TRANSACTIONS (TM)

The Institute of Marine Engineers

PAPER No. 13.

BIOLOGY IN SHIPS

D R Houghton and S A Gage

ISSN 0309-3948
Trans I Mar E (TM) Vol 91 Part 11
Paper No. 13

THE INSTITUTE OF MARINE ENGINEERS
76 Mark Lane, London EC3R 7JN

Telephone: 01-481 8493 *Telex: 886841*

All papers are indexed in the British Technology Index

Paper read at The Institute on 9 January 1979

BIOLOGY IN SHIPS

D R Houghton BSc MIBiol and S A Gage BSc PhD MIBiol *

SYNOPSIS

Biological aspects of the fouling of ships have been reviewed and the need for care in applying remedial measures stressed. Some microbiological aspects of attack have been considered, both with regard to their effect upon materials and, more particularly, in respect of the contamination of fuel used for gas turbine engines in RN ships. The importance of monitoring the Fleet to achieve early awareness of possible build-up of infection has been outlined. The role of the biologist in providing the research and support needed in both fouling and microbiological problems has been reviewed.

1. INTRODUCTION

Excluding human factors and infestation caused by rodents and insects, the biologist encounters many problems which are peculiar to ships and their operation. Some of these affect ships' systems directly whereas others, although less obvious, have a serious effect on overall efficiency. It will be convenient for the purpose of this paper to consider problems exterior to the vessel and those internal to the structure. It must, however, be appreciated that this is a purely arbitrary division which does not avoid certain overlaps. Biologically speaking, problems encountered in vessels cover a wide variety of organisms, ranging from fungi and bacteria through to simple plants and a number of animal species. This diversity often makes effective control difficult since the effect of any treatment on human beings has to be taken into account. Despite these difficulties, it is the function of the microbiologist and marine biologist to study these problems and provide the necessary remedial advice. However careful and diligent these specialists may be, they often rely to a very large extent on information and occasionally samples supplied by ship board personnel from which the case-history of a particular problem can be formulated. Accuracy is necessary to ensure that suggested control methods are in the first place effective and secondly, that if possible there will not be a re-occurrence. It is in this role that the engineer can be helpful. The problem areas will now be considered in greater detail.

2. EXTRA-HULL

These can be divided into those occurring below the waterline and those on the ships upper work where micro-organisms have caused serious problems in the biodeterioration of life-raft materials and cordage. To a large extent these have been overcome by the use of synthetic materials rather than natural products. In the case of wooden hulls boring organisms may be of considerable importance.

2.1 *Marine Fouling*

The importance of keeping the underwater surface of a ship's hull as smooth as possible to enable it to reach a performance approaching its design capability, is still not universally recognised by those most closely associated with the operation of ships. The present method of obtaining protection, both from the point of view of corrosion and fouling, is by painting the hull with a suitable composition. This operation is often the most hurried part of the in-dock treatment. Care in the application of these paints would pay handsome dividends. It is a case of out-of-sight out-of-mind because there are no immediately obvious indications of the benefits to be derived. There are, however, a few examples which emphasize the need in a dramatic way.

Admiral Rodney's victory over the Spanish in the West Indies in 1780 was, apart from tactical skill, attributed to the fact that the outer bottoms of his ships were clean because of their being coppered. Indeed, in the last war, the loss of the Pocket Battle Ship *Graf Spee,* was attributed by the German High Command to the fact that she was foul through being too long out of dock, with a consequent loss of speed and manoeuvrability. More recently, in 1968, the *RMS Queen Mary* was idle for 8 weeks in Southampton water due to a seamen's strike. The ship was cleaned by divers before sailing but took an extra day on her journey over the Atlantic. Part of the trouble turned out to be a cracked propeller. This defect was rectified and the opportunity taken to clean and paint the outer bottom. Significantly, on the return journey, she equalled the time of her record-making blue riband crossing which had been set up 30 years earlier.

* H M Naval Base Portsmouth

It is very difficult to obtain precise figures for the cost of fouling, but some attempts have been made to obtain reasonably reliable estimates. Among the more recent (1) it has been stated that even moderate fouling on a tanker can increase the fuel consumption required to maintain speed by 30%. Another estimate (2) states that during the life time of a frigate or destroyer about half the fuel consumed is used in overcoming the drag of the water on the hull. In addition, it records that of the RN fuel bill of £20m per annum, £3.8m is spent on overcoming the effects of roughness and fouling.

The recent economic crisis does appear to have produced a greater awareness of the fouling problem. The penalties involved are due to the increase in skin frictional resistance which reduces the top speed attainable by several knots and produces a marked increase in fuel consumption when maintaining the normal cruising speed. In addition, are the costs of taking remedial action and the loss of earnings during that period.

The species which constitute fouling are those sedentary organisms which occur in nature on substrates supplying a reasonably firm base on which to settle. Some of these species, or at least their near relatives, can be seen on the sea shore and others may be seen when diving in coastal waters. However, not all the species occurring in these habitats are found in ship fouling. Indeed, the list is short in comparison with the number available. The phenomenon is generally regarded as being restricted to harbours and coastal waters. There is an exception to this rule which was well known to the captains of the old Clipper Ships, who had a dread of being becalmed in the open ocean, not only because this cost them time on their journey, but also because they were almost certainly going to collect stalked barnacles on the outer bottom (see Fig 1). From experience they knew these would seriously effect the speed of their remaining journey. The problem has now re-appeared on tankers which have stopped to carry out cleaning operations at sea.(3)

FIG 1 *Photograph of living specimens of stalked barnacles removed from the sailing yacht British Steel*

When a non-toxic surface is immersed in the sea, it quickly absorbs organic compounds and within hours there will be a flourishing growth of bacteria. (4) This will be followed by the microscopic algae (the diatoms) and those animals, some of which show plant-like characteristics, the Protozoans, members of the so-called slimes. Subsequent colonization is by the macroscopic species of algae and animals, which are the ones commonly seen on ships' hulls. There is a good deal of speculation about the sequential nature of the build-up being due to the conditioning of the surface before settlement of further species can occur, and may be conversely, preventing others from settling. Whilst there is evidence to support these views, it has been difficult to establish such relationships with any degree of certainty. In practice it is observed that the most important fouling species appear to need little conditioning, if any, of the surface before being able to colonize it.

