definitions within the analytical studies community as a whole].

Operational. Datum search is a very significant element of ASW operations. It could be conducted by a number of vehicles each with differing sensor fits, deployment characteristics and costs and the question arises "How many vehicles are required to achieve a given effectiveness for minimum cost?".

If the simplifying assumption is made that datum inaccuracies are negligible compared with the distance travelled by the target in the deployment time t_d the probability that the target will have been detected by time t is given by

$$p = 1 - \exp\left(- n\alpha \frac{u}{u+1} \right)$$

where

$$\alpha = \frac{A_s}{\pi V_s^2 td} \qquad u = \frac{t}{td}$$

A_s = area search rate
V_s = target speed
n = number of search vehicles

If furthermore the cost per unit time on task for a given vehicle is known then it can be readily shown that the total cost for the search phase to achieve a given effectiveness decreases with the number of vehicles used. Furthermore if the maximum effectiveness is to be achieved within a given time and cost then the vehicle with the maximum value of A_s/td is the preferred choice.

However vehicles have to be deployed to and from the datum search area and the total time on task is accordingly increased. Taking this into account a minimum cost for the total operation ensues and a figure of merit for competing systems can be shown to be

$$f = \frac{A_s}{C_t \, t_d^2}$$

C_t = Cost per unit time on task

In this the more realistic case the significance of deployment time is more evident and cost per unit time on task comes into the equation.

With a relatively simple model the performance of systems which could be quite different in concept can be compared *e.g.* aircraft sonobuoy systems compared with surface ship duct sonars. The value of a simplifying assumption and the importance of modelling the total operation is evident.

Tactical. The problems of surface ship noise reduction are complex and considerable resource has been deployed investigating solutions. Some of the measures developed are already fitted to RN ships but the extent to which noise reduction measures should be fitted in new designs continually required reassessing. A need was identified therefore to determine the overall effectiveness of noise reduction in surface ships: this coupled with appropriate costs can lead to the definition of a degree of cost effectiveness on which future fitment policies can be based.

Noise aspects of an ASW situation can be considered in three parts

a. Detection
b. Fire Control
c. Weapon Effectiveness

After initial investigation it was decided that the most comprehensive method of determining the effectiveness of noise reduction would be to simulate an ASW engagement. By varying the noise inputs to the model a direct comparison could be made between the engagement outcomes of a submarine task force conflict before and after noise reduction. The model which has been developed now provides a very powerful tool not only for the specific purpose for which it was designed but also for other studies requiring a detailed ASW simulation.

The output of any attack situation will depend on the initial parameters and the model as developed is such that a great variety of situations can be simulated. Results are generated typically in the form shown in Fig. 2 which leads to an objective assessment on the effect of noise reduction on the decrease in mean attack range and the number of encounters which do not result in an attack at all.

This model is complex yet flexible but it is dangerous to assume that such models or studies utilising them always give definitive results. Often they expose problems to be explored or undermine previously preferred solutions.

FIG. 2.

Strategic. Some years ago the following question was posed. "What is the likely effectiveness of various weapon procurement policies against a projected specified threat over the next two decades?".

At the time one such weapon was in service, one was under development and another was in an advanced state of research. Additionally the possibility of the purchase of a foreign weapon could not be discounted. There were thus numerous procurement possibilities for example

(1) Continue with the weapon under development and delay the initiation of any new development resulting from the research programme.
(2) Extend the life of the weapon in service, cancel the weapon under development and accelerate a new weapon development resulting from the research programme.
(3) Cancel the weapon under development buy from abroad to establish an interim capability pending the introduction of a new weapon development from the research programme.

Guidance was thus required on the relative merits of the differing policies in providing an effective counter to the threat.

The effectiveness of a given procurement policy depended on

a. The characteristics of the weapons under consideration.
b. The characteristics of the total weapon system.
c. The capabilities and prevalence of the targets to be attacked.
d. The likely date of introduction and rate of build up of new weapons in the Fleet.

The general principle applied to arrive at the necessary guidance was that *if* a single figure for the effectiveness of a given weapon

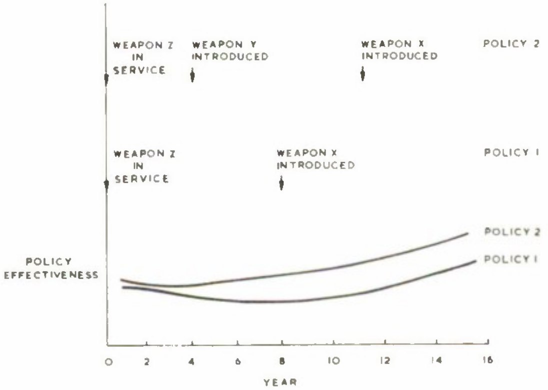

FIG. 3.

against a given target could be obtained then convolving this with the projected time spectrum of the targets, assuming random interactions, and the spectrum of weapons in the Fleet, assuming random usage, the overall effectiveness with time would ensue. The required single figure of effectiveness could be determined using already developed weapon system operational performance models by making assumptions as to the likelihood of occurrence of a given weapon system attack against a given target in given conditions.

A typical result is shown in Fig. 3 where the effectiveness of two different policies is compared. The benefits of an interim buy combined with a delay in introducing a more advanced weapon are evident.

Although other factors such as the industrial position and resource availability had to be taken into account before the final decision was made the approach outlined was largely instrumental in determining the procurement policy eventually implemented.

Conclusion

It is hoped that the examples have served to illustrate the ways in which operational analysis is being used in Underwater Warfare assessment studies. Assessments are no substitute for judgement and cannot dictate decisions. They can illustrate the value of options under given conditions but unless the decision criteria can be interpreted by measures of effectiveness relevant to the tactical scenarios, force levels and constraints applying at the time there may be a gap between the questions posed and the answers which can be provided.

EFFECTS OF JUVENILE HORMONE ANALOGUES UPON THE METAMORPHOSIS OF LARVAE OF THE BARNACLE *ELMINIUS MODESTUS* DARWIN

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Abstract

Two analogues of insect juvenile hormone have been shown to interfere with the development of barnacle larvae to the adult form. Stage VI nauplii metamorphosed to morphologically abnormal larvae which were intermediate in size between the nauplius and cypris stages and apparently retained some naupliar characteristics. Cyprids either metamorphosed to non-attached adults or formed larvae which were larger or morphologically abnormal. The responses resemble those arising from the hormonal imbalance which juvenile hormone analogues induce in holometabolous insects. The ability to prevent normal development to the settled adult barnacle may have antifouling applications.

Introduction

Part of the current antifouling research programme at CDL is aimed at understanding and attempting to exploit developmental processes of barnacles and algae. Studies with barnacles are being carried out in the context that the development and growth of these crustaceans is similar to that of other crustaceans and insects, which are the major classes of the Phylum Arthropoda. Two characteristics dominate the activity of arthropods: (i) a life cycle in which larval stages undergo a succession of changes of form and function (metamorphosis) before they enter the adult stage, and (ii) the possession of an outer integument which is periodically moulted to allow changes in form and increase in size. In common with other organisms, post-embryonic growth, moulting and metamorphosis are under hormonal control(1, 2, 3). In those arthropods so far studied moulting during larval and adult stages is controlled by steroid hormones termed ecdysones(4), in particular, crustecdysone and ecdysone (Fig. 1). It has been established that in insects juvenile hormone(s) (Fig. 1) is present during the larval stages and determines whether a moult brought about by ecdysones results in a larval stage, a pupa, or the adult form. In holometabolous insects, such as the blowfly *Calliphora erythrocephela*, relatively high levels of JH are produced during each larval stage, except the last, and ensure the formation of another larval form; production is diminished in the last stage and the moult to the pupa results. Before the final moult little or no JH is secreted and the adult then emerges. Although there are several theories as to the precise mode of action of JH, the presence of significant amounts of hormone mitigates against the expression of adult characteristics (probably at chromosomal/DNA level) at the next moult. Very little is known, however, of the mechanisms controlling the changes during crustacean larval development, although Schneiderman and Gilbert(5) showed that extracts of a number of crustacea possessed JH activity towards insects and suggested that JH may play a role in crustacean development.

The life cycle of a typical balanomorph barnacle comprises seven free-swimming larval stages (Fig. 2) and an attached sedentary adult. The first six larvae are termed nauplii, while the seventh is the cypris larva: progress through these stages is by a succession of moults, followed by the cypris moulting to the adult form after attachment to a substratum. Major structural features are illustrated in Fig. 3. Detailed studies of the changes during the life cycle(6) show that although the development of adult structures is evident in the later nauplius stages, the greatest rate of change is during stage VI and through the cypris larva to the young adult. Thus metamorphosis may be considered as comprising the changes between the stage VI nauplius and cypris larva, and between the latter and the adult.

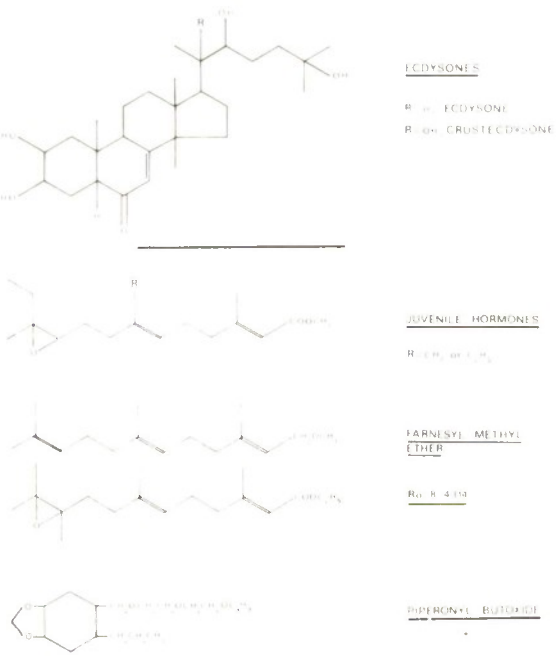

FIG. 1. The structure of two arthropod moulting hormones (ecdysones), two insect juvenile hormones (JH), two synthetic analogues of JH examined in the present study (farnesyl methyl ether and Ro-8-4314), and of a 'Bowers-type' compound (piperonyl butoxide) which exerts juvenilizing effects upon insects.

Investigations of the effects of injected crustecdysone and wounding upon adult barnacles have shown that moulting is apparently controlled by an ecdysone hormonal system(7, 8): this system may also be associated with the control of calcification and, possibly, cementation processes.(9) Studies following an MOD(PE) contract (No AT/2098/04 CDL) have established the natural occurrence of crustecdysone in adult *Balanus balanoides.*(10) Evidence for an ecdysone function in larvae is obtained from the ability of sea water solutions of crustecdysone to stimulate precocious metamorphosis of *Balanus eburneus* cyprids to adults(11). It would seem likely that, as in insects, a further hormone(s) may regulate larval metamorphosis and determine the form assumed after each moult. Larval development in barnacles is analogous to that of holometabolous insects, as in both there is a gradual development through the nauplius or larval stages, followed by a marked transformation into a quite different form (*i.e.* the barnacle cypris and the insect pupa) before the adult is attained. The cypris has been described as a 'locomotive pupa', because of the tissue histolysis and morphogenetic activity during metamorphosis to and from this stage(6).

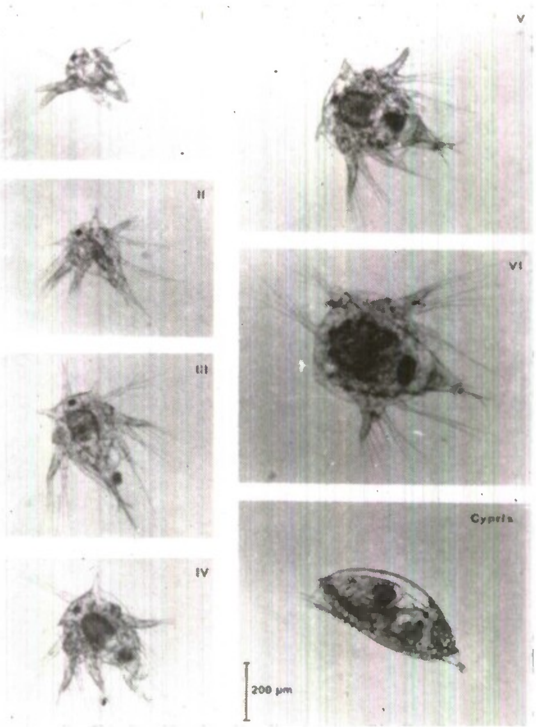

FIG. 2. The nauplius and cypris larvae of *Elminius modestus* Darwin.

Antifouling interest in the hormonal control of barnacle development is based upon the proven susceptibility of insect hormonal systems to exploitation. The activity of JH is mimicked by a large number of naturally occurring and synthetic compounds, including some whose structures does not resemble that of the natural hormones, *e.g.* the Bowers' compounds (Fig. 1). The structure of a number of compounds exerting 'juvenilizing' effects is given in reviews such as those of Karlson(12), Bowers(13), Sehnal(14) and Slama(15). Their effects can be summarized as follows:

> 'An exogenous supply . . . to last instar larvae or pupae before a certain critical period causes partial or complete inhibition of metamorphosis, manifested by partial or complete retention of the old epidermal structures on the next instar. The abnormal specimens thus formed are recognised as larval-pupal intermediates, larval-adult intermediates, . . . supernumerary or extra larvae, secondary pupae, etc.'(15).

The action of 'juvenilizing' compounds upon insects indicated that exposure of barnacle larvae might result in an interference with normal development. This was borne out by early studies(16) which showed that the JH analogue farnesyl methyl ether (Fig. 1) induced abnormal development in larvae of *Elminius modestus*. Later, Gomez *et al.*(17) reported that another analogue, ZR-512 (ethyl, 3,7,11-trimethyl-dodeca-2, 4-dienoate), stimulated the premature metamorphosis of cyprids to unattached adults. A similar phenomenon was also apparently induced by farnesol(18).

The results of a study of the effects of two JH analogues, farnesyl methyl ether (FME) and compound Ro-8-4314 upon the development of *Elminius modestus* larvae are given below.

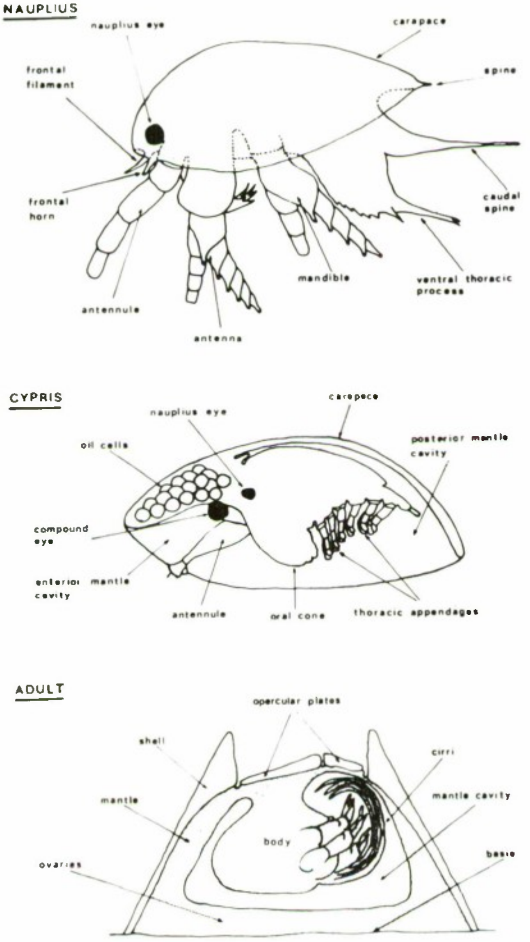

FIG. 3. Diagrammatic representation of major structural features of the nauplius, cypris and adult stages of operculate barnacles.

Experimental

Studies of the effect of analogues upon *E. modestus* larvae were restricted to stage VI nauplii and cyprids because both metamorphose to a markedly different form, so that any interference with development might be expected to be more evident than after a nauplius to nauplius moult; furthermore, the effects of JH analogues upon holometabolous insects are generally restricted to the last larval and pupal stages (*e.g.* (15)) when little or no JH is produced naturally — Gomez *et al.*(17) report that compound ZR-512, although active towards cyprids, had no effects upon stage IV nauplii of *Balanus galeatus*.

Juvenile hormone-analogues

Samples of two juvenile hormone-analogues, farnesyl methyl ether (FME) and Ro-8-4314 (ethyl, 10,11-epoxy-3,7,10,11-tetramethyl-2-*cis*-*trans*-6-*cis*-*trans* dodecadienoate) were supplied by Roche Products Ltd. as colourless, slightly oily liquids. Their structures are given in Fig. 1. The sample of FME contained approximately 75% of the *trans*-*trans* isomer, which is considerably more active towards the bug *Rhodnius prolixus* than the *cis*-*trans form*(19). The mixture of isomers in Ro-8-4314 is unknown. The analogues were examined as acetone solutions in sea water (0·1% v/v) at concentrations of 10^{-5} and 10^{-6}: control sea water contained 0·1% solvent.

Exposure of larvae

Stage VI nauplii and cyprids of *Elminius modestus* Darwin were reared in the laboratory at a temperature of 20°C, according to the technique developed at CDL(20). Batches of approximately 100 of the appropriate larval stage were added to each of a duplicated series of 250 ml beakers containing 225 ml of control sea water or a concentration of the hormone-analogue in sea water. Approximately 60 ml of a culture of the diatom *Skeletonema costatum* were added as a supplementary food to the beakers containing stage VI nauplii: cyprids do not feed. The larvae in each beaker were confined within a close-fitting plastic cup, with a nylon mesh base, to facilitate their removal for examination and changing of the media. In cyprid experiments, two ground glass slides, approximately 50 × 75 mm and fitted back to back, were added to each beaker. These were treated with settlement factor(21), prepared from a crude aqueous extract of crushed adult barnacles, to promote settlement of the cypris stage. To reduce bacterial growth 0·4 ml of a Crystamycin solution (prepared by dissolving 0·8 g/2 ml distilled water) was added to each beaker. The duration of an experiment depended upon the survival and progress of the larval population to the next developmental stage; at the end the larvae were filtered off and the number alive and dead recorded. These were then transferred in sea water to specimen tubes and the appropriate volume of fixative, buffered neutral formalin, added to give a final concentration of 10%. Populations were left for several days before microscopic examination in a free-floating condition to prevent damage. The dimensions of each larva were recorded and developmental stages determined from morphological characteristics; any abnormalities were also recorded.

The statistical significance of experimental results was examined by 't' test and chi-square analysis, as described by Snedecor and Cochran(22).

FME: Effects upon the Metamorphosis of Stage VI Nauplii to Cyprids

FME was examined for its effect on the metamorphosis of stage VI nauplii taken from a laboratory population in which the first cyprids were appearing. Approximately 200 nauplii were exposed to each of the analogue and control sea water solutions for a period of three days, during which they were examined daily and dead larvae were removed. Cyprids were defined as dead when no gut or muscular movement was observed under microscopic examination. Results are shown in Fig. 4.

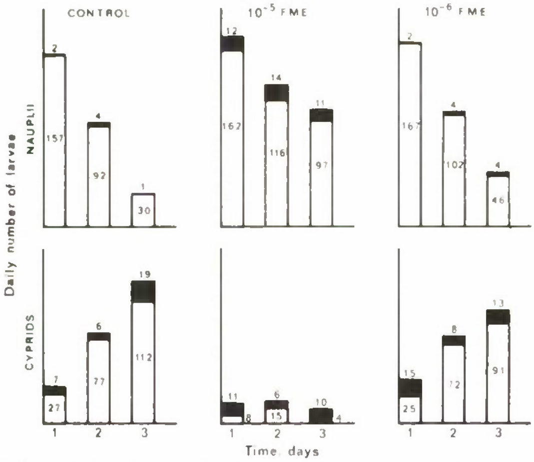

FIG. 4. *Elminius modestus:* metamorphosis of stage VI nauplii exposed to the juvenile hormone analogue, farnesyl methyl ether; daily number of nauplii, and of cyprids formed; dead larvae were removed each day: ☐, alive; ■, dead.

The number of nauplii metamorphosing at 10^{-5} FME differed markedly from that in the other two solutions. In both the control and lower FME concentration (10^{-6}) the number of cyprids formed increased with time, with a total of approximately 70% and 65% of the nauplii metamorphosing, respectively: overall nauplius and cypris survival was approximately 70%. However, although the survival at 10^{-5} FME was not much less (50%) only 15% of the nauplii metamorphosed and none did so on the third day. Furthermore, approximately 85% of the cyprids formed in this concentration died, compared with only 30% and 20%, respectively, in the 10^{-6} FME and control sea water.

It thus appeared that at 10^{-5} FME retarded or prevented the metamorphosis of stage VI nauplii and that the analogue either resulted in a moult to a non-viable stage or was more toxic to cyprids than to nauplii. Furthermore, size and morphological abnormalities occurred in cyprids formed in both concentrations of FME, although the stage VI nauplii appeared to be normal. The mean dimensions of cyprids in each experimental group are given in Table 1.

Cyprids formed in control sea water were closely similar in size to those reared under laboratory conditions(20), and there was no significant difference between alive and dead specimens (depth, $t = 1{\cdot}29$, $P > 0{\cdot}1$: length, $t = 0{\cdot}27$, $P > 0{\cdot}25$). However, the size of cyprids in the 10^{-5} FME concentration differed from that of control larvae, showing a significant increase in depth of carapace (dead, $t = 2{\cdot}85$, $P < 0{\cdot}01$: alive, $t = 2{\cdot}38$, $P < 0{\cdot}05$) and a highly significant decrease in length (dead and alive, $t = 6{\cdot}43$ and $6{\cdot}87$, respectively, $P < 0{\cdot}001$). At 10^{-6} FME, only the decrease in length of dead larvae was significant ($t = 2{\cdot}34$, $P < 0{\cdot}05$).

Approximately 45% and 10% of the cyprids formed in the 10^{-5} and 10^{-6} FME concentrations, respectively, exhibited morphological abnormalities. As illustrated in Fig. 5 these were of two main types: (i) a distortion of the anterior region of the larva, which ranged from a small swelling between extended antennules (Fig. 5, 1) to a gross extension bearing not only the antennules but also the lateral compound eyes (Fig. 5, 2 and 3) — each of the latter possessed a frontal filament and was mounted on a stalk arising from a lateral 'horn' of the anterior extension; and (ii) protuber-

TABLE 1.

Elminius modestus: **mean dimensions (μm) of cyprids formed from stage VI nauplii exposed to FME solutions, figures in parenthesis denote number of cyprids examined.**

Cyprid state		*Control sea water*	*FME Concentration*	
			10^{-5}	*10^{-6}*
Dead:	depth	264·1 ± 17·2 (27)	277·4 ± 16·8 (26)	261·4 ± 20·5 (26)
	length	554·4 ± 21·6	507·3 ± 28·1	539·1 ± 25·8
Alive:	depth	258·6 ± 14·9 (30)	277·8 ± 17·4 (4)	264·9 ± 17·9 (30)
	length	552·9 ± 22·6	472·2 ± 31·3	547·4 ± 19·9

ances arising approximately mid-way along the ventral carapace groove — the nature of these varied, ranging from an apparently single protuberance (Fig. 5, 1) to what appeared to be two, smaller pairs (Fig. 5, 4). Two cyprids exhibited, in addition to a single protuberance, ventral extensions which resembled part of a biramous nauplius appendage (Fig. 5, 5 and 6). Most of the larvae possessed only one abnormality, as shown in Table 2. All of the cyprids formed in control sea water appeared to be normal.

