SMOKE CLEARANCE

COMPUTERIZED PREDICTION FOR SHIPS

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ABSTRACT

A computer program has been developed that enables effective smoke clearance systems to be designed or existing systems to be optimized. This article chronicles the background and history of smoke clearance, outlines the development of the program and indicates the potential of future smoke clearance measures.

Introduction

The Falklands conflict of 1982 proved conclusively that one of the most serious aspects of battle damage is smoke (FIG. 1). Unless it can be localized, contained and subsequently removed, the task of damage control is increased to a degree where in some cases, recovery becomes impossible. If one has experienced the horror of thick, black, toxic smoke, it can be understood why the design of smoke clearance systems must be given high priority.

Existing damage control procedures, initiated to recover a situation in the event of fire on board ship, are well practised and centre on a philsophy of containment followed by localized actions to extinguish the fire. Specialized equipment and highly trained personnel are mobilized to achieve this. Once the fire is out, efforts can be concentrated on clearing smoke from the vicinity.

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In a comparison with land-based procedures, especially those adopted for shopping malls and public buildings, a fundamental difference becomes evident. Rather than exercising naval methods of containment and local fire fighting actions which inhibit spread, the presence of members of the public and much larger room volumes ensure that fire fighting and smoke clearance actions for these buildings must be carried out simultaneously. As an example, atrium type shopping malls often adopt natural ventilation methods when no threat is present. The free wheeling fan units in the roof only become powered in the event of a fire. These specialized fan units must be capable of dealing with high temperature smoke (up to 800 degrees C) for sustained periods of time. Smoke clearance operations in a naval environment do not have to deal with such high temperatures and consequently standard fan units can be used.

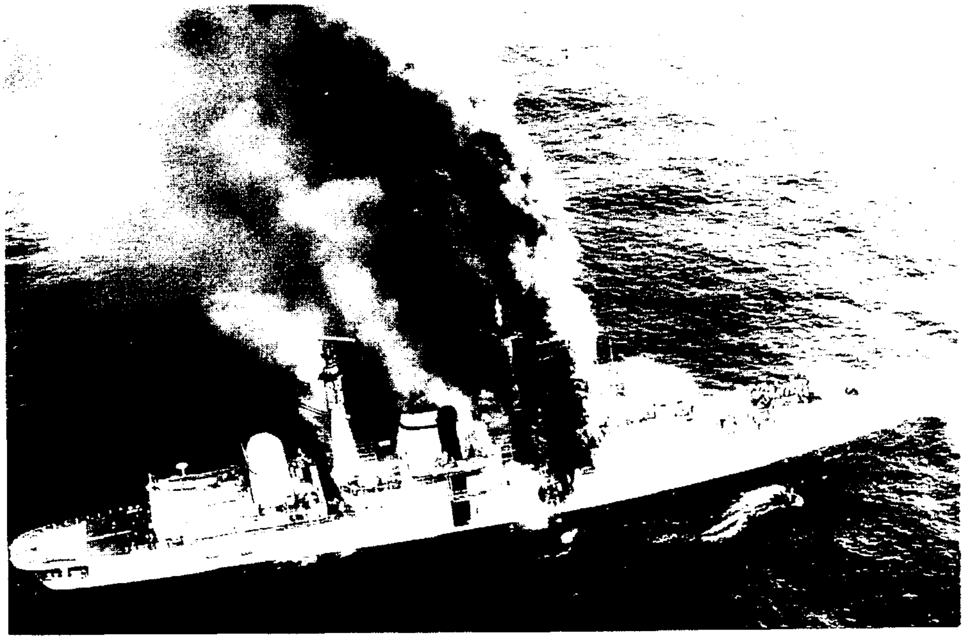

FIG. 1—H.M.S. 'SHEFFIELD', SHOWING THE AMOUNT OF SMOKE GENERATED DURING A FIRE

History of Smoke Clearance

Before the advent of powered fans in the 1930s, ventilation and smoke clearance operations were achieved using natural supply and exhaust methods assisted by wind scoops, doors and hatches. A limited number of supply fans were fitted before the second world war, to increase personnel comfort in populated spaces. Exhaust was still by natural methods. The application of supply and exhaust fans became more widespread in the 1940s, allowing smoke clearance operations to be fully fan-assisted for the first time. The large capacity machinery space exhaust fans were favoured for such operations, but the proliferation of powered direct exhaust routes ensured that a path out of the ship was never far away.