Fouling of ships occurs because of the overriding necessity for the sedentary organisms in the sea, whether they be plant or animal, to find a suitable firm substrate on which to settle in order to complete their life history. There are, however, certain differences between them. The most obvious is that the algae settles profusely in the more well lit areas close to the sea/air interface. Although on the whole the competition is not mutually exclusive, animal species tend to settle in greater numbers further down on the hull. An important difference also exists in the conditions under which they can settle. A water speed, over the surface, of 2 knots will effectively prevent the settlement of all animal species. But this is not true for the algae whose spores can attach even when the vessel is moving at apparently high speeds. (5) The explanation appears to be that the spores of the algae are small enough to enter that part of the hydrodynamic boundary layer surrounding the hull known as the laminar sub-layer immediately adjacent to the surface. They are thereby protected from the shear forces which would otherwise tend to dislodge them. The animal larvae, on the other hand, are by comparison large and can only obtain protection when the laminar sub-layer is relatively thick, which occurs only at low speeds.

One of the incidental consequences of ship fouling is the spread of species to other parts of the world where they have not previously been established. Perhaps one of the more spectacular instances was the barnacle *Elminus modestus*, which was well known in the temperate regions of the Southern Hemisphere but not in the Northern. In 1944 one specimen was found on a non-toxic panel exposed in Chichester Harbour (see Fig 2). The conditions obviously suited the newcomer for it is found all round the coast of the British Isles and along the European Coast from Spain to Denmark. The most probable explanation is that the species was introduced on the hull of a war ship making a fast passage to the United Kingdom and it was thus able to survive the journey through the tropics. The sea-squirt *Styela clava,* which was first found in Plymouth Sound in 1953, was almost certainly brought back to our waters on the bottom of a tank-landing craft returning from the Korean War. These two examples are interesting because in the case of the barnacle a fast ship was the means of introduction, whilst the sea-squirt was brought back by a slow moving vessel. If the position had been reversed, it is extremely unlikely that either species would have reached these shores: slow passage through the tropics would have been too much for the barnacle and with a fast moving ship the sea-squirt would have been torn away long before it reached these shores.

The most important fouling species are those with hard shells such as the calcareous tube-worms, oysters and barnacles. The latter are probably the most ubiquitous and are the dominant species in fouling in many parts of the

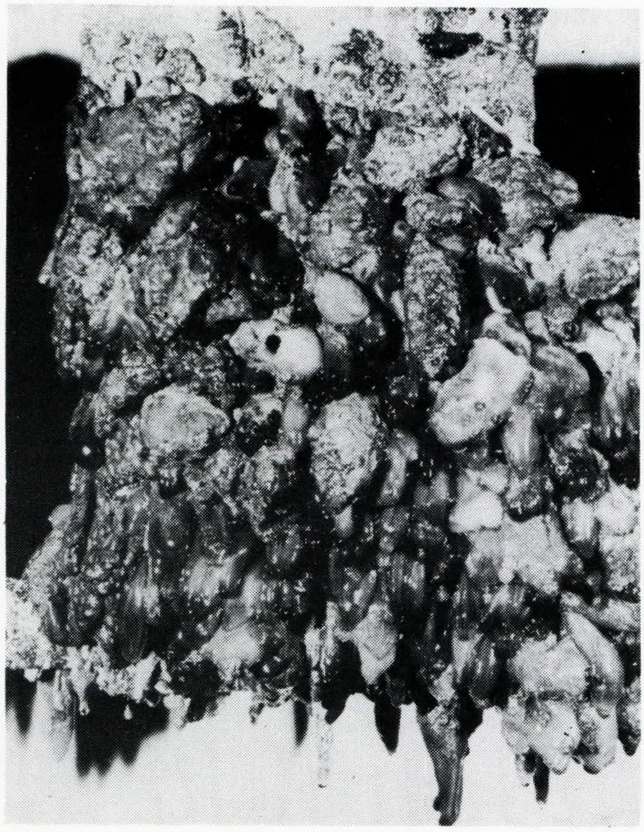

FIG 2 *Climax community of fouling species on a non-toxic panel exposed in temperate waters dominated by Tunicates (sea-squirts)*

world. However, in areas such as the Mediterranean the calcareous tube-worms dominate and the barnacles are more minor members of the fouling community. Mussels are of little consequence in the fouling of the outer bottom of active ships being quickly swept away, if they have settled, when the ship is moving at speed. They are, however, a problem when they settle in ships' sea water systems. Although they are usually the most troublesome, other organisms such as barnacles and hydroids are also frequent colonizers. The latter are often found in great profusion in the end-boxes of heat-exchange elements and the former frequently make a significant contribution to reducing the bore of the pipes associated with these systems. Another problem which arises, due to individual mussels, is that of inducing impingement attack and hence perforation of heat exchanger tubes. Intake screens may be locked by dense mats of free floating seaweed which get drawn over the inlet so forming a very efficient filter, which allows only a very much reduced quantity of water to flow through it. On odd occasions the soft bodied tunicates (sea-squirts) have been reported to have produced the same effect.

Not until the last two decades was very much attention paid to the algal fouling since it was not thought to contribute significantly to the drag. There was even a feeling among some people that as they contained mucopolysaccharides they would reduce the effect. This has been shown to be a nonsense since the order of increase in skin frictional resistance is comparable to that caused by animal fouling of a similar intensity. It has also been demonstrated that the presence of the slime-forming organisms contributes markedly to skin frictional resistance.

The way in which fouling organisms reproduce differs from species to species and from the plants to the animals, but this is one of the most important factors in their survival. The common element is that all the reproductive elements, whether it be spores of the algae or the larvae of the animal species, are shed into the sea and are at the mercy of the currents for some time. This period may be very short or of several weeks duration.

Probably the most common species of algae to be found in ship fouling are those of *Enteromorpha* which are usually responsible for the "grass" at the water line. These species reproduce by both sexual and asexual means. In the former, motile gamates are formed which fuse together producing a zygote which settles and grows into a new plant. Asexual reproduction is achieved by division of the contents of the cells of the thallus into 16-32 zoospores which are shed and settle without fusion to produce new plants. There is some evidence to show that in these species the gametes do not always fuse before settling and new plants are produced parthenogenetically. The period spent in the plankton can be extremely short in these species. The barnacles, however, reproduce by a sexual process but self-fertilization can occur, at least in some species. After fertilization, the eggs develop into larvae known as first stage nauplii which are released into the plankton, these then go through successive moults becoming increasingly complex through the naupliar stages I-VI and finally develop into a cypris stage, which is the one that settles on any available surface. The total length of time spent in the plankton can vary from one to several weeks which allows for a greater chance of dispersal.

