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CAA Paper 2007/02

Visualisation of Offshore Gas Turbine Exhaust Plumes

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Visualisation of Offshore Gas Turbine Exhaust Plumes

October 2007

ISBN 978 0 11790 821 5

Published October 2007

Enquiries regarding the content of this publication should be addressed to:
Safety Investigation and Data Department, Safety Regulation Group, Civil Aviation Authority, Aviation House, Gatwick Airport South, West Sussex, RH6 0YR.

The latest version of this document is available in electronic format at www.caa.co.uk/publications, where you may also register for e-mail notification of amendments.

Published by TSO (The Stationery Office) on behalf of the UK Civil Aviation Authority.

Printed copy available from:
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Foreword

The research reported in this paper was funded by the Safety Regulation Group of the UK Civil Aviation Authority (CAA) and the Offshore Safety Division of the Health and Safety Executive (HSE), and was performed by BMT Fluid Mechanics Limited and, under subcontract to BMT, QinetiQ (Pyestock). The work was commissioned in response to a recommendation (10.1 (vi)) that resulted from earlier research into offshore helideck environmental issues, reported in *CAA Paper 99004*.

The hazards that can be presented to helicopter operations by gas turbine exhausts on offshore platforms were graphically illustrated by the heavy landing on the Claymore Accommodation Platform on 18 August 1995 (AAIB Bulletin No. 3/96). Based on the analysis of helicopter operational flight data performed as part of this research however, turbine exhaust plume encounters are limited to a relatively small number of 'problem' platforms which can easily be identified.

The CAA considers that the work reported here has demonstrated that visualisation of turbine exhaust plumes is both practical and affordable. It is recognised that the installation and running costs are not insignificant and, consequently, CAA proposes to include a recommendation in *CAP 437 Offshore Helicopter Landing Areas - Guidance on Standards* that visualisation systems be seriously considered for 'problem' platforms only.

A further recommendation to be added to *CAP 437* will address the use of the helicopter operators' existing operational data monitoring programmes to establish and continuously monitor the temperature environments around all offshore platforms. This action is aimed at identifying any 'problem' platforms, supporting and improving the contents of the Helideck Limitations List, identifying any new problems caused by changes to the platform topsides or resulting from combined operations, and identifying any issues relating to flight crew training or procedures.

Safety Regulation Group
October 2007

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Executive Summary

Hot gas exhaust plumes from offshore platform power generation turbines present a hazard to helicopter operations. The hazard and potential effect on helicopter engines and rotor systems are described in detail in *CAA Paper 99004*. The temperature rises above ambient can have a significant effect on helicopter performance and need to be taken into account by the pilot when calculating the maximum operating weight of the aircraft. In addition, the rates of change of temperature in the plume can cause the helicopter engines to surge or flame out, and the turbulent flow in the plume can give rise to handling difficulties. *CAP 437 Offshore Helicopter Landing Areas - Guidance on Standards* recognises that in some circumstances the introduction of smoke into exhaust emissions to make them visible to pilots could represent a safety benefit, and anticipates a recommendation that installations with a known history of gas plume encounters give serious consideration to implementing systems to ensure effective visualisation of otherwise unseen exhaust gas plumes.

BMT Fluid Mechanics Limited (BMT) was commissioned by the Safety Regulation Group of the Civil Aviation Authority (CAA), and the Offshore Safety Division of the HSE, to perform a study to investigate the practicalities of generating smoke in gas turbine exhausts on offshore platforms. The study comprised five phases:

1 The purpose of the first phase of the study was to determine whether the proposal for the generation of smoke was viewed to be practical and beneficial by Industry experts, and to determine the feasibility and costs of an offshore trial to demonstrate and test the concept.

The study found that creating visible smoke plumes was believed to be practical and, in the view of those interviewed, was likely to improve safety. Two candidate offshore platforms were initially identified for the offshore trial, and it was determined that the offshore trial should run for at least one year in order to gain experience of the use of the smoke system over a wide range of meteorological and operational conditions.

The study concluded, however, that a preparatory onshore trial using a land-based gas turbine should be undertaken in advance of an offshore trial in order to:

- establish the best smoke generating agent to use;
- provide estimates of the quantity of smoke generating agent required to make consistent smoke;
- obtain the information necessary to design the offshore trial equipment.

Specifications were developed for both the onshore and offshore trials. The onshore trial specification was used as the basis for the trial that formed the second phase of the study.

2 The onshore trial constituted the second phase of the work described in this report. Six smoke producing agents were evaluated. The trial demonstrated that injecting agents into a gas turbine exhaust could produce plumes that were visible from several kilometres. Injecting diesel into the exhaust resulted in the best visualisation. Theatrical smoke oil and glycerol/water solution produced plumes that were less dense than those generated by diesel, although the plume produced by glycerol/water solution reduced in density after a short period. Nevertheless, both agents demonstrated potential. Water, kerosene and rapeseed oil were ineffective in creating a visible plume. Both pressure-jet and air-blast atomisers were employed, with the latter generally demonstrating better performance.

3 In view of the good performance of diesel during the onshore trial, an environmental impact assessment on the use of diesel fuel as a smoke agent in the offshore environment was undertaken in the third phase of the work. This concluded that the use of diesel would be unacceptable from both the personnel exposure and marine contamination points of view.

4 Theatrical smoke oil and glycerol remained as possible agent contenders but, since glycerol was considered better on grounds of cost, environmental acceptability and performance at low exhaust temperatures, this was selected for further study in the fourth phase of the work. The smoke generating performance of environmentally benign glycerol/water solution was investigated in a small, low cost, accessible, bench-top experiment. In particular, the experiment aimed to understand the cause of the intermittent behaviour exhibited in the full-scale onshore trials, and to define the limits of its operation. No intermittency was observed at any time during the small-scale experiment, although it was not possible to reproduce many of the conditions and dynamics of the full-scale onshore trial. However, the small-scale experiment did demonstrate that there is no fundamental obstacle to producing a constant, visible plume using a glycerol/water solution.

5 Finally, the fifth phase comprised an analysis of ambient air temperature data collected from helicopters during normal revenue service by the Helicopter Operations Monitoring Programme (HOMP). The objective of the exercise was to investigate the general extent of the hot exhaust gas plume problem. The study established that temperature increase due to hot gases is not a problem at the majority of offshore installations, and that ongoing, routine analysis of HOMP data to map and monitor the temperature environments around offshore platforms could yield worthwhile safety benefits.

Overall it is concluded that a gas turbine exhaust plume visualisation system would be beneficial to helicopter flight safety at platforms where significant exhaust plume encounters are experienced, and that such a system is feasible to design and operate using an environmentally friendly glycerol/water solution as the smoke generating agent.

Prior to implementing such a system in service, it would first be necessary to design, install and evaluate a prototype system offshore, i.e. conduct an offshore trial. The prototype system would need to be capable of generating smoke using a wide range of agent flow rates. This would enable the optimum smoke agent flow rates to be determined for a wide range of offshore meteorological conditions, and gas turbine exhaust temperatures and flow rates.

It is also concluded that, owing to the likely high cost of installing and operating such systems, attention should be focussed only on those platforms known to have a turbine exhaust plume problem. It is considered that HOMP data could be used to identify problem platforms amongst those that have not already been considered and monitor the situation to see, for example, how the addition of a smoke system has reduced the number and/or severity of the hot exhaust gas plume encounters.

Report Visualisation of Offshore Gas Turbine Exhaust Plumes

1 Introduction

One of the recommendations of the report on *Research on Offshore Helideck Environmental Issues* [1][1] was:

> "Review the long-standing recommendation in *CAP 437* that visible smoke be emitted from gas turbine exhaust outlets during helicopter operations, to determine why there has been a reluctance on the part of platform operators to act."

The purpose of the smoke proposed above is to make hot, turbulent exhaust gas plumes visible to helicopter pilots so that they can avoid them during the approach and landing and also during take-off. Exhaust plumes do have a significant effect on helicopter performance [1] and the temperature rise above ambient needs to be taken into account by the pilot when calculating the maximum operating weight of the aircraft [2]. In addition, the rates of change of temperature in the plume can cause the helicopter engines to surge or flame out, and the turbulent flow in the plume can give rise to handling difficulties.

The Safety Regulation Group of the CAA, and the Offshore Safety Division of the HSE commissioned BMT, to investigate the practicalities of generating smoke in gas turbine exhausts on offshore platforms. This report presents the results of all five phases of work undertaken comprising:

- a feasibility study;
- an onshore trial;
- an environmental impact study of diesel;
- a small-scale laboratory experiment and CFD study to investigate the performance of glycerol solutions;
- HOMP data analysis.

1.1 Summary of Study Objectives

The overall study objectives were:

Phase 1 –

- Determine whether there would be any safety benefit in making gas turbine exhaust plumes visible, whether it had been tried before and whether there were any likely hazards or operational difficulties.
- Determine whether there would be any major difficulties in developing and installing a smoke generating system offshore, and propose a way forward by producing a specification for the system.

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[1] References are listed in Section 14 on page 70.

Phase 2 –

- Perform an onshore trial to evaluate a smoke system and obtain information on the performance of several potential smoke generating agents, and to determine typical agent spray quantities.
- Obtain initial data to inform the design of an offshore smoke generating system for use in an offshore trial.

Phase 3 –

- Determine whether diesel would be environmentally acceptable as a smoke generating agent.

Phase 4 –

- Perform a small-scale laboratory experiment to investigate the intermittent behaviour of glycerol experienced during the onshore trial (Phase 2).

Phase 5 –

- Analyse data from the HOMP to investigate the general extent of the hot gas problem, and to determine whether data from HOMP could be used routinely to monitor the incidence of hot exhaust gas plume encounters.

2 Study Scope of Work

2.1 Feasibility Study

The feasibility study comprised two parts: a review and consultation exercise, and a trials feasibility study.

2.1.1 Review and Consultation Exercise

The purpose of this part of the study was to determine if there was a particular reason why the visualisation of gas turbine exhaust plumes had not been tried in the past, and whether there were any major reasons why adding smoke was not a good idea. The technical, practical and safety issues involved in making gas turbine exhaust plumes visible were also to be identified and listed.

The investigation included:

- Seeking the views of Industry representatives on the likely practicality and benefits of adding smoke to gas turbine exhaust plumes.
- Identifying techniques for producing the smoke.
- Identifying potential difficulties and safety hazards introduced by the smoke.
- Investigating operational issues such as who will activate the smoke and under what conditions.
- Identifying any significant operating costs.

In order to obtain the information required to perform the work, a number of key individuals and organisations were identified and visited or contacted by telephone. These included:

- A gas turbine manufacturer, Rolls Royce, Ansty.
- QinetiQ, Propulsion Department, Pyestock.
- Offshore operators, Total and Shell Expro.
- A helicopter operator, Bristow Helicopters Ltd, Aberdeen.
- CAA Flight Operations Inspectorate (Helicopters).

Part of the purpose of these contacts was to seek an initial willingness to be involved in an offshore trial, should the desk study indicate that the concept might be of benefit.

The results of this part of the study are presented and discussed in Section 3.1.

2.1.2 Trials Feasibility Study

Since the review and consultation exercise concluded that gas turbine exhaust plume visualisation was likely to be both practical and beneficial, the work continued with the feasibility study for an offshore trial to test the idea.

The purpose of the trials feasibility study was to determine:

- the smoke generation technique to be used during the trial;
- a candidate platform on which to perform the trial;
- a candidate offshore helicopter operator;
- the method to be utilised during the trial;
- any likely limitations;
- the required duration of the trial;
- an estimate of the cost of the trial.

The results of this part of the study are presented and discussed in Section 3.2.

2.2 Onshore Trial

A preparatory onshore trial using a land-based gas turbine was undertaken in advance of an offshore trial as recommended and specified by the trials feasibility study. The onshore trial sought to obtain sufficient information to design and construct a prototype smoke generation system that could later be fitted to a gas turbine exhaust system on an offshore platform. The onshore trial was performed at QinetiQ, Pyestock.

The aims of the trial were to:

- establish which was the best smoke generating agent to use;
- provide estimates of the quantity of agent required to generate consistent smoke;
- obtain information required for the design of the offshore trials equipment;
- determine any issues related to the risk of damage to the gas turbine units.

The results of the onshore trial are presented in Section 4.

2.3 Diesel Environmental Impact Study

The onshore trials showed diesel fuel to be the best performing smoke agent of those tested. An environmental impact study was therefore carried out which sought to determine whether its use as a smoke producing agent would be in accordance with the appropriate environmental, health and safety criteria.

The environmental screening was accomplished using background data on the properties of diesel gathered from a variety of sources, including:

- Manufacturer’s material safety data sheets.
- Compiled references such as the Merck Index, Handbook of Chemistry and Physics, WHO and OECD Reports.
- US EPA Integrated Risk Information System and other on-line databases.
- Internet and library searches.

The data to be gathered included:

- Physicochemical properties to: (a) predict diesel's stability with temperature and nebulisation; (b) identify possible by-products formed during usage; (c) to provide basic data needed for atmospheric emissions modelling.
- Health and safety properties.
- Solubility, oil/water partitioning, aquatic toxicity (LC_{50}[2] from standard toxicity texts), and biodegradability/ready degradability properties to assess the environmental fate of diesel.
- Applicable air and environmental quality standards for materials that are chemical components of, or have properties similar to diesel, e.g. benzene and polycyclic aromatic hydrocarbons. Reference was made to UK, US EPA and other standards.
- Composition, concentrations and volumes of the exhaust emissions.

The results of the environmental impact study are summarised in Section 5, and the study report is presented in full in Appendix C.

2.4 Small-scale Experiments on Glycerol

The environmental impact study concluded that the use of diesel as a smoke agent was environmentally unacceptable, necessitating the consideration of alternative agents. The recommendation of the onshore trial to investigate glycerol/water solution further was consequently progressed. This agent, along with theatrical smoke oil, had shown promising performance in the onshore trial. Glycerol/water was considered a better choice, however, on grounds of cost, environmental acceptability and performance at low exhaust temperatures but the optical density of the plume had been erratic.

The aim of the small-scale experiment was to investigate the influence of the following variables on smoke generation:

- Glycerol/water solution concentration.
- Agent pre-heating.
- Exhaust gas temperatures.
- Agent flow rate.

The results of the small-scale laboratory trial are presented in Section 6.

2.5 CFD Pipe Heat Transfer Analysis

A further attempt to understand the intermittent behaviour of the glycerol smoke generating agent during the onshore trials was made by modelling the agent flow through the pipework to the spray heads and analysing the heat transfer.

The results of this analysis are presented in Section 7.

2.6 Monitoring Hot Gas Effects Through HOMP

Finally, advantage was taken of other helideck safety research being performed concurrently to analyse the data available from the HOMP project [3, 4], for occurrences of helicopters experiencing raised air temperatures in proximity to helidecks on offshore platforms.

This work, including some example results mapping the occurrence of hot gas plume encounters around helidecks, is described in Section 9.

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[2] Lethal concentration that kills 50%.

3 Feasibility Study

3.1 Review and Consultation Exercise

3.1.1 Benefits of Visualising Hot Gas Plumes with Smoke

All those interviewed during the course of the consultative exercise thought that making gas turbine exhaust plumes visible to helicopter pilots would benefit safety[3]. It was thought that, provided the smoke generation system was designed properly, no significant additional hazards should be introduced. Care would need to be taken, however, to ensure that the smoke was not so thick that it obscured visual cues, did not cause unacceptable levels of pollution, and that the smoke generation system was inherently safe and could not cause damage to the gas turbine systems through misuse.

Although the smoke system might only provide a good visual indication of the plume during daytime, it was felt that this still represented a major safety benefit as the majority of offshore landings and takeoffs are accomplished during daylight hours[4]. Nobody interviewed could explain why the idea had not been tried before, despite being recommended good practice in *CAP 437* since 1981 [5].

3.1.2 Smoke Generation Techniques

Gas turbine manufactures spend much time and effort reducing or eliminating smoke from gas turbine exhausts in order to meet the strict emission controls. Generally, the technique for intentionally creating a smoky exhaust involves introducing an agent into the exhaust of the gas turbine that vaporises in the heat of the exhaust gas (around 300°C – 450°C). During the initial stage after agent introduction the exhaust plume is invisible but, when the vapour re-condenses as it cools, it becomes visible and can be seen as smoke or fog. The smoke eventually disappears as the droplets disperse and evaporate.

Some offshore gas turbines are fitted with a waste-heat recovery system. The exhaust gas temperatures for these units are lower (around 200°C – 250°C)[5]. However, it should be noted that the lower exhaust temperatures (and proportionately smaller fluctuations in temperature) also represent less of a hazard to the helicopter [1].

Several agents were identified as likely to create a visible exhaust plume:

- diesel fuel (as used by the Red Arrows flying display team);
- water;
- kerosene;
- vegetable oil (rapeseed oil);
- glycerol (also known as glycerine);
- theatrical smoke oil (a highly refined mineral oil).

The review determined that the equipment needed to introduce these agents into the exhaust stream should be relatively simple, comprising a reservoir, a pump or pressurising system, a control/metering unit, and a nozzle or spray unit. These

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[3] Thanks are due to all those organisations that participated in the consultative exercise – see Acknowledgements at Section 12.

[4] A recent examination of the HOMP database between July 2003 and June 2004 showed that less than 5% of deck landings were in darkness.

[5] The onshore trials were conducted with an exhaust temperature of 200°C representing the worst-case scenario for smoke generation – see Section 4.

components would be connected by tube, and smoke generated simply by switching on the pump/metering system.

3.1.3 Potential Difficulties and Safety Issues

The estimated pollution level for diesel fuel at the typical concentrations used by the Red Arrows display team is 900 ppm. This is approximately 100 times the limit permitted for normal combustion processes in gas turbine exhausts. It is not clear that such a regulatory pollution limit would be applicable to a separate smoke generation system rather than the combustion process itself. However, it clearly makes sense to apply it at this stage in order to judge the extent of the pollution aspect.

If continuous operation at Red Arrows levels of concentrations results in about 100 times the permitted pollution limit, it follows that if the system is operated for only about 1% of the time (say 1.5 hours per week) then the *average* level of pollution might be just acceptable. This level of activity would be sufficient to support three flights per week if the system is required to be on for about 30 minutes to support each arrival/departure. (Note that the system would be switched on for the helicopter approach and would remain on until the helicopter had departed and was clear of the platform.) However, it is expected that the plumes can be made considerably less dense and use a much lower concentration than that used by the Red Arrows, and still be visible to pilots. This suggests that significantly higher flight frequencies should be possible without violating the pollution limit. Reducing the density of the smoke plume will also have the secondary benefit of making it less likely to obscure any visual cues needed by the helicopter pilots during landing and take-off.

Plumes containing diesel vapour will smell strongly at these levels of concentration and, if they are blown back onto the platform, this may be unpleasant or even considered harmful to those workers on deck. Furthermore, it might be of even greater concern if the plume were to enter the air intakes of the platform heating, ventilation and air conditioning (HVAC) system. Clearly in all cases it is preferable to keep the concentration as low as possible, commensurate with having a visible plume. It is anticipated that kerosene would have a similar pollution problem to diesel fuel. Using fresh or salt water as an agent, however, would appear to involve no pollution issues. It is understood that refined vegetable or mineral oil is often used to generate smoke for stage and film productions, and is therefore presumably not considered to be a significant pollutant or to be harmful to those breathing it. Glycerol is water-soluble and is neither a pollutant nor harmful.

Offshore platforms are invariably fitted with more than one gas turbine. Where the exhaust stacks are close together it may be possible to have the smoke generating system on just one operating stack at any one time, even though there may be other gas turbines running. The smoke from one exhaust gas stack should be sufficient to show the position of the adjacent plumes and the amount of pollution may be kept to a minimum. Where exhaust stacks are widely spaced on the platform it might be necessary to have several smoke systems operating at the same time.

Injecting smoke generating agents in the quantities anticipated into engine exhaust ducts should pose no risk to the engine or the installation during normal operation. However, some form of safety interlocking should be in place to ensure that the agent can only be injected whilst the engine is running and can be quickly turned off should the engine shut down.

3.1.4 Operational Issues

3.1.4.1 Availability of the Smoke Agent

Offshore gas turbines generally use surplus natural gas as fuel. However, diesel fuel is readily available on most platforms as it is used as an emergency standby fuel for one of the gas turbines, which will have a multi-fuel capability. It is also commonly used for the engines that power the fire-fighting pumps.

If water were to be used as the agent then seawater is obviously available in unlimited quantities, and could probably be readily accessed through the fire deluge systems. If it were necessary to use fresh water (to avoid problems with corrosion or salt build-up), then special provision would have to be made to ensure that it was available in sufficient quantities (many offshore platforms already have difficulties storing sufficient fresh water to meet existing needs).

Some kerosene is often available on offshore platforms in the form of helicopter fuel, but special provision would need to be made to supply the required quantities to the smoke generation system. Similarly, the use of vegetable oil, glycerol or theatrical smoke oil would require the special provision and storage of the required bulk quantities.

3.1.4.2 Operating the Smoke System

Discussions with helicopter pilots revealed that they would like the smoke plume to be visible at all times during helicopter landing and taking off, even if the wind speed and direction did not warrant it. They felt that having a smoke plume operating and visible for *all* arrivals and departures would help to ensure that the system was always kept serviceable, and would also help to raise general pilot awareness of the presence of the gas turbine exhaust plume hazard. Pilots would also tend to gain experience of the behaviour of the plume under various conditions, which would be of help during those occasions when the plume would not be quite so easily seen, e.g. in poor visibility or at night.

