EVALUATION OF PERFORMANCE OF MARINE GAS TURBINE AIR FILTERS

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ABSTRACT

Early work by the Naval Engineering Department of NGTE Pyestock, now RAE Pyestock, sought to define the marine aerosol through simple relationships between wind speed and aerosol size and distribution. Experience has shown the resulting Standard Aerosols to be unrepresentative of the actual conditions found in service.

This paper describes a new approach using available ship and meteorological data and proven analytical techniques to generate a multivariable mathematical model of the marine aerosol embracing a wide envelope of operating conditions. It further describes how a simple model of a gas turbine air filter can be used in conjunction with the marine aerosol model and a model describing a ship's propulsion system to predict the performance of the filter in terms of probable salt ingestion by the ship's engines. This can be used for direct or comparative assessments of filters for marine gas turbines and can ensure that upper deck space is not wasted by over-designed filters.

Introduction

With the pressure to reduce warship top weight and to make more space on the upperdeck for weapons it is becoming increasingly important to keep the size and weight of marine gas turbine downtake systems to a minimum. To achieve this, as complete an understanding as possible of downtake systems and marine gas turbine air filtration is required. The comparative trial of gas turbine air filters carried out for the Type 23 frigate by the Naval Engineering Department at RAE Pyestock gave an opportunity for a reappraisal of the whole area of marine gas turbine air filtration. It also provided an opportunity for the updating of the filter test rig and its instrumentation.

The comparative trial highlighted the shortcomings in the definitions of the NGTE Standard Marine Aerosols against which the gas turbine air filters are tested. It also prompted the development of techniques to generate multivariable mathematical models of the marine aerosol and a ship's gas turbine air filtration systems. By simulating the ship's operating profile and the meteorological conditions the ship is likely to meet in service and by combining the mathematical models of marine aerosol, filtration and ship propulsion systems, a very powerful investigative design tool can be produced, outlined in FIG. 1, able to predict the amount and concentration of salt which will be ingested by a marine gas turbine. A simulation of this type based on empirical data, and known or proposed ship configuration, provides a very flexible means of assessing, directly or comparatively, air filtration systems.

This article describes the building of such a simulation and discusses its uses and merits.

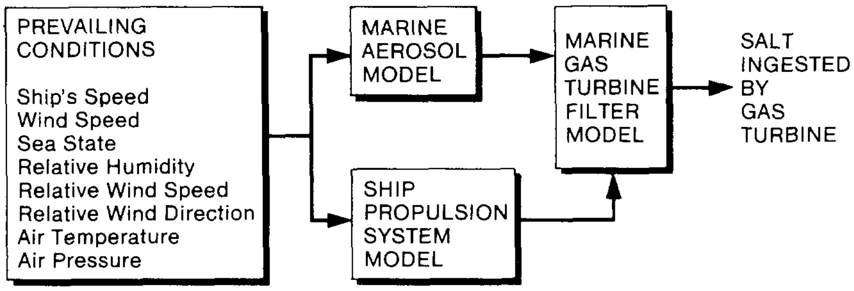

FIG. 1—OUTLINE OF SIMULATION

PREVIOUS WORK

The Comparative Trial

Following the requirement to carry out the comparative trial of air filters for the Type 23 frigate it was decided to update the instrumentation used for testing and the test rig itself. The main improvement was the acquisition of the Forward Scattering Spectrometer Probe (FSSP-100). This instrument replaced the Cassella Cascade Impactor as the means of measuring aerosol droplet size and distribution, dramatically improving measurement accuracy and resolution. The use of light-scattering rather than impaction techniques to measure droplet size and distribution has increased our knowledge and understanding of filtration. The light scattering instrument's vastly improved resolution has given a much more complete and practical description of a filter's performance. The comparative trial also provided the opportunity to review previous work carried out in the gas turbine air filtration field. It revealed the work carried out by Featherstone[1] which formed the basis for this paper. This review also raised two interesting and important questions which are fundamental to understanding how the testing of marine gas turbine air filters has evolved.

The first question concerns the levels of salt that are acceptable downstream of the marine gas turbine air filter. Rolls-Royce stipulate a concentration of 0·01 parts per million (ppm) sodium chloride by weight in air as the maximum allowable salt ingestion limit from the inlet air. That limit determines the performance of the filters.

How was the 0·01 ppm salt limit for Rolls-Royce engine derived?

The second question concerns the test used to check that filters are allowing through no more than 0·01 ppm salt. Obviously we would wish to test the filters against salt levels which are expected to be met in service in the marine environment. At the moment this is described by a range of three aerosols called the NGTE Standard Marine Aerosols.

How were the NGTE Standard 20, 30 and 40 knot aerosols derived?

The Rolls-Royce 0·01 ppm Salt Ingestion Limit

In the 1960s The Admiralty Test House at Pyestock carried out a series of trials on Proteus[2] and Tyne[3] gas turbines in preparation for their use for marine propulsion and power generation. This pioneering work included an investigation into the effects that the presence of salt, both in the marine atmosphere and in the fuel, had on the engines. It soon became apparent that the materials used in aircraft engines were unsuitable when the engine was subjected to even modest concentrations of salt. Following these trials Rolls-Royce set the limits for salt ingestion for their engines; the airborne part of which was set at 0·01 ppm sodium chloride by weight in air.

The NGTE Standard Marine Aerosols

In an attempt to provide adequate filtration against salt in the marine atmosphere, standards were devised against which gas turbine air filters were to be tested. These were called the NGTE Standard Marine Aerosols[4] and were intended to reflect the range of salt concentration levels and particle size distributions which the filters would be expected to deal with in service. The NGTE Standard Marine Aerosols, proposed in 1971, were originally based on extrapolated data taken on board the U.S.S. *Meredith* as part of the Gas Turbine Combustion Air Salt Aerosol Separation Programme undertaken by the Naval Ship Systems Engineering Station, Philadelphia in 1965[5]. They consist of three aerosols defined by sea salt concentration and particle size in relation to wind speeds of 20, 30 and 40 knots (the 40 knot aerosol has not been used for some time, however, due to a lack of confidence in the aerosol composition). No humidity data is contained in the descriptions. The NGTE standard marine aerosol sea-salt concentration and particle size data is shown in FIG. 2.