Introduction of the citadel concept for NBC defence in the 1950s did not greatly affect smoke clearance operations, as the filter units and recirculation fans were only put on line under NBC threat. Forced air cooling of equipment became more widespread, but machinery space ventilation fans and other units on the mechanical ventilation system still prevailed for smoke clearance.

With the introduction of TACS (Total Atmosphere Control System) during the 1970s, whereby continously running NBC filter units were used to supply fresh air to the citadel at all times, the need for mechanical ventilation systems diminished rapidly. Recirculation of air within the ship and mixing of the relatively small proportion of fresh air made-up (approximately 10%) was achieved for the first time using centralized ATUs (Air Treatment Units). Only difficult spaces such as the galley, heads and bathrooms, paint/flammable/hazardous stores and machinery spaces, remained under the jurisdiction of supply and exhaust fans. The corresponding reduction in the number of direct exhaust routes meant that during smoke clearance operations, smoke was often drawn through the ship before being ejected by the machinery space exhaust fans.

As a direct result of lessons learned during the Falklands conflict, a subdivision policy was introduced on new build ships to isolate regions of the ship into autonomous fire zones so minimizing the spread of damage. These zones possess self-contained air conditioning, cooling and fire fighting systems. Zoning may have reduced the vulnerability of ship systems to action damage, but smoke clearance problems have been compounded.

With subdivision enforced on TACS ships, it became evident that certain zones may have no mechanical exhaust fans suitable for smoke clearance. The machinery space exhaust fans could not be accessed without opening up the ship and as a result, a policy advocating the fitment of dedicated smoke clearance fans was introduced. These smoke clearance fans were fitted (one per zone) to ease the situation. However, the sizing and location of such units could not be accurately assessed and as a result of smoke clearance trials on Type 22 frigates, they have been shown to be ineffective. Larger fans could have been specified in their place, but in 1985 a complete programme of smoke clearance prediction was undertaken to establish the best methodology for clearing smoke from the complex ship layouts that had arisen.

Program Development

Initial investigation revealed that despite considerable amounts of literature on smoke behaviour in large buildings on land, virtually no useful information was available to assist the design of smoke clearance systems for warships. Work specifically aimed at rectifying this deficiency was required.

Scale Model Tests

The starting point in the provision of data was a set of smoke clearance experiments on 1/4- and 1/8th-scale room systems at University College London during 1985 and 1986[1]. Scores of tests on these models yielded results of practical value, and the establishment of fast and effective experimental procedures that could be applied to even more sophisticated models. The experimental work, however, also strongly emphasized what was already well known, namely that model tests in this situation are extremely expensive in terms of direct costs and time. In fact, scale model testing is arguably inappropriate as the investigative tool in smoke clearance work and is better employed in a validating role for cheaper and more convenient analytical predictive methods. The weakness in the experimental approach is that the geometry of the room system is a variable of primary importance. In almost all engineering systems geometric variables greatly outnumber the dynamic variables of interest, such as pressure and velocity. Dimensional analysis will typically reduce the list of variables determining system behaviour by three, and if the dimensionless geometric variables are fixed then the number of independent dimensionless variables remaining is very small and a correspondingly small number of model tests is sufficient to describe the behaviour of the prototype throughout its entire operation range. In smoke clearance studies, system geometry must be considered variable and to cover all realistic permutations of the variables involved is quite impracticable. Even when the geometry is nominally fixed, the consequence of re-positioning fans, or varying the open/closed status of one or more doors in the system produces a new geometry whose smoke clearance characteristics cannot safely be extrapolated from tests on any other variant of the same basic room system.

The preferred approach is to attempt an analytical method of prediction and to validate the method by a small number of model tests, thereby providing a reliable, flexible, cheap and extremely fast design tool. This attractive prospect prompted a two-stage analysis. The first stage was a rigorous treatment for a single room and the second, the subject of the present article, an approximate method aimed at realizing all of the desirable features just listed.