Having the smoke plume visible during all helicopter operations would also remove the need to decide which conditions require smoke and which do not. Switching on the smoke would simply be a matter of routine. The platform Helicopter Landing Officer (HLO) would be responsible for switching the system on as part of their normal preparations for landings and take-offs.

3.1.4.3 Cost of Ownership

The costs of ownership of a smoke system are as follows:

- Capital cost of the smoke generation equipment and its installation on the platform.
- Maintenance costs.
- Manpower operating costs.
- Consumable smoke agent supplies.

At this stage it is not known what the installed cost of a ‘production’ smoke system might be for an offshore platform, but it is considered to be most likely of the order of £100k[6]. Maintenance costs should be very small in comparison with the other maintenance requirements of the gas turbine power units and other platform systems, and would most likely be covered by the same maintenance resources without any measurable additional cost being incurred. It is considered that the HLO

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[6] A very approximate estimate made in 1999.

would operate the system and no additional manpower would be required in this respect. Based on a frequency of three flights per week, a system operating time of 30 minutes per flight, only one gas turbine plume visualised for each flight, an agent flow rate of 0.25 litres per second and an agent cost of £1 per litre, the cost of providing supplies of the smoke agent are likely to be of the order of £70k per year.

3.1.5 Alternatives Ways of Visualising the Hot Plume

During the interviews a number of people suggested the use of heat sensitive cameras as an alternative to smoke in the exhaust plumes. Examples of the type of equipment that might be used are the systems employed by police helicopters to locate suspects at night. This equipment tends to be quite expensive, costing between £50k and £100k per aircraft. Furthermore such equipment is understood to be designed to detect radiating bodies, and there is significant doubt whether it could be developed to detect a hot gas plume. There is continuous development of the technology, mainly for military purposes, but at the time of this investigation there did not appear to be a system that would be suitable for this requirement.

3.2 Trials Feasibility Study

3.2.1 Type of Offshore Trial

The form that an offshore trial should take was discussed with platform and helicopter operators during the review and consultation exercise. Two possible types of trial were envisaged:

- A short-term trial where a helicopter would be specially chartered to perform test flights over a short period of time (dedicated trial).
- A long-term trial where data would be gathered from normal revenue flights operating to the platform (in-service trial).

It was generally agreed that the long-term trial was much more likely to produce the desired results, and would also have the advantage of providing a more effective demonstration of the system to the industry. There are two main reasons why the long-term trial is preferred. Firstly, the tests would be undertaken over a wide range of weather conditions, including those during which a visible gas turbine exhaust would be helpful and those when it would be less so. Secondly, feedback from a broad range of operational helicopter pilots would be obtained (by their completing a questionnaire about the effectiveness of the smoke), rather than relying on a small number of test pilots. The long-term trial would need to be preceded with a check flight by a test pilot during a dedicated flight in order to ensure that the smoke system would not present a hazard to normal helicopter operations.

3.2.2 Candidate Platforms

The selection of the candidate platform for the smoke trials requires the identification of an offshore operator willing to collaborate in the study, and the selection of a suitable offshore platform belonging to that operator. The co-operation of the associated helicopter operator(s) would also need to be obtained.

Meetings were held with Elf Exploration and Shell Expro, and both organisations were very supportive of the objectives of the study and expressed willingness, in principle, to host the trials. The discussions produced two candidate platforms. Elf suggested that the trials might be carried out on the *Claymore* platform[7]. Shell proposed the FPSO *Anasuria*.

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[7] Since the discussions took place the Claymore platform has been sold to Talisman Energy.

The platform chosen for the trials should have a reasonably high helicopter flight frequency so that sufficient experience with the system would be gathered in a sensible period of time. It is considered that the target number of flights for the entire study should be at least 100. For example, it is understood that the flight frequency to the FPSO *Anasuria* is about three per week, hence a trial of about one year's duration would provide sufficient flights and include an appropriate margin to take account of a less than 100% return of questionnaires.

The ideal platform would also allow easy access to the gas turbine exhaust stacks. Access may be required to both the inside of the exhaust and the ends of the exhaust outlet. If access to the end of the exhaust outlet requires the erection of special scaffolding, then this might make the trial very expensive. Neither of the candidate platforms identified have good access to the ends of the exhaust stacks. Both have reasonable access to the interior and main body of the exhaust stacks.

3.2.3 Overall Trials Plan

3.2.3.1 Onshore Trial

As noted in Section 3.1.2, there are a number of design issues and smoke generation performance uncertainties which would need to be resolved before an offshore trial could go ahead, and the best way to resolve these would be to undertake some initial trials using a land-based gas turbine. A specification for the onshore trial was developed alongside the specification for the offshore trial during the review and consultation exercise. The onshore trials actually performed are described in Section 4.

3.2.3.2 Environmental Impact Assessment

It was proposed that, if the onshore trial concluded that the smoke generating agent needed to be a substance with environmental impact potential (e.g. diesel), then it would be necessary to determine the extent of any pollution and environmental health issues which might be posed by the smoke agent when used offshore. It proved to be the case that diesel performed strongly as a smoke agent and an environmental impact assessment was consequently performed - see Section 5.

3.2.3.3 Development of Smoke Generation Equipment

A number of different organisations may be capable of developing the smoke generating equipment for the offshore trial. A key factor in the choice of organisation may be the candidate platform and, specifically, the make of the gas turbines installed on that platform and to be used for the trials. For contractual/maintenance reasons it may be advisable to have the system developed and installed by the gas turbine manufacturer, or by the platform maintenance contractor. For the smoke generating equipment to be installed on the platform and used by non-expert operators over an extended trial period it will clearly need to be safe, reliable and robust.

3.2.3.4 Offshore Trial

The offshore trial itself is expected to consist of four main phases of activity:

- installation and commissioning;
- the flight trial period (estimated to be approximately one year);
- decommissioning and removal;
- assessment and reporting.

A draft pilot questionnaire was developed for the trials and is presented in Annex 1 of Appendix A. This draft will require review and agreement with the main interested parties before it is used.

3.2.4 Estimated Costs and Schedule of the Offshore Trial

In order to undertake the offshore trial it is first necessary to develop a specification for the work to be performed. BMT developed a specification for the offshore trial which is presented in Appendix A.

Budgetary costs for the platform operator's part of the offshore trial (design, building, installation, maintenance, and decommissioning of the smoke system) have been estimated by BMT. In determining the budgetary cost it has been assumed that the platform operator would provide helicopter flights to/from and accommodation on the platform for the trials personnel free of charge.

Clearly it will not be possible to arrive at an accurate cost estimate for the offshore trial until smoke system designers, manufacturers and installation contractors have been approached. However, the budgetary cost for executing the offshore trial was estimated to be in the range £120k - £225k[8]. The total duration of the trials including planning, installation, flight tests, and data assessment is expected to be approximately 18 months.

3.3 Conclusions of the Feasibility Study

The initial review and consultation exercise found that:

- Those involved in offshore helicopter operations interviewed for the study believed that a smoke generating system could provide a useful safety benefit, and that there were unlikely to be any hazards or operational difficulties introduced by a properly designed system.
- Nobody interviewed could say why such a system had never been tried before.
- The smoke system on the platform could be operated by the HLO, who would switch it on for the duration of all helicopter arrivals and departures, whatever the wind speed and direction or meteorological conditions.
- A number of different agents were identified that could potentially be added to the gas turbine exhaust to produce the smoke.
- The most effective smoke-producing agent is likely to be a hydrocarbon product such as diesel fuel (as used by the Red Arrows display team), but this might involve the production of unacceptable levels of pollutants.
- The use of water as an agent producing steam as the visible agent is the most attractive and simplest solution, but there were questions concerning its effectiveness, which needed to be resolved.
- The method of generating the visible plume should be developed by means of a trial using a land-based gas turbine.
- The capital cost of a production system is likely to be of the order of £100k, with a running cost of the order of £70k per annum.

The trial feasibility study went on to outline the means of performing the onshore and offshore trials, and found that:

- Two operators, Elf Exploration and Shell Expro were, in principle, willing to host the trial.
- It would be necessary to perform an initial set of trials using a land-based gas turbine in order to develop the smoke generation system for the offshore trial.

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[8] It should be noted that this cost estimate range was derived by the initial feasibility study conducted in 2000. It has not been revised to take account of inflation or changes in the smoke generation techniques developed during the subsequent phases of the study.

- An environmental impact assessment of the smoke agent may be required to deal with any pollution and environmental health issues posed by the use of the intended smoke agent offshore.
- The offshore trial should extend over a period of about one year during which it would be possible to evaluate the performance of the smoke system under a wide range of weather and operational conditions.
- The effectiveness of the smoke system and the benefit to safety afforded by it should be assessed by means of a questionnaire completed by those pilots flying to the candidate platform. (An initial draft questionnaire was developed and is presented in Annex 1 of Appendix A.)

4 The Onshore Trial

4.1 Test Programme Requirements

The trial was based on the specification developed during the feasibility study reported in Section 3.2. The main requirement for the tests was the ability to produce a gas turbine exhaust plume that was representative of those found on offshore platforms. This required the plume to have a mean temperature in the range 200°C to 250°C, and velocity of less than 30 m/s. This velocity is a typical industry standard for acceptable noise emissions.

Exhaust stack exit temperatures in the range 200°C to 250°C are typical for gas turbines fitted with waste heat recovery systems. Most units employed on offshore platforms however, are not of this type and typically produce plume temperatures of about 400°C. Conducting these tests with a 200°C plume reflects the worst-case scenario for visualising plumes, since smoke generation is generally easier at higher temperatures.

The other test requirements involved the provision for injecting smoke-producing agents into the exhaust plume and recording the results photographically. The Glen Test House (GTH), QinetiQ's ground-level engine test bed at Pyestock, was chosen together with their Rolls-Royce Spey Mk 202 engine.

4.2 Test Installation

4.2.1 Exhaust Detuner Modifications

In standard layout, the detuner exhaust plume temperature from the GTH/Spey installation was somewhat lower than the required 200°C. This was due to the large mass of ambient air entrained into the exhaust detuner in relation to the engine exhaust mass flow, typically a ratio of 3:1. The simple expedient of restricting the detuner entry area by means of blocking plates increased the plume temperature by reducing the mass ratio (Figure 1).

The GTH detuner exit diameter of 4.6 m was somewhat larger than for typical offshore platforms (2 to 3 m), but the only impact that this was expected to have on the trial was on the distance above the exit at which condensation occurred. This distance and the exit diameter are directly proportional.

Figure 1 Detuner blocking plates (exhaust nozzle of the Spey Mk. 202 engine can be seen on the left)

4.2.2 Agent Injection System

The overall concept for injecting the smoke generating agents into the exhaust plume was based on positioning an array of atomisers across the diameter of the exhaust stack (detuner exit). The size of the atomisers was selected such that, with four running, the amount of smoke generating agent (~1000 ppm) was comparable with that used by the Red Arrows display team for creating vapour trails during their displays. This defined the upper limit of agent quantity. The test system utilised a reservoir containing the smoke generating agent that was pressurised with nitrogen. Various stop valves permitted the operator to control the duration of flow and, additionally, to select the number of atomisers to be used. This latter facility provided the means to control the smoke density. Control of the nitrogen pressure provided the method for varying the flow rate through individual atomisers. Pressure gauges, positioned at various points, enabled the operator to monitor the operation of the system.

Both pressure-jet and air-blast atomisers were employed during the trials. Although it was anticipated that the former would be the preferred option based on simplicity of installation, the latter was fitted to provide an alternative should the performance of the pressure-jet units prove inadequate. Generally, air-blast atomisers provide a finer spray and are therefore more likely to promote evaporation, particularly in cool plumes. The disadvantage is the requirement for an air supply with the additional infrastructure that this entails, although suitable air supplies are generally available on offshore platforms.

The pressure-jet atomisers selected were of an existing QinetiQ design. The flow number sizing of four[9] was chosen in order that the agent, when injected through one atomiser alone, would be sufficient to ensure that the threshold contrast (visible level) would be exceeded locally to the atomiser (assuming still air conditions). The threshold contrast level of 2% had been determined from previous experience and analysis at QinetiQ of ship exhausts made visible through unburnt diesel [6]. By providing an array of four atomisers mounted across the diameter of the detuner exit, the density could be varied by sequential application of each atomiser. Observation was along the line of the atomisers. The atomisers were spaced at 600 mm intervals symmetrically about the exhaust centre-line and 200 mm above the exit plane.

Two commercially available air-blast atomisers were installed and operated as a pair, providing an agent flow rate comparable to two pressure-jet atomisers. The units were sourced from Spraying Systems Ltd (body type 1/4J fitted with fluid and air caps, part numbers PF100150-ss and PA189-6-62-70-SS, respectively). They were spaced 200 mm apart and straddled one of the pressure-jet atomisers. Alignment to the observer was identical to the pressure-jet units. In the event, the atomiser spacing and arrangement was found to be irrelevant since the agent was condensing substantially above the atomisers, by which time the agent and the gas plume were well mixed.

Routing the agent feed pipes across the full diameter of the detuner exit before returning to their respective atomisers was designed to aid atomisation by providing a degree of pre-heating to reduce the agent viscosity. A pitot tube and thermocouple were positioned adjacent to each of the four pressure-jet atomiser assemblies to measure the conditions within the exhaust gas plume. A schematic layout of the system is shown in Figure 2 with photographic views shown in Figures 3 to 5. General arrangement drawings of the system are shown in Figures 6a and 6b.

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[9] Flow number is expressed as the ratio of the flow in gallons/hour divided by the square root of the differential pressure expressed in lb/in^2 across the atomisers.