The *Meredith* results were later discounted by Philadelphia[6] as being incorrectly sampled following a further sampling trial carried out on board the Danish frigate *Peder Skram*.[7] In view of this and a general lack of reliable marine aerosol data, two sampling studies were initiated by MOD (Navy). The first of these studies was carried out by Lovett[8] on board U.K. weather ships stationed in the North Atlantic. The second far less extensive study was carried out by Westwood[9] in H.M.S. *Torquay* shortly afterwards. The results of the two studies confirmed the work of earlier researchers, such as Woodcock[10], and highlighted various anomalies in the NGTE standard aerosols.

TABLE I—*Comparison of the NGTE Standard Aerosols with Lovett, Westwood and Woodcock models*

Source	*Regression Model*	*Concentration at 20kt wind speed*		*Concentration at 30kt wind speed*	
		ppm	(μg/m)	ppm	(μg/m^3)
NGTE	—	0·22	(269·5)	3·6	(4422)
Lovett (all results)	$\mathrm{Ln}\theta = 0\cdot16u + 1\cdot45$	0·018	(22·0)	0·041	(50·3)
Westwood (all results)	$\mathrm{Ln}\theta = 0\cdot14u + 1\cdot7$	0·02	(24·5)	0·042	(51·6)
Woodcock	$\mathrm{Ln}\theta = 0\cdot16u + 0\cdot94$ u = wind speed m/s θ = salt concentration (μg/m^3 NaCl)	0·011	(13·1)	0·025	(30·7)

It can be seen from the data in TABLE I that there is good agreement between the relationships of sea salt to wind speed obtained by Lovett, Westwood and the earlier work of Woodcock. TABLE I also shows that the concentration of sea-salt contained in the NGTE standard aerosol is some 12 times the mean value measured by Lovett at 20 knots and 87 times greater than at 30 knots. However the NGTE standard marine aerosols were not amended to reflect the change in understanding of the marine aerosol. The *Meredith* data was regarded as an over-estimate of sea-salt concentration and would therefore serve as a severe testing standard for air intake sea salt separators.

In 1978 further work was done by Featherstone[1] who investigated the techniques of regression analysis and Monte Carlo simulation to try more accurately to describe the marine aerosol and assess filter performance. Unfortunately his work was not pursued at the time.