Despite the over-riding necessity for barnacle larvae to find new settling sites, and although they can "swim", they are largely at the mercy of the currents and will find a new surface mainly by chance. The process however, is not an automatic affair. The cypris will explore the surface "walking" on its antennae and will often detach and alight on another part several times before final attachment. They will also, when given the choice, settle in greater numbers on dark as opposed to light surfaces. Removal of the choice will lead to attachment to whatever surface is available. They also preferentially settle alongside protuberances such as a paintbrush hair trapped in the painted surface, aligning themselves neatly on either side. They also occur in grooves in the surface. In the motile larvae, such as a cypris, it is not difficult to see how this could be achieved, but the same phenomenon is also found in the settlement of algal spores.

The major problem is to prevent the attachment and development of fouling species, a process in which copper has been prominent, first as copper sheathing where the prime purpose was to prevent the ingress of "ship-worm" and to a lesser extent "gribble" into the ships' timbers. However, it was discovered that the copper would also protect the outer bottom against sedentary organisms. Later, when paints were developed, cuprous oxide was found to be a very effective poison and its use has continued until the present day. Even with modern paints which utilize other toxins (eg TBTO), copper is often included in the formulation. The main problem with the copper-only paints is that they lose their effectiveness after they are dried out for any prolonged period. Although it is difficult to establish a precise time limit, 7 - 10 days is usually sufficient to produce this effect. The phenomenon has considerable importance for ships with a large change of draught between the laden and unladen condition.

At present the only practical means of protecting a hull is by the use of a paint which provides a controlled release of an effective poison. Alternatives to the conventional paints, such as Self-Polishing Co-Polymer, have been devised to give greater controlled release, but they are not effective on ships which are stationary for a considerable amount of their operational time, as is the case with naval vessels in peace time.

3. INTRA HULL

Both fungi and bacteria are important with regard to problems occurring on board ships. They will attack singly, or in combinations, a whole range of carbon based materials and can damage others by products produced during their metabolism. Conditions within a ship are usually fairly ideal for micro-organism development, whether they be within "closed systems", e.g. fuel tanks, or the general environs of the vessel. Micro-organism development will proceed in the presence of small traces of water, e.g. condensation, and nutrients. In the case of the latter, volatilized lubricant and cooking oils condensing on surfaces can be sufficient for growth to take place.

Spoilage of materials may occur in several ways. With solid substrates the material may be directly attacked and undergo changes in tensile strength as the enzymes secreted by the organisms soften up the material. Examples of this are all untreated natural fibre products, e.g. ropes and cotton based fabrics, and some materials based on natural rubber. Polymeric products, such as plastics and neoprenes, which would not normally be attacked by micro-organisms, can become damaged through a secondary process of micro-organism growth on water/hydrocarbon condensate, where acidic metabolic by-products will attack or etch the material. This process may even cause enhanced corrosion or pitting of metals. (6) In addition, a heavy development of micro-organisms on equipment may even be enough to impair physically its efficiency. This can be serious with optical apparatus, electronics, and air conditioning equipment where extensive fungal/bacterial growth can occur on grilles.

The various fluid systems associated with ship operation may also be vulnerable to attack and the problems they cause are varied. In some cases, e.g. hydraulic fluids, development may lead to physical blockage within fine servo mechanisms. In others, where there is an interface between an aqueous and non-aqueous phase, micro-organism development will tend to encourage the formation of stable emulsions. This can be serious in lubricant systems where damage may occur to machinery.

The use of gas turbine main propulsion systems within the Fleet has brought to the fore the problems caused by "bugs" or micro-organisms aboard ships. The problem is not new and was first encountered some 20 - 25 years ago with fungal growth in aviation fuel. (7) It was discovered that where fuel was being stored in tanks and a water bottom was present, a thick slimy micro-organism mat would develop at the fuel/water interface. It was discovered that anti-icing additives would deter micro-organism growth and, with a policy of keeping fuel as dry as possible, and increased cleanliness in storage, the aviation operators have managed to contain the problem.

Although the Royal Navy has experienced problems with aviation fuel (AVCAT), these have largely been overcome. The prime problem at present is organism development in DIESO fuel, especially aboard gas turbine ships (see Fig 3). It would appear that growth in RN ship fuel tanks is not a new problem. The finer specifications required for fuel burnt in turbines has led to fine filtration and water removal equipment being fitted to ships with this type of propulsion, and it is here that microbiological contamination has become a major problem.

In the first place growth within fuel tanks will occur as soon as free water is present, which may either be condensate, or the result of adding seawater to ballast the system. There is good reason to believe that all fuel reaching a ship will be infected, to a greater or lesser degree, with either resting spores or with hyphal threads. These will arise from the storage and handling of the fuel after it has left the refinery, and by contact with already contaminated fuel.

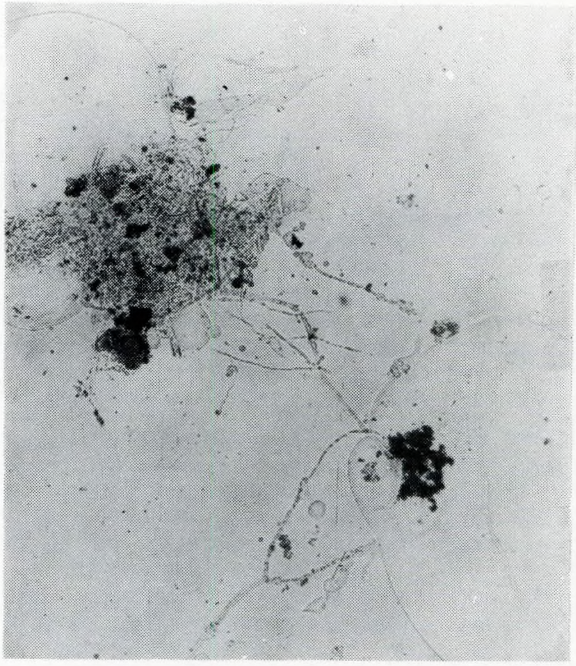

FIG 3 *Fungal hyphae in DIESO/water (x 400)*

Often the storage and handling will worsen the situation regarding contamination, since fuel may remain in land storage tanks for long periods, and it may be transported in Royal Fleet Auxiliary tankers where levels may be particularly high. Growth will start at the water/fuel interface as a brown slimy layer a few millimetres in thickness. Depending on temperature, development may be rapid and within six months may reach a thickness of 1 centimetre or more. Islands of slime will detach and sink to the tank bottom where a thick growing bottom layer will develop. At this stage organisms producing corrosive by-products can develop and pitting of the tank occurs if it is uncoated. There is also a tendency for the interface to form progressively stable emulsions, which contributes further problems. As the fungal mat develops it also tends to act as a trap for any particular matter present such as rust and paint flakes, leading to a rapid increase in depth. Additionally, micro-organism development will occur in other parts of the fuel system, and can be particularly heavy on coalescer elements.