The percentage of abnormal cyprids in the 10^{-5} FME concentration increased with time. None of those which died on the first day were abnormal, whereas 33% and 80% of those dead on the second and third days, respectively, and all those remaining alive at the end of the experiment possessed abnormalities. There was an indication that the extent, also, of morphological abnormality increased with time: both of the abnormal cyprids dead on the second day possessed ventral protuberances only, whereas on the third day three of the eight had ventral protuberances, three showed gross anterior distortion and two exhibited both phenomena. Of the four remaining alive, one possessed a ventral protuberance, two showed gross anterior distortion and the other exhibited both phenomena. In the 10^{-6} FME, abnormal cyprids were formed throughout the experimental period and all exhibited a distortion of the anterior portion alone.

In all three treatments, the thoracic swimming appendages of some cyprids were extended. The extent varied, ranging from only a slight protrusion in 5% of the control larvae to a marked extension in 30% and 7%, respectively, of those exposed to 10^{-5} and 10^{-6} FME (*e.g.* Fig. 5, 5). The occurrence at 10^{-5} FME was significantly higher than in the controls ($X^2_1 = 7\cdot94$, $P<0\cdot005$).

TABLE 2.

Elminius modestus: **incidence of morphological abnormality in cyprids formed from stage VI nauplii exposed to FME solutions.**

Number of Cyprids	*Control sea water*	*FME Concentration*	
		10^{-5}	*10^{-6}*
Total examined	57	30	56
Total abnormal	–	14	5
Ventral protuberances	–	6	–
Anterior swelling	–	5	5
Both phenomena	–	3	–

From these results there can be little doubt that FME interfered with the development of stage VI nauplii. The analogue exerted toxic effects, retarded metamorphosis and induced the formation of abnormal larvae. The nature of the morphological abnormalities and of the mechanisms involved would appear to be related to the structural changes normally involved in the stage VI nauplius-cypris metamorphosis. Walley (6) reported that immediately after ecdysis the young cypris retains some of the nauplius features — the antennae and mandibles briefly retain their biramous structure but, as post-ecdysial changes proceed, these regress and the antennules, the oral cone and the thoracic swimming appendages are withdrawn into the carapace cavity. FME appears to have interfered with this sequence and induced a permanent retention of some nauplius characteristics. Further evidence for such a retention is obtained from the size of cyprids formed in the 10^{-5} FME concentration — the mean length of those dead and alive (507·3 and 472·2 μm, respectively) was intermediate between that of controls (approximately 550 μm) and that of the stage VI carapace (approximately 450 μm) from which the

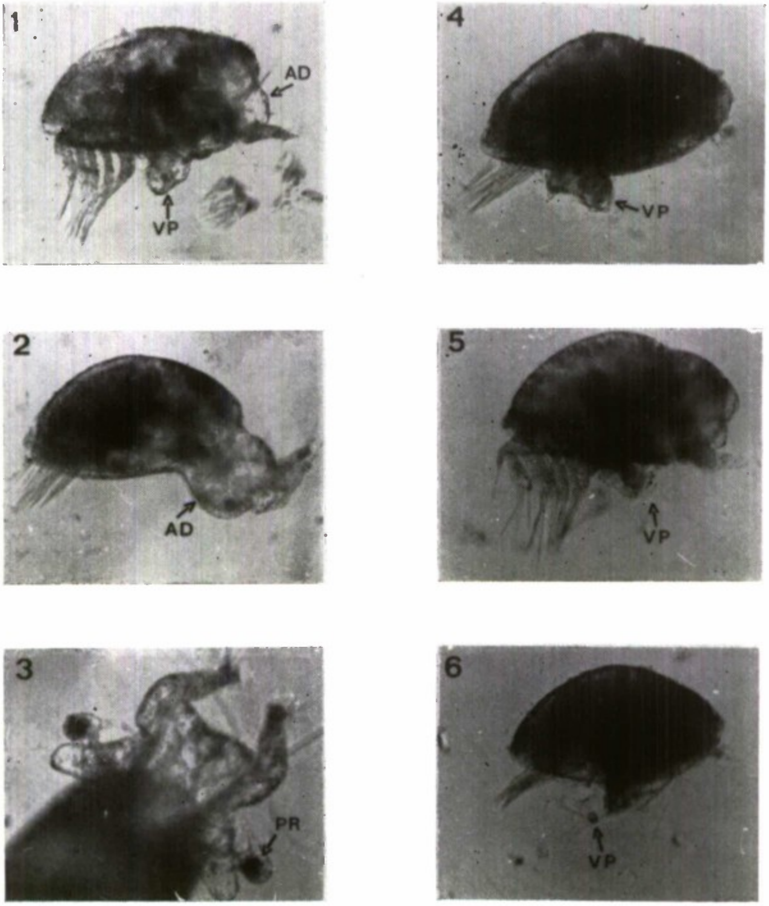

FIG. 5. *Elminius modestus:* abnormal cyprids formed by the metamorphosis of stage VI nauplii exposed to the juvenile hormone analogue, farnesyl methyl ether; the abnormal larvae exhibit anterior distortion (AD) and/or ventral protuberances (VP): 1, larva with anterior swelling and a ventral protuberance; 2, larva with gross anterior distortion, bearing the paired antennules and photoreceptors; 3, dorsal view of 2, enlarged to show photoreceptors (PR) borne on stalks arising from lateral 'horns'; 4, larva with two pairs of short ventral protuberances; 5, larva with long ventral 'appendage'; 6, larva with biramous ventral appendage.

cypris emerges. The reason for the gross anterior distortion of some cyprids formed in FME solutions is not known, although the abnormality appears to be similar to that arising from the incomplete metamorphosis of *B. eburneus* cyprids exposed to crustecdysone(11).

Morphologically abnormal cyprids were not always abnormal in size, indicating a range of response to FME which may depend upon the individual nauplius. As the incidence of abnormal morphology during the experiment apparently increased with time, it is possible that the effects of the analogue were related to the period of exposure before ecdysis occurred, *i.e.* to the state of development of the nauplius.

FME: Effects upon the Metamorphosis of Cyprids

Two studies were made of the effects of FME upon the formation of the young adult from the cypris. Approximately 100 cyprids were exposed to FME solutions, at 10^{-5} and 10^{-6}, and control sea water, in each of which were placed ground-glass slides treated with an extract of adult barnacles. The number of young adults was recorded daily.

Cyprids for the first experiment were removed from a laboratory population in which large numbers had settled and metamorphosed. The larvae were exposed to the experimental solutions for one week, at the end of which eight were alive and two dead in the control sea water; none were alive in the FME solution. The number of adults produced during this period is given in Table 3. Although virtually all of the control cyprids had settled and metamorphosed, this had only occurred in approximately 5% and 20% of those in the 10^{-5} and 10^{-6} concentrations of FME, respectively. Most settlement occurred on the first day: young adults continued to appear in the control sea water and, to a lesser extent, in the lower FME concentration. However, no further settlement occurred in the 10^{-5} FME concentration. All young adults appeared normal.

TABLE 3.

Elminius modestus: **formation of adults in populations of approximately 100 cyprids exposed to FME (experiment 1); cumulative number of live adults; figures in parenthesis denote deaths.**

Day	*Control sea water*	*FME Concentration*	
		10^{-5}	*10^{-6}*
1	72	4	9
2	89	4	11
3	102	3(1)	17
6	95(7)	3	19
7	94(1)	3	17(2)

The cyprids retrieved from the analogue solutions were accidentally combined and were, therefore, analysed together. There was no significant difference between the mean length and depth of 56 larvae examined (540·4 ± 28·2 and 248·0 ± 17·7 μm) and that of the ten remaining in the control population (541·4 ± 28·3 and 252·6 ± 20·2 μm). However, approximately 75% of the FME-treated population were morphologically abnormal, possessing a gross extension of the anterior region which bore the antennules and lateral photoreceptors — the nature of this phenomenon was the same as that described earlier (Fig. 5, 2 and 3). However, none exhibited protuberances along the carapace groove. In 31 of the cyprids the thoracic swimming appendages were grossly extended as illustrated in Fig. 6; slight extension was observed in three of the ten control larvae.

A further experiment was carried out with cyprids taken from a laboratory population in which no adults had been formed. The results were closely similar to those in the previous experiment, except that approximately 45% of the control larvae settled and metamorphosed to the adult stage during the exposure period of five days. The formation of adults were markedly less in the 10^{-5} and 10^{-6} FME concentrations (approximately 7% and 11%, respectively) and none appeared after the first day, although some further adults were formed in the control sea water. There was no significant difference ($P>0 \cdot 1 - >0 \cdot 25$) between the mean dimensions in the three groups of cyprids when examined at the end of the experiment; the mean depths and lengths, respectively, were as follows: controls, 247·9 ± 16·2 and 523·2 ± 19·0; 10^{-5} FME, 241·6 ± 13·9 and 523·7 ± 24·5; 10^{-6} FME, 242·4 ± 13·3 and 532·3 ± 21·0 μm. As in the previous experiment, approximately 75% of the non-metamorphosed cyprids remaining in the 10^{-5} FME concentration exhibited gross extension of the anterior region, bearing antennules and lateral photoreceptors. This occurred in 40% of those at 10^{-6} FME and in a further 45% the antennules, alone, were markedly extended. However, as in the previous experiment, none exhibited protuberances along the carapace groove. Controls were normal, although the thoracic swimming appendages were slightly extended in 30% of the larvae: gross extension occurred in approximately 60% and 90% respectively, at 10^{-5} and 10^{-6} FME as illustrated in Fig. 6.

Ro-8-4314: Effect upon the Metamorphosis of Cyprids

The JH analogue Ro-8-4314, possessing an epoxide ring and closely related to the natural hormones, was examined for its effects upon the development of cyprids to the adult form. Two studies were carried out using larvae which had been removed at different times from the same laboratory population, in which no adults were present; concentrations of 10^{-5} and 10^{-6} were employed and approximately 100 cyprids were used in each treatment. The experiments were terminated when virtually all of the larvae were dead, in the 10^{-5} Ro-8-4314. tration of the JH analogue.

The first experiment lasted 14 days and the results are given in Table 4. By the end of the experiment approximately 30% of the control population had settled and metamorphosed: however, no adults had been formed, and 99% of the larvae were dead, in the 10^{-5} Ro-8-4314. Despite high mortality (76%) in the lower concentration 9% of the larvae had metamorphosed into adults. One non-attached adult was found in both control sea water and the 10^{-6} analogue concentration.

The dimensions of cyprids in the experimental groups are given in Table 5. There was a highly significant increase in both the length and depth of the larvae in the 10^{-5} JH analogue concentration compared with those dead in control sea water ($t = 6 \cdot 42$, $P<0 \cdot 001$ and $t = 3 \cdot 24$, $P<0 \cdot 002$, respectively). Increases

FIG. 6. *Elminius modestus:* abnormal larva formed from cyprid exposed to the juvenile hormone analogue, farnesyl methyl ether. the larva exhibits anterior distortion bearing paired photoreceptors (c.f. Fig. 5, 2 and 3) and gross extension of the thoracic swimming appendages.

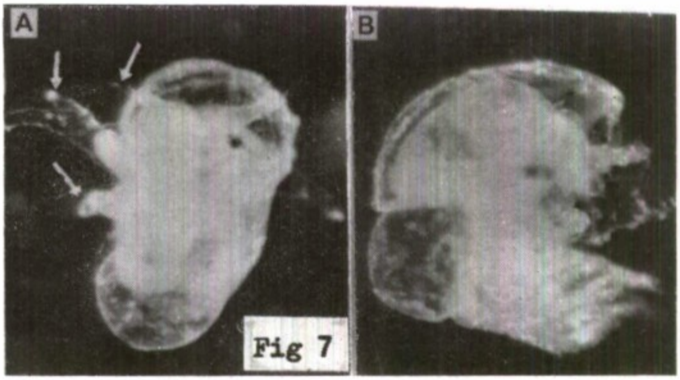

FIG. 7. *Elminius modestus:* abnormal cyprid formed by the metamorphosis of a stage VI nauplius exposed to juvenile hormone analogue.
A: ventral view showing three paired ventral appendages, the second of which is biramous, apparently representing partial retention of the nauplius limbs.
B: lateral view showing the characteristic cypris carapace (possessing neither the frontal horns nor the posterior spines of the nauplius), together with the thoracic appendages of the cypris.

TABLE 4.

Elminius modestus: effect of compound Ro-8-4314 upon the development of cyprids over an exposure period of 14 days (experiment 1).

Population	*Control sea water*	*Analogue Concentration*	
		10^{-5}	*10^{-6}*
Total number	78	89	80
Live cyprids	17	1	12
Dead cyprids	36	88	61
Settled adults	24	–	6
Non-attached adults	1	–	1

were also found in the dead larvae in the lower concentration (length, t = 4·15, P<0·001; depth, t = 2·44, P<0·02). Although the mean length of control cyprids remaining alive was rather higher than in those dead (t = 1·57, P>0·1) the increase in the length of the larvae exposed to the 10^{-5} analogue concentration was still highly significant (t = 3·14, P<0·002) — however, that in the dead larvae of the lower concentration was not significant (t= 1·39, P>0·1). The dimensions of living larvae in the latter did not differ significantly from the controls.

The morphology of the larvae appeared to be normal in all three treatments, although a slight extension of the thoracic swimming appendages was present in approximately 10% of the larvae. Thus, although the analogue apparently resulted in the formation of cyprids which were larger than control larvae, it did not induce the morphological abnormalities observed in cyprids exposed in FME.

TABLE 5.

Elminius modestus: mean dimensions (μm) of cyprids exposed to solutions of compound Ro-8-4314 (experiment 1), figures in parenthesis denote number of larvae examined.

Cyprid state		*Control sea water*		*Analogue Concentration*			
				10^{-5}		*10^{-6}*	
Dead:	depth	228·9 ± 18·2	(36)	239·9 ± 16·7	(88)	237·3 ± 15·2	(61)
	length	531·1 ± 25·3		562·0 ± 23·9		549·1 ± 17·4	
Alive:	depth	227·3 ± 16·5	(16)			231·5 ± 20·0	(12)
	length	542·2 ± 18·7				542·0 ± 16·3	

The second experiment was terminated after 12 days exposure to compound Ro-8-4314 and results are given in Table 6. These cyprids were removed from the laboratory population one week later than in the previous experiment and, as a group, may be considered to be physiologically older.

TABLE 6.

Elminius modestus: **effect of compound Ro-8-4314 upon the development of cyprids over an exposure period of 12 days (experiment 2).**

Population	*Control sea water*	*Analogue Concentration* 10^{-5}	10^{-6}
Total number	85	80	89
Live cyprids	16	–	23
Dead cyprids	18	63	60
Settled adults	50	5	–
Non-attached adults	1	12	6

The formation of adults from control cyprids was greater than in the previous experiment, with 60% metamorphosing by day 12. Only 21% and 7%, respectively, had done so at 10^{-5} and 10^{-6} JH analogue and there was high mortality. However, 12 of the 17 adults formed in the 10^{-5} concentration, and all six in the 10^{-6}, were found to be non-attached at the end of the experiment, compared with only one in the controls. The incidence in the Ro-8-4314 solutions is highly significant ($X^2_1 = 34{\cdot}6$ and $173{\cdot}5$, respectively, $P < 0{\cdot}001$). There was no significant difference between the dimensions of the cyprids in the three experimental groups (Table 7), except for a decrease in length of those alive at 10^{-6} JH analogue ($t = 2{\cdot}05$, $P = 0{\cdot}05$), the reason for which is not known. No abnormal morphology was observed.

In both experiments Ro-8-4314 interfered with the development of cyprids — in the first by resulting in the formation of larvae significantly larger than controls and in the second by being associated with the formation of non-attached adults. The latter effect could have arisen in two possible ways: (i) cyprids may have settled and metamorphosed to young adults which then, for some reason, became detached, or (ii) the cyprids may have metamorphosed without settling. Gomez *et al.*(17) observed that after exposure to the JH analogue ZR-512, B. *galeatus* cyprids ceased to swim, settled to the bottom of experimental dishes and formed non-attached adults. The difference in action of compound Ro-8-4314 between the two experiments described above may be related to the difference in the age of the two experimental populations.

Discussion

Two analogues of insect juvenile hormone, FME and compound Ro-8-4314, interfered with the development of larvae of *Elminius modestus*, confirming the activity of such compounds towards barnacle larvae reported earlier with this species(16) and with *Balanus galeatus*(17). The nature of the response in these studies appears to show similarities to those reported in insects and suggest that they were a consequence of hormonal action.

Exposure of stage VI nauplii to FME resulted in the formation of larvae which were intermediate in size between control nauplius and cypris stages, possessing ventral protuberances and a gross distortion of the anterior region. The ventral protuberances may represent a continued protrusion of the oral cone/second maxillae of the cypris and/or a partial retention of the antennae and mandibles of the nauplius.

TABLE 7.

Elminius modestus: **mean dimensions (μm) of cyprids exposed to solutions of compound Ro-8-4314 (experiment 2); figures in parenthesis denote number of larvae examined.**

Cyprid state		*Control sea water*	*Analogue Concentration* 10^{-5}	10^{-6}
Dead:	depth	225·6 ± 18·0 (18)	227·8 ± 18·7 (63)	224·4 ± 19·2 (60)
	length	533·7 ± 13·1	531·6 ± 20·9	531·6 ± 17·8
Alive:	depth	221·5 ± 14·0 (15)		231·0 ± 20·0 (23)
	length	531·2 ± 18·6		519·5 ± 15·2

The latter possibility is supported by the occurrence in some abnormal larvae of (i) two pairs of protuberances (Fig. 5, 4) and (ii) what would appear to be part of a biramous appendage (Fig. 5, 5 and 6). Definite evidence of some retention of nauplius appendages was obtained in a recent study at CDL(23) in which exposure of stage VI nauplii to JH analogue resulted in the formation of larvae which, although possessing the cypris carapace, antennules and thoracic swimming appendages, exhibited two distinct pairs of ventral appendages, the anterior pair of which were biramous (Fig. 7). The observation that some of these appendages were free of tissue may be related to the observation(6) that as the antennae and mandibles of the nauplius regress during normal metamorphosis the tissues within histolyse.

These results strongly suggest that exposure of stage VI nauplii to JH analogues can result in the formation of a cypris stage which has retained some nauplius size and morphological characteristics; such a larva could, alternatively, be termed a nauplius/cypris intermediate. The response would appear to be analogous to those in a number of insect species on which larval/pupal intermediates can be formed, *e.g.* (24, 25).

The metamorphosis of cyprids was affected by both FME and Ro-8-4314, although response to the two compounds differed. FME prevented development to the adult and resulted in the formation of abnormal larvae characterised by gross anterior distortion and extension of the thoracic swimming appendages. However, there was no evidence of the ventral protuberances present on cyprids formed from stage VI nauplii exposed to FME; this would support the suggestion that such protuberances represented a retention of some nauplius features. No distorted larvae were formed in Ro-8-4314 solutions; however, in one experiment there was a highly significant increase in size and in the other, with older cyprids, non-attached adults were formed. It is not known whether the abnormal cyprids were formed as the result of a moult and/or partial metamorphosis to the adult form. There can be little doubt that the experimental cyprids exposed to FME and Ro-8-4314 were capable of moulting, as evidenced by the formation of adults in control populations. The restrictive nature of the arthropod cuticle renders it extremely unlikely that an abnormality as pronounced as that found in the anterior portion of the larvae (*e.g.* Fig. 6) could have arisen except as the result of a moult or initiation of metamorphic processes. This supposition is strongly supported by the report of Cheung(11) that a crustecdysone-induced moult by cyprids resulted in the formation of abnormal larvae possessing apparently similar distortion of the anterior portion—Williams(26) commented that the visible effects of the disruptive action of JH analogues and ecdysones upon insects were similar, although arising from different hormonal mechanisms. A possible interference with the structural changes during barnacle metamorphosis described by Walley(6) could also explain the extension of swimming appendages and antennules often noted in abnormal larvae. The apparent ability of Ro-8-4314 to induce the formation of unattached adults, first reported with ZR-512(17), provides further evidence of the activity of JH analogues towards barnacle development. The overall response appears analogous to those of pupae of holometabolous insects, which will form supernumerary pupal stages or pupal/adult intermediates in response to compounds exerting juvenilizing effects *e.g.* (25, 27, 28).

The reason for the difference in cyprid response to FME and Ro-8-4314 is not known. This may be related to chemical structure, as the effectiveness of JH analogues upon insects is influenced by penetration through membranes and *in vivo* transport, metabolism, excretion etc., *e.g.*(14). An alternative explanation may lie in differences in the experimental populations of barnacle larvae. The increase in incidence of abnormalities during the development of stage VI nauplii in FME solutions, together with the difference in response to Ro-8-4314 between two cyprid populations of different ages, indicates a possible spectrum of response within a stage. The timing of treatment and the amount, or activity, of material are of crucial importance in determining the effect of JH analogues on insect metamorphosis, *e.g.*(14)

The observations upon *Elminius modestus* larvae appear to be the first report of the induction of size and morphological abnormalities in a crustacean species by analogues of an insect juvenile hormone. Gomez *et al*(17) reported no such response in *B. galeatus* cyprids exposed to ZR-512, but did observe a stimulation of metamorphosis. Although Cheung(11) considered that stimulation was contrary to the action of JH in insects, such a view does not take into account the ability of this hormone and its analogues to stimulate the activity of the insect prothoracic glands associated with the production of moulting hormones *e.g.*(28). However, there was no evidence of stimulatory effects by FME and Ro-8-4314. The difference in cypris response may be related to species, analogue structure, or to differences in the state of larval development. Alternatively, it may have been a consequence of the solvent employed — Gomez and co-workers used ethanol, not acetone. Insect studies (*e.g.*(28)) have shown the importance, at least in some species, of the solvent system employed with analogues: in certain solvents some compounds exert both juvenilizing and prothoracotrophic effects, whereas in other systems only the latter may occur. It is possible that with barnacle larvae the solvent may determine the rate at which material passes through the cuticle and, consequently, its effect within the larva in relation to the rate of metabolism of the analogue.

Conclusions

1. Available data suggest that JH analogues exert effects which are analogous to their juvenilizing and prothoracotrophic action upon insect larvae and pupae. Although the interference by analogues of insect juvenile hormone with the metamorphosis of barnacle larvae may be no more than effects of biologically active agents, the nature of the responses would appear to be compatible with a possible natural role for a system analogous to the controlling insect metamorphosis. Although there is no direct evidence for a JH role in the control of the development of barnacle larvae, it is reasonable to suppose that there is a system which determines the form assumed by each larval moult and thus regulates progression to the adult.