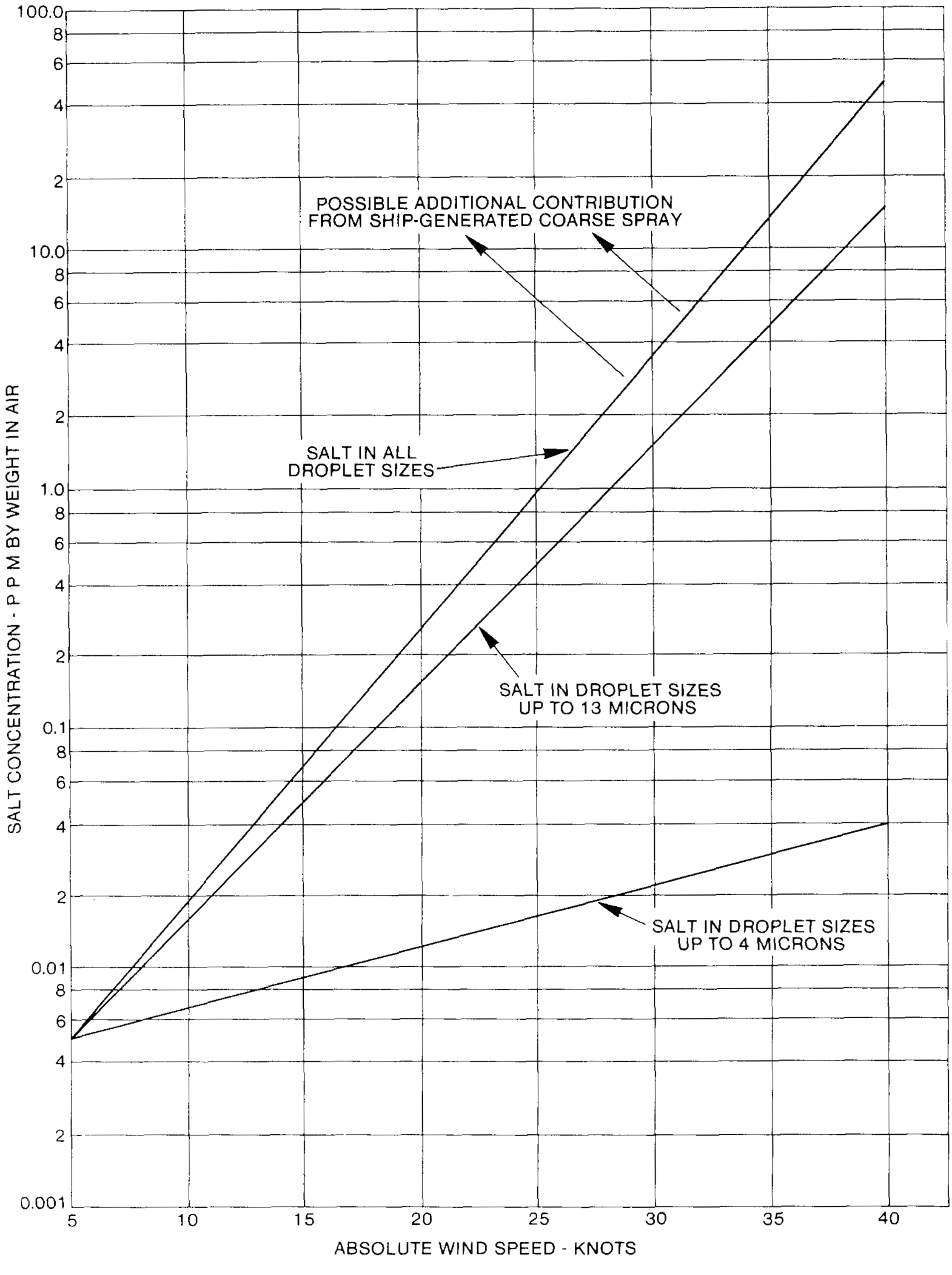

FIG. 2—THE NGTE STANDARD MARINE AEROSOLS
from Naval Engineering Standard

MATHEMATICAL MODELLING

The Aerosol Model—the Revised Marine Aerosol

A review of the measurements taken by both NGTE and the U.S. Navy has led to the conclusion that a revision of the standard aerosols for testing filters is required, not only in respect of the sea salt concentration and particle size data, but also whether those aerosol characteristics are solely dependent on the parameter of wind speed. When the first sampling trials were undertaken it would have been a very difficult and time-consuming task to analyse the way in which various parameters combined to influence the marine aerosol. It was recognized that wind speed played the major role in determining the salt concentration and particle size distribution and this determined the manner in which the marine aerosol was to be defined. With the advent of the computer more exotic and labour-intensive analytical techniques became available for general use, including multiple regression.

The data collected by Lovett[8] and Westwood[9] was used to produce regression models relating salt concentration to wind speed alone in the form:

$$Y = A1 + A2.X \tag{1}$$

where A1 and A2 are constants, Y is the dependent variable and X is the independent variable.

Multiple regression allows the relationship between one dependent variable and many independent variables to be described mathematically. It gives models of the form:

$$Y = AO + A1.X1 + A2.X2 + \ \ldots \ An.Xn \tag{2}$$

which describes the relationship between the dependent variable Y and the independent variables X1, X2, X3, . . . Xn.

Using the analytical technique of multiple regression it is possible to investigate the influence of any number of factors on the concentration of sea salt in the marine aerosol. Analysing the data collected by Westwood in this way, it was found that 80% of the variation in sea salt concentration could be accounted for by the inclusion of relative humidity, ship's speed, air temperature, relative wind speed and relative wind direction in the windspeed model—an improvement of 30% over the Westwood windspeed model shown in TABLE 1.

Having determined the relationships between these variables using multiple regression, a mathematical model of the marine aerosol was produced. It has the form:

$$\begin{aligned} LnTCUP = A1 + A2.WS + A3.S + A4.RH +& \\ A5.RWS + A6.RWD + A7.SS +& \\ A8.T + A9.ATM + A10.H& \end{aligned} \tag{3}$$

where A1–9 are the regression coefficients

TCUP: total salt concentration upstream of the filter (i.e. contained in the marine aerosol)
S: ship speed
WS: wind speed
RWS: relative wind speed
RWD: relative wind direction
RH: relative humidity
T: air temperature
ATM: air pressure
SS: sea state
H: inlet height, constant for a particular intake

By substituting values for each of the variables in equation (3) a value of the concentration of salt in the marine aerosol can be calculated. The mathematical model of the marine aerosol produced by this method from observed data gives a far more realistic description than the NGTE Standard Aerosols because it describes the influence of many factors, not just the single one of windspeed.

Different sets of such values can be put into the mathematical model in order to determine the variations in salt concentration upstream of the gas turbine air filter over a wide range of conditions. It is also possible to determine the affect one particular variable has on the downstream salt levels. This can be achieved by taking nominal mean values for all variables except the one under investigation.

The majority of the parameters used in the equation that describes the marine aerosol are weather-dependent; the others are influenced by the way the ship is being operated. Mean values of these parameters may be used to determine how much salt the ship is likely to meet in service but this would merely give some sort of mean answer. It would be far better to calculate the answer using the whole range of variation of each parameter and incorporating the proportion of time each parameter was at a particular value. In such a way a simulation of what a ship can be expected to meet in practice will be produced. This can be achieved using Monte Carlo techniques.

The Monte Carlo Simulation

Monte Carlo methods were first used in 1908 for determining the statistical t-distribution, but their present uses have evolved with the electronic computer from about 1947. The simulation of natural processes which are subject to continuing random disturbances is one application. It allows the use of chance to construct a simulation of a process under analysis in the same way that chance operates in the original system. All that is required is a mathematical model of the system under analysis and some sort of gambling device such as a roulette wheel weighted to simulate the input conditions of the model.

Rather than use weighted roulette wheels, one for each variable, to simulate the inputs to the model it is much more efficient to use the random number generator of a computer. A value for each of the independent variables used in the mathematical model is generated at random within the limits and probabilities of each variable's known occurrence. Each set of values generated in this way is substituted in the equation describing the model and the answer calculated and stored. This process can be repeated as many times as required (the accuracy of the simulation increasing as the square of the number of iterations). Once this has been completed the results can be presented graphically for easy analysis and comparison.

The input data required to carry out a Monte Carlo simulation of a ship's air filtration system can be obtained as follows:

(*a*) Wind speed, air temperature, air pressure, relative humidity and sea state are all weather-dependent. The Meteorological Office can supply data from all over the world's oceans describing how these values vary over a particular month or the whole year. The data can be presented in histogram form indicating the proportion of time at each value.

(*b*) The proportion of time a ship sails at a particular speed is determined by the way a ship is employed; and will either be known for a ship type or estimated for a new class of ship.