The effect of micro-organism growth is two-fold. Once the material becomes mobile it is effective in blocking filters and clogging coalescer. Also, it will tend to reduce water coalescing action through the production of surface active materials. These effects result in the reduction of turbine power, leading to a loss in the vessels operational efficiency.

4. CHARACTERISTICS OF MICRO-ORGANISMS

In the first place they are usually microscopic and can only be seen by the unaided eye in aggregate, or their presence inferred by the effects they have on materials. Biologically, the term "micro-organism" is somewhat artificial and does not infer that all micro-organisms are related or similar in their responses. Micro-organisms can be divided into fungi and bacteria, both groups showing wide variations in size, growth requirements and tolerances to physical parameters. With the possible exception of some small highly specialized groups of bacteria, they all require an organic source of carbon and cannot manufacture their own food from carbon dioxide and sunlight. They reproduce by the production of minute spores which are fairly remarkable structures. Spores are usually hard-coated and can remain dormant for periods of tens of years. In addition, the spore stage is also extremely resistant to adverse external parameters. It is not uncommon, for instance, for both fungal and bacterial spores to survive temperatures of 100°C for several hours. At the other end of the scale they can survive at temperatures of liquid nitrogen (- 195°C), and can resist desiccation. Regarding other parameters, spores may show a high resistance to acid and alkali conditions, ionizing radiation, and biological poisons. Both bacterial and fungal spores are produced in extremely large numbers, and being so small, easily become airborne. It is therefore fairly safe to assume that most surfaces are subjected to continual exposure and infection.

4.1 *Fungi*

Although some of the fungi or "moulds" produce macroscopic structures, e.g. mushrooms and toadstools, most of them remain microscopic becoming visible only when the thin threads, or hyphae, that constitute the colony, aggregate. [8] Some fungi, e.g. yeasts, remain one-celled throughout their life-cycle, though most of them will form loose colonies of ramifying threads. Hyphae are usually fairly simple in structure and can either consist of a chain of cells joined end to end, or a long continuous thread without cross divisions which, in effect, is a single giant cell. Growth will proceed from the hyphal tip, where the formation of branches may also occur. Reproduction in the fungi can be complicated since there are three types. In the first place small pieces of the hyphae may become broken off and form resting structures which will germinate to produce an exact replica of the parent. The second and third methods rely on spore production. These can be formed on simple branch-like structures produced from the parent hyphae (see Fig 4), or may be carried on complex hyphal aggregate structures, such as puffballs and truffles. Spores may arise either from asexual (from one parent) or from sexual (two parents) processes. As is the case with all living organisms, the latter carries with it the possibility of genetic recombination, and hence the manifestation of new characteristics in the progeny. In some of the fungi the possibility of genetic recombination no longer depends on a sexual phase in the life cycle. This happens in the "one celled" hyphae where there are no cross walls to impede the

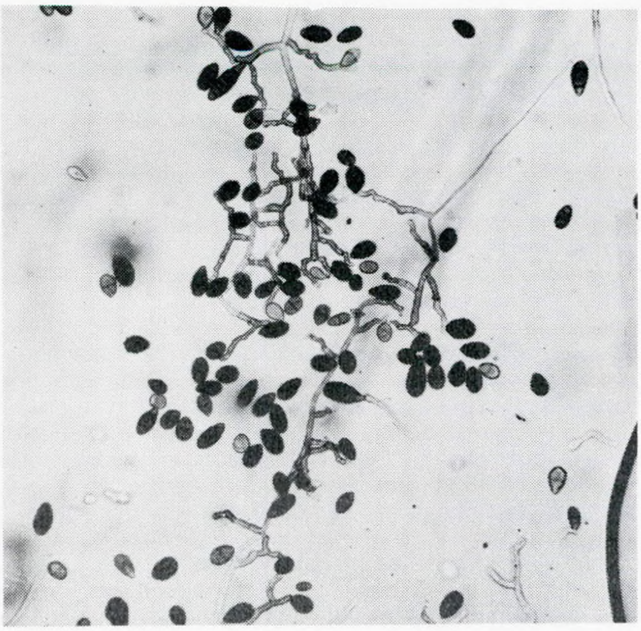

FIG 4 *Fungal hyphae producing spores (x 600)*

migration of nuclei (carriers of genetic material) throughout the colony. This process therefore allows the fungus to adapt continuously to the conditions in which it is growing and, as important, to overcome adverse conditions. This occurs whether the conditions are natural, or created by man's attempts to control fungal attack of a substance with the use of toxins.

Regarding fungal nutrition, all require a source of organic carbon as an energy substrate which is broken down in two ways. First, the fungus will secrete into the medium in which it is growing, a mixture of enzymes and, occasionally, organic acids. These will soften up the substrate and produce simple organic compounds which the fungus can then absorb. These then undergo further breakdown within the cell, with coupling to energy transference processes.

4.2 *Bacteria*

Essentially bacteria are simpler structures than fungi. [9] They remain as small cells (1 - 10 microns), though in some species simple filaments of loosely connected cells occur. Many bacteria are actively mobile and can swim rapidly through a liquid medium using a whip-like appendage or flagellum. They usually reproduce asexually by simple fission into two cells. Rates of division can be very high, in some cases every twenty minutes, allowing them to exploit extremely quickly good growth conditions. Nutrition of bacteria is similar to that of the fungi, with some being able to grow in the absence of oxygen when inorganic ions such as sulphate and nitrate are used instead.

5. THE ROLE OF THE BIOLOGIST

The role of the Exposure Trials Station, with regard to RN ship fouling and microbiological problems is to provide a "trouble shooting" service to the Fleet, both in the area of fouling/antifouling and where equipment/material failure is suspected of being microbiological in origin.