2. Interference with the development of barnacle larvae to the adult form has potential antifouling application. The limitation of such an approach, however, is that agents may be selective in their action. Nevertheless, there are indications that a common line of approach to the control of animal and plant fouling may be possible, through their sharing some biologically active compounds and pathways, *e.g.* steroids, sesqui-, di-and tri-terpenoids. The antifouling application of the susceptibility of barnacle larvae to JH activity would seem to reside not so much in analogues of JH but more in the ability of certain compounds, which do not structurally resemble the hormones, to exert juvenilizing effects. It has been suggested(29, 30) that compounds such as those with methylenedioxyphenyl moieties (benzdioxoles)(31, 32) do not mimic the action of JH but interfere with its degradation by enzymes. A review will be made of structures which exert juvenilizing effects upon insects: synthesis of a series of benzdioxoles and related dioxolanes is being carried out(33, 34) and these compounds are being screened for their antifouling potential.

3. Further studies have been made of the effect of other JH analogues upon larval metamorphosis and of the possible effect of solvents upon activity. These will be reported separately.

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THE INTERSERVICE HOVERCRAFT (TRIALS) UNIT

Part I

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Abstract

The military potential of hovercraft became evident after demonstrations of a man carrying hovercraft during 1959 and 1960. In February 1962 the Interservice Hovercraft Trials Unit (IHTU) was established at H.M.S. Daedalus *(at that time H.M.S.* Ariel*). Almost thirteen years later on 31 December, 1974 the Interservice Hovercraft Unit (IHU) was disbanded with the withdrawal of Army and RAF support. The role of IHU was taken over by the Naval Hovercraft Trials Unit, formed on 1 January, 1975.*

During the early days of IHTU the military evaluation of hovercraft was carried out on craft hired from their manufacturers. However in 1964 craft purchased for military trials were delivered to the Unit. Trials have been carried out in twenty two countries, in different climates and over various terrains. One of the first overseas detachments was to the Far East and led to the formation of the Army's 200 Hovercraft Squadron. The original trials craft were the SRN3 and SRN5's, but later SRN6's and BH7 were added to the craft based at Lee-on-the-Solent.

In addition to operational and trials tasks, the Unit has been responsible for the training of all military hovercraft pilots and navigators.

To service the hovercraft there are technical and stores personnel, with suitable facilities for first line servicing and the manufacturing of trials equipment. Full use is made of service and civilian facilities for second line servicing and supply of spares.

Introduction Many major developments have resulted from small beginnings, as witnessed by the quotation: "Large oaks from little acorns grow". So it was with the hovercraft industry, which had its origins in two coffee tins and a hair drier. For it was with these items in 1954 that Sir Christopher Cockerell first demonstrated the hovercraft principle of supporting a vehicle on "a cushion of air". It was with this demonstration that the dreams of many inventors, of reducing ships hull friction achieved practical fulfilment.

During demonstrations in 1959 and 1960 of the first man carrying hovercraft, the 30ft. long 3½ tons Saunders Roe SRN1, the military potential of this new vehicle was realized. Accordingly in 1961 an Interservice Hovercraft Working Party was set up, and one of their first actions was the establishment of the Interservice Hovercraft Trials Unit (IHTU), at H.M.S. *Daedalus* (at that time H.M.S. *Ariel*), Lee-on-the-Solent in February 1962. Hovercraft work had been executed at H.M.S. *Daedalus* for a few months prior to this date by personnel drawn from other units at Lee-on-the-Solent.

The IH(T)U personnel were drawn from the Royal Navy, Royal Marines, Royal Air Force and the Army, and this has sometimes led to interesting administrative situations. Working in a trials environment not only leads to requirements to work outside normal hours, often under difficult climatic conditions away from base, but also calls for personnel of a high calibre if work is to proceed efficiently. The Unit has indeed been fortunate in this respect, all ranks working well together, for the common good. On the technical side, the different service backgrounds and training has assisted not only in routine maintenance, but also in fault finding.

An additional advantage in the early period was that having completed a tour on the Unit, personnel left and were able to spread "the hovercraft gospel" throughout the services. It was a similar procedure that led to the detachment in late 1967, of a Royal Naval hovercraft to the Falkland Islands.

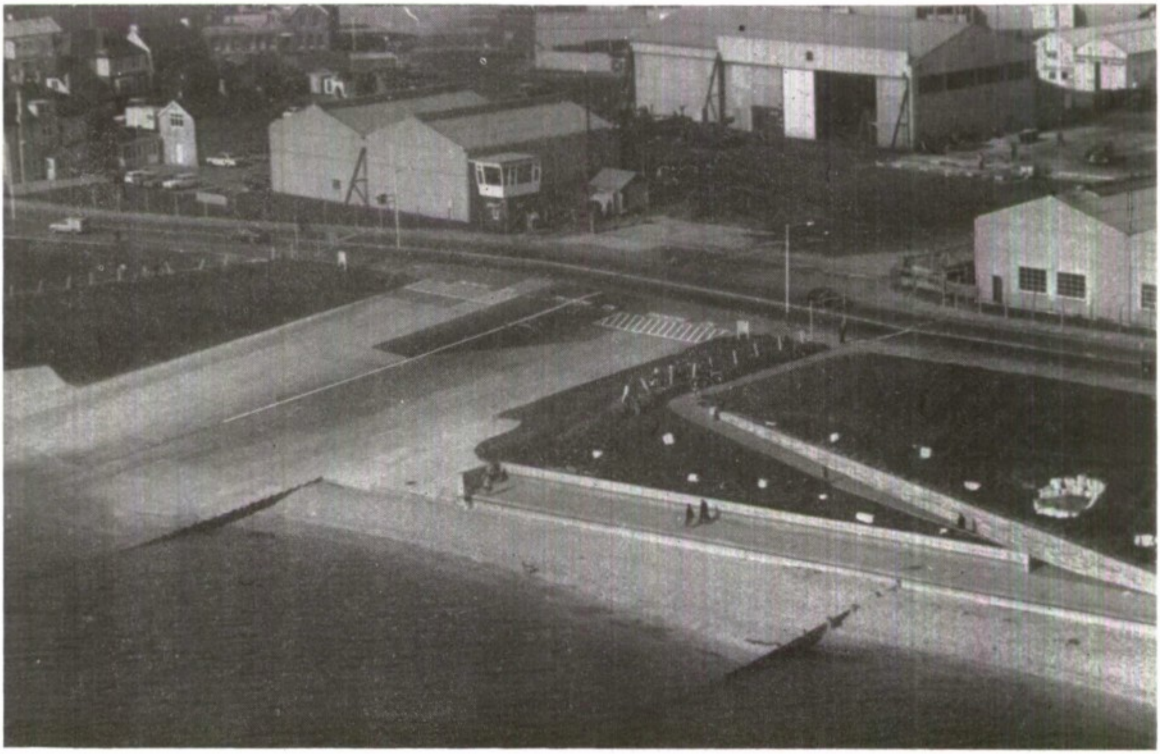

FIG. 1. The Interservice Hovercraft (Trials) Unit.

Nearly thirteen years after its formation the IH(T)U (The Interservice Hovercraft Trials Unit became the Interservice Hovercraft Unit in early 1968, when a training wing was added. For convenience use will be made of the title IHU throughout the main text) was disbanded on 31 December, 1974 and a chapter of military hovercraft history came to an end. During this time, trials and evaluations have been executed in many parts of the world, in differing climates and over various terrains. Trials have been executed in a total of twenty two countries and hovercraft evaluated in a variety of roles, including logistic support, missile firing, fire fighting and rescue, anti-submarine and Mine Countermeasures (MCM).

In this first part of a two part article, the history of the IH(T)U is outlined from its formation in February 1962 to mid 1971, (this date has been flexibly applied in the interests of lucidity) when practical work to investigate the use of hovercraft in the MCM role was commenced.

The Early Days

The IHU was set up under the command of Lt. Cdr. F. A. R. Ashmead, RN at H.M.S. *Daedalus* (then H.M.S. *Ariel*) in February 1962.

The hovercraft was in its infancy at this time and there were three main firms working on experimental hovercraft: Saunders Roe, based at Cowes on the Isle of Wight, Vickers Armstrong based at Southampton and Denny Craft based on the Clyde. (Saunders Roe and Vickers later amalgamated to form the British Hovercraft Corporation Limited (BHC) based at Cowes). The first two firms were developing fully amphibious craft, whilst the third concentrated on rigid sidewall craft, limited to overwater use.

In order to evaluate the military potential of hovercraft, craft were hired from their manufacturers and operated from Lee-on-the-Solent. These evaluations served the double purpose of enabling service personnel to gain experience of hovercraft operations and assisting manufacturers in the development of their craft.

Saunders Roe SRN1

The first major evaluation started on 28 February, 1962 when the SRN1, then fitted with an 18in. skirt, was hired from Saunders Roe by the Ministry of Supply. Initial operations included pilot training, demonstrations, seakeeping and performance trials. Instrumentation to record craft motions was fitted for the trials and the sea state was measured with the aid of the AEW Wave Pole. The craft completed several circuits of a "hoverway" constructed at the Army Camp at Browndown, Gosport and which included steps and "waves" constructed out of shingle.

The craft was returned to BHC on 15 June, 1962, having completed 52 hours with the Unit. Further MOD trials were executed in late October 1962 when the craft was based at RAF Thorney Island to investigate operation over saltings. The craft was fitted with 4ft. 6in. skirts by this time, which improved obstacle clearance, but reduced roll and pitch stiffness. The craft was successfully operated over saltings which included gullies 1½ - 2½ feet deep and between 4 and 15 feet wide.

Saunders Roe SRN2

The 64½ feet long 20 tons SRN2 completed trials at IHU in the period early December 1962 to late February 1963. The trials were divided into three main phases, consisting of general handling and performance measurement in the Solent area, ranging and seakeeping trials from HM Naval Base, Portland and sonar trials in the Solent and Isle of Wight areas. The craft was operated for nearly 47 hours, spread over fourteen days of actual operations.

Even though this craft was one of the first to be built and only had 2 feet skirts, she notched up some notable achievements. These included passage from Cowes to Portland and back, in seas measured to be 6 feet from trough to crest, and circumnavigated the Isle of Wight in calm conditions at an average speed of 58 knots.

IHU were also involved when the SRN2 was demonstrated in Montreal between 3 and 15 May, 1963, when one of the Unit's officers acted as co-pilot. The craft was based at the Royal St. Lawrence Yacht Club, the journeys to and from Montreal necessitating negotiation of the Lachine Rapids.

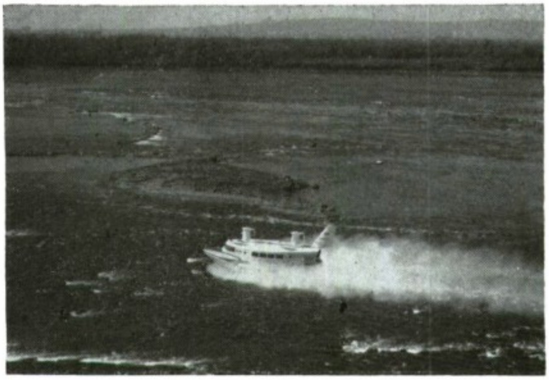

FIG. 2. SRN2 negotiating the Lachine Rapids.

Vickers Armstrong VA1

The 25 foot long 3 ton Vickers Armstrong VA1 was based at Lee-on-the-Solent from May 1962 until February 1963. Although the craft handled satisfactorily overland and in calm conditions, low obstacle clearance capability resulted in impacts even in small waves. The craft was instrumented to record craft motion and was operated over the Browndown hoverway.

Obstacle crossing trials were conducted on the airfield at H.M.S. *Daedalus*. A series of runs were made over sharp edged ditches made out of straw bales, the effect of speed of encounter, ditch depth and width being investigated.

Vickers Armstrong VA2

Lack of spacious areas suitable for overland trials of hovercraft in the United Kingdom, led to a survey of certain areas in the Near, Middle and Far East in April and May 1963. A decision was taken to conduct trials with the 30 foot long 4 ton VA2, in the Libyan desert, based at RAF El Adem.

FIG. 3. VA2 on H.M.S. *Ariel* (now *Daedalus*) airfield.

The object of the trials was to assess the problems of dust, visibility, sloping ground, negotiation of obstacles, navigation and the effect of abrasive conditions on skirt life. The craft was flown to and from El Adem in an RAF Beverley of Transport Command.

The craft successfully completed the first ever real overland trials of any hovercraft, completing 9 hours operating and covering some 150 - 200 miles. Speeds of up to 38 knots were achieved in great personal comfort compared with the bumpy ride experienced on conventional vehicles operating at considerably less speed in similar conditions. Skirt wear proved to be severe, but neither dust nor the terrain proved to be a problem. The VA2 was unique, being fitted with a two wheeled undercarriage which enabled the craft to stay on heavily cambered roads.

A demonstration was given to the Governor of Tobruk, the first time a Libyan had ridden in a hovercraft.

Denny Craft D2

The 84 foot long 25 tons Denny D2 was a rigid sidewall hovercraft designed to take 70 passengers. IHU conducted two trials with this craft, the first being the measurement of craft drag. This trial was executed in the Clyde in late February 1963, when the craft was towed by H.M.S. *Brave Borderer*.

The second trial was an investigation into performance and handling in the Lee-on-the-Solent area, conducted in December 1963 and January 1964. The craft was driven from Twickenham to Portsmouth in fairly difficult conditions. The D2 completed 20 hours operating on this trial, but unreliability of the propulsion units led to inconclusive results.

During this period IHU officers made visits to overseas hovercraft demonstrations and the areas where hovercraft might eventually operate.

It became obvious from the evaluations of hovercraft hired from their manufacturers that in order to fully evaluate the military potential of hovercraft, IHU would need craft of its own. Accordingly delivery was taken of the 77 foot long 35 ton SRN3 and three 28 foot long 7 ton SRN5's from the British Hovercraft Corporation (BHC) in July and September 1964, respectively.

The Interservice Hovercraft Unit (Far East)

Two of the SRN5's delivered in September 1964 — XT492 and XT493 — were military versions modified for operations in the tropics, to be used by the Interservice Hovercraft Unit (Far East). The Far East Unit was formed under the command of Major Harris, RCT as an independent unit in July 1964 at H.M.S. *Daedalus*, under the wing of IHU. Personnel were drawn from the Army, Royal Navy and Royal Marines.

On completion of acceptance trials, basic training and equipping, the Unit moved at the end of 1964 to Singapore for a two month period of work-up and preliminary trials. The craft were shipped to and from Singapore as deck cargo on merchant ships.

From mid March to mid December 1965, trials, operations and demonstrations were carried out in Eastern Malaysia, Singapore and Thailand. In general, trials included the logistic support of ground forces, naval patrolling, night operations and performance overland and on river rapids.

Logistic Trials

The Unit arrived at Tawau, Sabah in mid March 1965, with the aim of assessing the value of hovercraft as a general military load carrier in the type of terrain encountered in the area. Logistic support was normally carried out by road vehicles, civilian river craft, helicopters or assault boats. Road communications in the area were extremely poor, river craft were hampered by the profusion of floating debris and by shallow water at low tide, and the use of helicopters was strictly limited, in order to conserve hours for more important tasks.

Power loss due to high temperatures was experienced resulting in difficulty in maintaining directional control. However this effect was reduced by limiting the craft all up weight (AUW) to 17,000 lbs in temperatures up to 80°F and 16,000 lbs in temperatures over 80°F. (The empty weight of a military SRN5 is 11,000 lbs).

During the period at Tawau, from March to August 1965, the craft operated for 226 hours, covered nearly 6,400 nautical miles and carried 1,600 passengers and 110 tons of cargo.

Preliminary trials to ascertain the suitability of the craft in the evacuation of stretcher cases, were carried out in Singapore. It was found that stretcher cases could be carried or casualties could be carried on mattresses laid on the floor. On one subsequent occasion the craft was used to transport a seriously ill civilian woman from Kanowit to Sibu, 20 miles up the Rayong River.

Trials with RN Ships and Other Naval Operations

During trials with RN frigates and destroyers, various methods of coming alongside were tried for the transfer of personnel and stores. The best method was found to be for the hovercraft to nose up to the ship's stern, with the ship steaming ahead at around 10 knots.

Anti infiltration patrols were executed around Singapore, patrols of over 12 hours were achieved by crew changes and refuelling. The hovercraft with their higher speed proved a much more effective patrol craft than the coastal minesweepers and inshore patrol craft normally employed.

Amphibious Capabilities

The majority of overwater operations were carried out in relatively calm conditions, but while in Thailand winds up to 40 knots, seas up to 7 feet and 5 feet surf were encountered with little adverse effect on operations. Provided there was no strong tail wind, beaching the craft through surf did not present a problem.

The craft were driven up and down river rapids flowing at speeds in excess of 12 knots, with rocky outcrops and through gaps not much wider than the craft. Tight turns in the rivers were often negotiated by using the inflated skirt as a fender against the riverbanks. Part of the trials in Sarawak included a journey of 310 miles along the Rayong River. The first 110 miles were over open river, but from then onwards, commencing with the Pelagus Rapids, the route became increasingly difficult. The journey normally takes 8 to 12 days by long boat — the hovercraft completed the journey in under 8 hours driving time.

Operations in Thailand

Joint trials with the Thai Government were conducted in Thailand from 1 to 5 December, 1965. Preliminary trials were conducted on rivers and offshore, one of the interesting results being the achievement of higher operating speeds along the coastline, in the "twilight zone" above the surf — 45 knots as opposed to 30 - 40 knots.

The hovercraft was operated over rice paddy fields with crops and 30in. to 40in. bunds (the field boundaries) at an average speed of 13 knots. When the craft was operated over the fields at high speeds it caused less crop damage than at low speeds. Obstacles crossed include a steep sided 5ft. 2in. high laterite road, dykes and irrigation ditches. The craft was able to proceed at 20 knots through dense scrub vegetation 7 to 10 feet high.

Achievements of the Far East Unit

During the Far East Detachment, XT492 was operated for 320 hours and XT493 for 350 hours.

The trials with the SRN5 hovercraft proved in principle the value of such craft for military operations.

In Tawau — an effective logistic support craft.

In Sarawak — a suitable craft for crossing dangerous rapids.

Off Singapore — an efficient and effective naval patrol craft, particularly at night.

In Thailand — an excellent amphibious craft over the marshy plains, having superior performance to any conventional amphibian.

Trials

Whilst the Far East Unit was successfully completing its operations, IHU was commencing a trials programme, on its own and hired craft, aimed at evaluating hovercraft for military purposes. The trials were geared to obtaining performance data, or evaluating hovercraft in specific roles, or testing hovercraft against specifications before acceptance into military service.

In order to describe this trials programme, "potted histories" of the hovercraft that have made up the IHU fleet, are presented.

Saunders Roe SRN3

A more complete description of the operations of the 77 foot long 35 ton SRN3 may be found in Reference 1, but a resumé is presented for completeness.

In the course of her trials career, between handover on 2 June, 1964 and her last sortie on 21 February, 1974, the craft executed 570 sorties, completed 1,393 operating hours, and covered an estimated 40,000 nautical miles in German, Danish and UK waters. Despite what may seem to be rather limited operating hours within the span of nearly 10 years, she amply satisfied the objectives for which she was built. She laid the foundation against which subsequent craft have been developed for more specific roles. SRN3 was an experimental machine, and as such was not without her problems.

FIG. 4. SRN 3 operating in the Solent.

FIG. 5. SRN5 XT 493 operating in Borneo.

After initial pilot training, the craft undertook a series of role evaluation trials for the three services. These included an assessment of the ability of the SRN3 to perform the duties of an RAF marine craft; anti submarine warfare (ASW) trials for the Royal Navy and operations in the logistic role for the Army. Between June and August 1965 the craft was again exercised in the ASW role, this time based at Londonderry. These trials were concluded in late 1968 when the craft was exercised in the Fishery Protection role off the Thames Estuary.

In mid 1966 a series of trials was commenced to assist in the development of the Sealane navigation equipment currently fitted in IHU's BH7, a craft built specifically to continue with Naval Evaluation Trials. These navigation equipment trials mainly consisted of evaluating the Blue Orchid and Decca 71 helicopter dopplers in the hovercraft environment.

Performance trials were carried out during the life of SRN3, initially under a joint programme operated by RAE Bedford and AEW Haslar. During these trials the heave stiffness and hovering efficiency were evaluated and craft sea keeping quantified.

In 1969 - 70 a model correlation trial was conducted, the full scale tests being undertaken by IHU and model tests and subsequent correlation analysis being undertaken by BHC, the craft's manufacturers.

The SRN3 was used in many demonstrations, to military and civilian personnel from many countries, including Hovershow '66 and again at Browndown in June 1972 for delegates from CENTO.

British Hovercraft Corporation SRN5's and SRN6's

The SRN3 and later the BHC BH7 featured in the prestige trips abroad, but as with commercial hovercraft ferries, the smaller SRN5 and SRN6 craft have proved to be the "work horses" of the Unit.

The IHU SRN5's and SRN6's have been used for trials and for initial hovercraft pilot training. An additional task, when 200 Hovercraft Squadron was in existence was the testing of trial installations on an SRN6 MK2 on loan from the Army for this purpose.

SRN5 XT657 — Trials Craft

XT657 first put to sea on 30 October, 1964 and was delivered to IHU on 5 March, 1965, fitted with a jet skirt. One of the first tasks for the craft was in the production of a film illustrating obstacle crossing and rough terrain performance. Shortly after the craft was returned to BHC for the fitting of a new instrument panel, Decca 202 Radar, Marconi Doppler and military standard radios.

This hovercraft had a double association with Royalty, the first at the Amsterdam Trade Fair in June 1965, when Queen Juliana and Prince Bernhardt of the Netherlands and Princess Margaret were among the people who went for a ride on the craft. The second was in July 1965 when XT657 was used to transport HM Queen Elizabeth from Yarmouth, on the Isle of Wight, to RAF Thorney Island, near Chichester.

Overland Trials — Aden 1965

Trials including the measurement of hoverheight. static thrust, acceleration, stopping distance and turning circles were executed. The sand ingestion problem, when operating over desert, was severe and the two gas turbine engines used on this trial had an effective life of only a few hours. Although this problem significantly curtailed the trials, valuable data was collected on operating in a desert environment. Maximum measured overland speed was 52 knots.

Crash Rescue Trials

The craft was fitted with fire fighting equipment, including a 200 gallon water tank in the rear of the cabin, and external platforms to carry survivors and equipment. Trials carried out in March 1966 successfully demonstrated the potential of the SRN5 as a fire fighting and rescue vehicle, the demonstration at Hovershow '66, when approximately 50 survivors were "rescued" from a simulated vessel fire at sea, being extremely convincing.

The craft overturned in the Solent in calm conditions on 8 July, 1966 and during the subsequent refurbish at BHC, a comprehensive instrumentation package to investigate craft characteristics was fitted.

Performance Trials

These were a joint exercise by RAE Bedford and AEW Haslar and were to evaluate the SRN5 performance when fitted with various designs of hovercraft skirts.