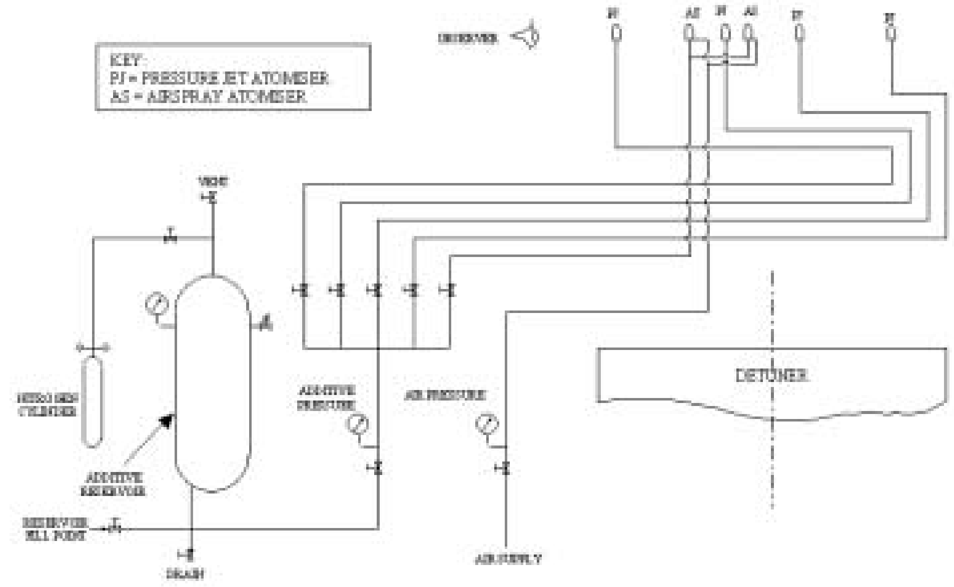

Figure 2 Schematic layout of the agent injection system

Figure 3 Spray boom with atomisers and instrumentation installed

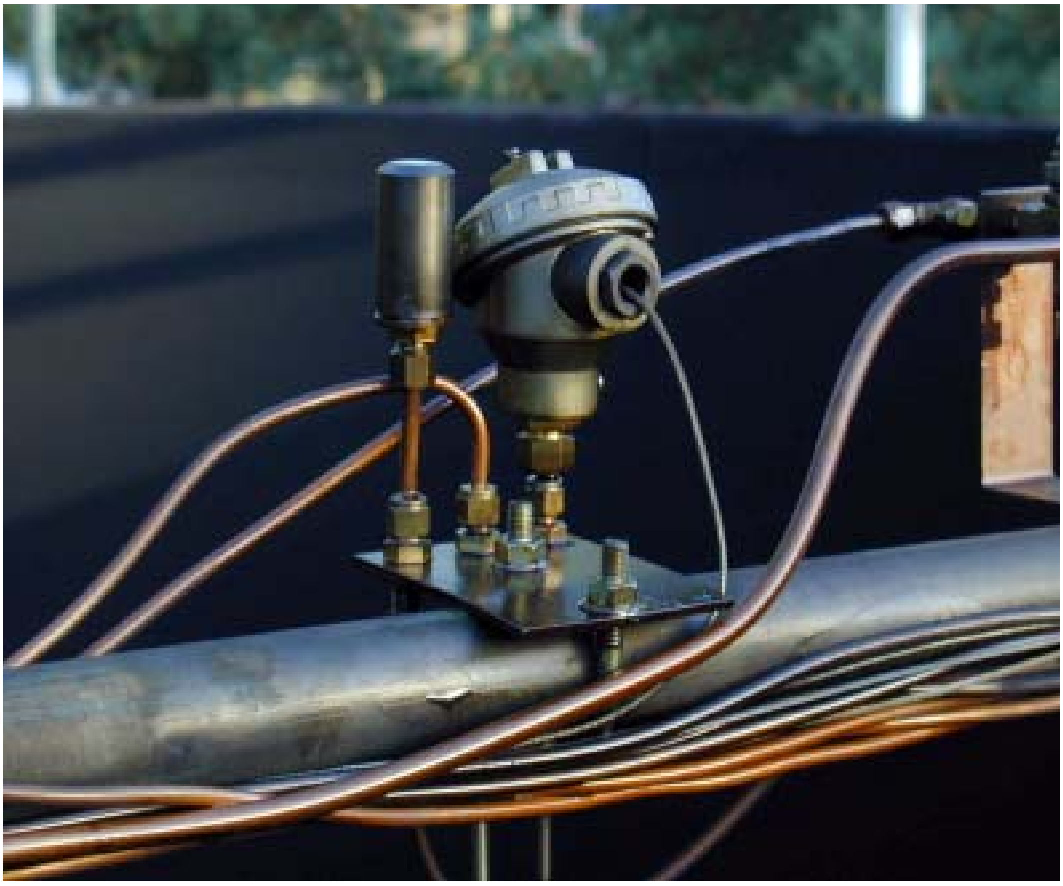

Figure 4 Pressure-jet atomiser

Figure 5 Air-blast atomiser

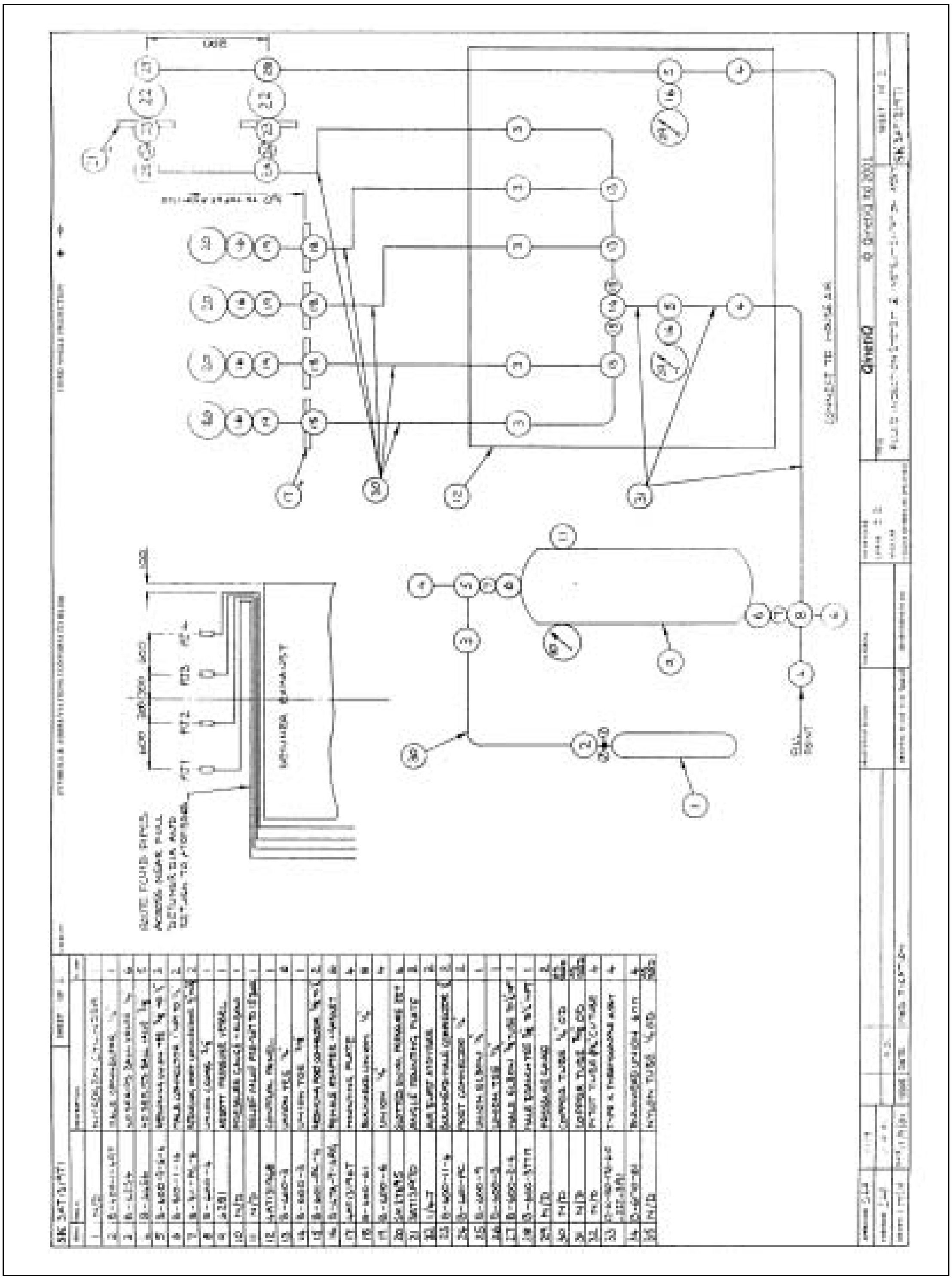

Figure 6a General arrangement drawing of the fluid injection system

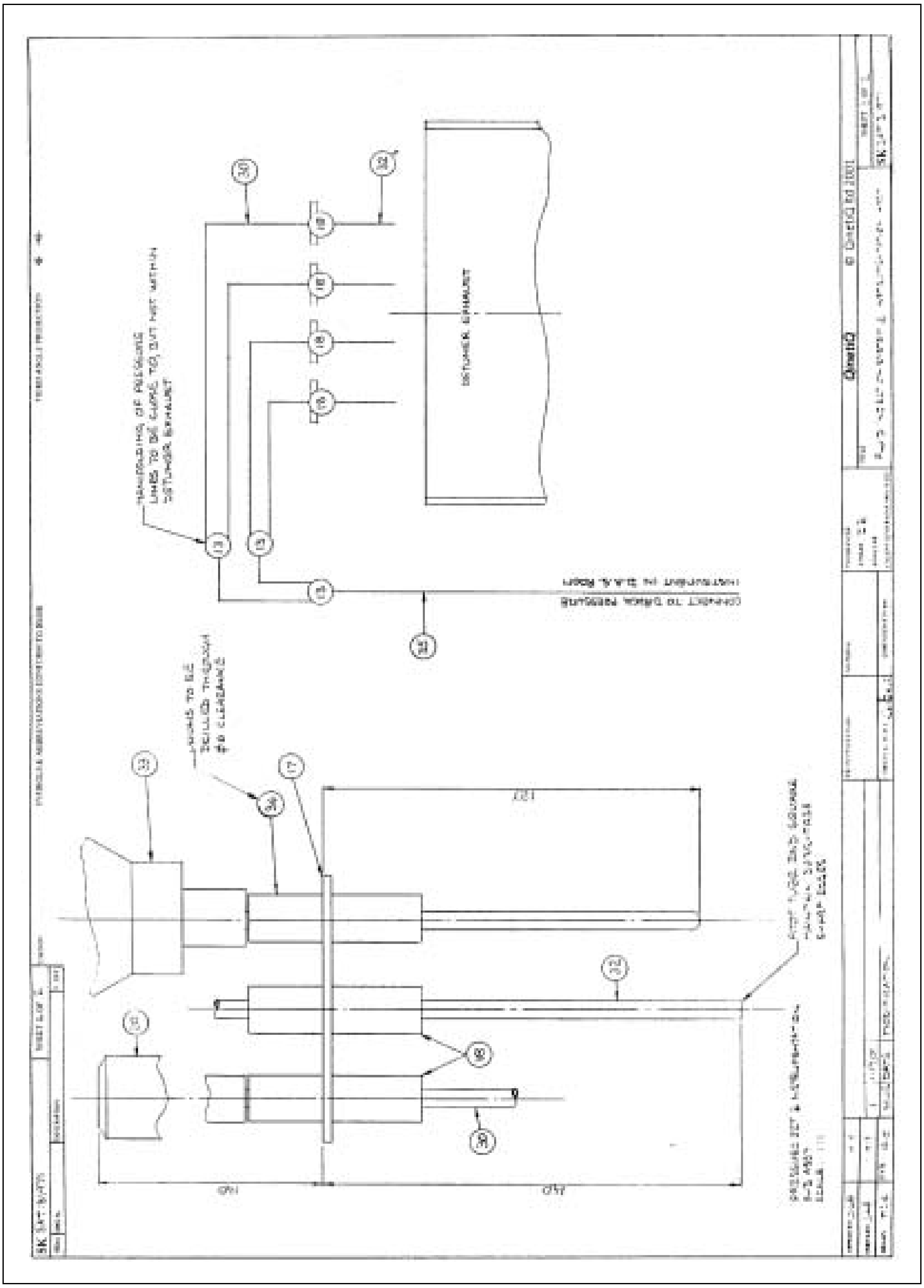

Figure 6b General arrangement drawing of the fluid injection system

4.3 The Trial Agents

The six different agents identified during the review and consultation exercise were included in the trial, namely:

- diesel fuel;
- water;
- kerosene;
- vegetable oil (rapeseed);
- glycerol (also known as glycerine);
- theatrical smoke oil (a highly refined mineral oil).

Diesel fuel is already used for generating smoke in other applications and was expected to work well. In addition, diesel is routinely stored on platforms and so is readily available, and most of the safety considerations in handling it are well established. The environmental impact of using diesel may, however, make its use unacceptable. Kerosene was selected for similar reasons, except no existing applications for smoke generation were known.

Water was an obvious choice for an agent as it is readily available, particularly salt water, and has no environmental impact. For simplicity, fresh water was used for the onshore trial but it will behave in an identical manner to sea water.

Rapeseed oil was included as it is a biodegradable, non-toxic vegetable oil. Consequently, its environmental impact is low. The safety case and logistics of storing and using it offshore would need to be assessed. Glycerol was chosen for similar reasons, and was dissolved in water for the tests to reduce its viscosity to sprayable levels.

The theatrical smoke oil used in the trials was Shell Ondina EL. This is a food quality mineral oil that has been highly refined to reduce the polycyclic aromatic hydrocarbon content to a very low level. This oil is routinely used in theatres and film studios to create smoke and, if used correctly, is non-toxic. It is, however, non-biodegradable and, therefore, there would be an environmental impact. This is the same oil that is used for producing battlefield smoke.

The material safety data sheets for all the agents are given in [7], [8], [9], [10], and [11]. No colouring was incorporated into the agents as white smoke was expected to provide the greatest contrast against a dark background (trees in the onshore trial, or the sea in the offshore trial and in-service use). Any form of colouring would reduce the contrast and, consequently, the visual effectiveness.

Two further potential smoke agents were proposed, but unfortunately too late to be included in the trial. The first was ethylene glycol, which is similar to glycerol and would therefore use a similar injection system. The second was a proprietary battlefield smoke generation system utilising a very small turbine combuster (similar to those used to start helicopter engines)[10].

4.4 Testing

4.4.1 Commissioning

The main objectives of the commissioning test were to demonstrate the effectiveness of the detuner blockage plates and to establish, by means of short bursts of agent, the effectiveness of each. It was intended that only those agents that showed promise would be evaluated during the main trial.

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[10] This equipment has been developed for the Ministry of Defence by Sommerwest Technical Services Limited.

The exhaust flow velocity and temperature were determined by the total air mass flow passing through the detuner and the mixed temperature of the system. The detuner blockage plates were effective in reducing ambient air entrainment from the test cell. The achieved plume temperature was 185°C at the de-rated nominal maximum operating condition of the research engine used. Increasing the engine thrust by approximately 17% increased the plume temperature to the required 200°C and resulted in a plume velocity of 23 m/s. No engine exhaust re-circulation was evident within the test cell.

All the smoke generating agents were tested during these initial trials. Water, kerosene and rapeseed oil were quickly eliminated on the basis of either producing no noticeable visible plume or such a low degree of visibility as to be ineffective. Water and kerosene were ineffective in the trial and were considered even less likely to succeed in higher temperature plumes as both have high vapour pressures that would prevent either agent condensing. Rapeseed oil might function in higher temperature plumes; the problem during this trial appeared to be a lack of vaporisation following injection.

Diesel, glycerol/water and theatrical smoke oil all showed positive results and were therefore selected for further study in the main trial. The difference in plume density between those selected and those rejected was so marked that subjective selection by the observer was sufficient. A discussion on the smoke generating mechanisms, agent properties and choices is presented in Appendix B.

The observation platform was initially located on the test house roof, approximately 20 m from and 3 m above the detuner exit. Experience during the commissioning test showed that the visible plume was developing some 10 m or more above the exit plane and, consequently, observation of the plume from this location was against the sky. The intention was to observe the plume against a background of trees, being representative of the sea that will normally form the background against which a pilot of an approaching helicopter will view a platform. To create a more realistic view, a new observation station was established at Caesar’s Camp, a hill 4.5 km south of the test facility and approximately 90 m higher. Viewing from this position provided a tree background and also maintained the correct alignment of the atomisers. Figure 7 shows a general view of Pyestock from Caesar’s Camp at normal magnification in which the exhaust plume is clearly visible in the centre of the frame. All the plume photographs presented, with the exception of the night trial illustration, were recorded from this position at 20 times magnification.

Figure 7 View of Pyestock from Caesar's Camp

4.4.2 The Main Trial

Three smoke producing agents were carried forward to the main trial: diesel, glycerol/ water and theatrical smoke oil. The test procedure chosen for the study involved switching on all four pressure-jet atomisers initially and then reducing the agent flow by progressively turning off the atomisers at one-minute intervals. Several photographs were taken at each interval to record both the smoke density and density changes, should any occur. On completion of the pressure-jet atomiser test points, the air-blast atomisers were switched on. A few test points were recorded with lower system pressures to bracket the threshold contrast limits by reducing the agent flow rate into the plume. There was little purpose in defining this further with the tree background employed for the trial. Final optimisation of the agent flow rates will, of necessity, need to be judged in the offshore environment. This exercise would be performed at the beginning of the offshore trial.

The density of the plumes formed was such that qualitative assessment was generally sufficient to determine the relative merits of each test point. However, optical reflectance measurements were recorded for the test points illustrated.

A log of the trial including the agent flow rates, optical reflectance, and the exhaust plume to smoke agent mass flow rate ratios, is shown in Table 1. The values of optical reflectance are quoted to the nearest 5% because, in practice, a 5% change in contrast is barely discernable to the human eye. The threshold contrast under ideal conditions is approximately 2%. This represents a very thin smoke through which it is easy to see the background. Normally 5% to 10% should produce reasonably robust viewing. However, the necessary smoke contrast needed for an effective offshore smoke system cannot be judged until an offshore trial is conducted in a range of sea, weather and ambient lighting conditions.

Table 1 Smoke agent test data (daylight trial)

Test Point	Agent	Injector Type	No of Injectors Flowing	Agent Flow (g/s[1])	Agent Press (b[2])	Air Press (b)	Plume Reflectance (%)	Plume/ Agent Ratio[3]
1	Diesel	Press-jet	4	261.5	13.5	-	35	1051
2	Diesel	Press-jet	3	204.8	14	-	35	1342
3	Diesel	Press-jet	2	133.4	14.5	-	20	2061
4	Diesel	Press-jet	1	66.69	14.5	-	15	4122
5	Diesel	Air-blast	2	133.4	14.5	2	25	2061
6	Diesel	Press-jet	1	32.8	3.5	-	-	8381
7	Diesel	Press-jet	1	45.7	6.8	-	-	6015
8	Diesel	Air-blast	2	91.3	6.8	2	30	3010
9	Glycerol/Water 50%/50%	Press-jet	4	312.9	14.2	-	35	879
10	Glycerol/Water 50%/50%	Press-jet	3	240.7	14.2	-	25	1142
11	Glycerol/Water 50%/50%	Press-jet	2	154.1	14.2	-	20	1784

Table 1 Smoke agent test data (daylight trial)

12	Glycerol/Water 50%/50%	Press-jet	1	77.8	14.5	-	15	3533
13	Glycerol/Water 50%/50%	Air-blast	2	155.7	14.5	2	30	1765
14	Glycerol/Water 50%/50%	Press-jet	1	38.2	3.5	-	-	7196
15	Glycerol/Water 50%/50%	Press-jet	1	53.3	6.8	-	-	5158
16	Glycerol/Water 50%/50%	Press-jet	4	216.6	6.8	-	-	1269
17	Glycerol/Water 50%/50%	Air-blast	2	106.6	6.8	2	25	2578
18	Smoke oil	Press-jet	4	271	14	-	30	1014
19	Smoke oil	Press-jet	3	212.2	14.5	-	20	1295
20	Smoke oil	Press-jet	2	133.5	14	-	-	2059
21	Smoke oil	Press-jet	1	66.7	14		-	4121
22	Smoke oil	Air-blast	2	133.5	14	2	20	2059
23	Smoke oil	Press-jet	1	33.3	3.5	-	-	8255
24	Smoke oil	Press-jet	1	46.5	6.8	-	-	5912
25	Smoke oil	Press-jet	4	188.8	6.8	-	-	1456
26	Smoke oil	Air-blast	2	93	6.8	2	30	2955
27	Glycerol/Water 30%/70%	Press-jet	4	302.3	14	-	-	909
28	Glycerol/Water 30%/70%	Press-jet	3	232.5	14	-	25	1182
29	Glycerol/Water 30%/70%	Press-jet	2	139	14	-	-	1978
30	Glycerol/Water 30%/70%	Press-jet	1	74.5	14	-	-	3690
31	Glycerol/Water 30%/70%	Air-blast	2	151.4	14.5	2	-	1816
32	Glycerol/Water 30%/70%	Press-jet	4	307.7	14.5	-	-	893
33	Glycerol/Water 30%/70%	Air-blast	2	151.4	14.5	2	-	1816

1. Agent flow rate expressed in grams/sec.
2. Pressures were measured in bar (b) referenced to atmospheric pressure i.e. gauge.
3. Mass flow rate of the plume/mass flow rate of the smoke generating agent.

4.4.2.1 **Diesel**

Diesel was the first agent tested and the effects of varying the flow from the pressure-jet atomisers is illustrated in Figure 8. The change in plume density between four and three atomisers operating (Figures 8a and 8b) is barely discernible. Reducing the flow to two, and then to one atomiser (Figures 8c and 8d) does indicate an observable reduction in plume density. There was no noticeable temporal variation in density. The air-blast atomisers, flowing at the same rate as two pressure-jets, provided a less dense but more uniform plume. Compare the air-blast plume (Figure 9a) with that from two pressure-jets (Figure 9b). The fluid pressure was maintained constant at 14 bar for all of these tests. The air-blast air pressure was maintained at 2 bar.

Figure 8a Variation in plume density using diesel agent – test point 1, four pressure-jet atomisers, 20 seconds duration

Figure 8b Variation in plume density using diesel agent – test point 2, three pressure-jet atomisers, 30 seconds duration

Figure 8c Variation in plume density using diesel agent – test point 3, two pressure-jet atomisers, 30 seconds duration

Figure 8d Variation in plume density using diesel agent – test point 4, one pressure-jet atomiser, 30 seconds duration

Figure 9a Comparison of air-blast and pressure-jet atomisers, diesel agent – test point 5, two air-blast atomisers, 60 seconds duration

Figure 9b Comparison of air-blast and pressure-jet atomisers, diesel agent – test point 3, two pressure-jet atomisers, 60 seconds duration

4.4.2.2 Glycerol/Water Solution

In its concentrated form glycerol is too viscous for atomisation to occur, hence some degree of dilution with water is necessary. For the trial, an initial mixture containing equal volumes of glycerol and water (50% solution by volume) was chosen as this reduced the viscosity to six centistokes, well within the atomisation range.

When injected into the plume, at the point of formation the visualisation was initially very dense for a period of approximately 30 seconds, following which a marked reduction in plume density occurred. Figure 10a shows the original dense plume, which, in Figure 10b, is dispersing with no new visualised plume appearing. A weaker mixture containing 30% glycerol and 70% water, resulting in a lower viscosity of 2.5 centistokes, was tested but the phenomena occurred again, confirming that simply reducing the viscosity was not the answer.

There appeared to be little qualitative difference between both glycerol concentrations at the higher flows (three or more pressure-jets operating) – see Figures 11a and 11b. The comparison was complicated by differing wind conditions and dispersion characteristics, however, and the weaker mix may be slightly worse.

The comparison of atomiser type performance using the more concentrated mix is shown in Figures 12a and 12b, and clearly demonstrates the superiority of the air-blast atomisers. The air-blast atomisers maintained the plume density for longer. The reduction in plume density as the pressure-jet atomisers were progressively turned off is evident and is illustrated in Figures 13a through 13d. Generally, the plume density was less than that achieved using diesel but was well above the threshold contrast.

Figure 10a Variation of plume density with time using glycerol/water 50%/50% concentration – test point 9, plume density, four pressure jet atomisers, 30 seconds duration

Figure 10b Variation of plume density with time using glycerol/water 50%/50% concentration – test point 9, plume density, four pressure jet atomisers, 60 seconds duration

Figure 11a Comparison of glycerol/water concentrations – test point 10, 50%/50% glycerol/water solution, three pressure-jet atomisers, 30 seconds duration

Figure 11b Comparison of glycerol/water concentrations – test point 28, 30%/70% glycerol/water solution, three pressure-jet atomisers, 30 seconds duration

Figure 12a Comparison of air-blast and pressure-jet atomisers using 50%/50% glycerol/water solution – test point 13, two air-blast atomisers, 60 seconds duration

Figure 12b Comparison of air-blast and pressure-jet atomisers using 50%/50% glycerol/water solution – test point 11, two pressure-jet atomisers, 60 seconds duration

Figure 13a Variation of plume density using 50%/50% glycerol/water solution – test point 9, four pressure-jets, 60 seconds duration

Figure 13b Variation of plume density using 50%/50% glycerol/water solution – test point 10, three pressure-jets, 60 seconds duration

Figure 13c Variation of plume density using 50%/50% glycerol/water solution – test point 11, two pressure-jets, 60 seconds duration

Figure 13d Variation of plume density using 50%/50% glycerol/water solution – test point 12, one pressure-jet, 60 seconds duration

4.4.2.3 Theatrical Smoke Oil

Theatrical smoke oil was the last of the agents to be tested. Reducing the flow by reducing the number of pressure-jet atomisers from four to three resulted in some reduction in plume density as illustrated in Figures 14a and 14b. Operation with either two or one pressure jets resulted in no plume visualisation; the air-blast atomisers, which are equivalent to two pressure-jets, produced a visible plume of similar density to three pressure-jets – see Figures 15a and 15b. Overall, the plume visualisation was not as good as that achieved with diesel, but was above the threshold contrast and was marginally better than that achieved using glycerol/water.

Figure 14a Variation of density using theatrical smoke oil – test point 18, four pressure-jet atomisers, 60 seconds duration

Figure 14b Variation of density using theatrical smoke oil – test point 19, three pressure-jet atomisers, 60 seconds duration

Figure 15a Comparison of air-blast and pressure-jet atomisers using theatrical smoke oil – test point 22, two air-blast atomisers, 60 seconds duration

Figure 15b Comparison of air-blast and pressure-jet atomisers using theatrical smoke oil – test point 19, three pressure-jet atomisers, 60 seconds duration

4.4.2.4 Effect of Reducing Agent Flow Rate

A series of tests was carried out to bracket the agent flows that would produce the minimum plume threshold contrast. This was achieved by reducing the agent injection pressures from around 14.5 bar to approximately 6.8 bar and 3.5 bar.

No plume visibility was achieved at 3.5 bar with either atomiser type or any agent. When operating the pressure-jet atomisers at 6.8 bar the diesel produced no visible plume, and both the glycerol/water solution (only the 50% solution was employed for these tests) and the theatrical smoke oil produced a thinly visible and ineffective plume. The superiority of glycerol/water and theatrical smoke oil over diesel at these low flows is logical; they have much lower vapour pressures and condense more readily, while much of the injected diesel will remain in the gaseous state.

Overall, the results from the air-blast atomisers were better than those from the pressure-jets for all of the agents. The results for each of the three smoke generating agents at injection pressures of 14.5 bar and 6.8 bar are shown in Figures 16a and 16b, 17a and 17b, and 18a and 18b. The corresponding flow rates are given in Table 1.