5.1 *Fouling/Antifouling Research*

The requirement to be met in the fouling/antifouling field is the development of longer lasting antifouling paints. Two approaches have been made, the first to attempt to increase the life of conventional paints by increasing the thickness of the applied coating and secondly, to procure, either by intra and extra mural research or through commercial sources, new poisons to replace the presently used copper I oxide (cuprous oxide). The drawback of using thicker coats of cuprous oxide paints is that they are subject to inactivation by "drying-out". Furthermore, in black paints the masking of the copper I oxide by carbon black gives rise to a markedly inferior paint with less than half the life.

Another approach to the problem is to find a new poison with a longer lasting action. This is no easy task. The compound must be capable of controlling all fouling organisms for periods of 4 to 5 years, it must have low solubility, be non-toxic or relatively so to man, be compatible with film forming media and present no environmental hazard. All candidate new poisons must be screened to determine their suitability for inclusion in paint media. This is carried out first by a simple raft test where the compound is held behind a porous membrane and, if it gives a promising performance, it is subjected to laboratory tests using barnacle larvae and algal spores. If the good performance on the raft is confirmed, the compound will be incorporated in experimental paint media and tested on raft exposure. If the paints are promising, further development of the media will be undertaken to obtain the longest possible lasting effect of the poison.

A sobering thought is that it can take anything from

10 to 15 years to get a new composition verified and into service. It is with this problem in mind that attempts have been made to develop accelerated tests for these paints. In addition we have to seek alternative practical methods for achieving antifouling, but up to the present no such system has yet been developed which would be suitable for use on ships.

5.2 *Equipment/Material Failure*

This work tends to be of a "one off" nature, unless a particularly susceptible material has been introduced in the Fleet. The work requires an analysis of the organisms found growing on materials and acquiring detailed information regarding conditions under which the item has been used. Occasionally, it is found that failure is caused by misuse, unfavourable storage, or the particularly severe conditions in which it has been applied. Advice can be given on the prevention of failures and problem areas arising from the working situation identified, an important factor in equipment/material usage and design for the future.

It is important to stress here that any samples forwarded to the laboratory for analysis should be accompanied with all relevant information, in order to allow an accurate assessment to be made of the reasons for failure and to prevent the probability of re-occurrence. Problems that have been encountered range from obnoxious smells emanating from sewerage treatment equipment, life jacket fabric softening, and micro-organism growth in drinking water tanks.

5.3 *Susceptibility of New Materials*

This is somewhat longer term work and encompasses a whole range of materials from electronic components through to neoprenes and hydraulic fluids. Each investigation must be considered individually since the test conditions must realistically reflect the environment in which the materials are to be used. Exposure may vary from a few days to one or several months, again depending on the location/function in which it is going to be incorporated.

5.4 *Monitoring and Research*

It is necessary to monitor the level of microbiological contamination (MBC) aboard individual units and from fuel storage systems. Monitoring from ships is conducted in two ways. First, from certain ships, filter pads (MILLIPORE) through which a known quantity of fuel has been drawn, are received from various parts of the fuel system. From counts of trapped hyphal fragments it is possible to make a semi-quantitative analysis of the MBC in that part of the system, or in the ship as a whole. The technique is slow, taking 15 minutes per filter, but is possibly the best indicator at present.

From both ships and fuel storage systems, "wet fuel" and "sludge" samples may be received. With full information these samples can be invaluable in indicating MBC levels. In addition, it is possible to culture organisms from these materials so that identification can be made of the fungi and bacteria present. However, it is necessary to apply some caution when using these samples as indicators, e.g. if a fuel sample is received and is found to be clear of serious MBC the following conclusions could be drawn:

a) the system has no serious MBC problem, or
b) the fuel sample was taken well clear of the water/fuel interface and as such does not reflect the true situation in this tank.

It is when sorting out the true level of contamination that information supplied with the sample becomes invaluable.

Having determined a true picture of MBC level it may then be necessary to recommend that

i) it is not serious and is not likely to impair the operational efficiency of the ship and therefore no further action is considered necessary,
ii) the system needs to be drained and cleaned at the earliest opportunity,
iii) contamination is serious and it is necessary for it to be drained, cleaned, and treated with biocide dosed fuel.

The latter option is to be avoided if possible, since biocide is expensive and a period of three days is required for exposure to eliminate effectively micro-organisms from the system. In addition, fuel tanks are inspected when possible in order to obtain first hand information on the extent of contamination and to obtain samples for research.

Research at the Microbiology Unit is aimed in two main directions. In the first place a team of chemists is investigating the possibility of replacing the present biocide BIOBOR JF with a material more suited to Fleet purposes. The main disadvantages with the current biocide are:

a) it requires a high dosage, in the region of 270 parts per million (ppm),
b) it is expensive compared with other anti-fungal materials available, and
c) with more than a 1% water bottom present in the tank the materials efficiency is considerably reduced.

A biocide for Fleet use should be economic, effective against all micro-organisms between 1 - 5 ppm and retain its efficiency in water bottoms as high as 10%. In addition, it must present neither a hazard to turbine machinery nor to the environment into which it is likely to be discharged. This aspect of the research programme entails both manufacturing toxins and testing materials already available, such as fungicides used in the agricultural sphere. If this aspect of the work is successful, it should, at a later date be both simpler and cheaper to carry out disinfectant type operations in cases of severe infection.

The second main area of research is directed towards a better understanding of the processes and organisms involved with MBC. By studying as many samples as possible from different ships, parts of the fuel system, and within the fuel supply chain, the identification of organisms responsible can be established. This is an important aspect since many biocides have "blind spots" regarding species selectivity. It would, for instance, be pointless to control organism X using a certain biocide if organism Y and Z were to develop in its place and cause as much trouble as the original. In addition, from the identification of organisms present in systems it may be possible to detect the onset of other problems, for instance, certain bacteria might indicate that the environment was becoming highly acidic and hence corrosive. This work has so far demonstrated that the fungus *Cladosporium resinae* which has been taken as the main culprit in MBC situations, may be to blame for only part of the problem and that species of *Penicillium* and *Fusarium* are just as important.