During the RAE trials, static tests to measure propeller thrust, control forces, pitch and roll stability, lift system efficiency, hoverheight and daylight clearance were executed. Sea trials included performance measurements to enable the variation of drag components with forward speed to be obtained, and control effect investigations. These tests were only executed with a jet skirt fitted.

Seakeeping trials were conducted by AEW, at three different craft weights, runs at various headings to the wind and sea being executed. Craft motion data was recorded and the sea state measured. These tests were executed with a jet and 30% fingered skirt fitted.

The craft was fitted with the latest skirt development, the 50% fingered skirt, in December 1968. After a general assessment the craft was employed on general trials, including the collection of turning data to assist in the development of BH7, and a model/full scale correlation trial.

FIG. 6. SRN6 Mk 2 XV 614 operating in surf on the north Devon coast.

Conversion

Various Army exercises had indicated that a hovercraft capable of carrying small vehicles would be a useful addition, and accordingly the SRN5's XT657 and XT493 (see next section) were converted during October 1971 to June 1972 to the SRN6 MK5 variant.

SRN5 XT493 — Trials Craft

On return from the Far East, XT493 was refurbished and employed on general logistic and training tasks.

Surf Trials

In November 1967 the craft was prepared for its first major trial in the United Kingdom, which was to investigate hovercraft operation in surf at Saunton Sands on the North Devon coast. The craft was transported from Portsmouth to Appledore by the RFA *Robert Dundas* between 14 and 16 February, 1968, and moved under its own power to the operating base at RAF Chivenor.

XT493 was instrumented to measure craft motion and accelerations, and the aim of the trial was to find the best ways of approaching and leaving a beach in surf. The best method of approach was to position the craft between surf crests and adjust speed until the craft and surf approached the beach at the same speed. Leaving the beach proved to be best on a track at 45° to the surf.

FIG. 7. SRN 6 Mk 2 XV 617 operating over the cross country hoverway, Longmoor, Hants.

Trials were prematurely curtailed on this craft when it suffered damage when proceeding to the trials area. The craft became airborne when it took off from the crest of a large wave and "pancaked" into the trough. The upper surface of the plenum chamber and supporting structure was damaged, but the craft was able to return to base, including transit through 8 to 10 foot surf and climbing the 10 foot sea wall around the RAF station.

Other Trials

After repairs, the craft was employed on a trial to measure the mooring forces on hovercraft when in a tidal stream. This was executed in the mouth of Langstone Harbour, where the maximum tide flow was measured at nearly 3½ knots.

The next major trial was executed between mid September and mid November 1969, with the Institute of Aviation Medicine, and was known as the Physiological and Psycological Trial'. This complex sounding trial (usually known as the Phys and Psyc trial or something similar!) was aimed at quantifying the deterioration of radar operators execution of their task, in increasing sea states.

In the last half of 1970 the craft was employed on a trial to assess the effectiveness of Closed Circuit Television as a driving aid. It was demonstrated, that given an optimum presentation, it was possible to drive a hovercraft from a flat screen presentation.

XT493 completed its service with IHU carrying out preliminary investigations in the MCM role, when it was used to tow an RPL (Ramp Powered Lighter) and drogues being developed as calibrated drag loads.

Conversion

Between October 1971 and June 1972 XT493 underwent a similar conversion to XT657.

SRN5 XT492 — Training Craft

On return from the Far East XT492 was operated by 200 Squadron from April 1967 to February 1970. The craft was loaned to the Army, initially to work up the recently formed hovercraft squadron, whilst delivery of their SRN6 MK2's was awaited, and later in lieu of the SRN6 MK2 XT614 which was based at IHU for trials.

Between February and November 1970 the craft was refurbished at RNAY Fleetlands, dual controls being fitted during this period. The dual controls enabled the craft to be driven from the pilot's or commander's position, immediately behind the pilot. This enabled the pilot to sit and drive the craft, as soon as he commenced training, from the normal position for standard SRN5's and SRN6's.

Since November 1970, XT492 has been employed on pilot and navigator training, and local logistic tasks. She has also been used to give familiarization trips to visitors to IHU and demonstrations to various RN ships during their "families days". The craft has also been used to give "rides around the airfield" during H.M.S. *Daedalus* Air Days.

When IHU took delivery of an SRN6 with dual controls, XT 492 became superfluous to requirements and was placed in suspension pending disposal. The last service sortie was executed on 23 October, 1975, at which time the craft had completed just over 3,020 operating hours.

SRN5 XW246 — Training Craft

XW246, then SRN5 006, first flight was on 17 November, 1964. After demonstrations in Japan and New Zealand, and use by BHC as a charter, training and demonstration craft, XW246 was delivered to IHU on 5 November, 1968.

The craft was purchased to cope with the additional pilot and navigator training commitment when 200 Hovercraft Squadron RCT was in operation. XW246 was fitted with dual controls, and to assist with navigator training, a nine inch slave radar display was fitted at the rear of the cabin, at a later date.

As well as the training task, the craft was also used to survey hovercraft landing sites in the local area, to be used in the event of a "SOLFIRE" — a major collision or fire at sea.

The craft also played an important part in the evaluation of the Optical Navigation aid, which enabled the hovercraft navigator to align a transparent map with the radar display and consequently identify navigation marks. Trials executed included transfer of fuel and personnel from Royal Navy ships and a docking trial with H.M.S. *Fearless*.

XW246 was used extensively for demonstrations, including a visit to Koksyde Air Station, Belgium in 1971. However the craft will probably be remembered best by the many people who had "rides around the airfield" during H.M.S. *Daedalus* Air Days 1971 to 1974. In fact it was on the occasion of the 1974 Air Day on 22 July that XW246 was last used by IHU.

In September 1974, the craft was sold to Hoverwork who have refurbished it at their works at St. Helen's, Bembridge, Isle of Wight. The craft left IHU on 30 September, 1974, having completed 2,250 hours operating in service colours and being used in the training of over fifty hovercraft pilots.

British Hovercraft Corporation SRN6 MK2's

The Far East detachment played an important part in the decision taken by the Army to form a hovercraft trials squadron, to evaluate the potential of hovercraft in the execution of various military tasks.

It was decided to purchase four 48ft. long, 9 ton SRN6 MK2's from the British Hovercraft Corporation. IHU conducted the acceptance trials on behalf of the Ministry of Technology (Mintech) and initial trials conducted in August and September 1967 showed that craft performance was below specification. Various modifications were incorporated, including skirt component changes, reduction in the rudder bleed area, extended engine exhausts, repositioning of the engine air intakes, engine uprating, repositioning of fuel tanks, life raft and batteries to achieve a forward movement of the centre of gravity, and the craft re-tested. Although performance was improved it was still below specification in moderate sea and turning performance, but it was decided to accept the craft into service. Three of the craft were delivered to 200 Squadron, the remaining craft — XV614 — being retained at IHU for trials purposes.

The first major trial was executed in February and March 1968 when XV 614 executed surf trials, with SRN5 XT493, in North Devon. Instrumentation and results were as described for the SRN5.

The second was in the last two weeks of June and the first week of July 1968 when the craft was used in Naval Trials at Portland. These trials were to evaluate the capability of the SRN6 MK2 to perform as an anti FPB training craft and as a Helicopter Safety Boat, and to perform various exercises with ships working up with Flag Officer Sea Training. The craft performed satisfactorily in these roles, but the limited moderate sea and turning performance reduced the capability in seas over 3 foot significant height.

Hoverway Trials

Between mid May and the end of July 1969, IHU, in conjunction with the Royal School of Military Engineering executed a Hoverway Trial at Longmoor, Hants. XV614 was the hovercraft employed and the trials objective was to determine the criteria for a hoverway that could be produced with the minimum of engineering effort and would enable a hovercraft to proceed over rough terrain. The craft was instrumented to record performance, craft motion and control use. Because operations would be in dust laden conditions, engine air was drawn from the plenum chamber. The trial was divided into three phases, operation on a straight course, operation on a test curve and the final phase over an overland hoverway incorporating the lessons learnt during the first two phases.

Phase 1

Vee sections are easier to construct and were tried first, but did not constrain the craft which often ran off the 1,000 foot long track. It was found necessary to produce a "slot" section track, approximately 20 foot wide and with 2½ foot to 3 foot high walls.

Phase 2

The cross section of the test curve was similar to the straight track, but with a super elevation for a speed of 25 mph. The craft was satisfactorily constrained and proceeded around the turn without use of hovercraft controls provided that engine and propeller conditions were maintained.

Phase 3

A hoverway some 0·83 miles long with curves, ascents and descents was constructed and the craft driven many times over this course. Once the pilot was confident that the craft was satisfactorily constrained by the hoverway banks, the target of a mean block speed of 25 knots was achieved.

About 30 hours operating was achieved during the trial and skirt wear was found to be less than would occur in normal cross country operation. Considerable wear to both the propeller and propeller erosion strips occurred, most of which must have happened when towing the craft to and from the test site and during turns, when the craft was enveloped in a dust cloud. This cloud was left behind, however, when operating at speed on the hoverway.

British Hovercraft Corporation BH7

It was during the development and acceptance of the IHU 77 foot long, 47 ton BH7 that the most comprehensive of hovercraft trials programmes was undertaken. Originally it was planned that the Contractors trials would be completed before the MinTech acceptance trials were commenced. However in the event only limited Contractors trials were completed before the craft was transferred to IHU on 28 September, 1970, from which date the two trials programmes proceeded in parallel.

The craft was fitted with a comprehensive automatic observer panel (AOP) with instruments monitoring engine and gearbox conditions, craft motion, speeds, etc, and Seafix pattern indicators. This panel was photographed at regular intervals by a 70 mm camera, for subsequent analysis. The Seafix data was also recorded as an alpha numeric printout and on punched tape for subsequent computer analysis. A Waverider receiver was carried to record sea conditions when trials were being executed adjacent to a Waverider Buoy.

Before transfer to IHU, static tests to measure roll and pitch stiffnesses, rise heights and skirt compartment pressures were conducted at BHC. Some performance trials to measure speed and acceleration in calm and moderate sea conditions were also executed. In calm conditions the craft achieved a sustained speed of over 60 knots. Anchoring trials and life raft deployment trials were executed near the Prince Consort Navigation Buoy in the Western Solent.

After transfer, Contractors and acceptance trials were conducted in parallel, the craft usually carrying a joint BHC and IHU team. Further speed and acceleration trials were executed in calm and moderate conditions, the craft achieving 40 - 45 knots, depending on the heading relative to sea, in a sea measured at just over 3 feet significant. The crafts turning performance in calm and moderate conditions was measured and behaviour during emergency stops was examined.

The safety of the craft when wallowing and drifting in gale force winds and significant seas of over 8 feet was investigated, craft motion being recorded. Roll motion was of the order ±4° and pitch ±3° and it is understood that the crew members did not always refer to the trial by its formal title.

After acceptance of the craft by MinTech, the craft embarked on a series of Naval Evaluation Trials, which will be described in Part 2.

Evaluations

As well as conducting trials on their own craft, IHU have conducted evaluations of light hovercraft (those less than 20 feet long and with AUW's below 3 tons). These evaluations were conducted for two reasons, to assess the craft

FIG. 8. BH 7.

FIG. 9. SKIMA 4. The author (left) enjoying a trial.

for possible military operations and to give IHU knowledge and experience to talk authoritatively on small craft to other interested parties. A typical example of a possible military operation would be to transport a four man patrol (each man with equipment weighing 250 - 270 lbs) at 30 knots over a range of around 65 miles.

Craft that have been evaluated are the *Pindair* (Gosport, Hants) craft, — the 10 foot long 200 lbs *Skima* 2 and the 13 foot long 650 lbs *Skima* 4; the 20 foot long 1·4 ton *Air Vehicles* (Cowes, Isle of Wight) AV2 and the *Sealand* (Millom, Cheshire) craft — the 10 foot long 220 lbs *Skitabug* and the 20 foot long 2·5 tons SH2. These evaluations took the same form in that the craft were hired from their manufacturers, the period being one week for the smaller craft and three weeks for the AV2 and SH2.

On receipt of the craft, an engineering assessment would be carried out, covering structures and system. Attention would be paid to design, ease of operation and effectiveness of controls.

Static Tests

Static tests would include roll and pitch stiffness measurements, clearance height and propeller thrust. During these tests the skirt would be checked for uniform inflation. In addition, internal and external noise measurements would be taken, as envisaged roles require a relatively quiet craft.

Overland Tests

These would commence with a handling assessment in confined places, followed by a gradient climbing assessment and obstacle clearance tests on Lee-on-Solent airfield.

Overwater Tests

These tests would occupy the largest part of any evaluation and areas investigated would be craft acceleration, maximum speed in various sea conditions, turning performance and stopping distances.

Some Examples of Test Results

To illustrate the evaluation aspects of confirming manufacturers specifications and assessing military potential, some examples of IHU trial results are presented.

During the evaluation of the *Pindair Skima* 2, measured distance runs were performed adjacent to the Lee-on-Solent shore, over a distance of 790m. In a 6 inch sea a speed of 19 knots was achieved, suggesting that in calm conditions the manufacturer's specification figure of 26 knots would have been achieved.

Part of the *Pindair Skima* 4 evaluation was an assessment of endurance — against the possible 65 miles requirement. This was done on a circumnavigation of the Solent area, when a block speed of 16 knots was achieved for a 28 nautical mile journey, using four gallons of fuel. Weather conditions varied from glassy calm to a 6 inch sea in certain areas. Fuel consumption for the journey, was 9·7 litres/hour, in close agreement with the manufacturer's quoted figure of 10 litres/hour.

In an exercise off the North Devon Coast, the Air Vehicles AV2 was used to transport Special Air Service personnel and their canoes from the beach to an area outside the surf line. Using techniques established during the SRN5 and SRN6 surf trials the AV2 found no problems in operating in the type of surf encountered.

Benefits

As well as providing data against possible government agency or military requirements, the IHU provides a completely unbiased and independent report, which the manufacturer is free to use for publicity purposes.

The IHU trials are aimed at operating the craft continuously, perhaps for the first time, and the manufacturer may benefit through the possible highlighting of weak design areas.

Training

Although the training procedures for hovercraft pilots and navigators has been developing since the Unit was formed, the basic concepts have remained the same.

Hovercraft Pilot Training

Prior to November 1970, when the first dual control SRN5 was delivered to IHU, training was done on a standard SRN5.

Hovercraft handling training is divided into Basic, *ie*, pre-solo and Advanced stages. During the basic stage the pilot is familiarized by lectures and demonstrations, where appropriate, with emergency drills, the effects of all controls and gentle manoeuvres. The trainee pilot will then progress onto more rigorous manoeuvres, emergency stops and slipway approaches, and eventually to manoeuvring the craft in the confines of the hardstanding at Lee-on-Solent.

All these exercises will have been completed in favourable weather conditions and will have taken around ten operating hours. The pilot then executes his first solo flight and proceeds *via* a five hours Solo Consolidation Stage to the Advanced Stage.

The Advanced Stage occupies around a further thirty five hours, and includes operation in strong winds and high seas, navigation under radar control, operation in poor visibility and extended Navigation Exercises away from base, around the Isle of Wight or to Portland. The pilot will then be acquainted with the techniques of approaching buoys, coming alongside vessels and operating over various terrains. Towards the end of this period night operations will be executed and a "Rule of the Road" examination taken, the successful pilot being given a Hovercraft Type Certification of Qualification.

The times quoted for the various stages are for guidance, flexibility catering for individual pilots' aptitude or previous experience.

Having completed the training course on the SRN5, the pilot would then usually progress to the SRN6, and complete a ten or twelve hour conversion course. Depending on the position held within IHU, the pilot would then act as an SRN6 pilot throughout his tour, or be trained to drive either SRN3 or BH7. The procedure for these conversions would be similar, craft and control familiarization during the basic stage, followed by solo operation in moderate conditions, operation in rough conditions and at night completing the conversion training course.

Hovercraft Navigator Training

Hovercraft navigator training commences with a period on a simulator, either at H.M.S. *Dryad*, or more recently at RNAS *Culdrose*. During this period the trainee navigator is acquainted with the use of radar and its use in techniques such as collision avoidance and parallel indexing.

Training continues at IHU with lectures and practical hovercraft navigating. The lectures commence with Radar Theory, and cover such topics as Principles of EM Propagation, radar interference, transmitter and receiver circuits and controls, stabilized and unstabilized displays and relative motion. The lectures are backed with practical demonstrations on the Decca 202 marine radars fitted to the IHU training craft. Recently a dual radar display has been fitted, to facilitate navigator training.

In parallel with the radar training, the navigators learn the "Rules of the Road", which include steering and sailing rules, seamanship aspects, charts and their symbols and use, and tides and the use of Tide Tables. At the end of this phase, an examination on this aspect is taken.

Inter-Linking Summary

In Part 1 of this article, the history of IHU has been described, more or less covering the period from formation in February 1962 to mid 1971. The early days, the Far East Unit, Trials, Evaluations and Training have been outlined.

The second part will cover the period from mid 1971 until the closure on 31 December, 1974, topics including IHU Facilities, Organization and Tasking, Recent Trials, Naval Exercises and the MCM Hovercraft Project will be described. The future and the first year of the Naval Hovercraft Trials Unit will also be covered.

Reference

(1) "The Operation of the SRN3 Hovercraft at the Interservice Hovercraft (Trials) Unit" *J.R.N.S.S.*, No. 6, Vol. 29, 1974.

THE PLACING OF CONFIDENCE LIMITS ON AN ANTISUBMARINE SONAR DETECTION CUMULATIVE PROBABILITY—RANGE CURVE

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Abstract

This article offers a new approach to the problem of placing confidence limits on a cumulative probability curve. A specific practical problem is studied, but the work should have wider application. The required solution is obtained analytically for certain practical cases and no difficult computational problems arise. However, there are other practical cases which are not yet adequately covered, although suggestions for their treatment are made. For the specific problem, a further method is proposed, using theory based on the mass of prior information available to interpret the particular sample being studied. In the course of developing the main approach, some fundamental errors in earlier published tables, giving confidence limits for a proportion, have been identified.

Introduction If the probabilities of detection by sonar of an approaching submarine are established in a number of range brackets, *subject to detection not having been made before,* then the successive products of probabilities of *no* detection give the probabilities of *no* detection as closure takes place up to and including the appropriate range bracket. In order to place confidence limits around such a "cumulative" detection probability-range curve, it is necessary to know the distribution of these probability products. This, in turn, depends on a theory which gives the distribution of the independent probabilities based on the data sample.

A generalised statement of the problem is as follows. Given $z_1, z_2, \dots, z_N$, independently distributed as $f_r(z_r)dz_r$, $0 \leqslant z_r \leqslant 1$, $r = 1, 2, \dots, N$, what is the distribution of $z_1 z_2 \dots z_N$? This is tackled by Bache in a draft paper⁽¹⁾ intended to replace an earlier memorandum⁽²⁾. His work shows the complicated nature of solutions and the need for considerable computation.

It is "possible" to tackle the problem analytically for uniform distributions of z_r. However, the distributions have to be expressed over a number of ranges; if $0 < a_r \leqslant z_r \leqslant b_r < 1$, the limits of these ranges are $c_1, c_2, \dots, c_N$, where $c_r = a_r$ *or* b_r. It can be shown that for $n = 8$, 735 distributions have to be calculated in all, the final solution containing 255 distribution ranges! Only when $a_r = 0$, $b_r = 1$ is there a simple result, namely that $z = z_1 z_2 \dots z_N$ is distributed as

$$\frac{1}{\underline{|N-1}} \left(-\log_e z \right)^{N-1} dz \quad .$$

The detail of the analysis carried out is not relevant here. The only value in examining the problem in this way was to make it clear that some *specific* continuous distribution approach was essential, if a manageable analytic solution was to be achieved.

The treatment given below therefore tackles the submarine detection problem directly. It provides a comparatively straightforward solution. It is based on some earlier work⁽³⁾ which commented on a USN study of a comparable problem ⁽⁴,⁵⁾, arising in a study of The Survivability of Aircraft Carriers. This earlier work was written primarily as a communication to Dr. J. H. Engel, then head of the USN Operations Evaluation Group, and it is not easy to read out of context. The theoretical treatment is, therefore, repeated here.

The Probability of Survival

Theoretical Argument

Consider a process in which the probability of failure (accident, detection, damage, death, for example) is h(t) per unit time at time t, *provided that* failure has not occurred up till time t. The probability of survival over time 0 to t, $P_s(t)$, is then given by

$$P_s(t+dt)=P_s(t)\left[1-h(t)dt\right],$$

$$\textit{i.e.}\quad P_s(t)=\exp\left\{-\int_o^t h(t)dt\right\}\quad\ldots(1)$$

If a sample r of such a process is taken, then the probability that the *earliest* failure occurs between t and t+dt is given by

$$\left[P_s(t)\right]^r\left[1-\left(1-h(t)dt\right)^r\right],$$

$$\textit{i.e.}\quad r\left[P_s(t)\right]^r h(t)dt,\ 0\leqslant t\leqslant\infty\ .\ \ldots(2)$$

which represents the distribution of t, the time of *first* failure. This when integrated over t=o to t=∞ will not be unity unless failure always, eventually, occurs, *i.e.* unless $P_s(\infty)=0$,

$$\textit{i.e.}\quad \int_o^\infty h((t)dt=\infty\ .\quad\ldots(3)$$

Note that, in the originally stated problem of a submarine closing a detecting unit, this *should* be true. Unfortunately, for reasons which are sometimes obscure, a submarine may close to zero range without being detected! A method of dealing with this is proposed in a later section.

From (1), we have

$$dP_s(t)=-h(t)P_s(t)dt,$$

so that (2) may be written

$$r\left[P_s(t)\right]^{r-1}dP_s(t).$$

$$1\geqslant P_s(t)\geqslant\exp\left\{-\int_o^\infty h(t)dt\right\}.$$

Assuming (3), for the moment, and writing $P_s(t)=z$, the probability of survival at the time of first failure, determined from r trials, is distributed as

$$rz^{r-1}dz,\ 0\leqslant z\leqslant 1\ .\quad\ldots(4)$$

When r=1, we obtain a flat distribution, since all we know is that detection has occurred and, in using this to establish a particular range, no data is left on which inferences about the probability z can be based.

The Cumulative Curve based on Simple Experimental Data

For the practical detection problem, the simplest form in which data may be provided is as follows.

On N occasions, submarines close from beyond maximum detection range and the eventual ranges at which detections take place are in descending order $R_1, R_2, \ldots, R_N$ (we take range as equivalent to time and range zero as equivalent to time ∞, in order to apply the theoretical argument above). The probability of survival at R_1 is then estimated by the distribution

$$Nz_1^{N-1}dz_1,\ 0\leqslant z_1\leqslant 1\ .$$

Of those that pass R_1, the probability of survival at R_2 is estimated by the distribution

$$(N-1)z_2^{N-2}dz_{12},\ 0\leqslant z_2\leqslant 1\ ,$$

and so on until we have a sample of one only giving us the distibution

$$dz_N,\ 0\leqslant z_N\leqslant 1\ .$$

for estimating the probability of survival at R_N.