Figure 16a Comparison of different flow rates for theatrical smoke oil using air-blast atomisers – test point 26, two air-blast atomisers at 14.5 bar , 60 seconds duration

Figure 16b Comparison of different flow rates for theatrical smoke oil using air-blast atomisers – test point 22, two air-blast atomisers at 6.8 bar, 60 seconds duration

Figure 17a Comparison of different flow rates for diesel using air-blast atomisers – test point 5, two air-blast atomisers at 14.5 bar, 60 seconds duration

Figure 17b Comparison of different flow rates for diesel using air-blast atomisers – test point 8, two air-blast atomisers at 6.8 bar, 60 seconds duration

Figure 18a Comparison of different flow rates for 50%/50% glycerol/water solution using air-blast atomisers – test point 13, two air-blast atomisers at 14.5 bar, 60 seconds duration

Figure 18b Comparison of different flow rates for 50%/50% glycerol/water solution using air-blast atomisers – test point 17, two air-blast atomisers at 6.8 bar, 60 seconds duration

4.4.2.5 Night Trial

The trials concluded with a short test performed at night. Four 250 W high-pressure sodium vapour (SON-T) lights were installed around the detuner exit in an attempt to simulate the ambient lighting on an offshore platform. Diesel was selected as the agent as it produced the densest plumes during the daylight trials. Photographs were taken from the original observation platform, as it was not considered safe to access Caesar's Camp at night due to the nature of the terrain to be covered on foot to reach the observation point. A log of the night trial including the agent flow rates and the plume-to-agent mass flow rate ratios is shown in Table 2.

Table 2 Night trial smoke agent test data

Test Point	Agent	Injector Type	No of Injectors Flowing	Agent Flow (g/s)	Agent Press (b)	Air Press (b)	Plume/ Agent Ratio
34	Diesel	Press-jet	4	271	14.5	-	1014
35	Diesel	Press-jet	3	206.3	14.2	-	1333
36	Diesel	Press-jet	2	132	14.2	-	2083
37	Diesel	Press-jet	1	65.8	14.1	-	4178
38	Diesel	Air-blast	2	131.5	14.1	2	2090

Although the atomisers were sequenced in the same manner as previously, no discernible differences could be observed. The Spey's naturally smoky exhaust was well illuminated and dominated all the photographs, however some agent-visualised wisps of plume were visible around and above – see Figure 19. The illuminated part of the plume provided no indication of wind direction. The useful part of the plume where most of the agent condensed occurred well beyond the range of the lights.

It is plainly obvious that the level of lighting required to illuminate a plume at night is considerably greater than that applied during this test. A similar situation may well occur offshore if normal platform lighting is not well spread. Offshore platform lighting normally covers the platform in a generous fashion, but additional lighting might be needed. Dedicated plume lighting may prove impractical due to the large coverage required for effective illumination and it is difficult to imagine how it could be provided without presenting a significant source of glare to helicopter pilots. This issue should be investigated further during the offshore trials.

Figure 19 Night trial using diesel

4.5 Discussion

4.5.1 Onshore Trial - General

The onshore trial demonstrated the proof of concept that exhaust plume visualisation is possible by the injection of smoke generating agents and, within the constraints of an onshore trial, the simulation worked well. However, it was not able to, and never could, simulate all the likely conditions that would be encountered offshore. Plume sighting in the current trial was against a background of pine trees. This provided similar contrast conditions to those offshore, but the glare from the sea was obviously absent as was the true effect of any wind. Wind clearly plays an important part in plume dispersal and a true assessment can only be achieved under offshore conditions. (There was a breeze from the prevailing westerly direction throughout the trial and the effect of this on the plume can clearly be seen in the photographs.) Consequently, agent flow rate will need to be checked and optimised during offshore trials.

4.5.2 Exhaust Exit Conditions

The test installation in the GTH was realistic in producing an exhaust plume temperature of 200°C, representing the most demanding test case. Higher temperature plumes would aid evaporation of the successful agents from the current trial[11]. Furthermore, developing an injection system targeted at this condition would provide a future-proof solution with the trend being towards gas turbine installations fitted with waste heat recovery.

The plume velocity of 23 m/s was close to typical for all gas turbine installations. Any difference between the trial plume velocity and offshore installations is unlikely to be significant in terms of agent and plume mixing. At 4.6 m, the exhaust exit diameter was larger than that typically found offshore, however its influence on the trial was limited to causing the agent to condense at a greater distance above the exit plane than would be the case with smaller exhaust diameters.

4.5.3 Smoke Generating Agent Performance

Six smoke producing agents were selected at the start of the trial. Of these, water, kerosene and vegetable (rapeseed) oil were ineffective, and were eliminated early in the trial. Diesel was found to be the best smoke generating agent and produced dense white smoke with a very visible, long lasting exhaust plume. Theatrical smoke oil and glycerol/water solution provided, respectively, less dense plumes, although the difference in performance between glycerol and theatrical smoke oil was found to be marginal. While not as effective as diesel, both glycerol/water and theatrical smoke oil can be considered possible candidate agents. In the case of glycerol/water however, the decrease in plume density observed in all test points would need to be addressed.

In addition to smoke generating performance, a number of factors will have to be taken into account when selecting the agent for the offshore trial and/or implementation in service, such as the cost and logistics of providing supplies in the quantities required. More significantly, however, the environmental impact of the chosen agent is crucial and will clearly need to be assessed.

4.5.4 Using the Smoke System at Night

The use of a smoke system at night is likely to be impractical given the inherent difficulties associated with illuminating the plume effectively. Although this might be overcome by the use of upward-pointing lights (see Section 4.6), insight gained through a questionnaire survey of operational pilot opinion into helideck lighting (*CAA Paper 2004/01, Appendix C* [12]) strongly indicates that upward-pointing lighting systems would be very likely to introduce a new and unacceptable source of glare to helicopters approaching to the platform.

4.6 Conclusions of the Onshore Trial

Tests have been carried out to determine a means of visualising the exhaust plume from a gas turbine engine operating in the Glen Test House (GTH) at QinetiQ, Pyestock.

The main conclusions of these onshore trials are summarised as follows:

- Of the six smoke producing agents that were tried, water, kerosene and vegetable (rapeseed) oil were ineffective, and were eliminated early in the trial.
- Diesel was the best smoke generating agent and produced dense white smoke with a very visible, long-lasting exhaust plume.
- Theatrical smoke oil and glycerol/water solution provided adequate but, respectively, less dense plumes.

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[11] Higher exhaust plume temperatures might possibly produce a positive result from rapeseed oil. Water and kerosene, which were ineffective in the trial, would be even less likely to succeed in higher temperature plumes as both exhibit high vapour pressures that would prevent either agent condensing.

- Two concentrations of a glycerol/water solution were tested, but in both cases the plume density decreased markedly after approximately 30 seconds of injection. The cause of this intermittency was not established.
- Of the two types of atomiser demonstrated, the air-blast type generally out-performed the pressure-jet atomisers. However, the plume quality did not seem to be particularly sensitive to the type of atomiser.
- The night trial demonstrated that the smoke system was ineffective in the dark with the lighting provided, and any additional lighting required in the offshore environment would likely present an unacceptable source of glare to pilots of approaching helicopters. It is therefore unlikely that the smoke system could be made to be effective for night operations in an acceptable manner.

5 Diesel Environmental Impact Study

5.1 Introduction

Diesel fuel was demonstrated to be the most successful smoke agent in the full-scale onshore trial (except at very low flow rates where glycerol/water and smoke oil were superior due to their lower vapour pressures). A further operational advantage of diesel fuel is its ready availability on offshore platforms. However, as diesel fuel is both toxic and non-biodegradable, its use as a smoke agent was in doubt for reasons of occupational health and environmental risks.

An environmental screening study was therefore undertaken to assess whether there were any environmental constraints associated with the use of diesel as a smoke generating agent. The full report of this study is reproduced in Appendix C, and the study and its conclusions are summarised below for convenience.

5.2 Summary and Conclusions

The study comprised:

- The collection and examination of data on the physical and chemical properties, the health and safety properties, and on the applicable air and environmental quality standards for diesel fuel and diesel exhausts.
- Atmospheric emissions modelling to predict the short-term dilution and dispersion pattern of the diesel fuel.
- An assessment of the fate of the diesel using a classical approach based on the 'hazard–receptor' pathway (human exposure, effects on the installation and the marine environment).

The air dispersion modelling indicated that the maximum diesel vapour concentration on the offshore platform would be below the relevant UK Occupational Exposure Limits (OELs) under the majority of atmospheric conditions. However, for the example platform modelled, a worst-case scenario was predicted to occur for northwest or southwest winds for stability categories D1, D2 and D3, where the OEL would be exceeded in close proximity to the platform. Consequently there was a risk to personnel on the platform or on adjacent vessels (e.g. standby vessels) under these conditions.

In addition to possible health risks, there are likely to be significant operational considerations. For example, there may be a requirement to disrupt normal working practices on the platform and associated vessels when diesel vapour is being released. In a worst-case scenario, deposition on the platform could potentially amount to 9.67 g/m^2 during each nominal 30 minute operating period, which is the equivalent to 1.005 kg/m^2 per year if there were two 30 minute sessions (helicopter flights) per week.

Though not acutely detrimental when examining individual receptors (platform personnel, marine flora and fauna, safety issues with respect to slippery surfaces, etc), the confluence of these factors was considered to render the use of diesel as a smoke generating agent rather problematic, especially considering the potential quantity of fuel vapour droplets that could be released into the marine environment.

6 Small-Scale Laboratory Experiments

6.1 Introduction

It had been established that, although very effective as a smoke generating agent, using diesel fuel was problematic from environmental, health, and safety points of view – see Section 5 and Appendix C. Attention was therefore turned to the other two smoke generating agents – theatrical smoke oil and glycerol/water solution – that had been successfully demonstrated during the onshore trials.

Although it worked well during the onshore trials, the evaporation characteristics of theatrical smoke oil in lower temperature plumes (e.g. 200°C) could be marginal, and good atomisation and the creation of a large surface area for good heat transfer may be critical (see Appendix B). Unlike diesel fuel, theatrical smoke oil is non toxic, but it is non-biodegradable and is therefore classified as a marine pollutant. Theatrical smoke oil is also relatively expensive, costing 60% more than pure glycerol.

In theory, glycerol should work well because of its boiling point and vapour pressure as indicated by the initial dense plumes generated using glycerol/water during the onshore trials. When combined with its relatively low cost, and benign health and environmental impact (see Appendix B), glycerol/water is almost an ideal agent. The only issue with glycerol/water is that of maintaining the density of the smoke plume.

Of the three smoke generating agents that showed promise during the onshore trial, glycerol/water was therefore judged to be the most suitable, subject to resolving the issue of the intermittency of the smoke plume.

6.2 Objectives

The overall aim of the small-scale trials was to generally assess the performance of glycerol/water as a smoke generating agent in terms of plume visibility as determined from contrast measurements. The specific objectives were to:

- determine the relationship between plume visibility, agent (i.e. glycerol/water solution) flow rate and exhaust gas temperature;
- determine the relationship between plume visibility, agent concentration (using pre-heat to make the higher concentration sprayable) and exhaust gas temperature;
- provide an indication of how much glycerol is needed at different gas turbine exhaust plume temperatures;
- investigate the intermittent performance seen when using glycerol/water during the onshore trials.

6.3 Set-Up and Methods

6.3.1 Agent Concentration

Pure glycerol is extremely viscous, would not be easy to pump and could not be sprayed effectively since, to be sprayable, a liquid typically needs to have a viscosity of less than 12 centistokes. Therefore, a 50% (by volume) aqueous solution of glycerol was used as the principal agent: this produces a workable viscosity (~ 6 centistokes) at ambient temperatures and, in practice, would give some margin for lower temperatures. In a second set of experiments, the agent was pre-heated to 100°C to reduce the viscosity of an 80% (by volume) solution to a level that allowed it to be sprayed and tested. Agent pre-heat to temperatures in excess of 110°C within the supply pipework would not be practicable because the water content would boil leading to unacceptable pressure and concentration excursions

In these small-scale tests, relatively high quantities of agent were employed compared with those that might be used with a full size gas turbine exhaust. This was to compensate for the small exhaust tube diameter and very short optical path length (4 cm) of the plume, and to provide sufficient plume luminance for adequate measurement accuracy. For example, at the highest airflow temperature and an 80% solution flow rate of 1 ml/s the agent concentration was ~13%w/w (by weight). The heat required to evaporate this additional smoke agent will have come from the plume and may have increased the cooling of the plume causing the plume contrast to not have increased by as much as expected.

6.3.2 Apparatus

A commercial, motorised hypodermic metering pump was used to pump the solution. Because of the small-scale of the experiment a miniature 'scent-spray' atomiser driven by compressed air was used to ensure that well-atomised droplets were added directly into the airflow. Droplet sizes were not measured, but the mass median diameter is not likely to have been significantly less than 20 microns and should be practicable to replicate at full-scale. The airflow was provided by a commercial hot air gun capable, in theory, of producing gas temperatures of up to 650°C.

A schematic of the experimental apparatus is shown in Figure 20. A heavily lagged aluminium pipe (40 mm diameter) was used as the exhaust pipe, with the hot airflow being provided at the upstream end by the hot air gun. A thermocouple was placed immediately downstream of the hot air gun to measure the air temperature at the 'inlet' (temperature T1). A plot of the air mass flow versus temperature is shown in Figure 21. The agent spray was injected into the airflow through a hole in the side of the tube using a 'scent spray' located just downstream of this thermocouple. There were two further thermocouples close to the exit end of the pipe, one that measured the temperature of the pipe wall itself and one that measured the temperature of the air at the 'outlet' (T2). In spite of heavy lagging, the exit wall temperature equilibrated at about 50°C lower than the local hot air temperature.

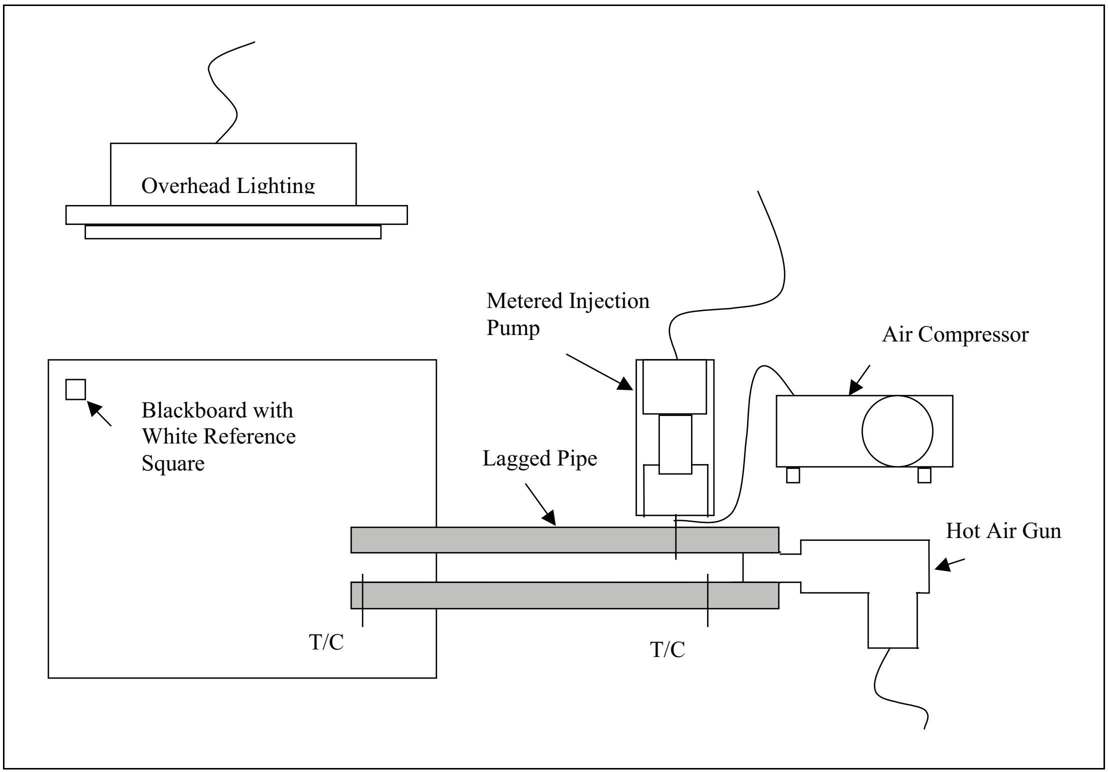

Figure 20 Schematic of the experiment apparatus

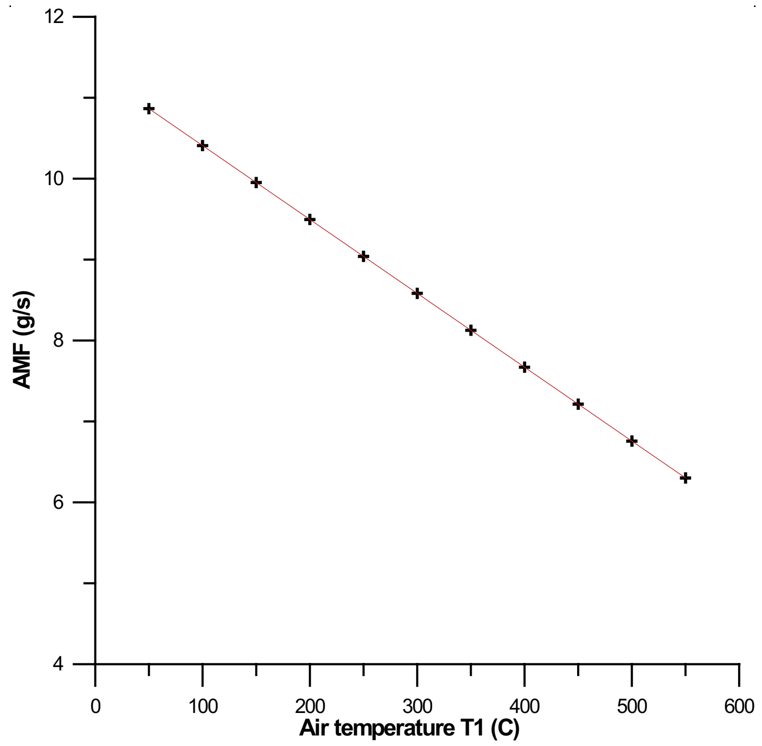

Figure 21 Air mass flow as a function of temperature

Because of the small-scale of the experiment and the relatively large wall area, some of the agent condensed on the tube walls, especially at the lowest gas temperatures, effectively reducing the agent flow rate. This will have resulted in increasingly pessimistic results, i.e. reduced plume contrast towards the lowest gas temperatures.

The glycerol solution was introduced into the airflow using a calibrated metering pump that pumped the fluid at pre-determined flow rates through small-bore tubing to the scent spray. The scent spray itself comprised a 0.5 mm ID liquid delivery tube at right angles to a 1 mm atomising air nozzle supplied with air at 2 bar gauge (29 psi). The resulting spray was directed into the hot airflow through a 5 mm diameter hole in the side of the test pipe.

Where applied, agent pre-heat was provided by running the supply tube through a container of simmering water (100°C). All the equipment was mounted on a large laboratory bench with the exhaust directed into a fume cupboard.

6.3.3 Optical Measurements

The exhaust plumes were photographed against a matt black background carrying one small reference grey-scale patch. The laboratory was an enclosed room providing a constant light level from overhead fluorescent fittings.

In preliminary tests using ‘time resolved’ (1/100 s) photographs (Figure 22), it became clear that the plume image contained far too much structure to allow the quantified measurement of average optical properties. In an attempt to avoid this problem a shutter speed of eight seconds was used with the camera stopped down to produce the correct film exposure. By eye, at least this technique produced ‘smooth’ images (Figure 23).

Figure 22 Time resolved (1/100 s) photograph

Initially, plume luminance (as reflectance) was measured on printed photographs using an optical densitometer. The results obtained showed a very high degree of scatter and anomalies. This was probably because the images still contained considerable structure and the densitometer could only measure a small area of the plume rather than take an average over a larger area.

In order to overcome this problem the images were re-analysed in electronic format using the PaintShop Pro v7 photo editing software. This package offers the facility to interrogate any specified area of an electronic image and display the average grey optical density. In this instance, a 250x250 pixel grid was superimposed on each photograph to ensure that measurements were made at consistent locations, see Figure 23. Using the grid, for each photograph a 250,000 pixel sample was taken of the plume, a 62,500 pixel sample of the background and a 10,000 pixel sample of the greyscale.