Since *Cladosporium resinae* is an important contaminant within fuel systems, work is underway to gain an understanding of the biology of this organism. Once this is known it will be possible to indicate its rate of growth under various circumstances and possibly to gain an insight into its effective control. For instance, until recently there has been some debate regarding the ability of this organism to grow in full seawater conditions, important when seawater displaced tanks are being considered. The results have indicated that it will grow under these conditions, though at a reduced rate, compared with conditions of reduced salinity. Another problem which is being pursued is the availability and requirements for micro-nutrients of the fungus. In undisplaced tanks all nutrients must derive from the fuel or tank coatings, and it is unclear at present where the organisms obtain substances such as phosphates, which are essential for growth.

A third aspect of the research programme is to look at fuel systems and the supply chain to establish where problems are being designed into the system. Some examples of this are fairly obvious, i.e. seawater displaced tanks, and tanks lacking water stripping facilities. Other examples may only come to light after some time, and it is here again that the co-operation between the engineer and the research worker can be invaluable. At present there appear to be anomalies which cannot be fully explained, e.g. ship X appears to have a full history of MBC, whilst her sister ship Y seems to be comparatively free of the problem.

6. CONTROL OF MICRO-ORGANISMS

Remedial measures, i.e. the use of fungicides, can alleviate problems but often there are limitations on material that can be used, especially within the closed environment of a submarine. There is no quick and easy answer to MBC development in fuel. Some navies believe in the continuous dosing of fuel with a biocide such as BIOBOR JF, but there are serious disadvantages in this approach. Firstly, the vessel must be able to accept and, if necessary, deal with contaminated fuel on board. If a biocide treatment is being used it raises additional logistic problems in operations. Secondly, present biocides are only useful in preventing growth if the tank water bottom is less than 1%. Above this figure biocide efficiency is reduced rapidly, and dosing the fuel ineffective and uneconomic.

In the Royal Navy, biocides are used only in severe cases of infection in order to disinfect a system. Occasionally, this may be a "consumer" warship where contamination has become serious over a period, or commonly, a Royal Fleet Auxiliary tanker where the problems are particularly acute, and the tanks difficult to clean. It is hoped that research will provide a better answer to the problem.

The role of the microbiologist is to investigate material failures when they occur through these agencies. Often the unravelling of a particular problem may be a long and difficult problem and it requires patience and good will on the behalf of the "consumer". The efficiency and accuracy of any laboratory based investigations, whether fuel monitoring or life raft failures, depends to a very large extent on the samples supplied for analysis, and here care must be taken. It is important for the expert to obtain as much information as possible, since failure may be linked to any number of causes in the history of the material.

7. CONCLUSIONS

The need in the field of fouling/antifouling research is for the development of a new poison capable of providing an effective long-life antifouling paint. Alternative methods of achieving antifouling should be investigated. Because of the long time required to develop new antifouling paints, particular attention should be paid to the development of accelerated tests.

Micro-organisms cause as many problems within the Fleet as there are materials used in the vessels construction. Some of the problems are immediate and obvious, whilst others, though less noticeable, become serious in time. The peculiar micro-environment of a ship, and particularly that of submarines is extremely favourable to the growth and attack of micro-organisms, and it is likely that problems will increase in the foreseeable future.

REFERENCES

1) CHRISTIE A O, 1977, "Recent Developments in Antifoulings" *Journal of the Oil and Colour Chemists Association 60,*p.p. 348-53
2) BROWN D, 1976, "Fouling and Economic Ship Performance" *Proceedings of the Fifth Inter-Naval Corrosion Conference Paper 7*
3) ANON., 1977, "The Goose Barnacle, costly return of an old enemy" *Seaways* 6 July
4) CORPE W A, 1976, "Primary bacterial films and marine microfouling" *Proceedings of the 4th International Congress on Marine Corrosion and Fouling* 105 - 8
5) HOUGHTON D R, PEARMAN I and TIERNEY D, 1972, "The effect of water velocity on the settlement of swarmers of *Enteromorpha spp*" *Proceedings of the 3rd International Congress on Corrosion and Fouling* p.p. 682 - 90
6) HENDEY N I, 1964, "Some observations on *Cladosporium resinae* as a fuel contaminant and its possible role in the corrosion of aluminium alloy fuel tanks" *Trans Brit Mycol Soc 47 (4)* p.p. 467 - 75
7) EDMONDS P and COONEY J J, 1967, "Identification of micro-organisms isolated from jet fuel systems" *Appl Microbiol 15 (2)* p.p. 411 - 16
8) STAINER R Y, DOUDOROFF M, ADELBERG E A, 1971, "General Microbiology" *Macmillan* London
9) BURROWS P J (unpublished observation)

Discussion

MR E C HILL (University College, Cardiff) congratulated the authors and pointed out that a minor revolution had occurred in the Marine Industry over the last ten years, and the biologist was no longer regarded as a long haired eccentric with a butterfly net, but a man who was involved in real problems and worked towards practical solutions with a favourable economic outcome: an approach admirably postulated by the authors.

The first section of the paper gave many documented instances of the adverse effects of hull fouling. Mr Hill understood that Lackenby's Relationship gave a 1% increase in drag for a 10 micron increase in hull roughness and he asked the authors at what point that relationship broke down for algal and animal species. He also wished them to comment on fouling rates following underwater scrubbing as he understood that they could progressively accelerate, as an "inoculum" of organisms always remained with regard to the development of new active chemicals, he said Dow Corning had a new product which remained attached to the surface and did not leach out. Toxic chemicals could also be encapsulated in soluble glass and Mr Hill wondered if that approach was feasible in anti-fouling paints.

Concerning their section "Characteristics of Micro-organisms" Mr Hill commented that not all bacteria reproduced to give resistant spores. Those which did, certainly persisted for many years. Anthrax spores could still be isolated from the contaminated shaving brushes which were issued to First World War troops and caused many deaths. Very many bacteria did not produce resistant spores and those were reasonably susceptible to heat and disinfectant chemicals.

The authors mentioned briefly physical fouling of air conditioning systems. There was growing evidence that inhalation of the air from such systems could constitute a health hazard, a problem which might have to be looked at much more closely. The authors also referred to spoilage of life-rafts. Regulations now in being compelled owners to change from cotton-based fabrics to fabrics based on synthetic fibres. As far as Mr Hill was aware, the rubber base had not changed and was still subject to microbial attack and perforation.

A major section of the paper referred to microbial growth in gas turbine fuel. The problem had largely been solved in the aviation industry by meticulous housekeeping and the use of anti-freezes in the fuel, which were also anti-microbial. Ships could only partly meet the necessary housekeeping standards and there was no justification for using anti-freezes. Indeed one of them, Ethylene Clycol Mono-methyl Ether, the additive used by the RAF, could actually cause accelerated growth on ships if used incorrectly or intermittently. A much more determined effort was needed to produce combustible chemicals specifically tailored to meet engine builders specifications and to suit the marine environment (sea water, temperature etc).