(*c*) Relative wind speed and direction could be estimated for new classes of ship from data collected from existing ships carrying out similar duties.

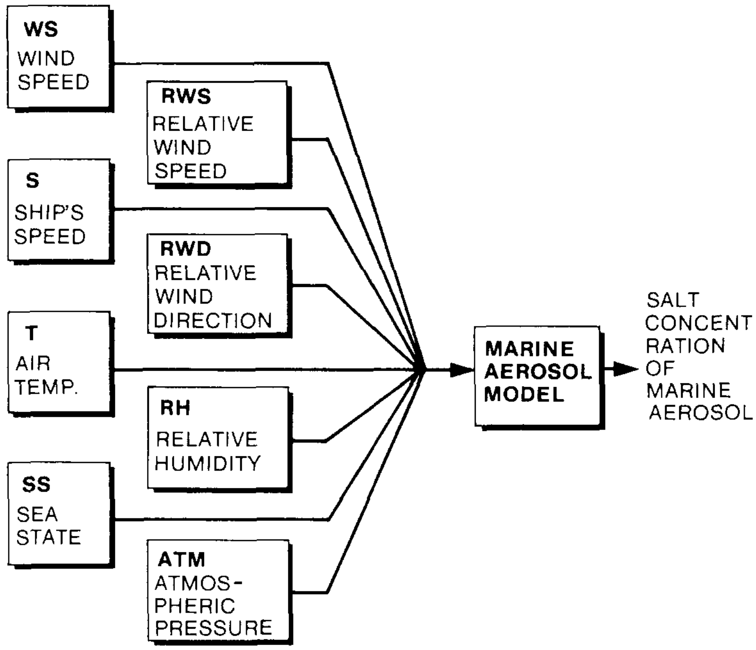

FIG. 3—MARINE AEROSOL MODEL

The process of calculating the concentration of salt in the marine aerosol is illustrated in FIG. 3. Statistical data describing each parameter's range of values and their frequency of occurrence is sampled at random to give one value for each parameter describing the marine aerosol to calculate the salt concentration. This process is repeated many thousands of times to ensure as accurate a result as possible. Each value of salt concentration calculated, is stored. The frequency of occurrences of a particular salt concentration as a percentage of the total number of occurrences (or iterations) is plotted against salt concentration. The fraction of the total number of iterations is equivalent to the fraction of the total time; thus if for 50% of the iterations the salt concentration was below 0·1 ppm then the ship is likely to meet salt concentration less than 0·1 ppm for 50% of the time it is on patrol.

The Monte Carlo approach allows a far more realistic and accurate means of describing the marine aerosol. It is a dynamic definition of a dynamic natural phenomenon. It gives the ability to predict the outcome of the interaction of many variables. In this case it can be used to determine:

(*a*) The range of salt concentrations which can be expected in the marine aerosol

(*b*) the proportion of time that a ship will experience each level of salt concentration in a particular geographical location, at a particular time of year, following a specific operating profile.

This can be expanded even further to simulate a ship's passage from A to B, patrol in area B and return to A over a time span of months.

Predicting Engine Salt Ingestion

The Monte Carlo simulation of the marine aerosol allows a prediction to be made of the salt concentration a ship's gas turbine air filtration system must be designed to cope with. This defines the performance required of the filtration system so that the ship's gas turbines are adequately protected.

In addition to estimates of salt concentration upstream of a gas turbine air filter, it would be very desirable to determine the salt concentration levels downstream of the filters—i.e. the levels of salt ingested by a gas turbine during its operation.

This information would be of great benefit in ship design; it would allow the selection of a filter for a particular ship's propulsion system to be made with much greater confidence. The possibilities of over or under design could be eliminated much earlier in the design process. Under-design increases salt ingestion reducing engine life, availability and reliability. Over-design may result in increased fuel consumption or increased ship topweight and reduced available space on the upper deck. Under- and over-design or inaccurate specification of filter performances can have very expensive consequences when a fleet of ships is considered.

In order to provide the designer with practical information which describes how the filter performs in the overall ship system, some means of including the filter's performance in a model of engine and ship operation is required.

The model of the marine aerosol has already been described. The models of the ship's filtration and propulsion systems are outlined below.

The Ship's Filtration System Model

To be able to model a ship's filtration system a mathematical description of how the gas turbine air filters operate is required.

The filter performs the function of removing salt water droplets and dry particles of salt from the gas turbines' intake air. The performance of a filter can be described in terms of the effectiveness with which it removes salt from the inlet air (the efficiency of salt removal) or the proportion of the salt in the inlet air which is not removed, the Penetration (P).

Penetration is a very useful parameter for modelling a filter because simple multiplication with the upstream concentration will give the downstream concentration using the following equation:

$$TCDN = TCUP.P \tag{4}$$

where TCDN is the total salt concentration downstream of the filter (i.e. ingested by the engine)

TCUP as before, is the total salt concentration upsteam of the filter (i.e. the salt concentration of the marine aerosol)

P is the air filter's value of penetration (the proportion of the upstream salt concentration it allows through)

If the concentration of salt in the marine aerosol and the filter's penetration are known at a particular instant, it is a simple operation to determine the salt concentration ingested by the engine. The problem arises, however, that the concentration of salt in the marine aerosol and the filter's value of penetration both vary. In order to calculate the salt ingested by the engine over a period of time the first task is to obtain an accurate description of both of these two variables. The means of obtaining these descriptions, in the form of mathematical models is outlined below.

The value of penetration for a filter is not a constant; it is affected by the filter face velocity, by the size distribution of the upstream aerosol spray (usually characterized by the Mass Mean Diameter, MMD), and relative humidity.