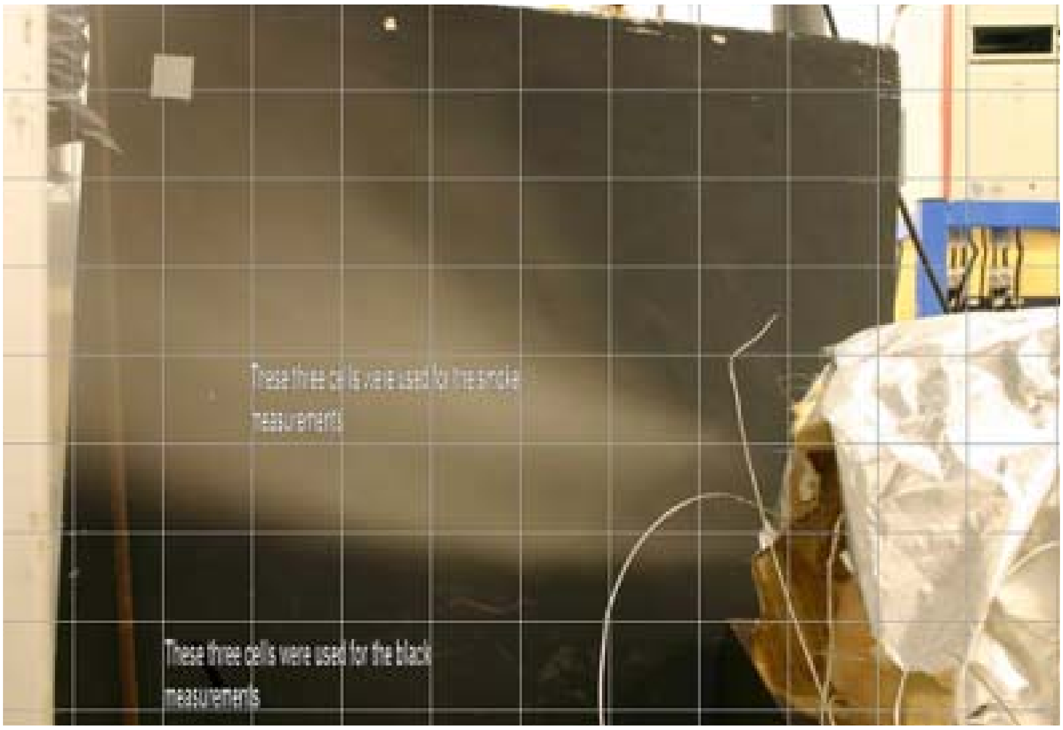

Figure 23 Example picture showing grid with plume and background analysis cells

In spite of the constant illumination, the electronic image analysis showed some variation in background and greyscale luminance (and therefore in plume luminance). This was particularly noticeable between runs when the camera had been moved. To compensate for this, a typical datum background luminance (and greyscale luminance) was defined. Measured plume luminances were then adjusted for each photograph using the ratio of datum luminance to measured background luminance. For the brightest plumes where the luminance was nearer to that of the greyscale than that of the background, the correction was made using the datum greyscale. For most plumes having intermediate luminances, corrections using either method produced very similar results.

Contrast, which is a better gauge of visibility, was calculated from the corrected luminance values using the relationship:

$$\text{Contrast} = (a-b)/(a+b)$$

where a and b are the luminances of the lighter and darker areas, respectively.

6.3.4 Methods

The heat gun was calibrated prior to the start of the experiments. The temperatures at the inlet (T1) and outlet (T2) thermocouple points were measured and compared with the adjustable settings on the heat gun, which ran from 1 to 15. The maximum temperature recorded at the inlet thermocouple was 566°C, while the maximum temperature recorded at the outlet thermocouple was 420°C. This is because heat transfer to the agent and heat losses through the pipe reduced the downstream temperatures. For each run the higher value was taken to characterise the temperature of the run.

The temperature was set to maximum for the start of each run to ensure that any agent that had condensed on the cool tube wall at the end of the previous run was boiled off. This cleaning process always produced some plume visibility, indicating that there had been a loss of agent at low air temperatures and therefore a pessimistic result compared to a system with no cool, solid boundaries.

For each run, the glycerol solution was sprayed into the pipe and the plume photographed as the air temperature was reduced. The agent concentration, pump setting and flow rate for each run are given in Table 3. Additional detail is presented in Appendix D.

Table 3 List of experiments performed

Experiment No.	Agent Concentration (% Solution)	Metered Pump Setting (No.)	Flow Rate (ml/s)
1	50	500	0.5
2	50	1000	1.0
3	50	750	0.75
4	50	625	0.625
5	70[1]	500	0.5
Pre-heat experiments:			
6	80	500	0.5
7	80	1000	1.0
8	80	500	0.5
9	80	1000	1.0

1. It was not possible to use an 80% concentration solution without pre-heat, as the solution would have been too viscous, so a slightly lower concentration of 70% was used.

NB: Experiments 8 and 9 were repeat runs of experiments 6 and 7 under identical conditions to gather more data.

6.4 Experiments

6.4.1 'Cold' Agent Experiments

The experiment run logs corresponding to the runs performed with the agent at room temperature are given in Appendix D. These show a record of each run performed together with the heat gun settings and the recorded temperatures T1 and T2. They also relate to the data photographs presented in [13].

Experiments 1 and 2 were effectively performed during the same test run. The run was paused halfway through to re-fill the metering pump with glycerol solution and to blow hot air through the tube in order to clean it out, so that any excess glycerol from the first run would not contaminate the second. The run matrix for experiments 1 and 2 is given in Appendix D, Table D1.

Experiments 3 and 4 were also performed during the same test run. Since the plume had been less visible at a pump setting of 500, these runs were used to find an intermediate agent flow rate at which the plume was still very visible. The run matrix for experiments 3 and 4 is given in Appendix D, Table D2.

Experiment 5 was used to investigate the effect of the glycerol solution concentration on the plume visibility. The solution concentration was raised to 70% by volume, which is as high as the concentration could be raised before the consequent increase in viscosity would adversely affect the flow rate and the droplet size. The run matrix for experiment 5 is given in Appendix D, Table D3.

6.4.2 Pre-heat Experiments

The pre-heat experiments provided the opportunity to investigate plume visibility at a higher glycerol solution concentration. The concentration was raised to 80%, and the solution fed through a tube immersed in a hot water bath before being sprayed into the airflow. The run matrix for experiments 6 and 7 is given in Appendix D, Table D4.

The pre-heat experiments were repeated to provide more data on the higher concentration solution, and to demonstrate the level of repeatability of the experiment. The run matrix for experiments 8 and 9 is given in Appendix D, Table D5.

6.5 Observations and Results

6.5.1 Observations

By eye, the exhaust plume exiting the pipe was transparent for all test points and temperatures. In other words, evaporation appeared to be complete. The plume then progressively formed smoke on contact with the cooler laboratory air.

Early in the plume development there was a transparent potential core (i.e. flow that hadn't yet mixed into the surrounding atmosphere), surrounded by an annulus of white 'smoke'. As the potential core mixed progressively into the cold surrounding air (~4 or 5 tube diameters downstream), all the agent condensed. Consequently, seen from the side, the areas of highest optical density were at the edges of the plume, where the optical path through condensed agent was longest. As the airflow was slowest and the buoyancy was greatest at the highest temperatures, the plume was seen to extend higher than it did at low temperatures. This 'loss' of smoke from the measurement cross-section must therefore have reduced the contrast to some extent. However, it is not clear how this reduction might be quantified.

6.5.2 Results

6.5.2.1 Repeatability

Figure 24 and the 0.5 ml/s runs in Figure 25 show the good repeatability that was demonstrated between repeat runs.

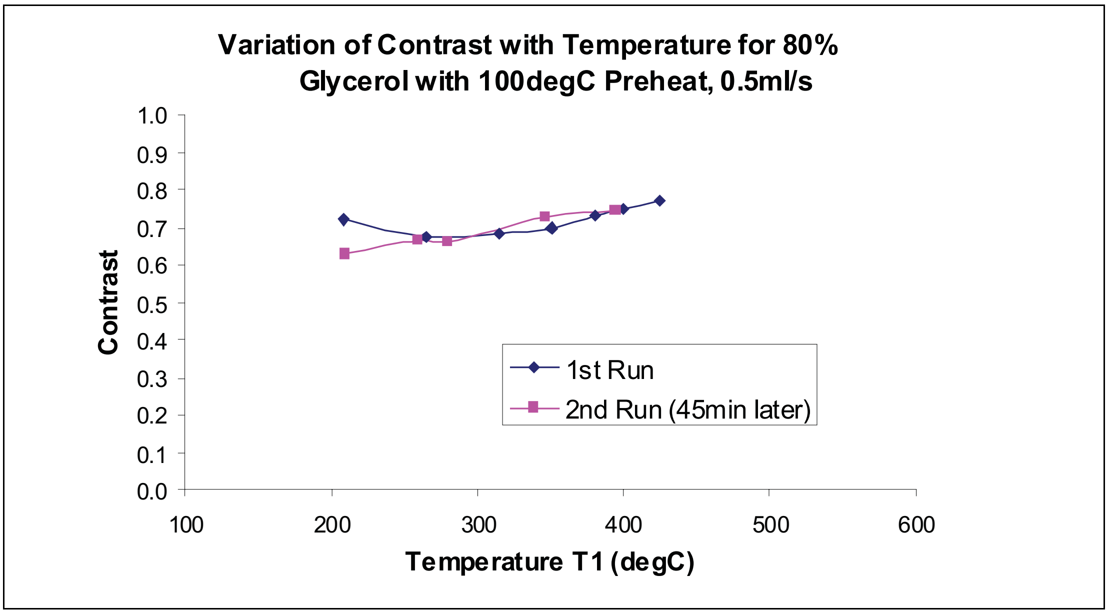

Figure 24 Repeatability of measurements

6.5.2.2 50% Glycerol Solutions

Contrast as a function of temperature for all the 50% solution runs is shown in Figure 25. This shows a progressive increase in contrast with increasing agent flow rate particularly from 0.5 ml/s to 0.625 ml/s. However, the contrasts at the highest flow rates (1.0 and 0.75 ml/s) are effectively identical. Contrast increases with gas temperature for each of the flow rates. However, the slope is much higher for the 0.5 ml/s flow rate and is minimal for the highest flow rates. The 0.5 ml/s flow rate results are confirmed, at the low temperature end, by six additional data points obtained during a setting-up run (0.5 ml/s #2 in Figure 25).

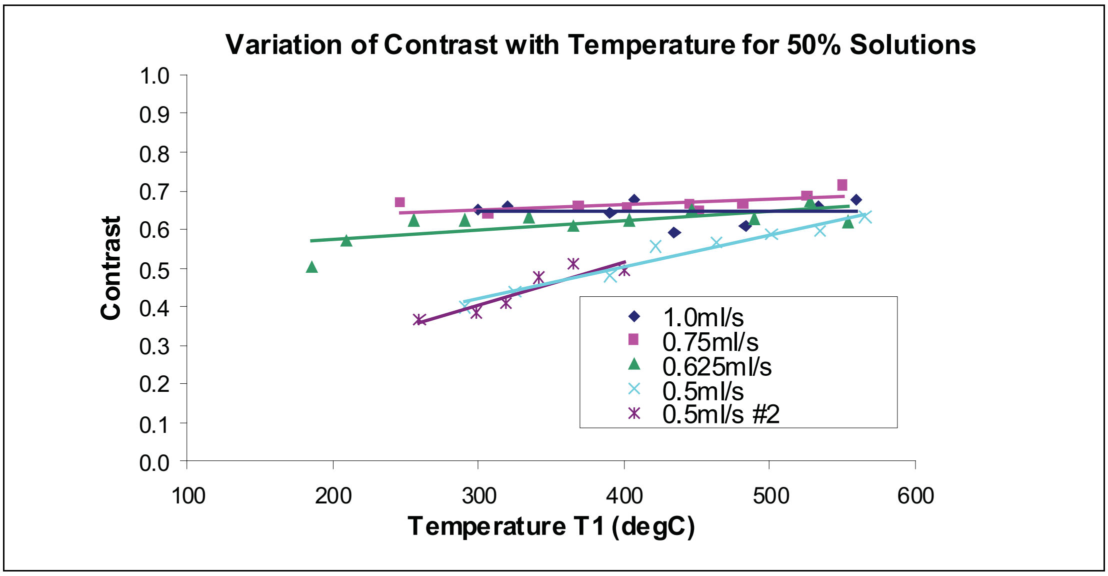

Figure 25 Contrasts for 50% solution – all flow rates

6.5.2.3 70% Glycerol Solutions

The 70% glycerol solution was tested at one flow rate (0.5 ml/s), and there was a small increase in contrast with gas temperature (see Figure 27).

6.5.2.4 80% Glycerol Solutions (With Pre-Heat)

The use of pre-heat enabled runs with a high glycerol concentration to be carried out to see if the increase in plume contrast with concentration was maintained. Figure 26 shows the results for an 80% solution with flow rates 0.5 and 1.0 ml/s. As with other results the higher flow rate produced a modest increase in contrast, and there was a small increase in contrast with gas temperature for the lower flow rate.

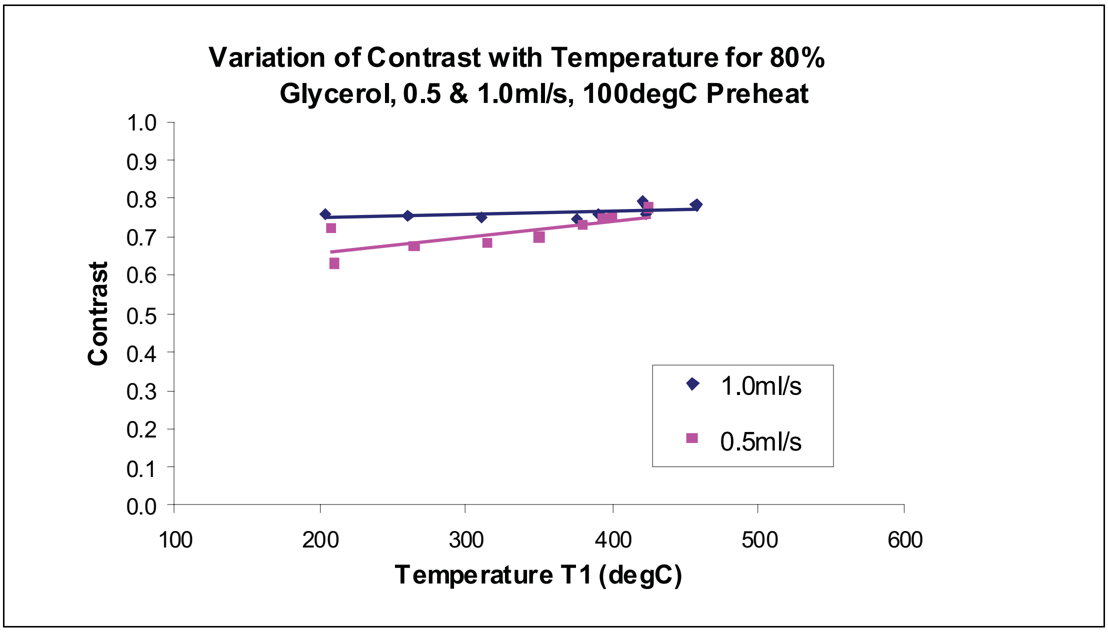

Figure 26 Contrast for 80% solutions 0.5 and 1.0 ml/s

6.5.2.5 Effect of Agent Concentration

Figure 27 shows the effects of solution concentrations (50%, 70% and 80%, all at 0.5 ml/s), on contrast. In all cases the contrast increases with increasing temperature. The 70% glycerol solution produced a higher contrast than the 50% solution at the same flow rate. In addition, the plume created using the 70% glycerol solution produced only marginally less contrast than the 80% solution and, as pre-heating is required for the spraying of the 80% solution, this suggests that pre-heat has little effect beyond reducing the viscosity of the higher concentration solution. Figure 28 shows that direct linear weighting collapses the data reasonably well. There appears to be no significant increase in contrast as a result of pre-heating the 80% solution[12] compared with the non pre-heated 70% solution.

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[12] It was not possible to run the 80% solution without pre-heat because it was too viscous.

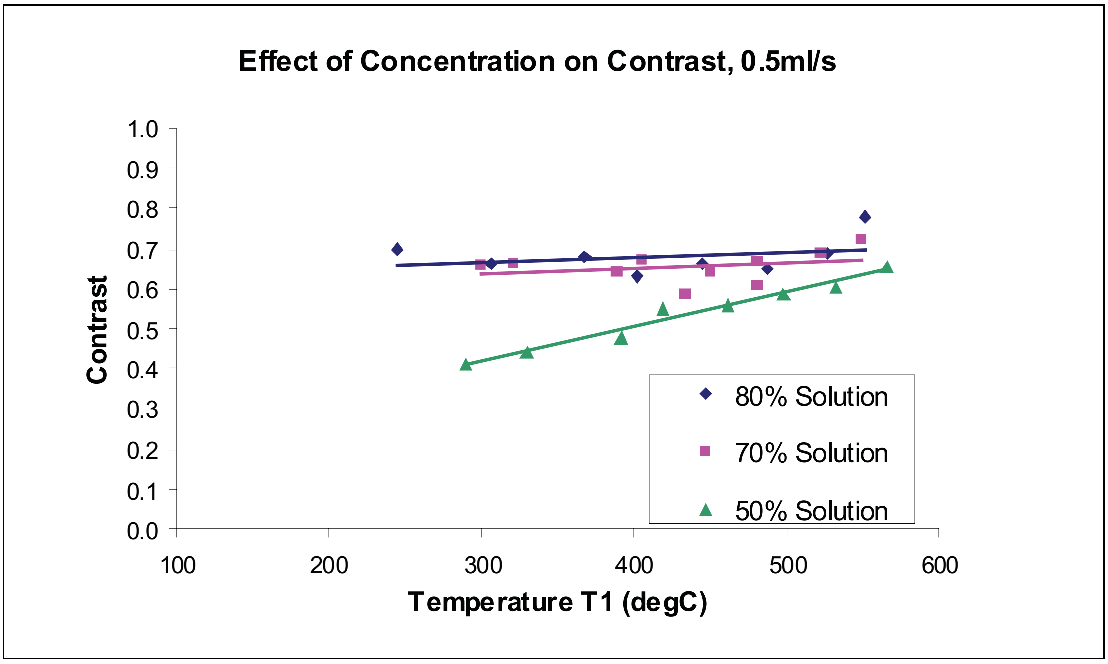

Figure 27 Effects of solution concentration – all at 0.5ml/s

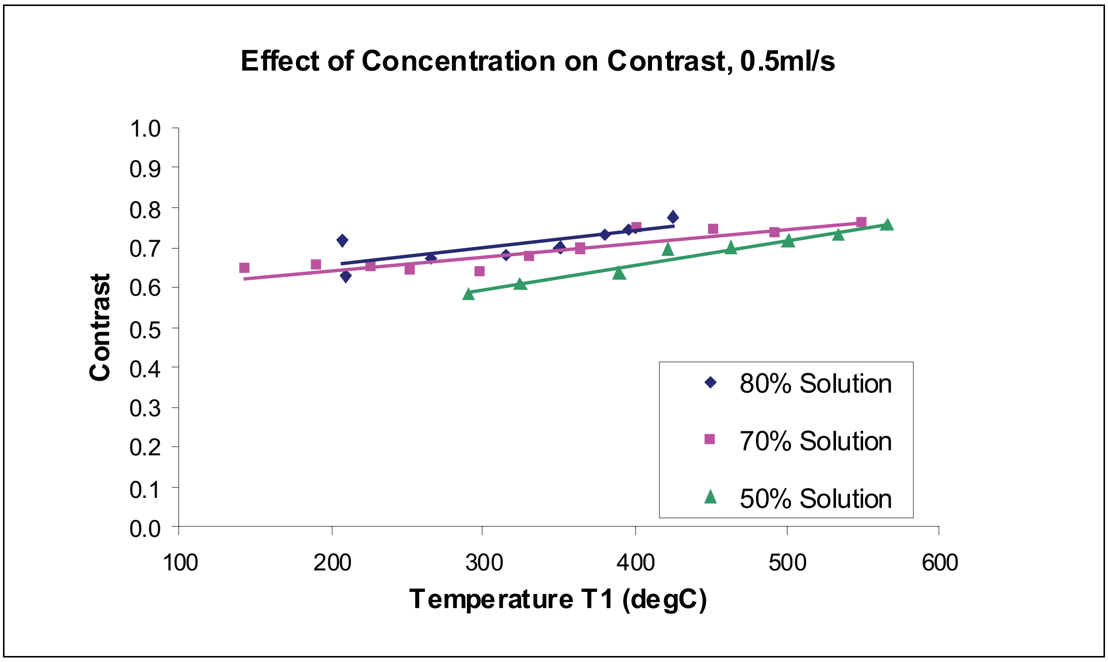

Figure 28 Effects of concentration – mass weighted results

6.6 Discussion

6.6.1 Effect of Background on the Visibility of the Exhaust Plume

For ideal geometries and viewing conditions, contrast ratios of about 0.02 (2%) can be detected. Under 'normal' viewing conditions contrast ratios of 0.1 (10%) should be easily detectable. On the other hand, factors such as low light levels or glare, a target with a diffuse edge or a very large or small subtended angle could lead to loss of detectability even with 0.1 (10%) contrast.

For clouds of particles, the extent to which incident light is scattered can be calculated as a function of path length, particle size and number density. For purposes of illustration, the scattering can then be approximated to contrast. Figure 29 shows a typical relationship between contrast and number density. What is clear is that a particle formation process that is already reasonably efficient will not increase contrast very substantially by being more efficient. There are other implications: for example, all other things being equal, doubling the flow rate should not double the contrast; and after a satisfactory contrast has been reached it would be easy to waste agent attempting to improve contrast further. Rather, it might be more effective to increase the area of treated plume by adding more spray heads in the plume cross-section.