Centrifuging was a practical method of removing microbes from fuel delivered to the engine. However, to control fouling and corrosion in the tanks, a separate installation would be necessary, drawing fuel from the dead bottom and recirculating it. Mr Hill wondered how far centrifuging had been considered in the Navy. The authors commented on the fact that *Cladosporium resinae* did not appear to be as important in ship fuel problems as in aircraft problems. The microbiology department of University College, Cardiff, had shown that the fungus was able to survive the freezing cycle (- 30°C) which occurred in aircraft fuel in flight and was thus selected preferentially. No such cycle occurred in ships.

Mr Hill finally endorsed the authors' pleas for good samples accompanied by an adequate description of their composition, location, timing etc. Even the best laboratory investigation was almost meaningless without that information and it was almost impossible to give helpful practical advice without it.

MR A N McKELVIE BSc, (The Paint Research Association, Teddington) said that the authors had highlighted the very large additional running costs incurred when fouling occurred on a ship bottom. They had also said that when a non-toxic surface was universal in seawater it was the bacteria, diatons and slimes that settled within hours of immersion. It seemed to him that it was those species that very often first settled on anti-fouling paint and when they did they provided an ideal substrate for the larger weeds and barnacles to settle, almost irrespective of the toxins remaining on the anti-fouling paint, because heavy settlement of the small materials effectively sealed off properties of the toxins. He therefore asked the authors how much research was directed to the prevention of settlement of bacteria, diatons and slimes and if they considered that the solution of that problem would sometimes greatly increase the expected life of the anti-fouling composition.

Another relevant point was the cleaning of a fouled bottom prior to recoating with anti-fouling. His experience had been that such cleaning very often left much of the bacteria, diatons and slimes and, as a consequence, further applications of anti-fouling had impaired adhesion characteristics leading to early flaking and failure of anti-fouling in batches and, after a number of recoats, the bottom became extremely rough with application of further anti-fouling paint. In his view much more attention should be paid to improved cleaning prior to reapplication of anti-fouling. Rapid and effective methods of doing that were now available but were not efficiently exploited. Mr McKelvie wished the authors to comment on that aspect of improving the efficiency of both Naval and Merchant Shipping, by obtaining great speeds with better fuel efficiency.

MR J J EVANS (General Council of British Shipping) noted with interest the development work on new anti-foulings on which the authors were engaged and confirmed that GCBS, in conjunction with PRA, was working just as hard to develop a composition which would keep hulls weed-free for four years. However, he wished to know whether the authors had evaluated anti-foulings of the SPC or reactivating type and what their findings were.

Although, he recognized that differences in equipment and operating procedures existed between the Royal and Merchant Navies, he was surprised to hear that microbiological problems in lubricating oil in RN ships were rare. He was sure the authors had heard of the disasters which had occurred as a result of that problem in merchant ships and he hoped to hear whether the authors could say, accepting the differences in equipment and operating procedures, why that problem was rare in RN ships.

Correspondence

MR A MILNE (International Paint) wrote that the authors had proposed as the four main requirements of the Navy's research and development in the antifouling field:

i) longer life materials;
ii) the prevention of inactivation on exposure from which the conventional anti-foulings suffer;
iii) a good black anti-fouling;
iv) new and more effective biocides.

It was strange, therefore, that the only alternative system to the traditional materials still in use in the Navy, which they had mentioned only to dismiss it, was the Self-Polishing Co-polymer system, which could solve at least three of their four problems, and would be an essential ingredient in the efficient exploitation of the fourth. The requirements could be considered as follows:

i) *Longer Life*
Unlike conventional materials, which were initially wasteful, and to which a law of diminishing returns applied in multi-coat systems, the SPCs had lifetimes proportional to the applied thickness. In round terms an extra year's service could be obtained for each additional coat applied.

ii) *Inactivation on Exposure*
A VLCC would draw some 20-25 m in the loaded condition and some 10-12 m in ballast. On a N Europe to Gulf run, the boot-topping area of 5,000 m^2 was therefore exposed for one month in two for periods of up to 30 months. The Self-polishing Co-polymers were not inactivated under those rigorous conditions, so what more did the Navy require?

iii) *Black Anti-fouling*
An excellent black self-polishing anti-fouling, considerably superior to the Navy Pocoptic Black, could be bought at any yacht chandlers'.

iv) *New Biocides*
Even if the authors found the vastly improved biocide for which they were searching, they would still require a mechanism by which it might be delivered to the point of action, i.e. to the spore or larva in the laminar sub-layer.

The advantage of the self-polishing co-polymer system was that it would deliver any suitable biocide, or combination of biocides, at the required rate and in the desired proportion, throughout the lifetime of the system. In their paper the authors indicated that research into media would still be necessary following the development of new biocides. He wondered if the authors had any alternative mechanisms in mind of such comprehensive utility as the self-polishing mechanism?

Even more important to the Royal Navy than the need for fuel savings was the state of readiness of the fleet. In dismissing the SPC system as unsuitable for naval use, the authors overlooked the fact that co-polymer anti-foulings could be tailor-made, to give optimum properties in static or dynamic conditions.

One could visualize a system in which the final two coats of anti-fouling were good for two to three years under static conditions and intermittent sailing, and the first and second coats were relatively slow polishing. Such a hull would be in a state of instant readiness and capable of three to five years service, without further attention. If the authors produced a specification, a co-polymer system could be provided to satisfy it.

MR A O CHRISTIE (International Paints) in his written contribution referred to the authors' statement that "alternatives to conventional paints, such as Self-polishing Co-polymer, had been devised to give greater controlled release, but they are not effective on ships which are stationary for a considerable amount of their operational time, as is the case with naval vessels in peace time". He wished to know the basis for that statement, especially in the light of practical experience with the SPC product with both the Norwegian and the Spanish Navy. In the case of the Norwegian Navy they took part in a half-ship test on a frigate with SPC competing against a traditional cuprous oxide anti-fouling. In drydock some 19 months later, SPC was found to be completely free from fouling, even slime free, while the traditional coating was fouled by slime and algae. Following that experience the Norwegian Navy had coated a second frigate with SPC.