The three-stage filters the Royal Navy uses remove virtually 100% of droplets/particles larger than 10 micrometre. The efficiency of removal of smaller droplets/particles reduces with size until at 1–2 micrometre the removal efficiency could be as low as 50% in some circumstances. This means that when the mass mean diameter of the upstream spray is small, denoting that a large proportion of the spray is made up of small droplets, more of the droplets and therefore more salt will pass through the filter than if the same concentration of salt was contained in an aerosol with a larger mass mean diameter.

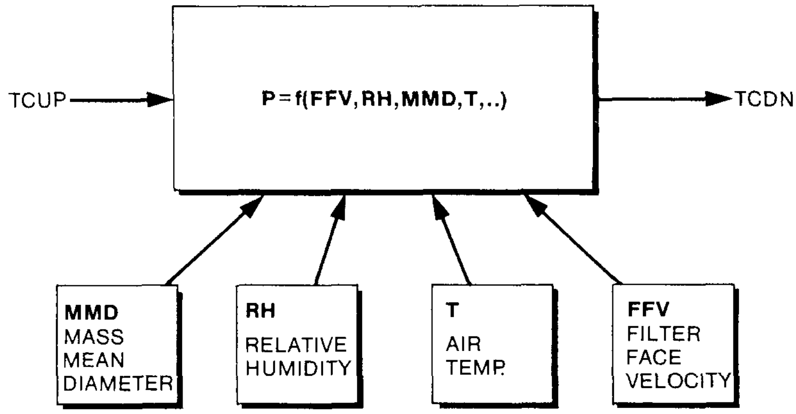

FIG. 4—THE 'OVERALL' FILTER MODEL

Bearing this in mind, there are two ways of modelling a filter:

(*a*) an overall view

(*b*) a composite model made up of descriptions of the filter's performance in distinct size bands.

Both of these models use the parameter of Penetration.

The 'Overall' Filter Model

In this model the filter is considered to be a black box as shown in FIG. 4. The total concentration downstream is calculated as the product of the penetration and the total concentration of salt upstream as in equation (4). However as the value of penetration is dependent upon relative humidity, mass mean diameter, filter face velocity, etc., all these parameters must be taken into account to give the best answer.

This is achieved using multiple regression to produce a mathematical model from experimental data. The model will be in the form:—

$$P = A1 + A2.FFV + A3.RH + A4.MMD + A5.T + A6.ATM + \ldots \quad (5)$$

The experimental data would be collected from rig testing under controlled conditions providing a wide variety of data.

The 'Composite' Filter Model

The composite model does not consider the overall penetration of the filter. It is composed of separate penetration functions for each particle size band width. Thus for each particle size band width there is a mathematical equation describing how the penetration varies with filter face velocity, relative humidity, etc, but, of course, not mass mean diameter. The concentration of salt downstream of the filter is calculated by summing the products of the concentration of salt and the penetration in each particular size band. This model is made complex by the need to apportion the appropriate amount of the concentration of salt to each size band. This is achieved by relating mathematically the mass mean diameter of the upstream aerosol to the proportion of the upstream concentration in each size band. This is illustrated in FIG. 5.

For any given upstream aerosol with a known concentration of salt and mass mean diameter, it is possible to calculate the concentration of salt downstream of a particular filter, given values for the variables which were used to produced the filter model, such as:

filter face velocity
relative humidity
air temperature
air pressure

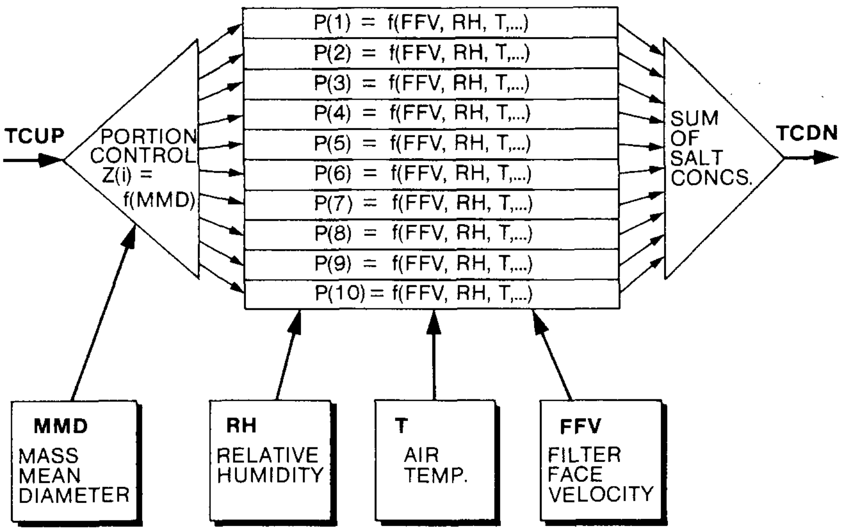

FIG. 5—THE 'COMPOSITE' FILTER MODEL

The Propulsion System Model

In describing the mathematical models of the marine aerosols and the filter we have found that both are functions of multiple variables:

filter face velocity
ship's speed
relative wind speed
relative wind direction
relative humidity
true wind speed
true wind direction
air temperature
air pressure
sea state

Some of these variables can be considered to be independent of one another, others are interdependent.

Wind speed, wind direction, air pressure, air temperature, sea state and relative humidity are all weather-dependent parameters. The geographical location and the time of year will have an overall affect on their range of values, however within that caveat the parameters are largely independent of one another (with the possible exception of wind speed and sea state).

Ship's speed is also taken to be an independent variable. In practice the ship is unlikely to proceed at 25 knots in a Force 10 gale; however this could be taken into account if required.

The filter face velocity of gas turbine air filters is a function of the ship's speed. The speed of a ship dictates the power required to propel it through the water and this in turn will determine a range of acceptable engine states and conditions. A propulsion system model describing these interrelations has been produced on the following basis.