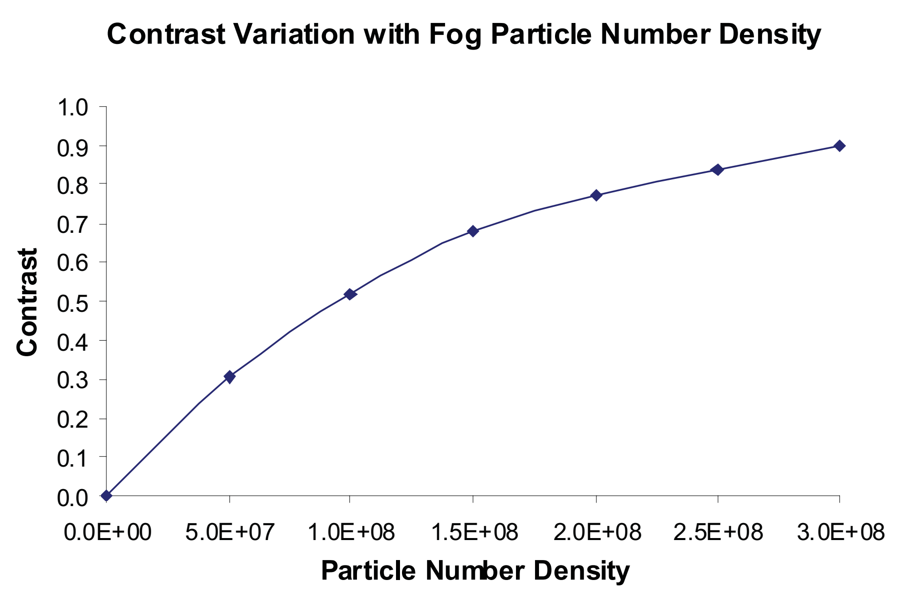

Figure 29 Contrast as a function of particle number density

From the point of view of detectability in the field, plumes with even the lowest contrast levels measured here would normally be easily visible to an observer expecting to see a plume (i.e. detection depends substantially on whether the observer expects to see an event and knows where to expect it). Detectability is also substantially enhanced if the plume, as might be expected, appears as a line source with 'hard, contrasting' edges. Conveniently, this is favoured by detection at a distance where the subtended angle of the plume is small. The extraordinary visibility of condensation trails from highflying aircraft illustrates these points well. Low light levels and the presence of glare, however, will detract from plume visibility.

Contrast against a more typical background, e.g. grey, can be calculated for these experiments. Figure 30 shows the contrast that is predicted (for this experiment/path length) against a mid-grey background 'typical' of sea under a blue sky. Given reasonable daytime viewing conditions, undiffused plume etc., the predicted contrasts shown in Figure 30 would be visible.

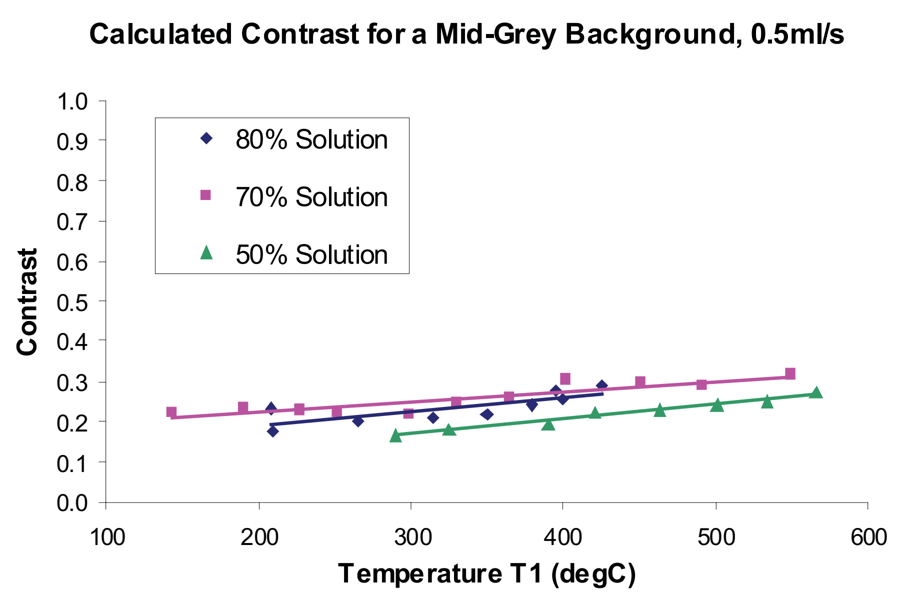

Figure 30 Calculated contrast against mid-grey background

6.6.2 Possible Sources of Plume Intermittency

One of the objectives of the small-scale trial had been to investigate the plume intermittency that had been experienced with the glycerol during the onshore trial. However, in this series of small-scale experiments, no plume intermittency was observed and the plume density remained constant for each condition. Reasonable plume densities were obtained down to 200ºC, albeit with higher concentrations.

Because of the small-scale of the laboratory experiments, there were necessarily very substantial differences of factors such as agent flow regime, pipe friction, surface-to-volume ratio residence time etc. compared with the onshore trial. However, the experiment has demonstrated that there is no fundamental problem and that glycerol has the potential to be used to make gas turbine exhaust plumes visible. Even in small-scale it can form a steady visible plume that has high optical density.

6.6.3 Agent Performance

The solution concentrations and gas temperatures were chosen to provide suitable viscosities for effective pumping and atomisation performance, but they do provide an indication on practical concentrations for use offshore.

As would be expected from theory, increasing the agent injection rate either through increased flow rate or increased solution concentrations led to increases in plume visibility. The relationships were found to be non-linear, however, and little increase in plume visibility was obtained for agent flows greater that 0.625 ml/s and for agent concentration above 70%.

Plume visibility was found to increase linearly with gas temperature, but the effect was very modest except at the lowest agent flow rate and lowest agent concentration. Pre-heating the agent allowed a concentration of 80% glycerol to be tested but there was little improvement on the plume visibility compared with the 70% concentration that needed no pre-heating, suggesting that the pre-heating had no effect other than to reduce the viscosity of the solution allowing it to be sprayed.

As explained in Section 6.3.2, the experimental set-up and agent concentrations employed for these trials will have resulted in reduced plume contrasts at the lowest gas temperatures. However, the plumes generated were still visible and have the potential to be much more visible given the available increase in optical path length at full-scale.

6.7 Conclusions of the Small-scale Experiments

Small-scale laboratory experiments have been undertaken to simulate the injection of a smoke generating agent (glycerol/water solution) into a hot gas turbine engine exhaust. The conclusions of these trials can be summarised as follows:

- The ability of a glycerol solution to generate visible white ‘smoke’ has been demonstrated in heated air flows over temperature ranges spanning those encountered in industrial gas turbine exhausts, and there is no reason to prevent glycerol/water being successfully used to make gas turbine exhaust plumes visible.
- Despite being adversely affected by the small scale of the experiment, the plumes for all of the test configurations exceeded the required threshold contrast and, in theory, should be visible in typical offshore environments.
- The results show a diminishing increase in contrast with increasing agent concentration and with increasing agent flow rate.
- Agent pre-heating had no measurable effect other than allowing a higher agent concentration to be used.
- The plume contrast increased with exhaust temperature for each of the flow rates, the gradient being steeper for the 0.5 ml/s flow rate cases compared with those for the higher flow rates.
- No signs of the intermittency of plume visibility experienced in the earlier full-scale trial were found at any condition in this small-scale experiment.

7 Pipe Heat Transfer Analysis

7.1 Introduction

During the full-scale onshore trials a glycerol/water solution was found to produce a dense white plume that lasted up to 30 seconds before fading into a thinner, less effective plume – see Section 4.4.2.2. In theory, glycerol should be an ideal smoke agent, and the small-scale trials subsequently performed failed to reproduce the intermittency – see Section 6.6.2.

A potentially significant difference between the full-scale and small-scale trials was the condition of the glycerol/water solution in the delivery pipework. An investigation was therefore carried out using CFD to determine likely agent exit temperatures and residence times for the full-scale onshore trials configuration in the expectation that this might provide insight into what happened to the solution up to the point of spraying into the hot exhaust plume.

7.2 Task Scope of Work

A steady-state CFD analysis of the agent pipe flow for the full-scale onshore trials was performed in order to provide:

- an estimate of the temperature of the glycerol/water solution when it arrived at the spray heads.
- a typical transit time during which the solution was exposed to the hot exhaust gas in the copper delivery pipe.

Input data for the study was as follows:

- Smoke agent: 50% water/50% glycerol.
- Glycerol density (@20°C): 1,260 kg.m^3.
- Glycerol boiling point: 290°C.
- Kinematic viscosity of 50%/50% solution (@20°C): 6 centistokes.
- Maximum mass flow rate: 313 gm/s.
- Minimum mass flow rate: 78 gm/s.
- Diameter of exhaust de-tuner is 4.6 m (the QinetiQ report on the trials says that the pipes were routed across the de-tuner and back to the sprayers: a length L = 4.6 + 2.3 m for the average exposure distance was assumed).
- Temperature of gas turbine exhaust: 200°C.
- Ambient temp: 20°C.
- Pipe material: copper.
- Pipe ID: 0.325 cm.
- Pipe OD: 0.635 cm.

7.3 Analysis Procedure

The method used to obtain the results is detailed below:

- A full-scale CAD model was built, defining the copper pipe exposed to the hot exhaust gas at the exit of the de-tuner, according to the dimensions given in Section 7.2.
- A computational mesh was generated using the specialised package ICEM CFD. Cells were concentrated on the inside walls of the pipe, in order to capture the effects of a viscous boundary layer. The mesh comprised approximately 700,000 tetrahedral and prismatic cells.
- Two simulations were performed, according to the maximum and the minimum mass flow rates given in Section 7.2. Fluid turbulence and heat transfer effects within the delivery were taken into account in the numerical simulations, having an input fluid temperature of 20°C and an exhaust gas temperature of 200°C.

The CFD model was specifically set-up to model single phase flow. As such, it was not intended to represent two-phase flow, and any evaporation/boiling of the fluid would, therefore, not be represented.

7.4 Results

The results of the simulations are summarised in Table 4 and Figure 31.

Table 4 Simulation results

Run No	Mass Flow Rate (kg/s)	Fluid Temperature at Outlet (°C)	Exhaust Plume Temperature (°C)	Average Velocity (m/s)	Transit Time (s)
1	0.078	180	200	8.47	0.81
2	0.313	175	200	34.01	0.20

The results show that the temperature of the fluid increases steadily along the pipe for both flow rates. Heat is transferred to the fluid immediately on entry, and the heat transfer rate decreases along the pipe as the fluid temperature increases. The higher flow rate results in a slightly lower exit temperature since heat is extracted at a higher rate. Nevertheless, both flow rates reached an exit fluid temperature in the range 175°C to 180°C.

Under atmospheric conditions, the boiling point of water is approximately 100°C and that of glycerol is approximately 290°C. Therefore, under similar conditions, the boiling point of a perfect solution of water and glycerol could be expected to be between 100°C and 290°C. By calculation, the boiling point of a 50% glycerol solution is 111°C, hence the temperature of the solution in the delivery pipework will have exceeded its boiling point by a significant margin. Any vaporisation that occurred would have caused the fluid to accelerate due to its expansion and would have shortened the residence within the pipe. It is likely that the exit temperature would also have been slightly lower than predicted due to the latent heat of evaporation.

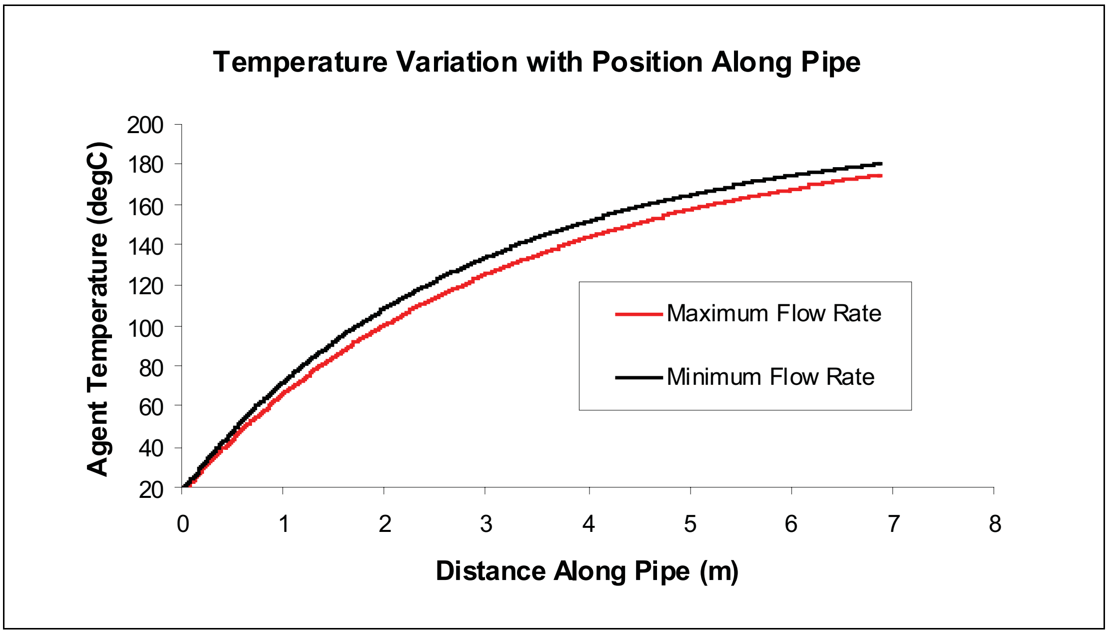

Figure 31 Temperature variation along spray feeder pipe

7.5 Conclusions

The study found that the fluid velocities are relatively high, and that transit times are subsequently very short. Nevertheless, the fluid inside the pipe experiences a significant temperature increase due to the large temperature gradient. The temperature of the inner surface of the copper pipe is barely reduced from that of the outer surface due to the high conductivity of copper.

It is therefore concluded that:

- the transit times, being less than one second, are too short to be related in any way to a transient smoke effect lasting around 30 seconds seen in the full-scale onshore trial;
- the glycerol solution was being heated beyond its boiling point in the spray feeder pipe as it passes across the top of the gas turbine exhaust detuner.

8 Discussion

8.1 Glycerol Intermittency

Of the six agents tested during the full-scale onshore trials, glycerol/water solution clearly emerged as having the greatest potential in terms of use in the offshore environment. The only issue with this agent was that of maintaining the plume density – the plume was found to effectively cease after about 30 seconds – see Section 4.4.2.2. Although the small-scale trials demonstrated that there is no reason why it should not work, as it was not possible to establish the cause of this behaviour a slight doubt remains.

At the time of the onshore trials it was considered that a possible explanation of the intermittent glycerol performance might be pre-heating of the fluid while stationary in the feed pipes prior to activation. This could have raised the fluid temperature sufficiently to promote evaporation in the engine exhaust, followed by a visible cloud as the fluid condensed. A progressive reduction in pre-heating could then have limited, and eventually prevented evaporation once the fluid was flowing. A later, alternative theory was that prior to activation of the agent, the pipes exposed to the hot exhaust gas were in fact empty – the water had boiled off leaving a neat glycerol residue at 200°C attached to the pipe walls. When the agent started flowing, the initial glycerol concentration would have been increased, and this might have caused the dense plume.

Neither of these explanations now seem likely as the agent transit time for the sections of delivery pipes in the hot gas plume were estimated by the CFD study (see Section 7) to be of the order of 1/3 second, and hence any effect due to initial conditions at activation would be expected to last a similar time, perhaps a little longer. In addition, the former of the two theories is not supported by the results of the small-scale trial where it was established that the only effect of pre-heating was to reduce the viscosity of the agent – see Section 6.6.3. Reducing the viscosity of the solution to 30% during the full-scale onshore trial had no effect on the phenomenon – see Section 4.4.2.2.

While it is not possible to draw any firm conclusions on this aspect of the work the following evidence is highlighted for consideration:

- Reducing the flow rate during the full-scale onshore trial caused the plumes generated by all three agents tested to extinguish when using pressure-jet atomisers. Visible plumes were obtained with all three agents at the same reduced flow rate, however, when air-blast atomisers were used – see Section 4.4.2.4.

- The duration of the plume generated by glycerol/water solution at the normal agent flow rate lasted longer when the air-blast atomisers were used – see Section 4.4.2.2.
- Plume contrast was found to be more sensitive to agent flow rate at lower exhaust gas temperatures during the small-scale trials, and would be expected to be particularly sensitive at the exhaust gas temperature of 200°C of the full-scale onshore trial – see Section 6.5.2.2.
- The temperature of the agent during the full-scale onshore trials where the intermittency was experienced was calculated to be in the range 175ºC to 180ºC (see Section 7.4), and exceeded the boiling point of the glycerol/water solution that was calculated to be 111ºC for a 50% solution. The temperature of the agent did not exceed 100°C, definitely below the boiling point of the glycerol/water solution, during small-scale trials where the intermittency could not be reproduced.
- The reduction of the concentration of the glycerol/water solution during the full-scale onshore trials would have reduced the boiling point of the agent, and had no effect on the intermittency.

All of the above suggests that the intermittency may have been caused by an agent flow problem related to the temperature of the agent relative to its boiling point, e.g. a build-up of undiluted glycerol or high concentration glycerol solution at the atomisers.

8.2 Alternative Method of Smoke Generation

The use of pre-generated smoke was proposed too late to be included in the full-scale onshore trials. This approach relies on equipment similar to that manufactured under licence by Sommerwest Technical Services Ltd for battlefield smoke production. With this equipment, the same type of (theatrical) smoke oil as used in the onshore trial is injected into a hot air supply (typically 450ºC) causing the oil to evaporate. The oil vapour from this generator would then be fed into the platform gas turbine exhaust system via suitable pipework. The smoke then forms as the oil condenses in the gas turbine exhaust plume.

Whereas theatrical smoke oil may well prove to be unacceptable for use offshore on environmental, health and/or safety grounds, the same generation method might advantageously be adapted for the smoke generating agent selected. In particular, this method may result in a more efficient and cost effective solution by installing a single smoke generator so that it can be switched to feed any one of a number of gas turbines, i.e. whichever is operating at the time of the helicopter flight.

8.3 Offshore System Design Issues

The information and ideas relating to the design of an offshore system generated during the project are collated here for convenience.

8.3.1 Smoke Generating Agent

Diesel fuel is considered environmentally unacceptable and should not be used. Theatrical smoke oil may be considered, but an environmental impact study must be performed before committing to this or any other agent that may be considered toxic or a pollutant[13]. If glycerol/water solution is to be used then the system should be designed to allow for some adjustment of the agent concentration.

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[13] Ethylene glycol was proposed too late to be included in the full-scale onshore trial, but its characteristics (see Appendix B) are such that it should also perform well. To its advantage is its low cost and routine provisioning on offshore platforms, although it is moderately toxic and dissolves some plastics and paints.

Regardless of the agent selected, the system should be designed with adequate margin for adjustment of agent flow rate. Predicting the agent flow rate required to generate sufficient plume contrast in any given environment (e.g. wind, visibility and viewing background) is difficult and an ability to increase the flow rate is essential[14]. Conversely, there is no point in generating a plume that is more dense than that required and the situation might arise where the agent flow rate could usefully be lowered to reduce any pollution and minimise running costs.

8.3.2 Atomisers

Both pressure-jet and air-blast atomisers were evaluated during the full-scale onshore trials. The prime reason for selecting pressure-jet atomisers was their simplicity of installation; air-blast atomisers were included to provide a comparison. In the event, the air-blast atomisers proved to perform better than the pressure-jet atomisers and fewer would be required to generate any given plume visibility.

Although air-blast atomisers are simpler in their construction and therefore cheaper, atomiser unit cost is likely to be insignificant in comparison to the total cost of installation. In addition, they do require an air supply in addition to the agent feed but appropriate air supplies are usually available on offshore platforms, so this option of atomiser is practical.

8.3.3 Atomiser Location

For simplicity, the agent injectors were positioned at the exhaust detuner exit plane for the onshore trial although this positioning may not necessarily have been ideal. Positioning within the detuner, and therefore closer to the engine where the exhaust temperature is hotter, may provide improved agent performance and facilitate installation and maintenance where access to the inside of the exhaust stack is available.

Consideration should also be given to positioning the atomisers around the circumference of the exhaust stack as opposed to across the diameter as per the onshore trial. This should concentrate the agent vapour in the outer edges of the plume which will cool more rapidly than the core, maximising the length of optical path through condensed agent and thereby plume density for any given agent flow rate. With this form of installation it should also be possible to keep the agent delivery pipework away from the exhaust flow and thereby avoid any possible problems due to agent overheating. In addition, it might be possible to install the atomisers without gaining access to the inside of the exhaust stack, facilitating installation and subsequent maintenance.

8.3.4 Gas Turbine Integrity

Injecting the smoke-producing agents in the quantities identified in the full-scale onshore trial into engine exhaust ducts should pose no risk to the engine or the installation during normal operation. Nevertheless, the engine original equipment manufacturer (OEM) and maintenance contractor must be consulted when designing the system to ensure that the safety and integrity of the engine is not compromised. It is recommended that all system designs incorporate safety interlocks to permit agent injection only while the gas turbine is operating.

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14. In the full-scale onshore trial it was found that 260 grams/second of diesel and 313 grams/second of glycerol/water solution produced a visible plume. However, agent flow rates sufficient to produce visibility in the marine environment will need to be established by means of an offshore trial.

9 Monitoring Hot Gas Effects Through HOMP

9.1 Introduction

In view of the relatively high cost of providing and running a gas turbine exhaust plume visualisation system on an offshore platform (see Section 3.1.4.3), it was decided that evidence of the extent of gas turbine plume encounters during normal service should be sought with a view to targeting the system only at those platforms that are most likely to suffer from the problem.

The HOMP project [3, 4] routinely analyses the information contained on the flight data recorders of helicopters operating on the UK Continental Shelf. The data is used to improve the safety of helicopter operations, and offers the potential to continuously monitor temperatures experienced by helicopters in normal service, and thus identify which platforms may be most at risk from the hazard.