In September 1976, the Spanish Navy coated a frigate with SPC. During a 27 month service period the vessel sailed a distance of only 60,000 nautical miles. That would represent some 85% stationary operation comparable to the operation of British naval vessels in peace time. In drydock that vessel was again completely free from macroscopic fouling, but did show some light slime. Considerable experience on commercial vessels had shown that those biological slimes which could occur on SPC in extended lay-up, were completely removed by short periods of steaming.

Mr Christie found it particularly sad that SPC, a product pioneered by British scientists and conclusively shown to give remarkable fouling control and smoothing benefits had (apart from some meagre test patches) been ignored by the British Navy.

It was especially strange when one considered that "the importance of keeping the underwater surface of a ship's hull as smooth as possible" was a direct quotation from the paper.

Authors' Replies

In response to Mr Hill's question concerning Lackenby's Relationship and the point at which it breaks down for algal and animal species the authors had no information. With regard to the scrubbing of ships to remove fouling it could only be regarded as a palliative as far as the animal species were concerned, and with the algae it tended to initiate the release of spores which could recolonize the surface and, as Dr Betty Moss had observed, small parts of the thallus left adhering to the surface could produce a dense bottle brush type of growth. The development of new active chemicals was a continuing process, being pursued in a number of laboratories throughout the world. Encapsulation of toxins in glass did not appear to be a very attractive proposition since it would reduce the volume of actual toxin capable of being included in a paint, and would thereby reduce its period of fouling prevention. In their opinion it was better to design the paint matrix to carry out that function.

It was certainly true that cotton-based fabrics had been replaced in life-rafts with synthetic fibres. It was now common practice to include in the fabric pentachlorophenyl laurate, which was an effective rot proofing. The RN had made that stipulation since 1959, and products such as those sold by RFD contained the chemical. The main problem with life-rafts, at present, would appear to be the breakdown caused by minute traces of copper, leading to the condition commonly known as "copper crack".

Concerning centrifugation, the RN experience was that it could be highly effective in controlling particulate matter in fuel. However, it was not the total answer since surviving spores might pass through with the clean fuel and develop at a later stage in the storage tanks. The other point was the question of available space for machinery since that tended to be somewhat limited in warships, and centrifuges capable of dealing in bulk with the fuel were necessarily large. On a smaller scale it was the practice in some RN ships to "cream off" the water bottom and collect the good fuel by passing it through an oil/water separator.

Mr McKelvie was quite right in pointing out that micro-organisms settled on anti-fouling paints. However, those with a very high initial leaching rate did, in fact, control those so-called slime-forming organisms. Nevertheless, a paint which was leaching at the rate of $10 \mu g/cm^2$/day, which was sufficient to control the macro-fouling species, did not prevent the settlement of bacteria, diatoms and the Protista.

Historically, the first major task in anti-fouling paints was the control of the heavily shelled animal species such as barnacles, calcareous tube-worms, etc. It later became obvious that it was also necessary to control the settlement and development of algal species. In more recent times attention had focused on the "slime-forming" organisms and, although little work had been carried out to date, it was in that area that research was becoming concentrated.

They thoroughly agreed that the slime-forming organisms needed to be removed before recoating and the way the RN was tackling that problem was by selective blasting to remove spent anti-fouling as well as the slimes. That had the added benefit of helping to keep the surface as smooth as possible.

The question posed by Mr Evans was an interesting one and they had, in fact, evaluated anti-fouling paints of the SPC and reactivating type. In the case of the former, which they regarded as a sound approach to the problem, the difficulty lay in the long periods that RN ships might spend alongside during peacetime. Their experience was that during those periods the SPC would foul. They believe the reasons that RN lubricants generally did not support mould growth was because of the dryness of the systems in which they were used, and it was possible that many of the additives, e.g. chromates etc., were fairly toxic. Mr Milne appeared to assume that the RN was in desperate need of a new anti-fouling paint. If the paper had given that impression they would say that the position was that they could obtain two and a half years out-of-dock with the cuprous oxide-based paint 161PE. Nevertheless, they had and would continue to have, an interest in extending the out-of-dock fouling free life for HM ships. Turning specifically to his four points:

1) *Longer life*
His assumption that a multi-coat system was subject to the law of diminishing returns was not borne out by their current trials of paints based on 161PE, which were designed to last for ten years on the raft (i.e. a four and a half to five year ship life). Those were still fouling free after nine years exposure.

2) *Inactivation on exposure*
The exposure to which they had referred was not that which occurred on a VLCC. The waterline on HM ships varied in centimetres not metres and was of no particular consequence for normal operations. The drying-out problem which concerned them was that which might occur during an emergency docking if the ship should be in for a period of a week to ten days. It would be very foolish to go to the expense of coating a ship for five years out-of-dock only to find after nine to twelve months it was in dock for a prolonged period. The selective blasting referred to above had some promise in that direction.

3) *Black anti-fouling*
The RN had not used Pocoptic Black for some considerable time.

4) *New biocides*
They agreed with Mr Milne that, even with a new, more highly effective, biocide they would need to present it in a manner which controlled the settlement of fouling organisms, but that was surely what any effective anti-fouling did.

The implication behind those points appeared to be that they should not consider any alternative to anti-fouling other than SPC. Mr Milne had claimed that the copolymer anti-fouling could be tailor-made to give "optimum protection in static or dynamic conditions". They had to provide for both on one and the same ship. Having said all that, they were sure that Mr Milne was aware that they had been testing SPC since before it was actually launched on the market, in raft trials, on harbour craft and on one of HM ships. He also could not be unaware that there was to be a trial of one of HM ships completely coated on the outer-bottom with SPC.

Mr Christie had wished to know the basis for their statement concerning SPC: it was quite simply their own experience from their tests. They were sure that he also knew the position regarding the testing of that product in the RN. It was a pity that he had not circulated his information derived from tests by foreign Navies, that would be helpful in coming to a considered opinion regarding the use of SPC for Naval purposes. They assured Mr Christie that they in no way wished to criticise his company's product but, until the case was proven in its favour, they would continue to observe developments and then, if they were favourable, consideration would be given to coating all HM ships with SPC.

Published for THE INSTITUTE OF MARINE ENGINEERS by Marine Management (Holdings) Ltd., (England Reg. No. 1100685) both of 76 Mark Lane, London EC3R 7JN. Printed by Crown Printers (Bedford) Ltd., Bedford (England Reg. No. 910307).