Marine gas turbine air filters are designed to operate with filter face velocities between 3 and 9m/s. The filter is matched to the engine by relating the swallowing capacity of the engine to the filter area to give approximately 3m/s filter face velocity at idle and 9m/s at full power. The relationship between engine power and ship's speed is a cube law determined during the ship's design. Thus it is possible to determine, for a specific ship's speed, the power generated by each of the ship's engines and therefore the filter face velocity of a particular engine's filter system.

The ship's operating profile may also be described, i.e. how the ship is going to be used to perform a particular duty. A model of the propulsion system can be produced which gives a realistic description of how the engines would be run in service by relating the ship's operating profile to the rules governing the use of particular engines.

A propulsion system model of this sort allows us to determine the filter face velocity for a particular engine intake filter at a particular ship's speed.

The Complete Model and the Whole Ship Simulation

Combining the three models of marine aerosol, filter and propulsion system, it is possible to calculate the concentration of salt downstream of the filter for any combination factors which may be found to have an effect. Such a model is illustrated in FIG. 6. Typical graphical representation of results produced using this simulation are shown in FIGS. 7 and 8. FIG. 7 shows what can be expected upstream of the air filters, i.e. the marine aerosol. FIG. 8 shows how effective the filters are at keeping the salt ingestion limit below 0·01 ppm.

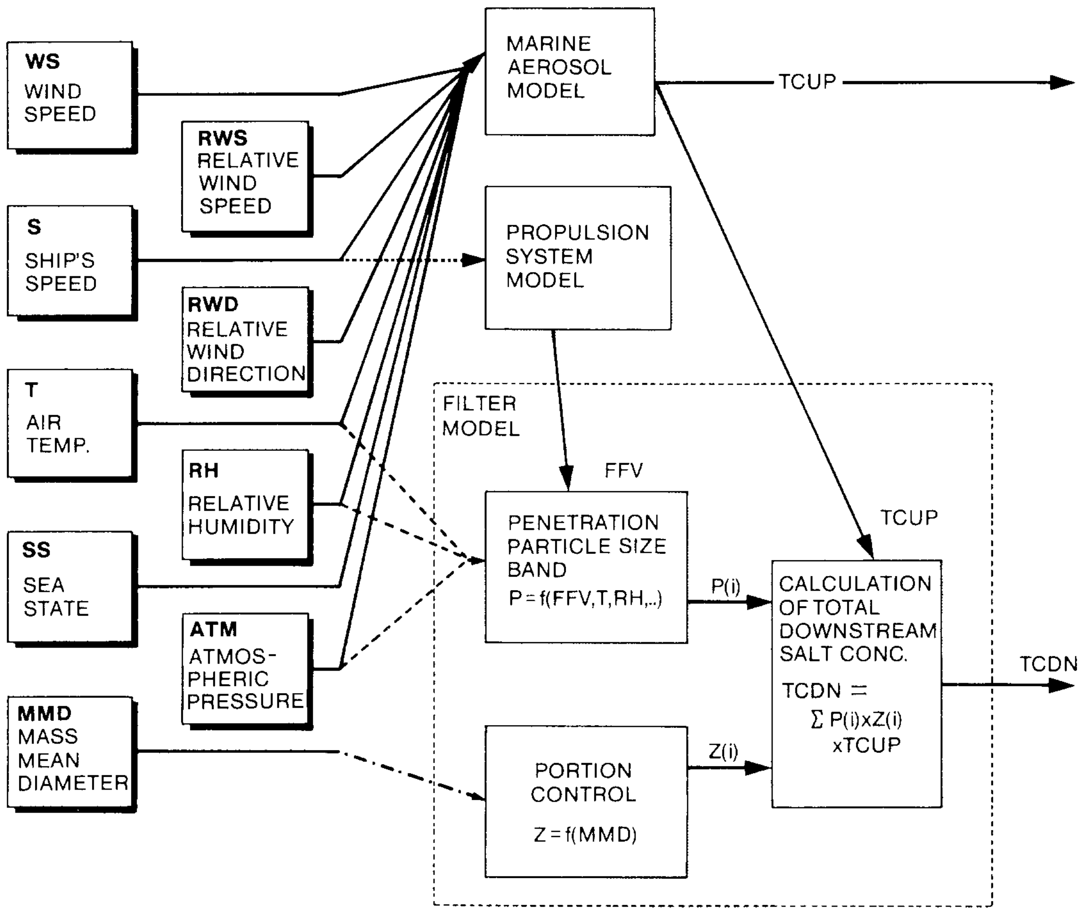

FIG. 6—THE COMPLETE MODEL

By using the model to simulate various situations it is possible to make a prediction of the salt levels each of a ship's engines is likely to encounter. The situations would differ due to many factors such as geographical location and time of year (both of which would determine prevailing weather conditions), and ship's operating profile or type of duty (which will affect ship's speed and if helicopter operations are a significant factor, relative