A HOMP data archive was already being analysed in connection with the validation of a helideck turbulence criterion. It was decided to take advantage of the opportunity presented and extend the analysis to encompass ambient temperature measurements. The measurements were based on data from the aircraft's normal outside air temperature (OAT) sensor.

Temperature increases in the vicinity of the helideck were of interest, and so it was necessary to first measure the ambient temperature some distance from the helideck and then detect significant increases above this ambient temperature. Owing to the fact that the value of the ambient temperature was taken 500 m from touchdown at an altitude somewhat higher than the helideck, it was decided to apply a correction to account for the increase in ambient temperature with reducing altitude (the so-called environmental lapse rate of temperature). A standard lapse rate correction of 2°C per 1000 ft was applied. Clearly this correction introduces a potential error in weather conditions where the atmosphere is not in a standard still and stable condition. However, the altitude difference was on average only about 200 ft, resulting in an average correction of about 0.4°C, so any errors are likely to be insignificant.

9.2 Results for Example Platforms

The analysis of the HOMP archive used data from approximately 13,000 offshore helideck landings made by Bristow Helicopters over the 16-month period between July 2003 and October 2004. The analysis of the OAT readings proved very effective in identifying platforms that suffer from raised temperatures in the vicinity of the helideck. Some example results are given in the following figures.

Figure 32 shows an example result for a platform that does not suffer significantly from a hot gas problem. Each coloured point on the plot represents the maximum temperature increase experienced during a single landing, and the location of the point on the plot indicates the wind speed and direction (from). The colour and size of a point indicates the magnitude of the maximum temperature increase (averaged over 1.5 s) experienced during the last two minutes of the flight. In the case of the Brae A platform data shown in Figure 32 it can be seen that the vast majority of the 407 landings plotted experienced a temperature increase of less than 2°C. Some 15 of the 407 landings experienced temperature increases in the range 2°C to 4°C.

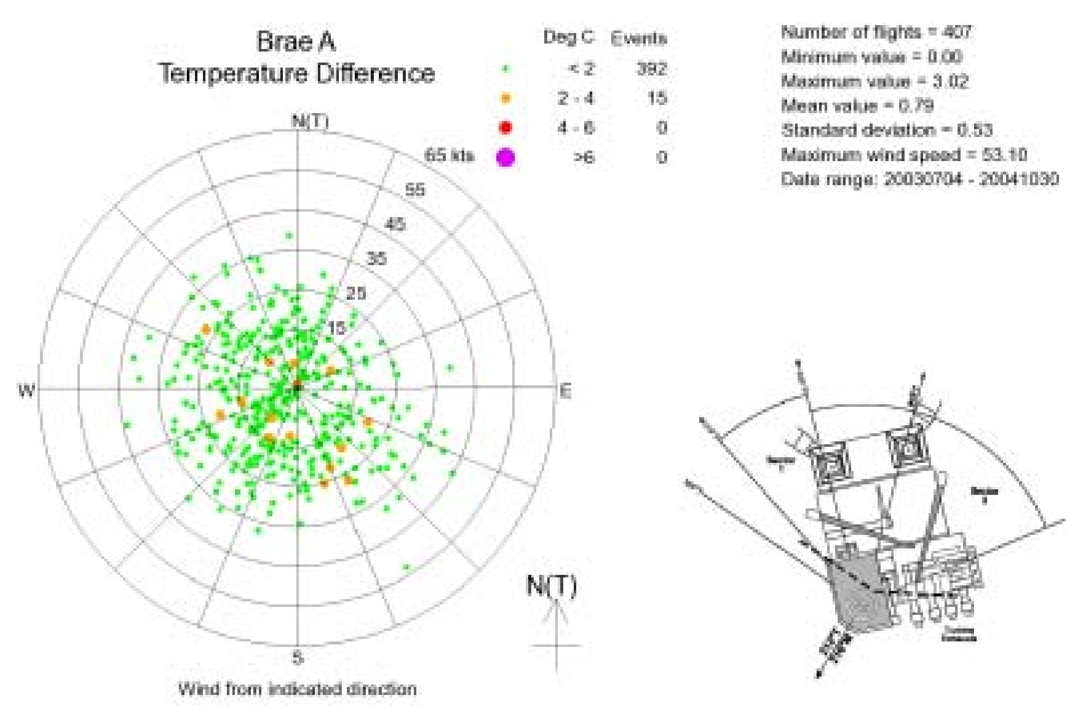

Figure 32 Maximum temperature increase plot - Brae A

Figure 33 shows similar data for the Brent C platform. This platform has 399 landings during the analysis period of the archive. Just two of these landings experienced temperature increases over 4°C, with the highest at 6.2°C. It can be seen from the sketch alongside the plot that these events, which occurred during winds from the south, are understandable because the helideck will have been downwind of the gas turbine exhausts and flare.

Results for two further platforms are shown in Figure 34 and Figure 35, which are for Ninian Central and Ninian Southern respectively. It is clear that both these platforms experience significant numbers of high temperature events. Ninian Central can be seen to suffer from many raised temperature encounters when the wind is in the south-easterly sector. Ninian Southern suffers the same problem when the wind is from the west-southwest sector. [15]

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[15] Note that only a partial sketch is currently available for the Ninian Southern platform.

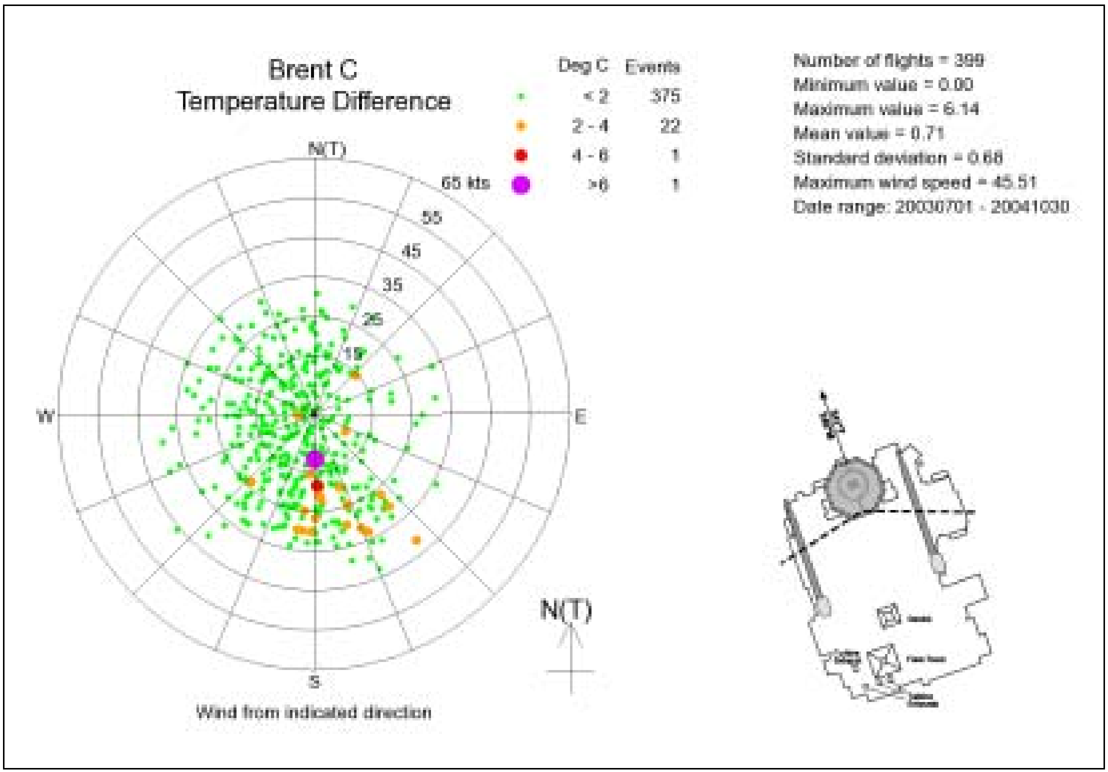

Figure 33 Maximum temperature increase plot - Brent C

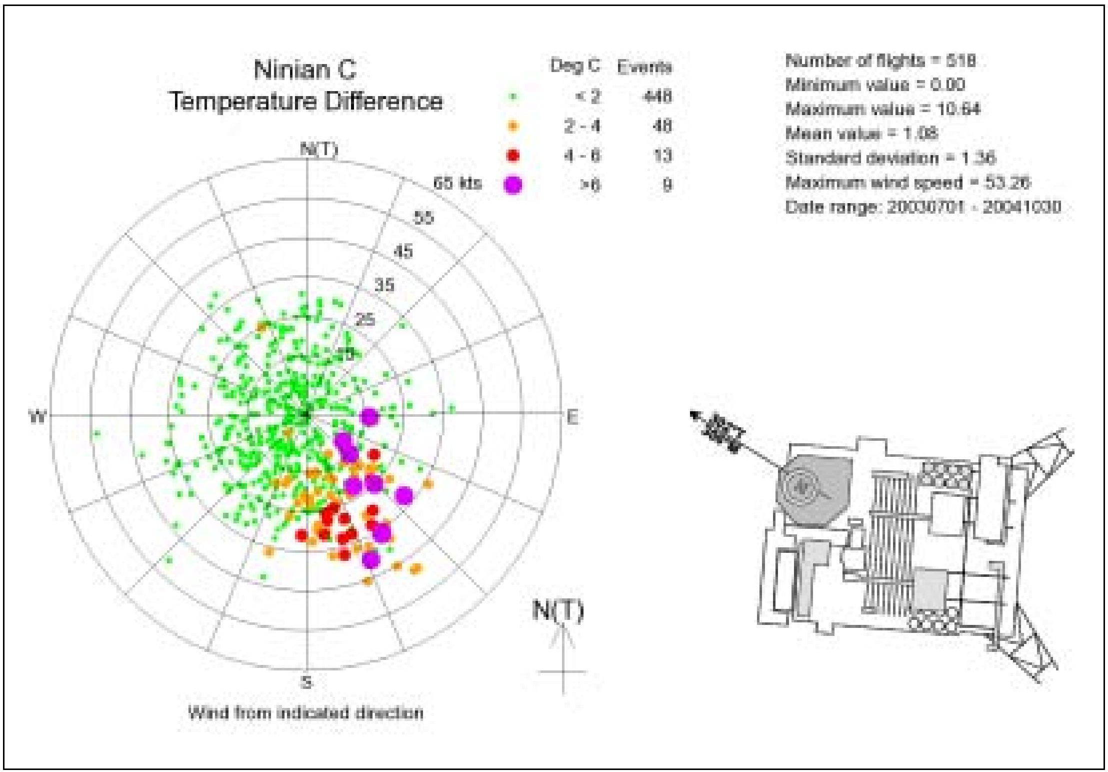

Figure 34 Maximum temperature increase plot - Ninian C

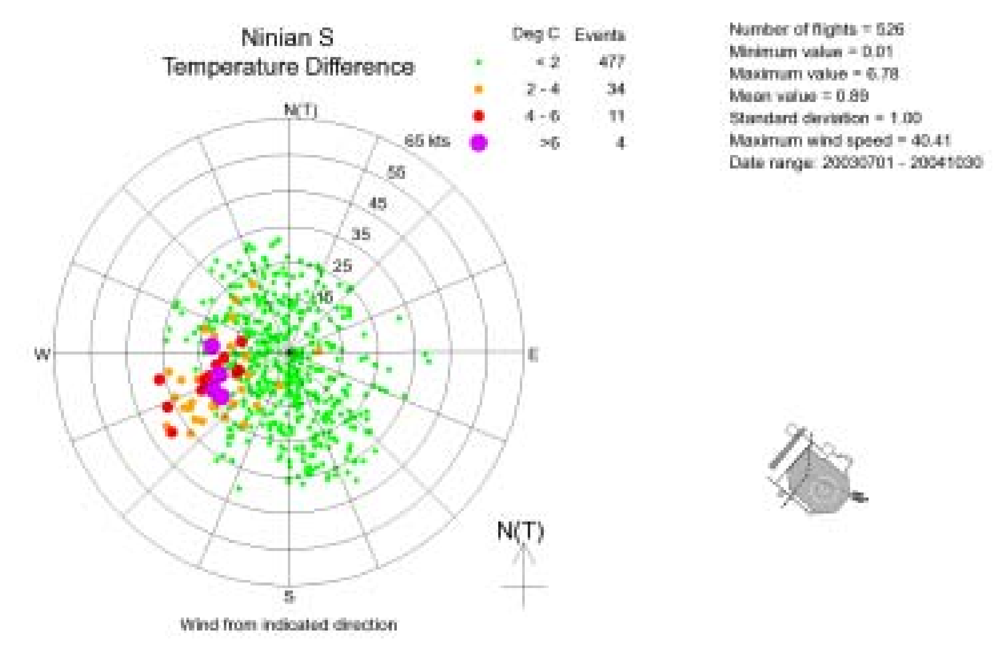

Figure 35 Maximum temperature increase plot - Ninian Southern

9.3 Overall Results

The maximum temperature increases experienced for some 12,000 landings are presented for the 70 platforms (with 20 or more landings in the database) in Figure 36. It can be seen that the majority register increases of 3°C or less. Only ten of the 70 platforms have a maximum temperature increase over 4°C, and only five platforms (7%) have a maximum over 6°C. One platform (1.4%) had a maximum increase of over 10°C (Ninian Central). This demonstrates that, if the population of installations included in the 16 months of Bristow Helicopters HOMP archive landings is reasonably representative, then temperature increase due to hot gases is not a problem at the majority of offshore installations.

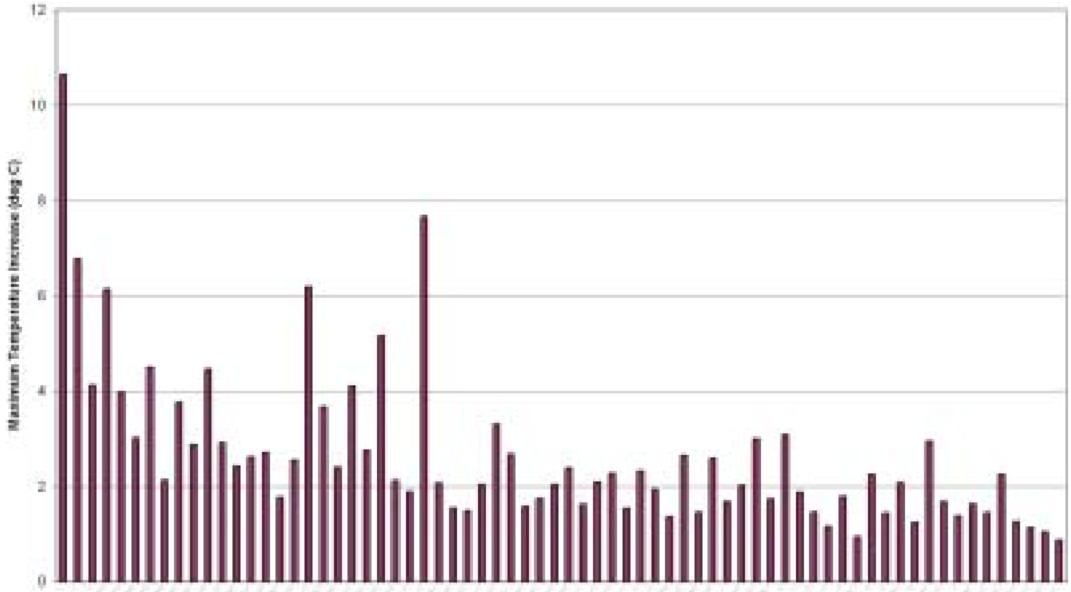

Figure 36 Maximum temperature increase registered for 70 offshore installations

The five platforms with >6°C temperature increases in the archive were: Anasuria (FPSO); Brent C; Fulmar; Ninian Central; and Ninian Southern. These installations are clearly potential candidates for the installation of a gas turbine exhaust plume visualisation system to highlight the hazard to helicopter pilots. However, the frequency of occurrence of high temperatures would also need to be taken into account. Table 5 below shows the percentage of flights that experience temperature increases greater than the *CAP 437* threshold of 2°C on the five highlighted offshore installations.

Table 5 Frequency of high temperature increases

Installation	% landings above 2 deg	% landings above 4 deg	% landings above 6 deg
Anasuria	10.0%	2.9%	0.5%
Brent C	6.0%	0.5%	0.3%
Fulmar	2.5%	0.7%	0.4%
Ninian Central	13.5%	4.2%	1.7%
Ninian Southern	9.3%	2.9%	0.8%

It can be seen that high temperatures above 6°C affect about six times as many flights to the Ninian Central Platform as are affected on Brent C.

9.4 Correlation of Results with the HLL

The plots for all platforms in the HOMP archive were compared with the entries given for the various platforms in the Helideck Limitations List (HLL) [16]. Of the 70 platforms for which sufficient HOMP data was available, 18 include in their HLL entry some element of hot gas hazard, or mention of turbulence related to exhausts. In the latter case it is often not clear whether the hazard relates to temperature, or to physical obstruction and turbulence caused by the exhaust stacks.

In a number of these cases there was no evidence of a temperature-related problem in the HOMP data. In three cases there were relatively few landings Maculloch (52 landings), Miller (23) and Tiffany (94) and drawing any conclusions is therefore risky. However, in four cases the number of landings was quite significant: Captain (331 landings); Gannet (490); Thistle (376); Triton (286). It might be concluded from this that, either the hazard alluded to in the HLL is overstated, the HLL warning of the hazard has been effective in enabling the helicopter pilots to avoid it, or the orientation of the platform relative to the prevailing wind is such that the hazardous conditions rarely exist in practice.

In 11 cases the HLL warning is confirmed by evidence of high temperature rises in the HOMP data: Anasuria (328 landings); Brent B (671); Brent C (674); Brent D (638); Fulmar (451); Heather A (391); Magnus (413); North Cormorant (650); Ninian C (839); Ninian S (778); and Tern (532). However, in the case of Tern, there was only one >4°C event in 532 landings.

In the case of Ninian C and Ninian S the HLL says that "flight through the exhaust plume should be avoided at all times", but clearly with 22 and 15 high temperature events, respectively, this is not always being achieved.

Note that for three platforms, Brent C, Brent D, and Heather A, there is a general turbulence warning in the HLL, but it does not make specific reference to high temperatures, exhausts or flares. Also, the temperature events recorded for

Heather A were when the wind was from the ‘open’ 45-60 degree sector, and so the source of these high temperatures is not obvious.

9.5 Ongoing Application of HOMP

Although not an objective of this exercise, the use of archived HOMP data to map the temperature environments around offshore platforms has demonstrated the potential benefits of using HOMP to monitor hot gas plume encounters on an ongoing basis. The benefits could include:

- The production of maps for platforms for which there is presently insufficient data in the HOMP archive or, in the case of those platforms served by helicopter operators who have yet to implement HOMP, no data at all. The maps could be used to refine and improve the entries in the HLL or, in extreme cases, indicate the end objective of any platform modifications under consideration.
- The routine monitoring for hot gas plume encounters in order to identify any deficiencies in operating procedures or pilot training.
- The routine monitoring for hot gas plume encounters in order to identify any changes to platform topsides affecting the temperature environment, including any situations that might arise as a result of combined operations.

9.6 Conclusions

The following conclusions are drawn from the analysis of the archive of HOMP data:

- If the 70 installations included in the 16 months of HOMP archive landings are reasonably representative, then temperature increase due to hot gases is not a problem at the majority of offshore installations.
- Of the five (7%) platforms exhibiting temperature rises in excess of 6ºC, the frequency of events was significant at three (4%).
- Of the 18 platforms included in the analysis having a gas turbine exhaust related warning in the HLL, evidence of high temperature rises was present in the HOMP data for 11 of them.
- There was no evidence of a temperature related problem for seven of the 18 platforms included in the analysis and having a gas turbine exhaust related warning in the HLL.
- No evidence of a temperature related problem was found for any of the 52 platforms not having a gas turbine exhaust related warning in the HLL.
- Ongoing, routine analysis of HOMP data to map and monitor the temperature environments around offshore platforms could yield worthwhile safety benefits.

10 Overall Study Conclusions

The main conclusions from the different phases of this research project are summarised in the following sections.

10.1 Feasibility Study

NB: See Section 3.3 for the full list of conclusions from this phase of the project.

- The initial review and consultation exercise found that the general consensus was that visualising gas turbine exhaust plumes could provide a useful safety benefit, and that there were unlikely to be any hazards or operational difficulties introduced by a properly designed smoke generation system. Nobody interviewed could say why the concept had never been tried before.

- The smoke generating system should be operated during all helicopter flights regardless of the meteorological conditions, in order to improve pilot awareness of the plume and its behaviour, improve the availability of the system, and avoid the potentially complicated process of deciding when to use it.
- The most effective smoke-producing agent is likely to be a hydrocarbon product such as diesel fuel (as used by the Red Arrows display team), but this might involve the production of unacceptable levels of pollutants. Unless obviously benign, an environmental impact assessment of the smoke generating agent proposed would be required.
- Although the operation and maintenance of a smoke generation system would not require additional manpower the installation and annual operating costs, estimated at around £100k and £70k, respectively, are potentially significant.

10.2 Onshore Trial

NB: See Section 4.6 for the full list of conclusions from this phase of the project.