We require to estimate confidence limits on the cumulative curve (range-probability) of detection. We therefore need to know the probability distributions of $w_1, w_2, \ldots, w_N$, where

$$w_1=z_1,\ w_2=z_1z_2,\ w_3=z_1z_2z_3,\ \ldots,\ w_N=z_1z_2\ldots z_N.$$

The joint probability distribution of $z_1, z_2 \ldots z_N$ is, since the observations of successive failures are independent.

$$N(N-1)\ldots 2.\,1.\ z_1^{N-1}z_2^{N-2}\ldots z_{N\text{-}1}\,dz_1\,dz_2\ldots dz_N.$$

Transposing variables we obtain the distribution

$$\lfloor\underline{N}\,w_1w_2\ldots w_{N\text{-}1}\frac{dw_1\,dw_2\ldots dw_N}{w_1w_2\ldots w_{N\text{-}1}}$$

$$\textit{i.e.}\quad \lfloor\underline{N}\,dw_1\,dw_2\ldots dw_N\,,$$

$$0\leqslant w_N\leqslant w_{N\text{-}1}\leqslant\ldots\leqslant w_1\leqslant 1\ .$$

since the Jacobian is

$$(w_1\, w_2 \ldots w_{N-1})^{-1} \;.$$

By repeated integration, we obtain

$$N(1-w_N)^{N-1}\, dw_N, \;\; 0 \leqslant w_N \leqslant 1 \;.$$

In general, the joint probability distribution of w_r is

$$N(N-1)\ldots(N-r+1)\, z_1^{\,N-1}\, z_2^{\,N-2} \ldots z_r^{\,N-r}\, dz_1 \ldots dz_r ,$$

i.e. $N(N-1)\ldots(N-r+1)\, w_r^{\,N-r}\, dw_1\, dw_2 \ldots \ldots dw_r, \; 0 \leqslant w_r \leqslant w_{r-1} \leqslant \ldots \leqslant w_1 \leqslant 1 \;.$

Integrating, we get the distribution*

$$\frac{N(N-1)\ldots(N-r+1)}{\underline{\left| r-1 \right.}} \times (1-w_r)^{\,r-1}\, w_r^{\,N-r}\, dw_r \;, \; 0 \leqslant w_r \leqslant 1 \;. \quad \ldots (5)$$

(5) gives all the information needed to plot the cumulative curve and its confidence limits.

If the distributions were Normal there would be no need to do more than estimate variance and show ranges $\pm\sigma$, $\pm 2\sigma$, . . . about the mean to give 67%, 95%, . . confidence regions. One of the criticisms that was made of the USN work previously referred to⁽⁴⁾ was that such an assumption had been made, although, as here, the distributions were markedly skew. It should be noted that, with a unimodal symmetrical distribution, confidence limits symmetrical about the *mean* also give regions of *minimum* extent for the chosen confidence percentage. Equivalent minimum concepts are needed in the case of skew distributions; the confidence region will *not* be symmetrical about the mean. There is no elementary solution. We have to put the integral of (5) over the range a to b equal to the appropriate confidence level (say 0·9) and minimise (b-a). It may be shown that, for a distribution $f(w_r)dw_r$, the minimisation procedure requires $f(b)=f(a)$. The calculation of a and b can therefore be most easily achieved, and to the accuracy required, by drawing the distribution curve and its corresponding cumulative curve and using graphical/arithmetic methods. In effect, we would calculate, for a number of ranges (a,b) where $f(a)=f(b)$, the corresponding percentages and interpolate for the required percentage. Those who require to avoid arithmetic would need to program a rather more complicated, but equivalent, algebraic process. Tables of a and b for various r, N could thereby be obtained.

The mean value of w_r is $\frac{N-r+1}{N+1}$; the modal value is $\frac{N-r}{N-1}$. Again we observe the effect of the loss of "degrees of freedom" through using data to establish R_1, R_2, . . . , R_N. It could be useful to plot modal values rather than means to establish approximately the cumulative curve at R_1, R_2, . . . , R_N.

It should be noted that, to obtain the conventional form of range-probability curves, $(1-w_r)$ are the probabilities wanted. The confidence regions can be drawn as lines parallel to the cumulative probability axis (these lines will include modal and mean values) at *each* range point where a detection has been observed.

The Probability of Never Being Detected

Operational data have a natural tendency not to fit simple models. Submarine detection data do not depart from this "law". The first complication to consider is that not all submarines will be detected, even at (effectively) zero range. Let the number of these be c out of N+c. We could treat the N that *are* detected in the manner shown above and then multiply $(1-w_r)$ by $\frac{N}{N+c}$ to give a cumulative probability of detection that approaches this value rather than unity. This would be crude since $\frac{N}{N+c}$ is an estimate only, and a biased estimate at that. We require, ideally, to obtain a probability distribution based on a Bayesian argument (see Appendix A). It can be shown that, conditional on the data, which is assumed to be a random sample, the probability distribution of the probability of non-detectability is

$$\frac{\underline{\left| N+c+1 \right.}}{\underline{\left| N \right.}\;\underline{\left| c \right.}}\, p^{\,c}\, (1-p)^{N}\, dp \;, \; 0 \leqslant p \leqslant 1 \ldots (6)$$

When N and c are zero, the probability distribution is just dp, (*i.e.* no information), and the mean value of p is $\frac{c+1}{N+c+2}$. This distribution provides confidence limits on the cumulative probability at range zero: when c=0, p will not be deterministically zero unless N is infinite, although it will be zero, in effect, for most practical data samples for which c=0.

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* (5) may be obtained more directly by an argument comparable to that used later to give (6) (see Appendix A), but the method used here is needed in more complicated cases; see, for example, the section titled *Missing Data.*

The distribution of $(1-w_r)\,(1-p)$, obtainable through a convolution of (5) and (6), provides the confidence limits at the points $R_1, R_2, \ldots, R_N$.
If $(1-w_r)\,(1-p)=u_r$, we find that the distribution of u_r is

$$\frac{\underline{|N+c+1}}{\underline{|N-r}\ \underline{|r-1}\ \underline{|c}} \times$$

$$u_r^{\,r-1} \left| \int_{u_r}^{1} (1-v)^{c}\,(v-u)\,dv^{\,N-r} \right| du_r, \qquad 0 \leqslant u_r \leqslant 1 \quad \ldots (7)$$

When $c=0$, the distribution of u_r becomes

$$\frac{\underline{|N+1}}{\underline{|N-r+1}\ \underline{|r-1}} \times$$

$$u_r^{\,r-1}\,(1-u_r)^{\,N-r+1}\,du_r, \quad 0 \leqslant u_r \leqslant 1, \ldots (8)$$

which is not the same as (5), since it is *not* now assumed that the probability of detectability is ultimately unity.

Missing Data

In typical data that are accumulated, while all submarines will start outside maximum detection range, they will not necessarily close to zero range, *i.e.* they may not be detected but they may have been detected had they approached closer. In such cases, there is negative information about detection probabilities which must be used, *viz* that they have *not* been detected in some range up to R_g.

This has been dealt with by Frost⁽⁶⁾ in a straightforward interval detection probability analysis, but is rather easier to deal with by the distribution of probability of survival analysis developed here. Changes are needed in the numbers in the samples for estimating $z_1, z_2, \ldots, z_N$. Instead of having N, $(N-1)$, $\ldots$, 1 in the samples which fail at $R_1, R_2, \ldots, R_N$ or earlier, we now have $N+m_1$, $N+m_2-1, \ldots, m_N$, where $m_1 \geqslant m_2 \geqslant \ldots \geqslant m_N$.

For convenience, we will call these $M_1, M_2, \ldots, M_N$.

The distribution of w_r is found to be

$$M_1\,M_2 \ldots M_r \sum_{i=1}^{r} \frac{w_r^{\,M_i-1}}{\prod\limits_{\substack{j=1\\ j\neq i}}^{r} M_j - M_i}\,dw_r\,,$$

$$0 \leqslant w_r \leqslant 1 \quad \ldots (9)$$

It will be noted that none of the M_r are equal, so that no difficulties arise in obtaining this distribution, which, in the more general case of some equal M_r, would involve polynomials in w_r and $(-\log_e w_r)$. In a time of survival experiment in which new elements are introduced, or old elements which are "dead" are allowed to continue in the process, provided that this is acceptable without making the process "unreal", the additional complexity would have to be accepted. This would mean a convolution of distributions (9) and (6) which, although algebraically messy, would be quite straightforward.

Computational Problems

For small samples of data, the computational effort required is not great. For large samples (which are always difficult to acquire as part of a homogeneous population), the confidence limits are of little practical importance. In the middle zone, it might be necessary to program the computation.

There are two tasks, the first being the calculation of the various coefficients in the distribution formulae*, the second being to find the minimum range over which the distribution function integrates to a chosen percentage confidence limit. There seem to be no particular difficulties in either calculation process. The second calculation would be guided by the order of accuracy required and, as indicated earlier, this could easily be done graphically from cumulative probability distributions of w_r, or, if greater accuracy is required, by a comparable computer program.

An Alternative Approach

Several years ago, Mr. T. L. Mack, now of SACLANTCEN, but then a member of the Directorate of Naval Operational Research, examined a considerable amount of data from UK and NATO trials and exercises, under different conditions of propagation, operational realism and types of detection equipment⁽⁷⁾. He concluded that cumulative probability range curves were all of the type

$$P=1-\left(\frac{R}{R_{\max}}\right)^{I} \quad \ldots (10)$$

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* For $n \geqslant 4$, Stirling's approximation

$$\underline{|n} = \sqrt{2\pi}\, n^{\,n+\frac{1}{2}}\, e^{-n}$$

can be used and for $p<0{\cdot}2$ or k large an exponential approximation can be made to $(1-p)^{k}$

where R_{max} was an "estimated" maximum range of detection and I was a constant for a particular homogeneous set of data. It appeared, to the present author, that I could be interpreted as an information index, being infinity when the position of the submarine was, in some way, fully known, and zero when no detection was possible under any circumstances. The first case is unlikely, but the index I, does in fact become very large in fully alerted conditions. The index would be effectively zero, of course, if equipment was not working, if bathythermal and weather conditions were extreme, or if the submarine was operating at a depth which made detection impossible.

Interest in the value of the hypothesised relationship waned when it was realised that it did not cover the case in which the probability of submarines being undetected up to zero range was non-zero. Writing

$$P=K\left[1-\left(\frac{R}{R_{max}}\right)^{I}\right]$$

for example, would have destroyed the interpretation of I.

Recently, however, the present author suggested that

$$P=1-\left[1-k+k\left(\frac{R}{R_{max}}\right)\right]^{I} \qquad \ldots(11)$$

was a possible formulation. P goes to $1-(1-k)^{I}$ as R goes to zero. k can be interpreted as a reliability factor of the detection system and I as an information index for the external factors of the overall detection process. To date, no checks have been made on the validity of this formulation in relation to experimental and operational data.

Assuming (11) — or (10) — to hold, a curve fitting technique could be produced to calculate I and k — or I alone — and to establish confidence limits for the fit. Because further work is needed to check that the empirical formulae match available data satisfactorily, no development of these ideas is given here. It should however be said that the approach is attractive, since it uses a wealth of data other than those which are contained in the particular sample being investigated. If these former data can lead to a valid model for operational purposes, no subtle treatment of the limited sample data is required.

Exchange of views with SACLANT ASW Research Center

Comments on the Mathematical Treatment

An earlier form of this article, essentially as written above, was passed to Bache of SACLANTCEN for critical comment. He remarked that the section titled *The Cumulative Curve based on Simple Experimental Data* contained the essence of the logical development of the argument and, although he had "tried hard" (*sic*), he had found no error, conceptual or computational. This was encouraging, but he added that the treatment did not go far enough and would only cover simple cases. He put forward three cases which needed to be dealt with:

(a) targets, starting outside the maximum range of detection, which are not detected, including these which do not close to zero range (these, despite the somewhat awkward algebra, are, as Bache agrees, covered by the sections titled *The Probability of Never Being Detected* and *Missing Data*;

(b) targets which "start late", *i.e.* which are not effective targets until some range less than maximum detection range or are discontinuous targets (this case arises, for example, when only detections of submarines below the layer are to be studied); and

(c) targets which "turn-around" and move away from the detecting unit (see Perneski *et al.*)(8).

Treatment of Cases (b) and (c)

If we had to take into account some specific detection model, it is apparent that there would be a requirement for special methods, since h(t), as defined earlier, would not be independent of the type of data used. In general, however, it may reasonably be assumed that a target, in a particular range element, has some probability of detection which is independent of its prior behaviour. In other words, there is no gradual learning process being followed by the detection system, which will either record a detection or not as a result of sensor information analysed over a short period of time. The vagaries of the human element that may be part of the detection process are not therefore adequately modelled, and, indeed, it is hard to see how they can be, other than by approaches such as that based on Mack's formula as already discussed.

It is suggested that, in case (b), the "effective" number of trials be established by an exponentially (range) weighted combination of the varying numbers of detectable targets available in the period up to the first range of detection, and similarly for the periods between detection. The procedure would be empirical, although an exponential form of weighting seems desirable to deal with the fact that at greater ranges there would be a lesser likelihood of detection, which must reduce the "effective" number.

This draws attention to the fact that the time spent in the various range brackets is important and might need to be taken into account generally. Time is usually disregarded, presumably because, by and large, the progress of a target towards the detecting unit is at a reasonably constant rate. In principle, time weighting can be carried out in an analogous manner to range weighting. In all cases, and especially in case (c), the "effective" sizes of the samples of *detection opportunities* would be the criteria on which confidence limits would be established. These sample sizes would be treated by the methods already outlined.

Range Intervals

When confidence limits are established for probabilities of detection over variously defined range brackets, some anomalies and difficulties have been experienced. The advantage of the method proposed, is that range intervals are *not* arbitrarily chosen, and every piece of information is used fully and correctly, in the statistical sense. As has already been noted, flat distributions properly arise when there is *no* information other than that which establishes a particular range point.

It is important to note that there is no way of extending the treatment of the problem beyond the range of closest and furthest detections observed (except in the context of non-detection), unless external experimental evidence and theory can be introduced. Bache and others have commented that a fully theoretic treatment is desired. They imply that, if the problems which they have raised can be overcome, the analysis described here would be acceptable and certainly would be preferred to computer simulation such as that proposed by Perneski *et al.*(8).

There is not yet, however, a *fully* satisfactory and proven analytic treatment. The latest attempt is that of Collins and Pepper(9). It is urged therefore that the suggestions of the section *An Alternative Approach*, following Mack(7), should not be forgotten.

Final Comments

This article is far from being a full treatment of the analytical approach proposed. What is suggested has considerable advantages, but may have practical limitations. Further development is needed, and computations need to be made to compare results with those obtained by Bache and others. All that is claimed is that the analysis adds to the understanding of the nature of the problem and offers a *possible* way forward. It may attract the attention of probability theorists, so that fresh ideas can be developed towards a solution. It may also prove to be mathematically relevant to conceptually similar problems in fields other than anti-submarine warfare.

Finally, it may be said that statistical treatment of this type of problem is far from simple. The distributions involved are skew to a degree which makes any straightforward application of confidence limits, based on standard deviations, naive and misleading. It will also be seen that "expected" values from the distributions estimated are not those that would be obtained by a simple-minded approach. And in order to deduce some of the distributions involved, Bayesian argument is evoked which, as I am sure the Reverend Bayes would have agreed, requires an act of faith.

APPENDIX A

The Distribution of p the Probability of Success, given r Successes out of n Events

For the mathematical development in the main text, the distribution of the probability of success, p, given r successes out of n events, needs to be established. For some purposes, it will also be useful to calculate confidence limits on p, although, for the general treatment of probability-range curves, limits have to be placed on the convolution of the distribution of p with associated distributions. However, since the calculation of confidence limits on p requires knowledge of the underlying distribution, it seemed worth while examining available work in this area.

A paper by Cockcroft(10) provides tables of two-sided and one-sided confidence limits, the former being done on an equal tails basis. It is, of course, preferable to calculate the confidence limits on a minimum range (of values of p) basis, but Cockcroft's paper which is based on work by Clopper and Pearson(11), and others, is nevertheless relevant.

Despite the fact that many people appear to have accepted the basis of the calculations which Cockcroft has used, both the logical arguments and the subsequent tables are incorrect. Taking r successes in n trials, Cockcroft provides results for n=1 to 50, for all possible values of r, and for 80%, 90%, 95% and 99% confidence limits. The fact that something is wrong is seen from the tables for n=1. Not only does 0 appear as the lower limit for r=0, and 1 as the upper limit for r=1, *in the two sided case,* but the single sided limits are equal to the confidence range (upper, r=0; lower, r=1) and the double sided limits are equal to half the confidence range (upper, r=0; lower, r=1). Thus, the probability distribution for n=1 is being taken as uniform for both r=0, and r=1. This is clearly untrue, since the probability distribution is only uniform for n=0 (r=0), which properly implies no information.

Referring back to Cockcroft's text, it seems (pages 4 and 5) that the probability of various lower limits, L, taken from a given formula, being less than a given p has been taken to be the same as the probability that for various p, a particular L will be less than p. This argument is the point at which error first appears. There is also a peculiarity in the way in which, at an earlier stage of the argument, the discreteness of r is treated. It is relevant that the distribution (continuous) of p is never establishd directly. It is also noted that Cockcroft's equation (4) has no solution for 0 successes and his equation (7) has no solution for n successes.

The Bayesian argument for the distribution of p is as follows. Let f(p)dp be the probability of p between p and p+dp, *given* c out of m successes. The probability of c out of m successes *given* p is

$$\frac{\underline{|m}}{\underline{|m-c}\;\underline{|c}}\,p^{c}(1-p)^{m-c} \, .$$

The *prior* probability of p between p and p+dp (no information) is dp.

The *prior* probability of c out of m is $\frac{1}{m+1}$.

Therefore,

$$f(p)dp =$$

$$\frac{\underline{|m}}{\underline{|m-c}\;\underline{|c}}\,p^{c}(1-p)^{m-c} \quad dp \bigg/ \left(\frac{1}{m+1}\right),$$

i.e. f(p)dp=

$$\frac{\underline{|m+1}}{\underline{|m-c}\;\underline{|c}}\,p^{c}(1-p)^{m-c}\,dp\,,$$

$$0 \leqslant p \leqslant 1\,, \quad \ldots (A1)$$

which is the formula used in the main text. From the formulae quoted by Cockcroft, it is clear that his equivalent density function, integrated between 0 and p, would be equivalent to a similar integration based on equation (A1), *provided that* the results for m, c were used as if they were for n=m+1, r=c+1 in Cockcroft's tables, and the Cockcroft figures for 0 successes (lower) and n successes (upper) were *taken to be* 0 and 1 respectively. This has also been checked from his tables. Exactly how the discrepancy arises in this form is difficult to judge, but it is certainly the type of discrepancy that might be expected from the arguments that Cockcroft used. It seems worth stressing again that the formula (A1), which is equivalent to formula (6) in the text, *does* give a uniform distribution when m and c are zero.

Acknowledgements

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RADIO NUCLIDES IN THE SEA

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Abstract

The behaviour of artificial radio nuclides in the marine environment is better understood than the behaviour of any other marine pollutant. The ability to detect and measure with increasingly sophisticated equipment, the fact that the wastes generated by an advanced technology were of known high toxicity, the increasing concern of a world public introduced to them in the context of nuclear weapon testing and world tension were all factors conducive to a rapid evaluation of their significance. However, the major factor leading to control was a good quantitative understanding of their toxicity and an early and sound foundation for acceptable radiation exposure standards, a major element lacking in our assessment of many other pollutants.

The exploitation of nuclear power is vital to a world where overpopulation and underfeeding are problems of major concern. The development of such power inevitably implies some radioactive contamination of the environment, including the seas. The principles and procedures for limiting the introduction of artificial radioactivity to the seas and oceans are well founded, and environmental dispersion of radio nuclides should and will play a part in waste management practices in the future.

Application of similar methodologies to the control of other pollutants will be rewarding and radioactivity labelled marine tracers will also play an important part in elucidating mechanisms controlling their distribution.

Introduction

In view of the interest which the Royal Navy has in nuclear weapons, nuclear reactors and the sea; this article is a general description of the sources of radio-active materials present in the sea, the ways in which radio nuclides have been used to investigate the properties of sea water and a discussion of man's present and possible future effect on the radio-activity of sea water.

Sources of Radio Nuclides in the Sea

There are three sources of radio nuclides in sea water, *viz*:

(a) NATURALLY OCCURRING nuclides of very long half-life which have persisted since the formation of the earth, and their shorter lived daughter nuclides which are continually renewed by decay.

(b) The COSOMOGENIC nuclides — *ie:* those nuclides produced by the interaction of cosmic radiation with the atmosphere.

(c) The MAN-MADE nuclides released through the explosion of nuclear weapons and through planned or accidental discharges of radioactivity from nuclear installations.

Naturally Occurring Nuclides of very Long Half-Life and their Shorter Lived Daughter Nuclides

It is interesting to note, in these days of concern about the quantity of radioactivity present in the environment, that more than 90 per cent of the total radioactivity present in the sea is provided by the naturally occurring nuclides.

The prime members are Potassium-40 (^{40}K) and Rubidium-87 (^{87}Rb). ^{40}K half-life $1 \cdot 27 \times 10^9$ years) is the most abundant radioisotope in the sea, accounting for just over 90 per cent of the radioactivity of sea water, due to the high concentration of potassium in sea water. Rb (half-life $4 \cdot 7 \times 10^{10}$ years) constitutes approx 28 per cent of natural rubidium, however, the concentration of rubidium in sea water is very much lower than that of potassium and therefore this isotope accounts for less than one per cent of the total radioactivity present in sea water.

Other nuclides falling into this category are Vanadium-50, Indium-115, Lanthanum-138, Lutetium-176, Tantalum-180, Rhenium-187, Neodymium-144, Samarium-147, Gadolinium-152, Hafnium-174, Platinum-190 and 192 and Lead-204. These nuclides are of little immediate interest since their abundances in sea water are low and often their concentrations are unknown or uncertain.