Single Room Rigorous Prediction

A rigorous analysis implies the solution of the Navier-Stokes equations, the continuity equation and the concentration equation. This was carried out for unsteady laminar and turbulent flow, and for the turbulent case it required also the solution of the equations associated with the k-ε model of turbulence employed. The computational effort required in this study obliged its restriction to a single room but it provided important results. It showed the sensitivity of the smoke clearance rate to geometric changes in the room, in particular the importance of inlet and outlet vent positions. It also showed that clearance air jet disruption caused by jet impingement on walls is much more important as a mixing mechanism than is turbulent flow, so making the distinction between laminar and turbulent flow unnecessary. (Jet disruption and the consequent vigorous mixing is conducive to rapid smoke clearance.) An exceptional case is when inlet and outlet vents are perfectly aligned on opposite walls of the room. Here the clearance air jets tends to pass straight through the room and through the outlet vent with little disturbance and, in the case of laminar flow, with negligible entrainment of smoke from the rest of the room. The smoke clearance rate is very low. The absence of impingement of the jet in this special case makes the small-scale fluctuations in a turbulent jet relatively more important as a mixing mechanism.

The rigorous analysis also gave an insight to the detailed behaviour of the smoke throughout the room, particularly when graphics presentations were used. This detail is something that is virtually impossible to achieve experimentally. Finally, the rigorous treatment provided a datum for the development of the approximate model.

A detailed discussion of the single room model is published elsewhere[2,3], but because it underpins, to some extent, the approximate model now to be described it is worth dwelling a little longer on its findings. FIG. 2 shows the average smoke concentration c in a room as a fraction of the initial concentration c_0 following the start of the extraction fan at time $t=0$. Q is the eventual steady flow rate through the inlet (and outlet) vent and V is the room volume. Line 1 is the case of perfectly aligned vents referred to above, the remaining lines progressing from slight mis-alignment (line 2) to extreme mis-alignment (line 5-inlet and outlet vents close together but on adjacent walls.) Excepting the unlikely case represented by line 1, the smoke clearance rates for slightly and extremely mis-aligned vents are different by a factor of about 2 as measured by the time for c/c_0 to reach 1/2. This suggests that in the absence of better information for any room having one inlet and one outlet vent a rule-of-thumb value of 1·0 for QtL/V when $c/c_0 = 1/2$ will not be seriously in error, but may well be somewhat pessimistic since vents will usually tend towards the condition of extreme rather than slight misalignment.