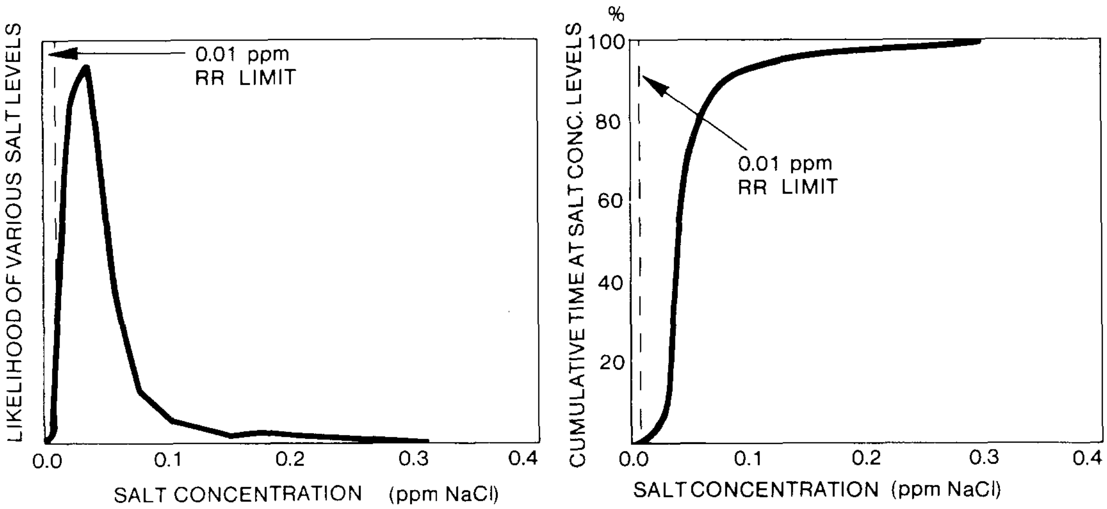

FIG. 7—PREDICTED SALT CONCENTRATIONS UPSTREAM OF FILTER

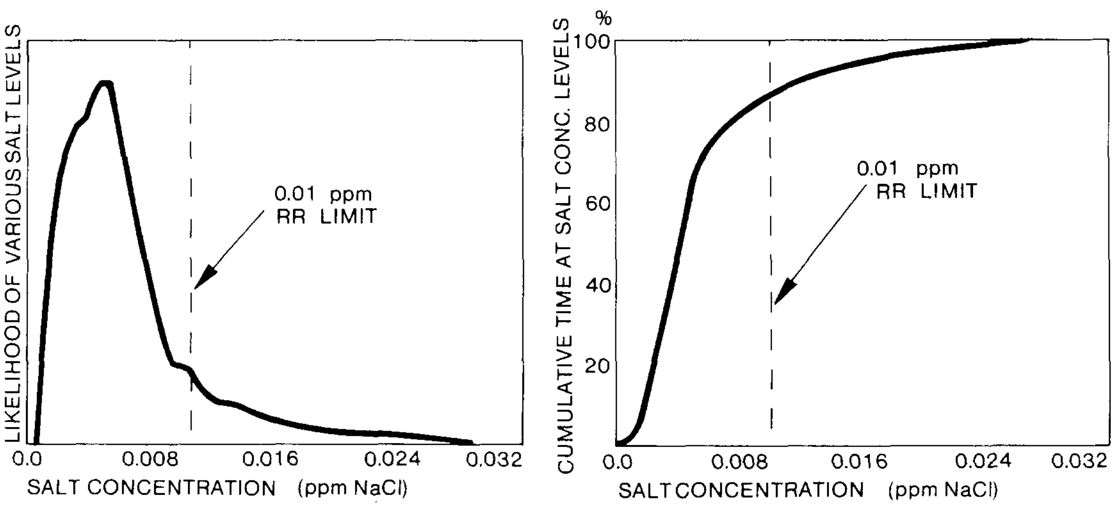

FIG. 8—PREDICTED SALT CONCENTRATIONS DOWNSTREAM OF FILTER

wind speed and direction). It is also possible to compare the modelled in-service performance of different designs of air filter by keeping the geographical location, time of year and operating profile constant. This is illustrated in FIG. 9 by comparing the downstream results from one filter, Filter A, with the downstream results from a rival filter, Filter B. It can easily be seen that Filter B if used in this propulsion system would allow the 0·01 ppm salt limit to be breached 70% of the time whereas with Filter A the limit is breached only 5% of the time.

Filtration systems may be tailored to suit different operating situations using information from this model. One filter may perform better in conditions of low humidity; another may be better suited to North Atlantic duties.

Perhaps the greatest benefit of this type of modelling is that the extent to which our ship's gas turbine filters are over- or under-designed may be determined. For many years we have been testing air filters against rough approximations of the marine aerosol. We have marine gas turbine air filters which perform adequately. But can we say with confidence that the 0·01 Rolls-Royce salt ingestion limit is never breached? Can we quantify by how much the filter is more efficient than the minimum requirement? If such information were available we would be able to see by how much our filters are over-designed. An excessive margin of safety may be exchanged for a decrease in pressure drop accross the filter with consequent saving in fuel costs.

The future should also be of concern. The next generation of marine gas turbines may have air filtration requirements which are altogether different from today's. Certainly reducing the size and weight of the filtration and intake systems will become even more important; the need to reduce warship topweight and provide more room on the upper deck for weapons and sensors will increase. This may involve the development of radically different air filters. The Monte Carlo simulation method described in this article would provide a very flexible and powerful design tool which could be used to assess and match any filtration system to an engine thus avoiding the costly mistakes of over- or under-design.