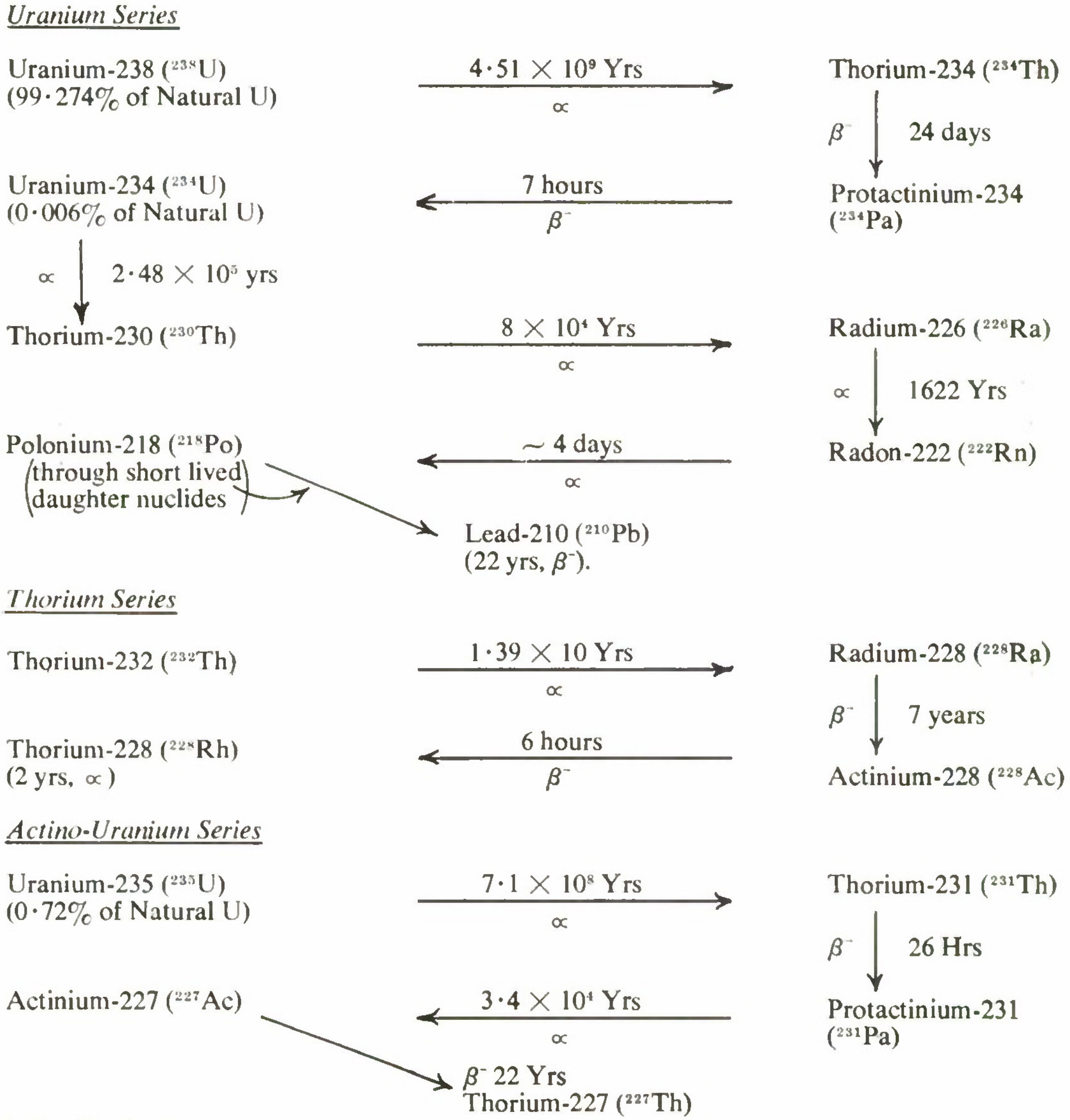

FIG. 1. Nuclide chart.

(b) *Uranium, Thorium and Actino-Uranium Series*

These series are complex chains of decay products from the respective parent nuclide. The important nuclides in a marine environment along with their half-lives and modes of decay are represented in Fig. 1.

Each series consists of a range of elements with very different chemical properties and, in the marine environment, the most striking feature of their behaviour is the complete disruption of the radioactive equilibria by geochemical processes. For example, the ^{230}Th: ^{238}U and ^{231}Pa: ^{235}U ratios which are only 0·05 - 0·2% of the expected equilibrium values. The reason for this is that both Thorium and Protactinium are rapidly deposited in sediments. Other examples will be discussed later.

Nuclides Produced by Cosmic Radiation

It was only as recently as 1946 that it was suggested that Carbon-14 (^{14}C) and Tritium or Hydrogen-3 (^{3}H) should occur in nature as a result of nuclear reactions between the neutrons produced by cosmic radiation and the nitrogen in the atmosphere. Since then a range of nuclides formed by the interaction of cosmic radiation with the atmosphere have been found and studied, these include Beryllium-7 and 10 (^{7}Be and ^{10}Be), Aluminium-26 (^{26}Al) and Silicon-32 (^{32}Si).

Carbon-14 and Tritium are both found in sea water and their removal is slow compared to both the rate at which they undergo radioactive decay and the time-scale of oceanic circulation.

^{7}Be is only detectable in surface waters due to its very short half-life and ^{10}Be is only detectable in marine sediments due to its very long half-life.

^{26}Al has a very characteristic gamma ray spectrum but is difficult to find in sufficient concentrations to do any useful work on its spread throughout the ocean.

^{32}Si has a long half-life (500 years) and has proved to be a valuable tracer although it is difficult to detect.

Other radio- isotopes which may be formed are Sodium-22, Phosphorus-32 and 33, Sulphur-35, Chlorine-36 and 39, and Argon-37 and 39; but little is known of their presence in sea water. Argon-37 and 39 have been detected in the atmosphere and a method has been suggested for the extraction of Argon from sea water. These two isotopes could prove to be of immense value in the future as they have half-lives of 35 days and 270 years respectively which are useful for various oceanic studies.

Artificial Nuclides

There are two prime sources of artificial or man-made radioactivity — *viz:* Nuclear Explosions and Nuclear Reactors.

(a) *Nuclear Explosions*

The fission products from a nuclear explosion comprise more than 200 nuclides of elements ranging from Zinc to Dysprosium. The fission product mixture can be defined fairly accurately but the composition of the fallout on entry to the ocean will generally be very different as a result of the different decay rates of the fission products many of which have a very short half-life. The principal fission products are shown in Table 1.

TABLE 1.

Nuclide			Half-Life
Strontium-89	(^{89}Sr)	—	50 days
Strontium-90	(^{90}Sr)	—	28 years
Yttrium-91	(^{91}Y)	—	58 days
Zirconium-95	(^{95}Zr)	—	63 days
Ruthenium-103	(^{103}Ru)	—	41 days
Ruthenium-106	(^{106}Ru)	—	1 year
Tellurium-129m	(^{129}mTe)	—	33 days
Caesium-137	(^{137}Cs)	—	30 years
Cerium-141	(^{141}Ce)	—	33 days
Cerium-144	(^{144}Ce)	—	290 days
Promethium-147	(^{147}Pm)	—	3 years

Shorter lived nuclides particularly Praseodymium-143 (14 days), Barium-140 (13 days), Neodymium-147 (11 days) and iodine-131 (8 days) make a substantial contribution to the total activity of mixed fission products in the early stages but become unimportant several months after fission.

In a sample of fission products about one year old, more than three-quarters of the activity is attributable to Zirconium-95/Niobium-95 (its daughter product) and the rare earth nuclides; after 20 years Strontium-90/Yttrium-90 (48%), Caesium-137/Barium-137 (45%), Promethium-147 and Samorium-151 (7%) account for all the activity present. There are also a number of "induced nuclides", produced during a nuclear explosion, present in the marine environment, the more important of these are listed in Table 2.

TABLE 2.

Nuclide			**Half-Life**
Hydrogen-3 or Tritium	(^{3}H)	—	12 years
Carbon-14	(^{14}C)	—	5568 years
Phosphorus-32	(^{32}P)	—	14 days
Sulphur-35	(^{35}S)	—	87 days
Chromium-51	(^{51}Cr)	—	28 days
Manganese-54	(^{54}Mn)	—	300 days
Iron-55	(^{55}Fe)	—	3 years
Iron-59	(^{59}Fe)	—	45 days
Cobalt-57	(^{57}Co)	—	270 days
Cobalt-58	(^{58}Co)	—	72 days
Zinc-65	(^{65}Zn)	—	245 days
Cadmium-113m	(^{113}Cd)	—	14 years

These are produced by neutrons from the explosion bombarding materials such as the weapons casing, earth, water, air etc.

The fallout from nuclear explosions can be classified into three parts, *viz:*

(i) Close-in or Local.

(ii) Tropospheric.

(iii) Stratospheric.

The local fallout is intense and initially located in a small area adjacent to the site of the explosion.

Tropospheric fallout is the most widespread; it is mainly deposited between latitudes 50°N and 50°S (≈80%) due to prevailing wind patterns. The majority of this fallout is found between 30°N and 50°N because of the siting of nuclear test areas. It is noteable that the settling of tropospheric fallout is not even but that it tends to be scrubbed from the atmosphere during rainstorms and very little is deposited gravitationally as dry particulate matter. A certain amount of the fallout occurring over land is leached back into the oceans *via* the rivers. This is, however, a very slow process, for example, it has been estimated that from 1% to possibly 10% of the yearly deposition of ^{90}Sr on land finds its way back into the oceans.

Stratospheric fallout is not very important, the effect being to raise the natural background slightly.

Strontium-90 and Caesium-137 are normally used to determine the quantity of fallout deposited since their relatively long half-lives make detection and calculations relatively easy. It is, however, likely that this is only an average figure — *i.e.:* Iron-55 is quantitatively the most predominant nuclide and it is likely that more ^{55}Fe has been deposited and the pattern of deposition could be calculated more accurately from measurements of this nuclide.

(b) *Nuclear Reactors*

The composition of the nuclides produced in a nuclear reactor is similar to that from a nuclear explosion. The release of these nuclides is, however, much more controlled and the sources of radioactivity in the environment are detailed below:—

(i) *Low Level Wastes*

The Noble gases and Tritium constitute by far the greatest proportion of the radioactivity released from most Water Cooled Reactors. Krypton-85 (^{85}Kr) because of its relatively long half-life (10·4 years) may build up in substantial quantities in the atmosphere and concomitantly as dissolved gas in the oceans. Tritium is not easily concentrated by present waste treatment procedures and is normally released into the oceans as water.

These nuclides are also formed in the reactors of Nuclear powered ships and submarines which use a modified water cooled reactor. They may release radioactivity into the oceans from any one of the following sources:

(1) The expansion volume of primary coolant during warm-up of a pressurised water reactor.

(2) Leakage during routine operation, wastes from the laboratory, from equipment decontamination and from showers and laundry associated with the reactor.

(3) The Ion-exchange resins which remove activated corrosion products from the primary coolant.

(4) Other contaminated solid materials.

The major potential source of liquid waste is the primary coolant and (1) above provides the major part of the radioactivity released directly into the environment from ships. Other sources of low level wastes include the reactors for producing material for nuclear weapons — *e.g.:* at Hanford in the USA and Windscale in the UK. Some Plutonium-239 (^{239}Pu) is released, but very little; the main release again being large quantities of Tritium. The reprocessing of nuclear fuel at the above establishments also leads to the release of large quantities of low level waste containing a wide range of isotopes.

(ii) *High Level Wastes*

These mainly consist of Strontium-90 (^{90}Sr), Caesium-137 (^{137}Cs) and Cobalt-60 (^{60}Co) produced at the nuclear fuel reprocessing plants and at various establishments which produce radioactive isotopes for research work. The normal methods of dispersal are:

(1) To contain in stainless steel vessels in concrete bunkers in the ground.

(2) To seal in concrete and dump at sea.

(c) *Other Sources*

(i) *Radio Isotope Applications*

A lot of radio isotope work is now carried out in research laboratories all over the world. The majority of this work involves short-lived isotopes but some release into the oceans is to be expected. This release will probably contain all the previously mentioned nuclides.

(ii) *Accidents*

The growing use of radio nuclides leads to the possibility of local effects due to accidents. Examples of this are:

(1) The loss of the two American Nuclear submarines U.S.S. *Thresher* and U.S.S. *Scorpion;* which undoubtedly lead to radioactive release in the ocean, and

(2) Accidents involving nuclear weapons — *e.g.:* at Palomares in Spain.

As the role of nuclear propulsion increases — *e.g.:* we have seen the introduction of nuclear power into merchant shipping, the probability of this type of release is increasing. The use of nuclear power in both aircraft and space rocketry is also being investigated and any accident occurring over the oceans is bound to lead to contamination of sea water.

Studies of Radio Nuclides in Sea Water

(a) *Distribution of Radio Nuclides in the Marine Environment*

In the marine environment, radio nuclides may:

(i) Remain in solution,

(ii) Be absorbed on suspended particlate matter or bottom sediments,

(iii) Flocculate and precipitate to the bottom, or

(iv) Be accumulated by plants and animals.

In addition to these factors radio nuclides are diluted and dispersed by currents, turbulent diffusion, isotopic dilution and the movement of animals; simultaneously they can be concentrated by bio-accumulation and passage through food webs, physicochemical adsorption, ion-exchange, flocculation and precipitation.

These competing processes obviously render interpretation of results difficult and if we add the practical problems of studying these nuclides *viz:*

(1) The levels of the nuclides are low even in surface waters.

(2) Large samples must be analysed.

(3) Radio-chemical problems; particularly in the unequivocal identification of separated samples and in the control of contamination.

We begin to appreciate the careful work and care which must go into any studies of these nuclides. Furthermore, the direct deposition of radio nuclides into the ocean varies in a complex way with place and time. An example of this is the way in which the concentration of Radium-226 (^{226}Ra) varies with depth. It is found that this concentration actually increases with depth, and at all depths considerably more of it is present than could be accounted for by equilibrium with the dissolved Thorium-230 (^{230}Th) (see Uranium Series Decay Table). The only satisfactory explanation for this situation is that ^{226}Ra is dissolved from the surface of deep sea sediments in which ^{230}Th becomes concentrated. The distribution of ^{226}Ra in deep sea profiles is then largely a result of upward displacement and diffusion. This hypothesis is supported by the known mobility of radium in sediments — *e.g.:* the ^{230}Th:^{210}Pb ratio in sediment cores is not the equilibrium value indicating loss of one of the intermediate nuclides (see Uranium Series Decay Table); ^{226}Ra is the only one with a sufficiently long half-life to affect the values.

It has also been found that there is a marked increase in the ^{222}Rn content of sea water in the immediate neighbourhood of the ocean bed as a result of the decay of ^{226}Ra in the sediment.

A further factor which could influence the concentration of ^{226}Ra is its concentration by biological organisms in the upper layers. When these organisms die their skeletal remains then sink towards the ocean bed concentrating the radium in the lower layers of the ocean. This is emphasised by the marked settling of particulate radium from the surface waters in which the radium bearing particles were closely related to siliceous organisms.

Bearing these problems in mind we will now go on to see what experiments have been done using radio nuclides in the marine environment.

(b) *The use of Radio Nuclides as Tracers of Water Movement in the Oceans*

Radio nuclides have not been used to directly determine the mechanism of water movement but they are used in conjunction with classic oceanographic mixing patterns to outrightly reject certain theories and produce rate patterns for others.

In order to be useful for these studies the isotopes should have the following ideal characteristics:

(i) Be present in measurable quantities in all parts of the ocean.
(ii) Differences in concentration which lie well outside the limits of measurements error should exist.
(iii) The mode and rate of injection of the isotope the system must be known both as a function of TIME and of SPACE.
(iv) The isotope should move with the water acting as an infinitely soluble salt.
(v) Contributions of natural and artificial production of the isotope should be distinguishable.

These formidable conditions restrict the useful nuclides to six — *viz:* ^{3}H, ^{14}C, ^{32}S, ^{226}Ra, ^{90}Sr and ^{137}Cs.

^{3}H has a short half-life and this restricts its application to the more rapid processes which occur in well mixed waters. It also suffers from excessive injections *via* man-made sources — *i.e.:* the nuclear bomb and nuclear reactors and may only be of future value as an experimentally injected tritium tracer — *i.e.:* in tritiated chemical compounds.

^{14}C has a sufficiently long half-life for it to be of value not only in the dating of deep waters, but also in the study of the deposition rates of recent sediments. It has received a great deal of attention and it is considered that more than 90% of the transport of radio-carbon within the ocean occurs within the water itself and that interaction with the sedimentary reservoir is negligible.

One rather serious complication enters into the interpretation of radiocarbon results; whereas the transport of dissolved solids or even of water itself through the atmosphere is of little importance that of carbon dioxide has great significance. The quantitative evaluation of this mode of transport is therefore necessary if ^{14}C data is to be used for water circulation estimates.

It is noteworthy that an important source of ^{14}C for water tracer studies is that produced during nuclear weapon testing. This is due partly to the large quantities produced and partly to the unambiguous assignation of the source which simplifies studies enormously. This is, however, not considered suitable justification for the resumption of testing!

The isotopes ^{90}Sr and ^{137}Cs produced from nuclear weapon tests are also suited to tracer studies, particularly, since they weren't present before, no corrections for natural background are required. They may be affected by uptake in organisms and particulate matter but it is expected that water movement is dominant.

The half-life of ^{32}Si lies between that of ^{3}H and ^{14}C and it can, therefore, be used to fill the gap about processes occurring on an intermediate time scale. Its disadvantages are that it is present in low concentrations, it is adsorbed onto minerals, it is removed from the system by the biological activity of organisms such as diatoms and siliceous sponges and its deposition tends to vary with time. (For example this makes it unsuitable for age determinations of ice). Its main advantage is that it is free from contamination by nuclides from man-made sources.

^{32}Si has been found to be useful as a tracer for the study of the near coastal structure of the ocean and of seasonal variations in the type of water entering coastal regions. It has also been used to determine the rate of mixing of layers on the simple two layer model of the sea.

^{226}Ra has proved of unusual interest as a tracer for circulation studies since it is added to the oceans largely at the sea bed (see earlier). The determination of vertical diffusion currents has been done in a few cases mainly by the comparison of the ^{226}Ra:^{222}Rn ratio in various parts of the ocean.

The classic oceanic mixing models are separated into four groups *viz:*

(i) The two layer model.
(ii) The outcrop model.
(iii) The three base model.
(iv) The world ocean model.

and it is interesting to see how experimental results with radio nuclides fit with the above models which are all very much mathematical simplifications. A variation on the world ocean model produces the best explanation of the ^{14}C distribution; however, none of the above models can satisfactorily explain the ^{226}Ra distribution and a four reservoir model has been developed based on the world ocean model to account for the distribution of ^{226}Ra, and ^{90}Sr distribution is different again and a satisfactory model for this has not been developed yet.

This may appear to be a hopeless situation but it does in fact indicate that the use of radio nuclide tracer techniques is widening our knowledge of the processes actually occurring in the sea and is leading to a constant improvement of the simple theories concerning sea water circulation.

(c) *The Use of Radio Nuclides in Dating*

This is a widely used technique on land for dating trees, fossil remains etc. and it has also been prominent in dating studies in the marine environment.

The ^{40}K to ^{40}Ar ratio has been used for sediment dating in those sediments which contain these nuclides in the same crystal matrix; similarly the ^{87}Sr (from ^{87}Rb — see Naturally Occurring Nuclides) to ^{86}Sr ratio has also been used for geochronological measurements.

Most dating is affected by the half-lives of the radio nuclides concerned, in order to go back a very long time it is necessary to study those nuclides arising from the three heavy metal series.

Work on the ratio of ^{230}Th:^{238}U has produced dates going back 300,000 years and the ^{231}Pa:^{235}U ratio 100,000 years; similar methods using ^{234}Pa:^{230}Th and ^{230}Th:^{234}Th ratios have been tried but the results are suspect at the moment. It is to be expected that this area will give rise to a lot of research activity in the future.

Carbon-14 dating which is the most widely used method on land has also been the most prominent in the marine environment. It produces dates going back 30,000 years or slightly longer depending on the accuracy of the measure ments. However, ^{14}C dating is complicated by two problems:

(i) The decrease of the ^{14}C:^{12}C ratio in the atmosphere through the addition of carbon dioxide from the burning of fossil fuels in the shape of oil and coal, and

(ii) The increase in the same ratio due to the production of ^{14}C during the nuclear bomb tests in the last few decades. Both these effects have been allowed for mathematically and recent uses of ^{14}C analyses include:

   (1) Analyses of the dissolved inorganic carbon for all the oceans; the ages determined from these studies have also given valuable information on ocean mixing and circulation processes.

   (2) Attempts to determine the age, or average age, of particulate and dissolved organic matter in the oceans; the values found for particulate matter are still unreliable, but for dissolved organic matter in deep water an average age of 3,400 years was found.

It is possible that in the future the ^{26}Al:^{10}Be ratio (cosmogenic nuclides) could also be used when sufficiently accurate detectors have been developed. This would significantly increase the range of dating producing dates from 500,000 to 10 million years back; some work in this area is beginning to appear in the literature and should lead to a significant advance in our knowledge of past patterns of ocean development.

(d) *Bio-Accumulation of Radio-Nuclides by Sea Animals*

This is a problem with other non-natural elements present in sea water — *e.g.:* heavy metals such as mercury, and organic chemicals like DDT have been found to accumulate in very large amounts in fish due to the ability of the fish and its food to concentrate these pollutants from the water. These elements then present a direct threat to the health of the human race; the situation with radio nuclides is slightly different. In both the above cases the concentration of the pollutant gets higher the further along the food chain you travel; this has not been found to be true for radionuclides.

Radio nuclides appear to concentrate very rapidly at the lower end of the chain — *e.g.:* phyto-plankton (a micro-organism floating in the upper layers of the sea and a basic food source in the food chain of the sea) accumulates trace metals very rapidly but higher up the chain this concentration is not increased and in some cases there is evidence for a possible decrease since the metabolism in the fish rather than working towards concentration actively works to excrete these metal ions from its body.

The primary reason for the heavy accumulation of radio nuclides in phytoplankton is the simple physical adsorption of particulates onto the outside of the organism which results in a concentration gradient which enables adsorption to take place. The concentration of a particular radio nuclide is, therefore not dependent upon the metabolism of the organism at all.

From the work that has been done until the present moment it can be seen that the problem with bio-accumulation of radio nuclides is not its direct effect on man but on fish. Most fully grown fish can counteract the effects by excretion; however, it kills fish at the embryonic stage thus prejudicing future generations and a vital food source for man.

The problem, at the moment, appears to be concentrated in areas of high radio nuclide release and may account for the agitation of inshore fishermen about the possibilities of accidentally high radioactive release from power stations or nuclear fuel reprocessing plants stationed close to shore.

In order to determine how best to deal with such a release a lot of work is being carried out into the mechanism of adsorption by phyto-plankton and similar organisms, into the metabolism of radio nuclides by fish and the whole progress of radio nuclides through the food chain.

Contamination of the Oceans by Radio-Active Waste

As we have noted earlier there are three main sources of contamination of the oceans by artificial radio-active substances — *viz:* NUCLEAR PLANTS ON LAND, NUCLEAR POWERED SHIPS AND SUBMARINES and NUCLEAR WEAPON TESTING.

Radio-active wastes from nuclear plants on land are disposed into the ocean in two ways:

(a) Packaged disposal to the deep sea floor, and

(b) Liquid effluent pumped into coastal waters.

The former are packaged in steel containers surrounded by concrete and are disposed into the sea usually deeper than 2,000 metres. Until recently some 10,000 curies of radio-active wastes were deposited in the oceans ANNUALLY by this method.

The lifetime of these packages is considered to be 10 to 20 years and there is, therefore, gradual leakage of radio-active materials from the packages.

The largest liquid effluents come from fuel reprocessing plants where from several hundred to a few tens of thousands of curies a year are being discharged directly into the oceans. The nuclear power plants producing electricity only add a few milli-curies to these values.