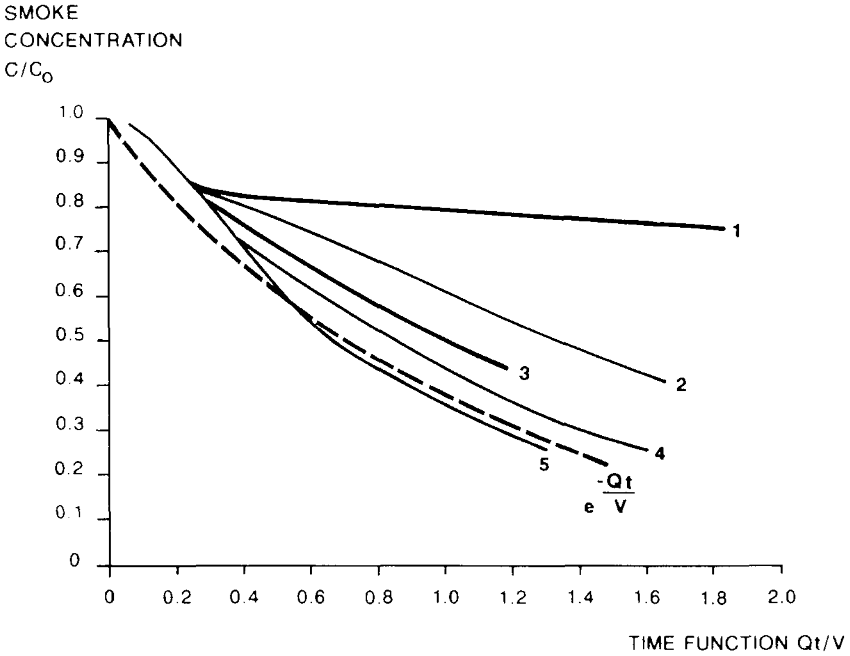

FIG. 2—AVERAGE SMOKE CONCENTRATION IN A RECTANGULAR ROOM WITH 1 FRESH AIR INLET VENT AND 1 EXHAUST VENT. SOLUTIONS, FROM RIGOROUS MODEL, FOR DIFFERENT VENT ARRANGEMENTS.

Single Room Approximate Prediction

The association of rapid smoke clearance with a high degree of mixing between the clearance air jet and the smoke-air mixture leads to the idea of perfect mixing and a simple approximate model. If the clearance air mixes instantly and perfectly with the mixture in the room so that the concentration in the room is spatially uniform then an *exact* solution to the smoke clearance problem would be

$$c/c_0 = \exp(-Qt/V)$$

This equation is plotted on FIG. 2 and shows an interesting correspondence with line 5 (high degree of mixing). (The distortions and coincidence of lines 1 to 5 near the start of smoke clearance are results of the fan starting characteristic and a 'positive displacement' effect[3].)

If mixing is not perfect then the jet passing through the exhaust vent will have a lower concentration than before. This will result in a lower clearance rate which can be represented by a 'mixing factor' k such that

$$c/c_0 = \exp(-kQt/V)$$

By choosing the value of k this equation can be used to approximate any of the vent arrangements involved in FIG. 2. In practice k is expected to be rather close to 1·0. The importance of this is that with sensible choice of mixing factor (perhaps between 0·8 and 1·0) the shape of the room (the most troublesome feature of smoke clearance) may be dispensed with while still obtaining practically useful results from a greatly simplified numerical model.

Multi-Room Approximate Prediction

Consequently an approximate model has been developed on the following premises:

(*a*) Room shape can be represented by a single mixing factor.

(*b*) Laminar and turbulent flows need not be distinguished.

The model accounts for the following effects:

- number of rooms in the system
- individual room volumes
- NBC connections to individual rooms
- mixing factor for each room
- door and grill connections between rooms
- door connection between a room and the atmosphere
- door connection between a room and an adjacent zone
- number of fans (1 or 2) in the room system
- location(s) of the fan(s) in the room system
- fan characteristics
- ship speed
- wind speed and heading relative to ship ahead
- initial smoke concentration in each room

For simplicity, a room is the generic name for any space that is to be identified as an entity. Thus a room may be a cabin, the space around a hatchway, a gangway, and so on. Similarly, doors, grills and NBC connections are all referred to as vents. To avoid unnecessary use of computer memory the maximum number of rooms in a system is set at 80 but this is easily increased if required. Any room in the system can be directly connected to as many as 15 other rooms in the system. Again, this can easily be increased.

Pressure differences throughout the system are so small in relation to the general pressure level that the flow can be treated as one of constant density. Conservation of mass therefore reduces to conservation of volume so that for each room in the system, the sum of the volume flow rates into the room is always zero (flow balance).

The model consists of two programs: ROOMPLAN and CLRSMOKE. ROOMPLAN enables the user to create and modify room systems incorporating the geometric elements in the above list (i.e. all but the last three). CLRSMOKE then calculates the steady state flow and pressure distributions throughout the room system, and the smoke concentration as a function of time for every room in the system, subject to the user's choice for the dynamic variables indicated.

CLRSMOKE assumes that the volume flow rate of clearance air to a room via the NBC filter is proportional to the difference between atmospheric pressure and the pressure in the room. The constant of proportionality can be estimated from such factors as the length and cross-sectional area(s) of the ventilation trucking and the area of diffusers into the room. The volume flow rate Q through grills and doors is assumed to be given by

$$Q = C_D \times A \times (\Delta p)^n$$

where C_D,A and Δp are the coefficient of discharge, the area and the pressure difference between the rooms, respectively. The exponent n is taken equal to 0·5.