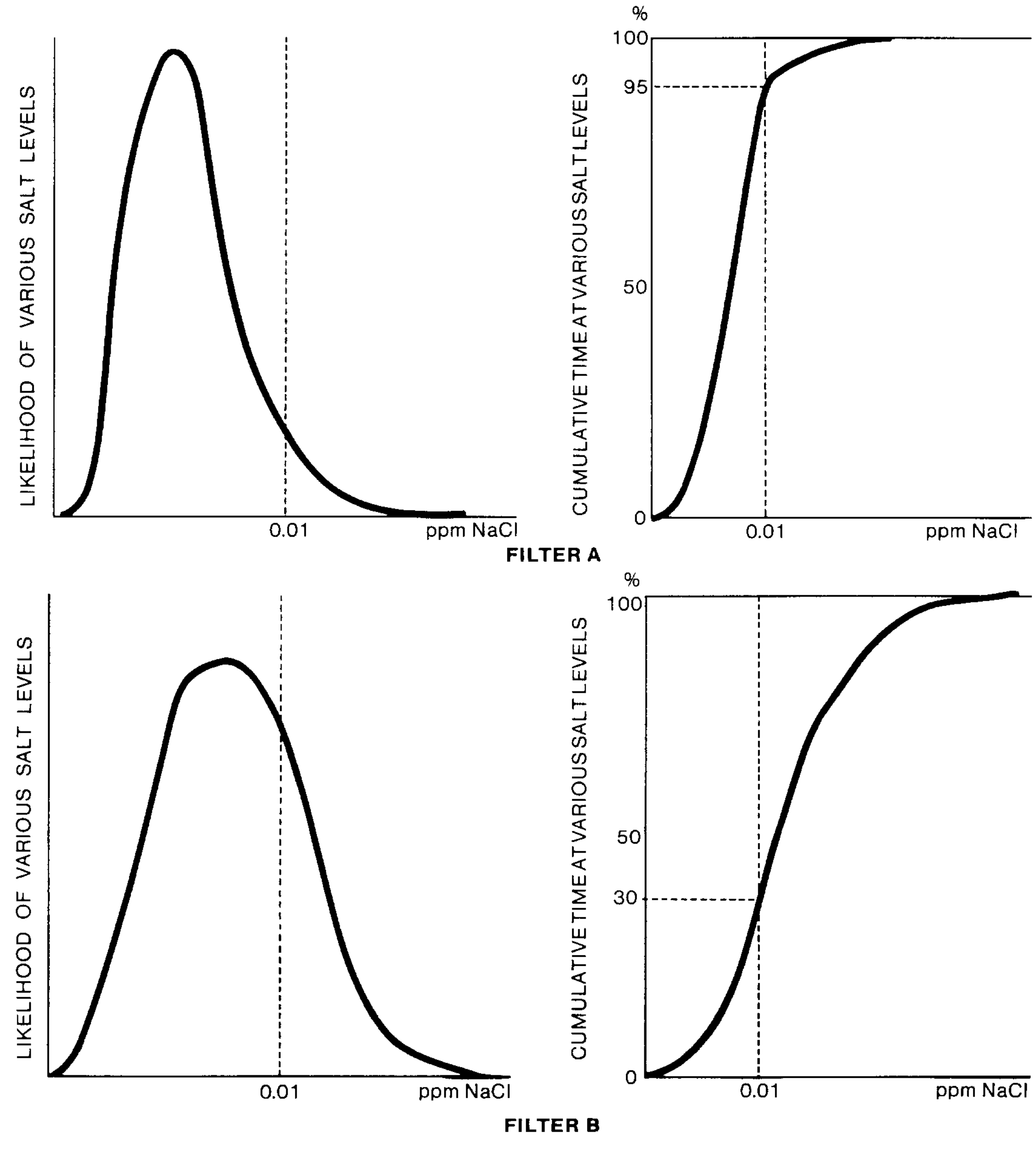

FIG. 9—AN EXAMPLE OF FILTER PERFORMANCE COMPARISON

CONCLUSION

The Standard NGTE Aerosols as accurate descriptions of the Marine Aerosol are questioned. A multiple regression model of the Marine Aerosol based on empirical data would give a much more accurate description.

By adopting multiple regression models of the marine aerosol and a marine gas turbine filtration system and combining them with a mathematical model of a ship's propulsion system, a whole ship model can be produced.

By using the whole ship model in a Monte Carlo simulation it is possible to predict the levels of salt ingested by a ship's gas turbines.

This whole ship simulation provides a flexible and powerful design tool which can be used in the following ways:

(*a*) comparison of performance of filters of different design;

(*b*) the matching of filters to ship's propulsion system and ship's operating profile;

(*c*) determining whether and by how much filters are over- or under-designed for the protection which they are installed to provide.

References

1. Featherstone, C. C., 1979; The application and analysis of marine aerosol data in the evaluation of marine gas turbine air intake sea-salt separators; *National Gas Turbine Establishment Memorandom* M179120(M).
2. Young, L. J. 1967: Proteus salt ingestion trial; *Naval Marine Wing Note* No. 2/67, National Gas Turbine Establishment, Pyestock, Hants.
3. Clark, A. J., 1967: Endurance testing of a Rolls Royce Tyne engine in a marine environment; *Naval Marine Wing Note* No. 7/67, National Gas Turbine Establishment Pyestock, Hants.
4. Randles, R. H. and Ansari, Z., 1972: Evaluation of the Peerless Mark 1 spray eliminator for protection of marine gas turbine air intakes; *Naval Marine Wing Note* No. 30/71, National Gas Turbine Establishment Pyestock, Hants.
5. Kaufman, P. E., and Pollini, R. J., 1968: Gas turbine combustion air salt aerosol separation program; *NAVSECPHILADIV Project* T-454, Naval Ship Engineering Center, Philadelphia Division, Philadelphia, Pa.
6. Mihalek, E. W., and Shen, C. N., 1977: Real time test techniques for sea-salt aerosol-separator evaluation; *ASME Publication* 77-GT-29.
7. Young, L. J., 1967: A report of the salt in air sampling trials carried out in HDMS Peder Skram, October/November 1966; *NGTE Note* No. NT. 648, National Gas Turbine Establishment Pyestock, Hants.
8. Lovett, R. F., 1975: The occurrence of airborne sea-salt and its meteorological dependence; unpublished M.Sc. thesis, Heriot-Watt University.
9. Westwood, S. P. C., 1976: An investigation into the effects of ship movement on the concentration and particle size and distribution of the marine aerosol; unpublished M.Sc. thesis, Royal Naval Engineering College, Manadon, Plymouth.
10. Woodcock, A. H., 1953: Salt in marine air as a function of altitude and wind force; *Journal of Meteorology*, Vol. 10, pp 362–371.