Another area which is starting to produce large quantities of waste are the factories producing specialised chemicals for research laboratories — *e.g.:* the Radio-chemical Centre at Amersham. This is likely to increase due to the wide and ever widening use of these chemicals for radio-active tracer studies etc.

The wastes from university research laboratories and industrial research centres is negligible at the moment and may only produce a local contamination problem. However, it is probable that in the future, effluent treatment will have to be improved to prevent contamination of the marine environment from these sources.

The main waste from nuclear powered ships and submarines is the expansion volume of the primary coolant, but there is a build up of radioactivity in the spent ion-exchange resin which has been used for decontamination of the primary coolant water. This is easier to quantify and ion-exchange resins containing 10 to 100 curies of ^{60}Co and other radionuclides are disposed of from ships to the sea surface at least 12 miles off-shore at intervals of six to nine months.

It is to be hoped that the majority of contamination from nuclear weapon testing has occurred although some nations, mainly France and China, continue with above ground testing and the "Nuclear Club" is possibly going to widen in the next decade with the proliferation of nuclear reactors. This is evidenced by the Indian test and the probability that Israel possesses atomic weapons. The major powers are still testing weapons underground and there is the possibility of the radio-nuclides from these tests leaking into the ocean *via* the water table and run off from the land.

Predictions of Future Radio-Active Release

(a) *Existing Methods*

The increasing demands for energy show that, by the year 2000, 800 tons per year of fissionable materials will probably be required to satisfy our energy needs. The nuclear fission of 800 tons of fissionable material will, for example, produce 5,600,000 curies per year of ^{90}Sr which is 560 times the total ^{90}Sr released by nuclear weapon tests up until the end of 1962.

It is also probable that around the same time the number of nuclear powered ships and submarines in the world will reach approximately 500. Using a production rate of ^{60}Co of a few tens to a few hundreds of curies per ship per year, the total production of ^{60}Co will range from about 10,000 to 100,000 curies per year.

(b) *Possible Technological Advances*

(i) *Nuclear Excavation*

This has been proposed since a nuclear explosion is ideally suited for large scale excavation projects — *e.g.:* the construction of deep water harbours and canals.

The most familiar proposal is the construction of a sea level canal

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Note: A curie is the standard unit of radio-activity describing the number of atomic fissions taking place per second. One gram of radium transforms 37,000,000,000 (37 billion) atoms per second; and that, or its equivalent in some other radio-active nuclide is a curie. Therefore, 10,000 curies is equivalent to 10,000 grams (or approx 22 lbs) of radium being dumped at sea.

across the isthmus of Central America. It is considered that it will be possible to engineer such an explosion so that very little radio-activity is injected into the strato-sphere or troposphere with 80 - 85% of the radio-activity remaining in the bottom of the cavity and the remainder being local fallout.

The water and earth near the centre of the fission reaction would be made radio-active due to bombardment with neutrons and there is a significant possibility that this would then leak into the rivers and ocean. This type of excavation is unlikely to be allowed for political reasons at the present time, but should "laser-induced" fusion explosives become available (these use a very high temperature laser beam to activiate the fusion or nuclear re-action which is at present done by an "atomic bomb" detonator—this essentially makes it a "cleaner" explosion although high speed neutrons are still produced) and man learns to "live with" or become "familiar" with nuclear explosives, it is possible that this may be attempted in the not too distant future.

(ii) *Fusion Reactors*

This is much more a long term scientific dream, as the practical problems of harnessing the power of the "Hydrogen bomb" for peaceful use, seem to go up exponentially with time. There is always the possibility of a breakthrough and work on laser beams may be the key to this breakthrough.

If this method of power production becomes feasible it will produce fewer problems than those of the present nuclear reactors, as the only waste product is tritium (^3H) and there are no fuel re-processing problems.

In conclusion it is worthwhile to try and put the preceding figures into perspective.

It has been calculated (Food and Agriculture Organisation (FAO) 1971) that by the year 2000 the total quantity of artificial radioactivity in the oceans will be approximately 10^9 Curie; however, 5×10^{11} Curie of naturally occurring Potassium-40 will be present in the marine environment at that time — *i.e.:* the quantity of artificial radioactivity may be as little as 1/1000 of the overall radioactivity in the marine environment.

This apparently small overall problem is not as insignificant as it may appear since the local concentrations of artificially produced nuclides are much higher than the overall figure tends to indicate and a number of these nuclides — *e.g.:* Strontium-90 and Caesium-137 have never been encountered by man and their long term effects may be harmful.

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THE USE OF LINEAR SYSTEM THEORY IN ACOUSTIC RADIATION AND SCATTERING ANALYSIS*

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Abstract

A description is given of the output of most linear systems in terms of certain properties of the system's impulse response function and of the input signal. The description is particularly simplified when the input signal has a small fractional bandwidth; furthermore, this simplified description, although based on the supposition of a small fractional bandwidth, is shown numerically to apply well even when the fractional bandwidth is as large as unity.

The author's "Image Pulse" theory of acoustic echo formation and "Replica Pulse" theory of acoustic radiation are demonstrated to be particular cases of the small fractional bandwidth version of the linear system theory. Examples are provided showing the very good agreement between radiated waveforms obtained using the band limited formulae of the Replica Pulse theory and the non-band limited formulae of the linear system theory, even though employing input pulses of only a few cycles duration.

Introduction

Some years ago I put forward theories relating to mechanisms of scattering(1-4) and of radiation(2,5-8) of pulsed waves. Those theories were based upon certain physical approximations of the physical optics type and were also limited to input signals of small fractional bandwidth. I shall refer to the above as the Image Pulse theory of echo formation and as the Replica Pulse theory of radiation.

More recently Wickhorst brought out a very general theory(9, 10), applicable to most linear processes, and the picture it provided of system outputs is free of bandwidth limitations. I have considerably developed the formalism of this linear system approach and this has included deriving the solution when small fractional bandwidth conditions apply. This has made it possible to show directly that the Image Pulse and Replica Pulse theories are particular cases of the wider linear system theory. (Fig. 1). It has also enabled, on the one hand, the former band-limited results of the Image and Replica Pulse theories to be presented free of bandwidth limitations, and, on the other, it has enabled one to see the limits of useful applicability of the previous band-limited theories.

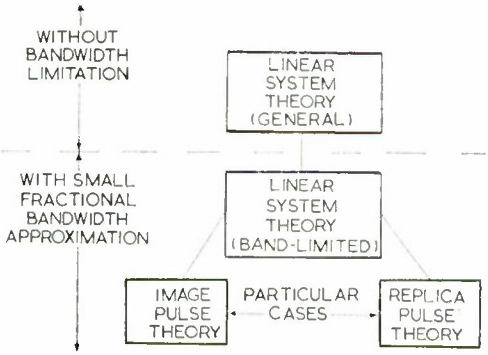

FIG. 1. Relationship between Image and Replica Pulse theories and linear system theory.

In this paper I propose to do the following. Firstly, for the benefit of those who are not familiar with the Image Pulse and Replica Pulse mechanisms, I shall briefly describe the underlying concepts. Then I shall summarise the salient features of the linear system theory and show its relations to the Image Pulse and Replica Pulse theories. Finally I shall present examples of results obtained using the non-restricted and the restricted bandwidth formulae.

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* This is the text of a paper presented in March 1976 at a symposium on "Recent developments in underwater acoustics" held at Portland, Dorset, under the auspices of the Institute of Acoustics.

The Image Pulse Concept

For simplicity, the description I shall now give of the Image Pulse concept will be for backscattering and for non-directional transducers, although the theory can cover bistatic situations and can also take account of directional transducers.

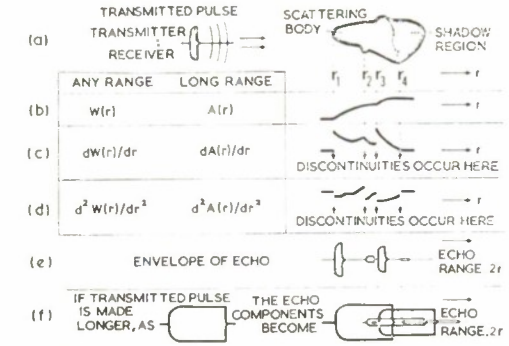


FIG. 2. The Image Pulse echo mechanism.

In Fig. 2 we have at (a) on the right a rigid scattering body, and on the left the transmitter and receiver, which are treated as coincident at a point. The portion of the scatterer in geometrical shadow plays no part in the model. The quantity W(r) represents the solid angle subtended at the transducers by those parts of the scattering body within range r, and this quantity and its first two derivatives are shown at the right of the picture at (b), (c) and (d). If the range to the scattering body is large enough, the range variations over the body can be ignored and, apart from a constant of proportionality, the solid angle, W(r), can be replaced by the projected area, A(r), of the scattering body. Discontinuities may occur in W(r) or A(r) or in their first and subsequent derivatives. Whenever such a discontinuity occurs, it engenders an echo component. Thus, if the transmission consists of a single pulse, as indicated at top left of Fig. 2, the echo here consists of four time-resolved components corresponding to the four ranges at which discontinuities occur. The envelope of each echo component is an approximate replica of that of the transmitted pulse. If the transmission is made long enough for the output components to overlap at steady level, the resultant in that overlap region is the CW level.

Fig. 3 provides a simple example of the Image Pulse theory. Incidentally, it uses the convention that an order of differentiation is denoted by an upper, positive number in brackets, and elsewhere I shall use the corresponding convention that an order of integration is denoted by an upper, negative number in brackets. The illustration shows the composition of the long range axial echo from a spherical cap. One component arises at the near point of the dome and a second component arises at the base rim. The echo is thus as shown schematically at the bottom of Fig. 3.

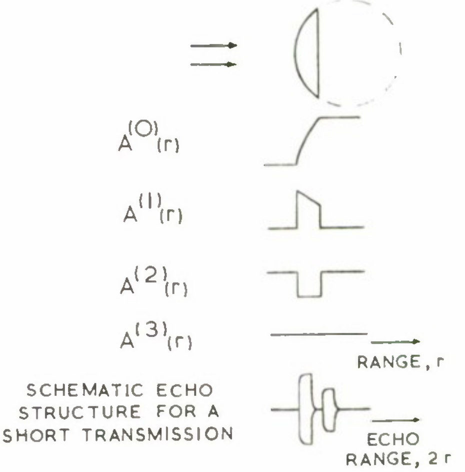


FIG. 3. Example of Image Pulse theory. Echo from spherical cap.

The Replica Pulse Concept

The Replica Pulse theory yields a very analogous interpretation of radiated fields. The input is now the normal velocity of the radiating surface and the output is the pressure at a field point. (Fig. 4). Again the output is described in terms of a set of pulses whose envelopes are approximate replicas of the

INPUT : RADIATOR NORMAL VELOCITY
OUTPUT : PRESSURE AT FIELD POINT

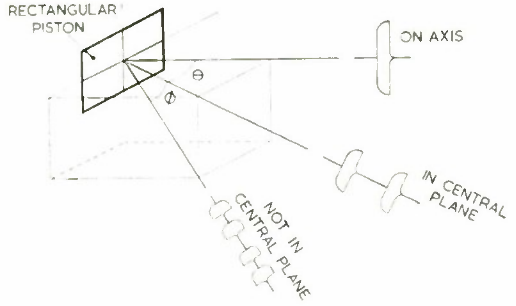
B(r) = AREA WITHIN RANGE r

$\frac{1}{r}\,dB(r) = dC(r)$

	Image Pulse case		Replica Pulse case
Any Range	W(r)	→	C(r)
Long Range	A(r)	→	B(r)

FIG. 4. Parameters relevant in Replica Pulse theory of radiation.

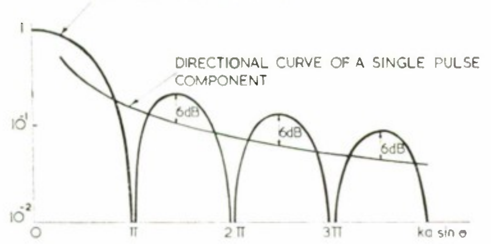
envelope of the input pulse. The quantities W(r) and A(r) which occur in the echo formation theory are replaced in the radiation theory by the quantities C(r) and B(r), where B(r) is simply the area of radiating surface within range r of the field point and C(r) is a similar quantity, but with a range normalisation.



Schematic representation of the far field behaviour for a pulsed rectangular piston.

FIG. 5. Example of Replica Pulse mechanism.

As an illustration of the Replica Pulse mechanism, if a single pulse is applied to a rectangular piston, the field at a distant point not in a central plane consists of four pulses associated with the corners. (Fig. 5). In a central plane these coalesce to two pulses associated with two edges. On the axis these coalesce to one. To help link the concept with the more familiar CW viewpoint, Fig. 6 shows a comparison between the far field directivity of each of the two Replica Pulses in a central plane with the CW directivity. It is the interference between the two Replica Pulses that produces the familiar CW directivity.



Theoretical comparison, for a rectangular piston, of the C. W. and pulsed directivity curves in a central plane.

FIG. 6. Illustration of how C. W. field is due to superposition of Replica Pulses.

The Linear System Approach

I now turn to the linear system approach. If a Dirac pulse is applied to the input of an arbitrary, linear system, then, as shown in the upper part of Fig. 7, the output is the so-called impulse response function, h(t), of the system. For an arbitrary input signal, s(t), the output e(t), is given by the convolution integral*, as shown in the lower part of Fig. 7.

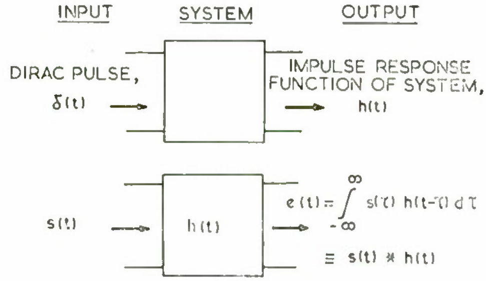


FIG. 7. Basic relations for a linear system.

In general, the impulse response function or its derivatives of any order may contain Dirac pulses. At the left of the upper diagram in Fig. 8 such an impulse response function with Dirac pulses is shown, and on the right this is separated into two parts, the Dirac pulses and the residue. I shall call the latter the "stripped" impulse response function. The derivative of the stripped impulse response function is shown at bottom left of Fig. 8, and this also contains Dirac pulses. On the bottom right, this derivative is again split into two parts, the Dirac pulses and the residue. We could continue with this procedure of differentiating and splitting

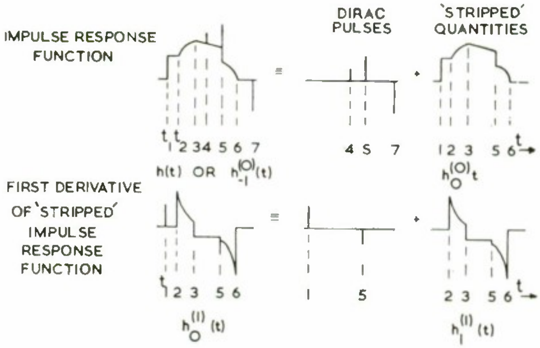


FIG. 8. Schematic illustration of impulse response function and of its first derivative after "stripping" of any Dirac pulses.

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* There are some special circumstances where this is not applicable.

off any Dirac pulses present. I shall clarify the nomenclature of the h(t) types of term which you see in Fig. 8 under the unstripped and stripped quantities. The order of derivative is shown by the raised number in brackets, and stripped quantities have the same number as a subscript, while unstripped quantities have a subscript one integer less.

Letting the magnitude of a Dirac pulse occurring at time t_g in the nth derivative of the impulse response function be denoted by a(g,n), we can write the equation for each order of derivative by separating it into two parts, namely the Dirac pulses and the residue, (Fig. 9). We denote the last derivative to yield Dirac pulses as the mth, and m may have any integer value from zero to infinity.

LET

$a(g,n) =$ MAGNITUDE OF DIRAC PULSE, AT TIME t_g, IN nTH 'STRIPPED' DERIVATIVE OF THE IMPULSE RESPONSE FUNCTION

$h(t) \equiv h_{-1}^{(0)}(t).$

THEN

$$
\begin{aligned}
h_{-1}^{(0)}(t) &= \sum_g a(g,0) \quad \delta(t-t_g) \quad + \quad h_0^{(0)}(t) \\
h_0^{(1)}(t) &= \sum_g a(g,1) \quad \delta(t-t_g) \quad + \quad h_1^{(1)}(t) \\
&\vdots \\
h_{m-1}^{(m)}(t) &= \sum_g a(g,m) \quad \delta(t-t_g) \quad + \quad h_m^{(m)}(t)
\end{aligned}
$$

FIG. 9. Impulse response function and its derivatives after "stripping" of any Dirac pulses.

Then it can be proved that the output signal may be expressed as shown in Fig. 10. We recall that terms such as $s^{(-m)}(t)$ denote the mth integral of s(t). The quantity y is an integer, and it has the value unity in the cases of direct interest to us. The equations show that the output of a linear system consists, in general, of two parts, $e_A(t)$ and $e_B(t)$. The first is made up of what I shall call Diracian output components; each of these is associated with a Dirac pulse, at time t_g, in the nth derivative of the impulse response function of the system. Each such component is a scaled and appropriately delayed signal whose nth derivative is a replica of the input signal. I shall call the output due to all such Diracian output components associated with a given time t_g a Diracian summation pulse. Such a Diracian summation pulse is the sum of a set of signals, each starting at the same time and each having a waveform of different shape, as each is associated with a different value of the order of derivative, n. As all components of a Diracian summation pulse start at the same time, they are not physically resolvable from one another, and a Diracian summation pulse forms a physical output entity. Its envelope shape will, in general, depend upon the relative distribution of the amplitudes of its components. The various Diracian summation pulses start at different times, and, subject to appropriate conditions, are in principle resolvable from one another. The second part of the output of a linear system, $e_B(t)$, consists of the convolution of the mth integral of the input signal with the mth stripped derivative of the impulse response function; the shape of this second part is thus not simply related to that of the input signal, and its duration could be the sum of the durations of the input signal and of the impulse response function. Either of the two output parts, $e_A(t)$ and $e_B(t)$, may be zero. When the first part is zero, the second part degenerates to the convolution of the input signal and the impulse response. Almost all the cases I have investigated so far have either yielded outputs where $e_B(t)$ is zero or small, or, in a few instances, where $e_A(t)$ is zero.

$$
\begin{aligned}
e(t) &= e_A(t) + e_B(t) \\
e_A(t) &= \sum_g \sum_{n=0}^{m} a(g,n-y) \quad s^{(-[n-y])}(t-t_g) \\
&= \sum_g \sum_{n=0}^{m} \text{DIRACIAN OUTPUT COMPONENT} \\
&= \sum_g \text{DIRACIAN SUMMATION PULSE} \\
e_B(t) &= s^{(-m)}(t) * h_m^{(m)}(t)
\end{aligned}
$$

($y=1$ FOR ACOUSTIC RADIATION AND SCATTERING)

FIG. 10. Output of linear system. (With no bandwidth limitations).

I shall illustrate the principles involved by an example. In that example I shall use the simple impulse response function shown in Fig. 11, which yields three Dirac pulses. When one feeds the wide-band input signal shown at top of Fig. 12 into a system with the impulse response function we have just considered, the three Diracian output components are as illustrated in Fig. 12; the total output is as shown at the bottom of the picture. There are two Diracian summation pulses, the second being composed of only one Diracian output component. The envelope shapes of the two summation pulses are obviously different.

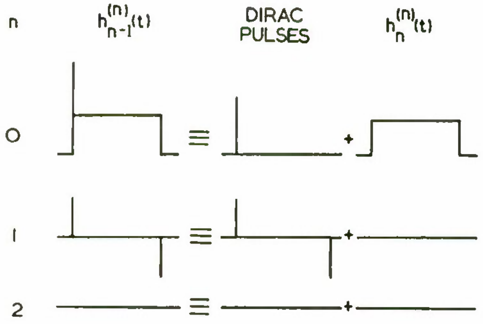

FIG. 11. Simple impulse response function used in next example.

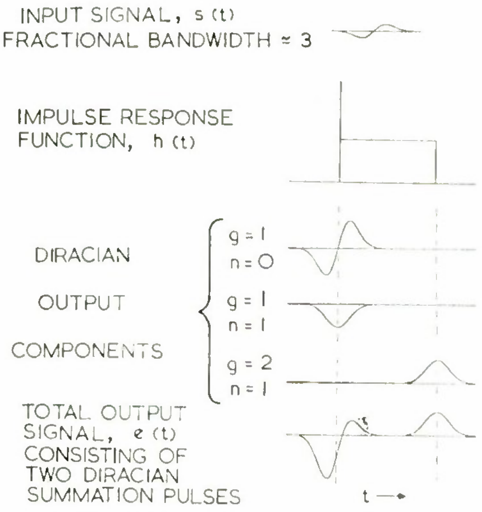

FIG. 12. Example of exact output waveforms for wide band input.

The Small Fractional Bandwidth Solution

When, in the general case, the bandwidth of the input signal is appropriately restricted, a considerable simplification is brought about. Denoting that the results are band limited by use of an upper tilde, the previous formulae reduce to the expressions shown in Fig. 13. Each Diracian output component associated with a Dirac pulse, at time t_g, in the nth derivative of h(t) is now a scaled, phase shifted and appropriately delayed replica of the input signal and not of the nth integral of the input signal. $e_B(t)$ consists of a scaled convolution of the mth stripped derivative of the impulse response function with the input signal and not with its mth integral.

For an input signal consisting of an amplitude modulated pulse with half sine envelope and containing 10 cycles at carrier frequency ω_0, a comparison is made in Fig. 14 of Diracian output components given by the exact expression and by the small fractional bandwidth approximation. They are plotted for three values of n-y. It turns out that, in the case of backscattering of a plane wave or of farfield radiation, these values of n-y are associated with certain geometrical features of the scattering or radiating surfaces, and these are also indicated in Fig. 14. For n-y=0 the approximate and exact curves are identical; for the other values of n-y the agreement is very good, and you may have difficulty in distinguishing that there are two curves. For an input signal of 5 cycles (Fig. 15), the agreement is still good. Even for an input signal of 3 cycles (Fig. 16), the agreement is still acceptable. Thus, the so-called small fractional bandwidth approximation appears to be satisfactory for fractional bandwidths as large as unity.

(SUPERSCRIPT ~ DENOTES BAND LIMITED APPROXIMATION)

$$\tilde{e}(t) = \tilde{e}_A(t) + \tilde{e}_B(t)$$

$$\tilde{e}_A(t) \simeq \sum_g \sum_{n=0}^{m} a(g,n-y)\;(i\omega_0)^{-(n-y)}\;s(t-t_g)$$

$$\simeq \sum_g \sum_{n=0}^{m} \text{BAND LIMITED DIRACIAN OUTPUT COMPONENT}$$

$$\simeq \sum_g \text{BAND LIMITED DIRACIAN SUMMATION PULSE}$$

$$\tilde{e}_B(t) \simeq (i\omega_0)^{-m}\;s(t) * h_m^{(m)}(t)$$

FIG. 13. Output of linear system. (Small fractional bandwidth approximation).