CLRSMOKE simultaneously solves the equations for all the vents in the system, the equations representing the fresh air inlet duct flows, the continuity (flow balance) equation for every room, and the equations representing the fan characteristics. As well as ship and wind speeds, allowance is also made for the orientation of fan exhausts and doors opening to atmosphere.

The user is then invited to choose a uniform or non-uniform initial smoke concentration for the room system. Choosing a non-uniform distribution enables the user to input abitrary values for user selected blocks of rooms in the system so that any desired initial smoke distribution is easily established.

The flexibility and speed of the model are important features. For example, to change the location and size of a fan using ROOMPLAN takes about one minute, regardlesss of the computer used. A complete run of the computationally intensive CLRSMOKE on a Vax machine for a 50 room system and 250 timesteps also takes about one minute, excluding the graphics presentation of results, if this is required. A comprehensive results display routine enables data and results to be shown for any selected room, or for the entire system, or the smoke concentration may be shown graphically for any selection of up to ten rooms at a time.

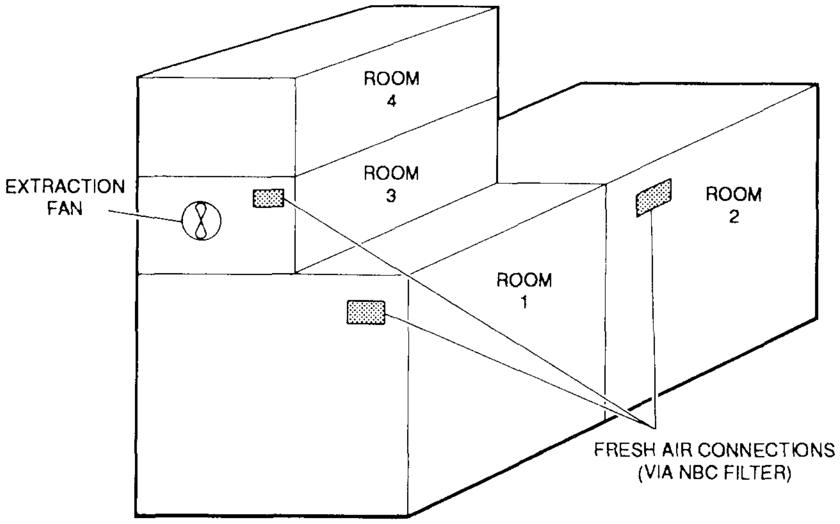

FIG. 3—SIMPLE 4-ROOM SYSTEM USED FOR SIMULATIONS IN FIGS. 4 TO 6

Results

Space does not permit an adequate description of the results of calculations for a large room system but by way of illustration the graphic outputs for a simple 4-room system (FIG. 3) with three different initial concentrations are shown in FIGS. 4, 5 and 6. For the present purpose it need only be noted that there is only one extraction fan in the system and its inlet is in room 3; rooms 1,2 and 3 are connected to the NBC filter; room 3 is connected to rooms 1 and 4. The door between rooms 2 and 1 is closed so that there can be no smoke extraction from room 2. Room 1 is large relative to rooms 3 and 4. The initial concentrations are evident from the figures. The connections amongst the rooms result in rooms 1 and 4 clearing as single rooms and it is a simple check on the numerical accuracy of the results that both rooms can be shown to be clearing exactly as exp(-Qt/V), as they should. Room 3, on the other hand, is affected by the smoke being received from rooms 1 and 4, as is particularly clear from FIGS. 5 and 6. In larger room systems quite complex clearance patterns can result from different choices of initial smoke concentration distribution, patterns that are not always easy to anticipate.