The Effect of Asymptotes

In some quite ordinary physical situations, at a given t_g, no Dirac pulses occur for any order of derivative of the impulse response function; instead asymptotes are encountered. For example, Fig. 17 shows the impulse response function relating the normal velocity of a circular piston to the resulting velocity potential at a nearfield point; the first two derivatives are also illustrated, and asymptotes are met from the first derivative onwards. Present information indicates that where the lowest derivative of h(t) in which an asymptote occurs is the nth, an output contribution is produced which is intermediate between what would be produced by Dirac pulses occurring in the nth and (n+1)th derivatives.

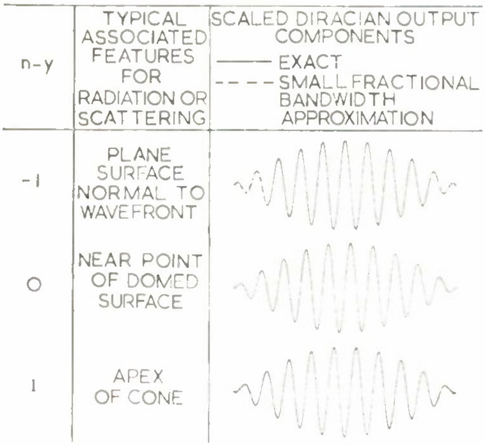

FIG. 14. Comparison of approximate and exact waveforms of Diracian output components. (Assuming input pulse with half sine envelope)).

Input pulse of 10 cycles and fractional bandwidth of 0·3.

The Effect of Dirac Pulses in the Input Signal or its Derivatives

Where the input signal or any of its derivatives also contain Dirac pulses, further series of output components result. For brevity, I shall not deal with these here.

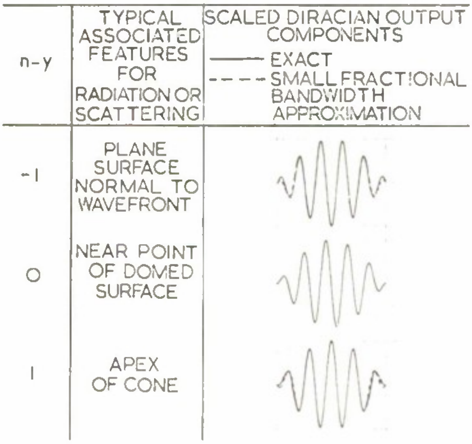

FIG. 15. Comparison of approximate and exact waveforms of Diracian output components. (Assuming input pulse with half sine envelope).

Input pulse of 5 cycles and fractional bandwidth of 0·6.

Relationship of Image Pulse and Replica Pulse Theories to the Linear System Theory

I shall next show the links between the Image Pulse and Replica Pulse theories on the one hand and the band limited solution of the linear system theory on the other.

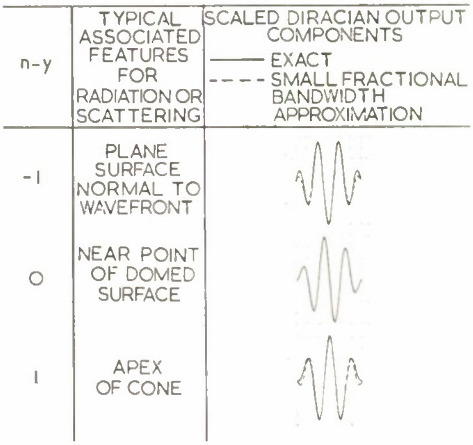

FIG. 16. Comparison of approximate and exact waveforms of Diracian output components. (Assuming input pulse with half sine envelope).

Input pulse of 3 cycles and fractional bandwidth of 1·0.

It can be demonstrated that the impulse response functions relating to the conditions of the Image Pulse and Replica Pulse theories are given by the expressions shown in Fig. 18. We need not bother about the definitions of the terms in square brackets. On substitution of these values of the impulse response functions, it is found that the output solutions previously given in the literature correspond identically to band limited expressions for $e_A(t)$. Addition-

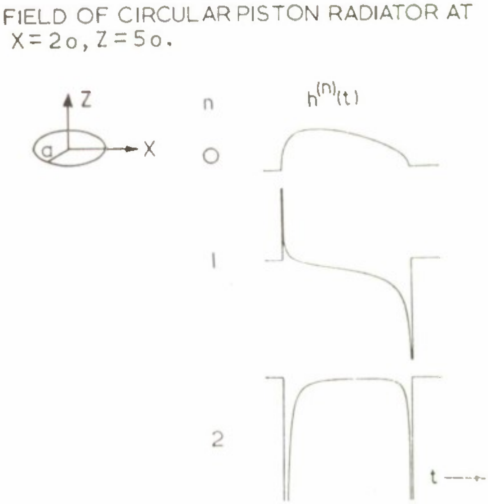

FIG. 17. Impulse response function and derivatives yielding asymptotes and no Dirac pulses.

	IMPULSE RESPONSE FUNCTION
IMAGE PULSE THEORY	$\left[\frac{-c}{2\pi}\right] W^{(2)}(r)$
REPLICA PULSE THEORY	$\left[\frac{\rho c^2 u}{2\pi}\right] C^{(2)}(r)$

SUBSTITUTING THE ABOVE:

THE OUTPUT SOLUTIONS PREVIOUSLY GIVEN IN THE LITERATURE CORRESPOND IDENTICALLY TO $\tilde{e}_A(t)$.

PREVIOUSLY DISCARDED REMAINDER TERMS CORRESPOND IDENTICALLY TO $\tilde{e}_B(t)$.

FIG. 18. Demonstration that Image Pulse and Replica Pulse theories correspond to particular cases of the linear system theory.

ally, it can be shown that previously discarded remainder terms correspond identically to the band limited expression for $e_B(t)$. Thus, the Image Pulse and Replica Pulse theories have been proved to be particular cases of the band limited solution of the linear system theory approach, and Image Pulses and Replica Pulses can be equated with band limited Diracian summation pulses.

Comparison of Band Limited and Non-Band Limited Results given by Replica Pulse Theory

We are now in a position to compare the approximate, band limited results given by the Replica and Image Pulse theories with the results when there is no bandwidth approximation. For convenience, examples of radiated fields are presented, but similar results could be shown for backscattering. Of course, any inexact physical assumptions will result in approximations in the impulse response function, h(t), and we are not here considering the effects of such assumptions. What we are considering is, given an impulse response function, what is the effect of using the small fractional bandwidth approximation.

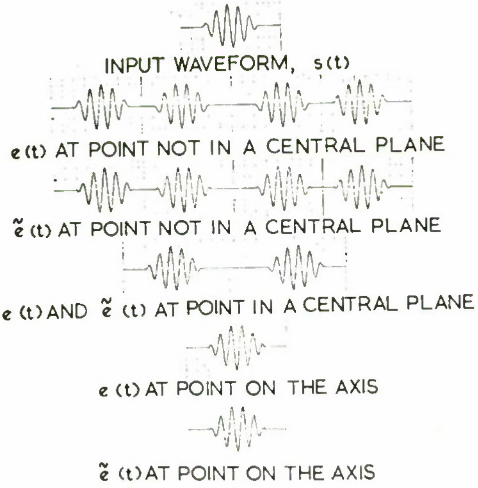

FIG. 19. Pressure in farfield of rectangular piston.

Three types of situation will be illustrated. The first is one in which, for given t_g, Dirac pulses occur in only one order of differentiation of h(t). This situation is illustrated in Fig. 19 by the farfield of a rectangular piston. We recall that e(t) represents the output calculated using the formulae without bandwidth approximation, while $\tilde{e}(t)$ represents the output when the small fractional bandwidth approximation is employed. Careful examination will reveal only very minor differences between approximate and exact curves. The second situation is one where, for given t_g, Dirac pulses occur in more than one order of differentiation of h(t). The example presented in Fig. 20 of that type of case is the axial farfield of a uniformly vibrating, conical radiator. Output components are associated with the cone apex and with the base rim, and the Diracian summation pulse associated with the rim is furthermore made up of two components. The waveforms of the

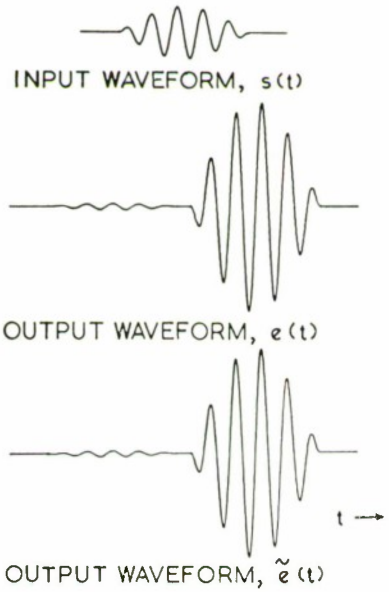

FIG. 20. Axial pressure in farfield of conical radiator of height $5{\cdot}5\lambda_0$.

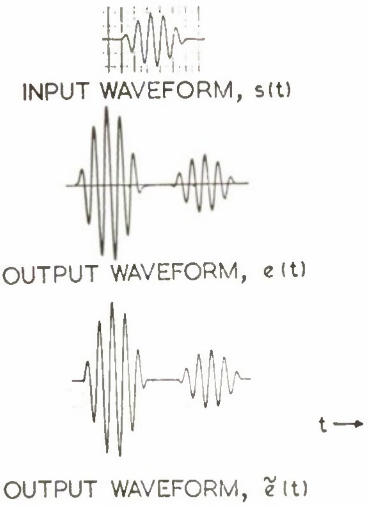

FIG. 21. Pressure in nearfield of circular piston ($a=10\lambda_0$, $X=2a$, $Z=5a$).

band limited and non-band limited solutions are such that no difference is distinguishable by eye. The third situation is one where no Dirac pulses occur at any time in any derivative of h(t). This is illustrated in Fig. 21 by the field of a circular piston. For this example, the Replica Pulse approach was supplemented by an asymptotic expansion treatment(11) in order to get the small fractional bandwidth solution. The two field components you see in Fig. 21 are associated with the near and far points of the radiator, respectively. I think you will agree that Figs. 19, 20 and 21 demonstrate that, for an input pulse containing even a very few cycles, the restricted bandwidth approximations used in the Image and Replica Pulse theories give results very close to the true, non-band limited waveforms.

Conclusion

In conclusion, looking at the linear system interpretation in a wider context than acoustic scattering and radiation, I believe the concept could have worthwhile applications in a number of areas. The theory is still in process of development, and I expect applications will emerge. Some suggested potential applications include estimating the distortion in servo-mechanism transients, filter design, classification and signal to noise problems.

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Admiralty Underwater Weapons Establishment

Retirement of Dr. G. L. Hutchinson, Director of AUWE

Most of Dr. Hutchinson's career was spent in the radar and guided weapon fields. He was involved in radar from the very beginning of the last war when he joined the Air Ministry in 1939. He was then posted to RAF 60 Group and in 1942 went to TRE to work on airborne radar. Subsequently he spent seven years in the GW Department of RAE followed by a tour with BDS Washington after which he returned to Malvern. In 1963 he was appointed DCSO Head of the Electronics Group at RRE and also became Chairman of the CVD Technical Committee. Towards the end of 1967 he was promoted to CSO and appointed Deputy Director (Military and Civil Systems) at RRE. In both these posts Dr. Hutchinson was always concerned to ensure that the advanced research in the establishment was relevant to applications in practical systems.

Dr. Hutchinson was appointed Director of AUWE in March 1971. He quickly familiarised himself with the many new technologies of the underwater field and the special problems of the Naval environment. Above all he devoted himself to promoting the interests and well being of all members of his staff, and his personal knowledge and familiarity with so many individuals in his establishment was quite outstanding. The same straightforwardness and sympathy have characterised his dealings with various groups, notably the Staff Associations and Trade Unions.

Dr. Hutchinson came to office at a critical period when the building up of large development teams in industry required the smooth transfer of specialised knowledge from AUWE. He was also at the helm during the reorganisation following the Rayner Report, which affected AUWE more than most establishments. During his term of office many important projects in which AUWE has played an essential part have come to fruition or have achieved significant milestones. He will be particularly remembered for AUWE's first ever Open Days in 1974 and was the inspiration behind all the hard work and enthusiasm which made these occasions an outstanding success which did a great deal to increase the awareness of AUWE's capabilities and achievements.

Dr. Hutchinson's retirement was marked by a dinner in his honour held on Tuesday 30th September, 1975 at which Mr. S. E. Shapcott, Director of Underwater Weapon Projects, presided and Mr. B. W. Lythall proposed the toast.

Admiralty Surface Weapons Establishment
C. P. Fogg, C.B., M.A., i.d.c.

Mr. Fogg, Director ASWE since January 1973, retired from the Service in December 1975.

After leaving Gonville and Caius College, Cambridge, taking a 1st Class Honours in the Mechanical Sciences Tripos, Mr. Fogg had a period at the Research Laboratories of the General Electric Company engaged on the early development of television. He joined the Government Service in 1937 as a member of the early radar team led by Watson-Watt, which was working at the Air Ministry Research Establishment at Bawdsey. He remained with that establishment during its wartime moves and several changes of name and held a number of senior posts including Superintendent of the Basic Techniques Division and Head of the Ground Radar Department in the then Radar Research Establishment. On transfer to London in 1959, Mr. Fogg held senior positions in the fields of Guided Weapons and Electronics Research and Development, ultimately holding the appointment of Deputy Controller, Electronics.

In January 1973 Mr. Fogg was appointed Director ASWE. He came to the establishment when it had recently undergone a radical reorganisation following the Rayner Report and at the same time was under great pressure to support an increasing Naval Weapon Equipment Programme. In leading the establishment during this difficult period, and responding to these pressures, Mr. Fogg also stressed the need for a systems approach to weapon equipment design, the maintenance of a healthy balance between project and research activities, and a strengthening of the professional quality of the establishment by attention to all aspects of personnel development-recruitment, training, career planning, etc. This latter aspect was a continuation of an interest and concern which he had shown throughout his career.

The photograph shows Mr. Fogg leaving the establishment on his last day.

Mr. Fogg was President of the ASWE Sports and Social Club and he and Mrs. Fogg took a keen interest in its many activities. His leisure pursuits include foreign travel, caravanning and 'Do-it-Yourself'. Mr. and Mrs. Fogg will continue to live at Bosham in retirement. The photograph shows him, in company of his colleagues, leaving ASWE for the last time.

Director of Research (Ships)

F. S. Burt, the first Director of Research (Ships) retired at the end of May 1976, after four years in a most difficult and demanding post. In addition, he was the Chief Scientific Adviser to the Director General Ships. Either role demands the patience of a Job and the judgement of a Solomon. That he managed to be really effective in both at the same time speaks volumes for his technical ability, his powers of communication and his energy.

Francis Burt, B.Sc., A.C.G.I., D.I.C., C.Eng., F.R.Ae.S.

After graduating at Imperial College in 1937 with a First in civil engineering, his initial intention was to pursue an academic career and he took a post graduate DIC in aeronautics. However, the war came. In 1940 he joined the Admiralty Research Laboratory to work under Dr. Townend on problems of air flow over ships.

In 1947 his ability was recognised when he was promoted SPSO and appointed Assistant Director in the Department of Aeronautical and Engineering Research. He was 31 at the time and it is thought that he is the youngest SPSO ever. With the Department of Aeronautical and Engineering Research he was mainly involved with the problems of naval aircraft and was largely instrumental in setting up the steam catapult group at Farnborough.

In 1949 he returned to ARL at Teddington to set up a completely new fluid dynamics group and laboratory. There he created a strong and enthusiastic team backed by major research facilities such as the rotating beam tank and the water tunnels. The quality and impact of his work and leadership was such that he was promoted Deputy Chief Scientific Officer in 1953. Some idea of the range of the work of this group can be gleaned from Mr. Burt's 92 page contribution to the Book 'Advances in Hydroscience' published in 1964 by the Academic Press. In 1968 he moved to the Admiralty Underwater Weapons Establishment at Portland. As Deputy Director, under Dr. Benjamin, he was responsible for the day to day running of the Establishment and was particularly concerned with torpedo and weapon problems.

In 1972 he was appointed Director of Research, Ships, responsible for the whole research programme for ships and submarines which takes place both in industry and in many service Establishments, principally AEW, NCRE, AEL, AOL, ARL, AUWE, AML, NGTE and AMEE. During the last four years in Bath Mr. Burt has welded together the research activities of Ship Department over a vast field, driving himself hard and keeping others on a steady course. Anyone who has been to one of his progress reviews will appreciate his alertness and grasp of fundamentals, coupled with a quiet insistence of keeping to a consistent policy.

Four years is a short time in which to produce spectacular results from research and development. Nevertheless, he has laid secure foundations in many fields and the Navy will benefit for many years to come.

Francis married in 1944 and his family now includes three daughters, two sons and one grandchild.

NOTES AND NEWS

Admiralty Underwater Weapons Establishment

Mr. I. L. Davies, the new Director of the Admiralty Underwater Weapons Establishment, was educated at Barry Boys' County School and St. John's College, Cambridge. He took the Mechanical Sciences Tripos in 1944, and was then directed to TRE Malvern, which he joined as a JSO, and worked on ASV radars. A year later he became one of the founder members of the joint RAE/TRE Blind Landing Experimental Unit at Martlesham Heath, and for the next two years contributed to the establishment of the techniques which led to the "Autoland" system. He then returned to Cambridge to read mathematics, and became a Wrangler in 1949. Rejoining TRE at Malvern he worked in the mathematics group on the applications of information theory to radar with P. M. Woodward for a couple of years, and then began to turn his theory to more practical use in Airborne Radar Group where he worked on the techniques and applications of sideways-looking airborne radars, and, later, on the development of coherent air intercept radars.

He was promoted SPSO in 1960 on appointment as Superintendent, Microwave and Quantum Electronics Research, leading teams working on masers, lasers and millimetre wave diagnostic equipment. Five years later, in 1965, he returned to Airborne Radar Group on promotion to DCSO, as its Head.

He left Malvern to join the 1970 Course at the Imperial Defence College (now the Royal College of Defence Studies) and at its conclusion was promoted to CSO as Assistant Chief Scientific Adviser (Projects) on MOD Central Staffs. In 1973 he became Deputy Controller Electronics in CGWL, and later that year, on the disbandment of that Controllerate, he became Deputy Controller Air Systems (D), having responsibility for the procurement of airborne radar, communication equipment and air launched guided weapons for all three Services, and for the ground based radar and communications for the RAF. He remained in this appointment until his transfer to AUWE in 1975.

Mr. Davies has played an active role in the Institution of Electrical Engineers, and is currently Chairman of the Electronics Divisional Board, and a member of the Council.

Mr. I. J. Campbell, at present Head of XW Department, has been appointed to the post of DR Ships, on promotion to Under Secretary.

Dr. J. L. Willis has been promoted to SPSO and appointed as Head of Submarine Discharge and Ship Engineering Division, as from 7th April, 1976.

Dr. T. Buckley, at present an SPSO at RSRE, has been appointed as Head of the Data Processing and Displays Division, AUWE. The date on which he will take up this appointment has yet to be determined.

Over 130 delegates from six countries visited the Establishment for a conference, organised by the Institute of Acoustics, entitled 'Recent Developments in Underwater Acoustics'.

During the two days 17 papers were presented on subjects ranging from 'Underwater Sound Transmission' to 'Laser excited thermo-acoustic arrays'.

The delegates attended a cocktail reception at H.M.S. *Osprey* on the first evening.

Sir Eric Eastwood, retiring chairman of the Electronics Research Council made a farewell visit to AUWE on 27th April.

Dr. W. H. Penley, C.B., C.B.E., C.E.R., made an introductory visit on 23rd March.

Admiralty Surface Weapons Establishment

Dr. J. E. Wood, D.C.S.O., has been transferred to the Establishment from AUWE on taking up his appointment as Head of the Weapon Systems Department. Dr. D. H. Davies, the former holder of this post, has now taken over as Assistant Chief Scientific Adviser (Projects) and works from his office in the Main Building in Whitehall.

Mr. A. F. C. Sleigh, DCSO, who had been serving as Deputy Director to DSWP(N) responsible for Surface Guided Weapon Projects and Gun Systems has now taken over as Head of the Sensors and Structures Department on the staff of Director/ASWE. Mr. A. S. Martyn has been promoted DCSO on taking up Mr. Sleigh's former appointment as DD in DSWP (N).

Mr. D. McArthur was promoted to SPSO on taking up his new appointment as Assistant Director in charge of AIOs, Data Links and Trainers in DSWP (N).

Mr. G. H. Glover, SSO, has now returned to the Establishment following his attendance on the Guided Weapons Long Course at the Royal Military College of Science at Shrivenham.

Recent months have seen the retirement of some long-standing senior members of the Establishment's staff. These include Mr. J. T. McKenna, SPSO, Mr. F. M. Foley, SPSO, Mr. C. W. Brooks, SSO and Mr. E. D. Young, SSO.

(Left to right) Messrs. Lythall, Mountain, Penley, Alvey, and A. F. C. Sleigh, new Head of Sensors & Structure Dept.

Dr. W. H. Penley, CER, accompanied by Mr. B. Lythall, DCERA, visited ASWE on 3 February, 1976. The photograph shows Mr. D. S. Mountain discussing with Dr. Penley aspects of the work undertaken in the establishments Mechanical Engineering Laboratory.

Admiralty Research Laboratory

Mr. K. A. G. Taylor, PSO retired from ARL on 28th May after almost 40 years service, most of which he spent in the Navy Department.

Mr. Taylor joined ARL in 1937 as a laboratory mechanic and during his 16 years there he was promoted to SEO before moving to Portland with the Admiralty Gunnery Establishment. After four years at Portland he moved to AWRE where he was in charge of the Radioactive Component Manufacturing Workshops until 1959. He then moved to ASWE where he was responsible for the Workshop.

After a short spell in London with SSP in 1970 he returned in 1973 to ARL where he has been employed in Management Services, dealing with training, recruitment and career development.

At his retirement party Mr. A. B. Mitchell, the Director of ARL, presented him with a set of binoculars from his colleagues.

Mr. H. G. Rissone, who has served in Underwater Acoustics Groups at ARL since 1951, has been promoted to SPSO in the post of Superintendent of Noise Ranging.

This post has recently been created to take account of the greatly increased responsibilities of the Noise Reduction Group, headed by Mr. G. J. Barber.

Naval Construction Research Establishment Anglo French Collaboration Committee

The latest of the regular meetings of the above committee was held at NCRE Dunfermline on 6th May 1976. The representatives from France were headed by Monsieur Pinchon and those for the UK by Mr. R. Hawkes.

The discussion which took place concerned the progress and problems encountered in surface ship research and development, of mutual interest. In particular the vulnerability and the structural design of all types of surface craft were discussed.

The following day, 7th May, 1976, the committee were taken on a conducted tour of the facilities at NCRE. The tour enabled the committee to gain at first hand an idea of work and the scale of the tests being carried out at NCRE into surface ship design and construction problems.

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