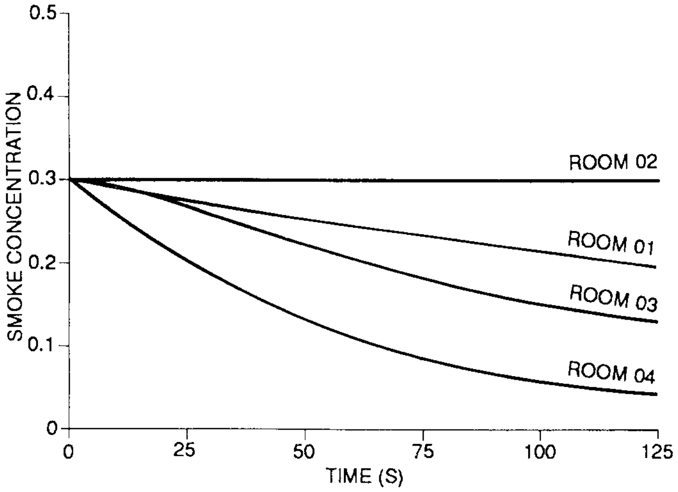

FIG. 4—EXAMPLE RESULTS FROM APPROXIMATE MODEL OF SMOKE CLEARANCE—ONE INITIAL SMOKE CONCENTRATION

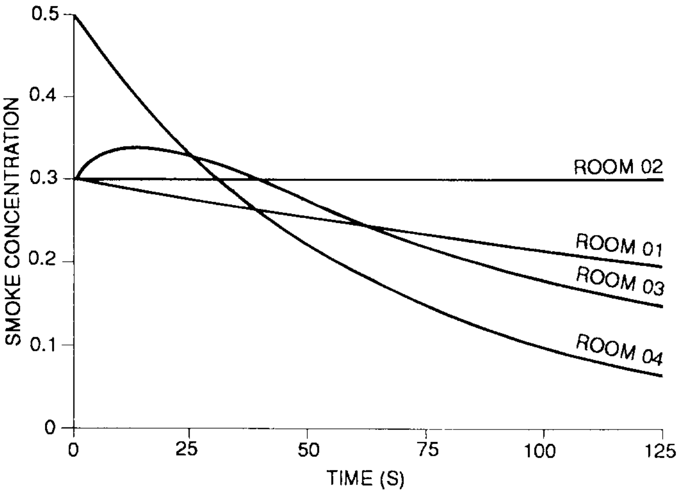

FIG. 5—EXAMPLE RESULTS FROM APPROXIMATE MODEL OF SMOKE CLEARANCE—TWO INITIAL SMOKE CONCENTRATIONS

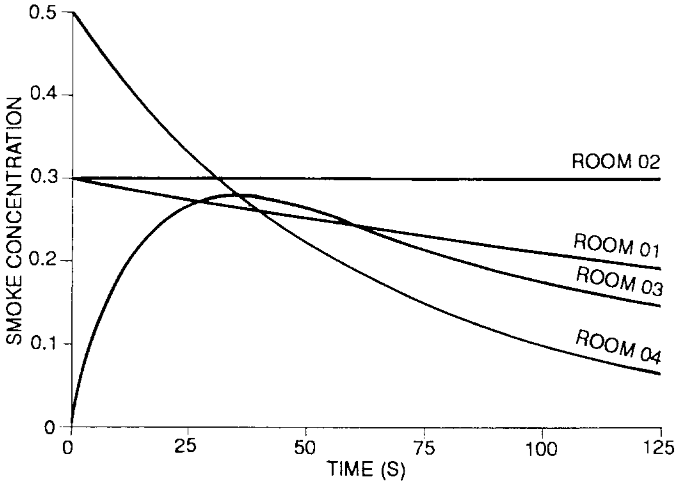

FIG. 6—EXAMPLE RESULTS FROM APPROXIMATE MODEL OF SMOKE CLEARANCE—THREE INITIAL SMOKE CONCENTRATIONS

Conclusions

The computer model described here provides a versatile, rapid and easy-to-use facility for investigating the clearance of smoke from zoned ships. The model has a sound physical base and should yield results of sufficient accuracy to permit the designer to choose from alternative smoke clearance proposals. The programs should also assist in the formulation of operational strategies, such as deciding the benefits or disadvantages of opening doors to atmosphere and/or to adjacent zones during smoke clearance.

Smoke is the substance of concern in the present context but the programs are also applicable to the removal of any offending gas and may be of use to air conditioning studies in general.

References

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3. Barclay, W. H. and Aston, J. G. L.: The influence of vent positions in the smoke clearance from a room; *International Journal of Heat and Fluid Flow*, to be published.