- Of the six smoke producing agents evaluated diesel fuel was found to be the most effective and produced dense white smoke with a very visible, long lasting exhaust plume.
- Theatrical smoke oil and glycerol/water solution provided adequate but, respectively, less dense plumes, although with the glycerol/water solution the plume density decreased markedly after approximately 30 seconds of injection; the cause of this intermittency was not established.
- Water, kerosene and vegetable oil were all ineffective in visualising the gas turbine exhaust plume.
- The air-blast atomiser performed better than the pressure jet unit and maintained the glycerol plume density for longer. The plume quality did not seem to be particularly sensitive to the arrangement of the spray heads.
- The night trial demonstrated that, with the lighting provided, the smoke system was ineffective. Any additional lighting required in the offshore environment would likely present an unacceptable source of glare to pilots of approaching helicopters. It is therefore unlikely that the smoke system could be made effective for night operations in an acceptable manner.

10.3 Diesel Environmental Impact Study

NB: See Section C.5 in Appendix C for the full list of conclusions from this phase of the project.

A study of the occupational and environmental effects of using diesel fuel as the smoke agent concluded that it would be unacceptable to release the quantities necessary for effective operation into the marine environment.

10.4 Small-scale Experiments

NB: See Section 6.7 for the full list of conclusions from this phase of the project.

- The ability of a glycerol/water solution to generate visible plumes exceeding the required threshold contrast was demonstrated in heated air flows over temperature ranges spanning those encountered in industrial gas turbine exhausts.
- The plume contrast increased with exhaust temperature for each of the flow rates, the gradient being steepest at the lowest flow rate investigated. The results show a diminishing increase in contrast with increasing agent concentration and with

increasing agent flow rate. Agent pre-heating had no measurable effect other than allowing a higher agent concentration to be used.

- No signs of the intermittency of plume visibility experienced in the full-scale onshore trials were found at any condition in the small-scale experiment, and there is no reason to prevent glycerol/water solution being successfully used to make gas turbine exhaust plumes visible in typical offshore environments.

10.5 Pipe Heat Transfer Analysis

A small CFD study was performed on the full-scale onshore trial spray pipe layout. It found that the transit time of the glycerol/water solution smoke generating agent in the delivery pipework exposed to the gas turbine exhaust flow was too short to be related in any way to its intermittent performance. However, the agent was being heated to beyond its boiling point.

10.6 HOMP Data Analysis

NB: See Section 9.6 for the full list of conclusions from this phase of the project.

- If the 70 platforms included in the 16 months of HOMP archive landings are reasonably representative, then temperature increase due to hot gases is not a problem at the majority of offshore installations. The magnitude and frequency of plume encounters were judged to be potentially significant at only three (4%) of the platforms.
- Of the 18 platforms having a gas turbine exhaust related warning in the HLL, high temperature rises were found in the HOMP data for 11 of them. No evidence of a temperature related problem was found for the other seven, or any of the other 52 platforms not having a gas turbine exhaust related warning in the HLL.
- Ongoing, routine analysis of HOMP data to map and monitor the temperature environments around offshore platforms could yield worthwhile safety benefits.

11 Recommendations

The following recommendations are made:

11.1 Primary Recommendations

- Consideration should be given to installing a gas turbine exhaust plume visualisation system on platforms having a significant gas turbine exhaust plume problem in order to highlight the hazard to pilots and thereby minimise its effects by making it easier to avoid encountering the plume. It is recommended, however, that an offshore trial should be conducted on a candidate platform prior to developing a ‘production’ gas turbine exhaust plume visualisation system – see Appendix A.
- It is recommended that the trial smoke system should employ glycerol/water solution as the smoke generating agent, and be designed to allow flexibility in the key parameters of agent mass flow rate, agent concentration and agent temperature, in order that the system can be fine-tuned to suit the offshore environment.
- In the event of a non-environmentally benign smoke generating agent being used, an environmental impact assessment should be performed to establish the acceptability of the use of the agent in the quantities expected.

11.2 Other recommendations

- The HOMP data analysis should be extended to cover all offshore installations on the UK Continental Shelf (UKCS) to map the associated temperature environments, and thereby identify platforms having a severity and frequency of gas turbine exhaust plume encounters that might present a safety hazard to helicopter operations.
- Consideration should be given to making the analysis of HOMP data for mapping temperature environments around offshore platforms a continuous, routine process. This information could be used to support and improve the contents of the HLL, identify any new problems due to changes to the installation or due to combined operations, and identify any issues relating to flight crew procedures or training.

12 Acknowledgements

Thanks are due to all those organisations that participated in the consultative exercise: Bristow Helicopters, CAA Flight Operationss Inspectorate, DERA (now QinetiQ), Elf Exploration (now Total), Rolls Royce, and Shell Expro.

Thanks are also due to Bristow Helicopters and Smiths Aerospace for facilitating access to the HOMP data archive.

13 Glossary

BHAB	British Helicopter Advisory Board
BMT	BMT Fluid Mechanics Limited
CAA	Civil Aviation Authority
CAP 437	*Offshore Helicopter Landing Areas: Guidance on Standards.*(published by the CAA) [2]
CFD	Computational Fluid Dynamics
EPA	Environmental Protection Agency
Flow number	Ratio of the flow in gallons/hour divided by the square root of the differential pressure expressed in lb/in^2 across the atomisers
GTH	Glen Test House, QinetiQ engine test bed at Pyestock
HLL	Helideck Limitations List
HLO	Helicopter Landing Officer
HOMP	Helicopter Operations Monitoring Programme
HVAC	Heating, ventilation and air conditioning system
HSE	Health and Safety Executive
LC_{50}	Lethal concentration that kills 50%.
Number Density	The number of particles divided by the volume they occupy
OAT	Outside Air Temperature
OECD	Organisation for Economic Co-operation and Development
OEL	Occupational Exposure Limit
OEM	Original Equipment Manufacturer

POPA	Prevention of Oil Pollution Act 1971
ppm	Parts per million
UKCS	UK Continental Shelf
WHO	World Health Organisation

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Appendix A Offshore Smoke Generation Trial – Outline Specification

A.1 Objectives

The aims of the offshore trial are to:

- determine the safety benefit to helicopter operations to offshore platforms of making the gas turbine exhaust plumes visible through the generation of smoke;
- evaluate the performance of a gas turbine exhaust plume visualisation system under a wide range of weather and operational conditions, and expose it to a large number of pilots;
- generate the knowledge and experience necessary to support the design and development of a 'production' gas turbine exhaust plume visualisation system.

A.2 General

The objective will be achieved by undertaking a long-term in-service trial on an offshore platform. A smoke generation system will be installed, and will be operated by the platform crew while helicopters are arriving and departing. The benefit in terms of safety will be judged by analysing the opinions and comments of helicopter pilots, which will be captured and recorded by means of a questionnaire. An example questionnaire is presented in Annex 1.

It is expected that a number of different organisations will be involved in the conduct of the offshore trial as follows:

- Project Management Contractor.
- Platform Operator.
- Smoke System Designer.
- Smoke System Manufacturer.
- Smoke System Installation Contractor. [16]
- Helicopter Operator.
- Regulatory bodies (CAA/HSE/BHAB).

A.3 Tasks

The tasks to be performed for the offshore smoke generation trial together with the organisation responsible are as follows:

1 Using the design information produced by the onshore trials, design a prototype smoke generating system sufficiently well engineered to be operated safely and reliably by platform staff for an extended period of time (up to one year) – *Smoke System Designer.*

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[16] For practical convenience it is likely that this contractor will be the general maintenance contractor for the candidate offshore platform.

2 Manufacture the smoke generation system. (Hardware manufactured for the onshore trial may be used if appropriate.) – *Smoke System Manufacturer.*

3 Approval of smoke system design, and installation plan – *Platform Operator*.

4 Facilitate the installation of the smoke system on the candidate offshore platform – *Platform Operator*.

5 Install and commission the smoke system on the candidate offshore platform – *Smoke System Installation Contractor.*

6 Design pilot questionnaire, and obtain approval of the questionnaire from BHAB/ CAA – *Project Management Contractor.*

7 Train the offshore platform crews in the use of the system (HLO, safety officer or representative, etc.) – *Smoke System Designer.*

8 Provide a supply of the smoke generating agent to the platform – *Smoke System Installation Contractor.*

9 Approve the smoke system for normal flight operations (by means of a check flight) – *Regulatory Body (CAA)*.

10 Maintain the smoke generation system throughout the trial period – *Platform Operator.*

11 Remove smoke generation system equipment from the platform and make good at the end of the trial period – *Smoke System Installation Contractor.*

12 Issue and collect pilot questionnaires – *Helicopter Operator.*

13 Analyse questionnaires – *Project Management Contractor.*

14 Produce Platform Operator report – *Platform Operator.*

15 Produce Installation Contractor report – *Smoke System Installation Contractor.*

16 Produce Helicopter Operator report – *Helicopter Operator.*

17 Interview platform staff and other interested parties to elicit their views on the success or otherwise of the trial – *Project Management Contractor.*

18 Prepare a report on the trial as a whole – *Project Management Contractor.*

A.4 Smoke System Specification

The smoke system to be installed on the candidate offshore platform will need to be sufficiently well engineered to be operated safely and reliably by the platform crew for a twelve-month period. It shall be designed and constructed in accordance with the necessary standards for offshore platform temporary equipment.

The system is expected to have the following components, but the precise list may depend on which type of agent is to be used:

- Agent reservoir.
- Pipework and connections.
- Valves to control the agent flow.
- Control system with any necessary interlocks to guarantee safety and to protect equipment from damage.
- Pump.

- Injector head(s).

The smoke system will have the following functional specification:

- To be fitted to sufficient gas turbine units on the platform to ensure that smoke generation is available for the vast majority of the time[17].
- To require minimal maintenance, including agent replenishment, which can readily be performed by the platform's normal maintenance staff.
- To be fail-safe and not have any detrimental effect on any of the other platform systems.
- To have all necessary safeguards so that it is not possible to damage the gas turbine by incorrect operation, tampering with the system, or failure of the system.
- To permit the HLO to switch on/off the smoke on demand.

A.5 Deliverables

At the end of the trials the report is to include:

- Conclusions and recommendations regarding the use of smoke to improve the safety of helicopter operations.
- Detailed description of the conduct of the trials including the installation of the smoke generation system, and any practical problems encountered and overcome.
- Recommendations for the specification of a production smoke generation unit.

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[17] The number of systems/pipework arrangements required for this clearly depends on the physical arrangement of the gas turbines on the platform and their normal pattern of use.

Annex A to Appendix A
Offshore Trial - Draft Pilot Questionnaire

A study on behalf of the CAA and HSE, to determine the effectiveness of using smoke in offshore gas turbine exhausts to make the hot gas plume visible and to help pilots avoid the hazard.

General Flight Data:	
Flight Date	
Time	
Wind speed kt Wind direction deg	
Temperature (OAT)	
Precipitation	
Visibility	
Ambient Light	

Smoke Performance:	
Was the smoke system operational?	Yes, ☐ No ☐ Don't Know ☐
Did you ask for it to be switched on?	Yes ☐ No ☐
What was the gas turbine exhaust plume visibility?	None ☐ Poor ☐ Adequate ☐ Good ☐
Should the smoke be more or less dense?	Less dense, ☐ OK, ☐ More dense ☐
Did the exhaust smoke plume obscure any visual cues during landing or take-off? If yes, which visual cue(s) were obscured?	Yes ☐ No ☐
Based on your experience of the smoke system, do you consider using smoke to make the gas turbine exhaust visible to be a good or bad idea?	Bad idea, ☐ No view, ☐ Good idea ☐
Would you like to see visible gas turbine exhaust plumes on more offshore platforms and vessels?	Yes ☐ No ☐
Have you flown to this installation previously in the last 6 months?	With smoke Yes ☐ No ☐ Without smoke Yes ☐ No ☐
Have you had first-hand experience of a hot gas plume hazard?	Yes ☐ No ☐

Please add any additional comments:

Appendix B Smoke Agent Materials, Mechanisms, Properties and Choices

B.1 Theory

'Smoke' generation consists of heating the smoke producing agent until it is largely or completely in vapour form, and then allowing it to cool in contact with the cool atmosphere where it re-condenses to form smoke (solid particles) or fog (liquid particles). The re-condensation process takes place on naturally occurring background nuclei. These are present in ambient air at very high number densities[18] that are typically of the order of 10^6 nuclei per cm^3 of air. This condensation, therefore, produces a similar number density cloud of minute condensed liquid or solid particles. These intercept incident light from all directions (most of which would not have arrived at the observer) and refract and scatter it in all directions, including to the observer, producing the characteristically white fog.

For the process to be efficient it is clearly important that most of the original liquid agent should be vaporised and it must, therefore, evaporate at the temperature of the plume. In other words, it needs to have a low boiling point and a high vapour pressure. Conversely, the agent should also condense fully when the temperature of the plume reduces as it mixes with ambient air. Therefore, it needs to have a high boiling point and a low vapour pressure. For example, gasoline, which evaporates even at room temperature, would vaporise easily. However, when it comes into contact with the cool environment, it would remain in vapour phase and would not form a fog. In contrast, vaporised candle wax, having a very low vapour pressure, would condense almost perfectly but would need a very high temperature to evaporate it in the first place. To some extent poor evaporation characteristics can be improved by spraying the agent to produce many small droplets with a very large overall surface area. However, materials possessing high boiling points and low vapour pressures tend to be viscous liquids (or solids) that are difficult to spray. In turn, this can be countered by pre-heating the agent. This reduces its viscosity and reduces the time taken to heat the spray droplets to a temperature where they will evaporate. On balance, materials with high boiling points and low vapour pressures are desirable. These should produce good visibility at low concentrations and have low odour.

Some agents, such as kerosene and diesel, are not pure compounds and therefore boil over a wide range of temperatures. For example, kerosene first boils at about 150°C (its 'initial boiling point') at which point the most volatile material is being evolved. As the temperature is increased, progressively less volatile material boils off until finally, at about 300°C (its 'final boiling point'), even the least volatile components have been boiled off. The wide boiling range means that some (possible small) fraction of the agent will have optimum properties to match a similar range of plume temperatures so that the agent will always produce some visibility. On the other hand, much of the agent may produce little or no smoke and the overall efficiency of smoke production will be low.

Other agents which are pure compounds (such as water and glycerol) boil at a single characteristic temperature (the 'boiling point'). Although this presents a problem of matching the agent properties to the plume properties, the effectiveness of the agent will be very high provided a reasonable match can be achieved.

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[18] Number density is the number of particles divided by the volume they occupy.

In the context of the present requirements:

- Water has a low viscosity, a low boiling point and a high vapour pressure so it is easy to spray and evaporates easily. However, at ambient temperatures above 0ºC, it only re-condenses to a limited extent and then only in very high concentrations.
- Similarly, kerosene has low viscosity and a relatively low initial boiling point of approximately 140ºC. However, it also contains a proportion of less volatile material which, when there is a high concentration of kerosene in the plume, will condense to form a fog. Nevertheless a large proportion will not condense and, as the plume becomes diluted with ambient air, even the initially condensed material will re-evaporate. As a result, kerosene is likely to be an inefficient fog making agent.
- In contrast, diesel fuel is relatively non-volatile with an initial boiling point in the region of 190ºC and a final boiling point in excess of 350ºC. Provided it can be evaporated, a large proportion will condense. Although its viscosity at one to four centistokes is higher than that of water and kerosene, it is well within the sprayable range.
- Vegetable oil (rapeseed) has a very high boiling point in the region of 400ºC. Consistent with this, the vapour pressure is very low and excellent condensation and smoke-forming properties would be expected. However, the viscosity is higher than the generally acceptable viscosity limit of 12 centistokes for spraying and it is clear that effective evaporation would be difficult in an exhaust plume at 200ºC.
- Glycerol[19] boils at 290ºC but has an appreciable vapour pressure even at 200ºC. Condensation in the cooled plume should be practically perfect and it is reputed to produce an intense white smoke on condensation. Because of its very high viscosity, it is not sprayable in its pure form. However, a 50/50 solution in water has a viscosity of six centistokes, which is well within the sprayable range and has the advantage of producing very small droplets with a very large surface area. Smoke production performance may be marginal at 200ºC but should be excellent at higher temperatures.
- Although ethylene glycol boils at 207ºC, and therefore should vaporise easily, more than 99% should have re-condensed in a plume cooled to 50ºC. In its pure state, its viscosity (19.8 centistokes at 20ºC) may be too high to spray even with an air-blast atomiser. However, its viscosity may well be within the sprayable range if it can be moderately pre-heated in the supply pipework leading to the atomiser. If this is not possible, dilution with a small percentage of water will be needed.
- Shell Ondina oil (theatrical smoke oil) boils at or above 350ºC and is clearly formulated to condense very efficiently following evaporation in contact with a high temperature surface or gas. However, its evaporation characteristics in a plume at only 200ºC may be marginal and good atomisation and the creation of large surface area for good heat transfer may be critical. At room temperature its viscosity of 15 centistokes is probably too high for effective spraying. As with ethylene glycol, however, even modest pre-heating in the atomiser supply pipework would probably bring it into the sprayable range.

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[19] Glycerol is environmentally benign. In fact, glycerol is widely used in food products, and is water-soluble so it can be washed away with ease. It is not considered harmful although it attracts the EC Risk and Safety Phrases S23 and S24/25, "Do not breathe vapour" and "Avoid contact with skin and eyes". However, this warning is typical of otherwise benign hygroscopic liquids and dusts such as glucose and sucrose, which, in massive doses, upset the body's isotonic balance. LD_{50}s for such materials are in the > kilogramme range. In terms of its ecotoxicological effects, its LC_{50} for fish is high, and it is classed as a non-hazardous material for air, sea and road transport by IATA, IMDG and RID/ADR respectively.

Significant properties of the various agents are shown in Table B1.

Table B1 Significant properties of the agents

Agent	Boiling Point (C)		Vapour Pressure at 20°C (mb)	Kinematic Viscosity at 20°C (cSt)	Flash Point (C)	Auto-ignition Temperature at 1013 mb (C)	Toxicity	Cost
	Initial	Final						
Water	100	-	0.14	1.0	-	-	nil	-
Kerosene	140	300	7.2	1.0 to 2.5	~40	~250	moderate	£0.15/litre
Diesel	~190	>350	0.24	1.0 to 4.0	~61	~250	moderate to high	£0.15/litre
Vegetable oil	~400	?	?	160	288	?	nil	£0.936/litre
Glycerol	290	-	<0.1	6.0 (50/50 in water)	~160	393	nil	£2.02/litre
Theatrical smoke oil	>350	?	< 1.0	15 at 40°C	175	>250	nil	£3.15/litre
Ethylene glycol	207	-	0.13	19.8	96	?	moderate	£1.44/litre

'?' Indicates where no value is available

Appendix C Diesel Environmental Impact Study

Diesel was the most successful smoke producing agent (except at very low flow rates where glycerol/water and smoke oil were superior due to their lower vapour pressures), and is readily available on offshore platforms. Concerns were expressed, however, regarding the environmental acceptability of diesel, and an environmental screening study was consequently undertaken.

C.1 Study Methodology

The scope of work and the associated methodology used for the study comprised:

1. **Pre-screening of diesel and diesel exhaust data** achieved by collection and evaluation of the following information:
   - Physico chemical properties to: (a) predict diesel's stability with temperature and nebulisation; (b) identify possible by-products formed during usage; and (c) to provide basic data needed for atmospheric emissions modelling.
   - Health and safety properties with regard to human exposure by skin contact, inhalation or ingestion of diesel droplets that may be in the air or on the structure of the installation.
   - Solubility, oil/water partitioning, aquatic toxicity (LC_{50} from standard toxicity tests), biodegradability/ready degradability properties to assess the environmental fate of diesel.
   - Applicable air and environmental quality standards for diesel.
   - Composition, concentrations and volumes of the exhaust emissions from gas turbines used for power generation on offshore structures, and investigation of the possibility of synergistic effects.
2. **Atmospheric emissions modelling** to predict the short-term dilution and dispersion pattern (concentration at varying distances from the release point) of diesel under: (a) operational rates of usage, and (b) the range of meteorological conditions that occur at a 'typical installation' on the UK Continental Shelf. The study models the gas turbine exhaust plume from a fixed offshore production platform where the accommodation, processing, other working areas and gas turbine exhaust ports are located on a single topsides supported by a steel jacket.
3. **Assessment of the fate of diesel** using a classical approach based on the "hazard – receptor" pathway (human exposure, effects on the installation and the marine environment).

C.2 Technical Background

Smokes (obscurants) are anthropogenic or naturally occurring particles suspended in the air that block or weaken the transmission of a particular part or parts of the electromagnetic spectrum, such as visible and infrared radiation or microwave. Smoke, in particular, is an obscurant normally produced by burning or vaporising some product.

Diesel fuel smoke is formed by injecting diesel fuel into the exhaust duct of a gas turbine where it is vaporised and expelled with the turbine's exhaust. Upon dilution and cooling to the ambient temperature the fuel condenses into a dense white smoke. The effectiveness of the smoke generated depends on its ability to enhance visibility of the hot gas exhaust plumes (by reflecting, refracting, and scattering light), and it is for this reason that the smoke consists of aerosols with particle dimensions approximating the wavelength of visible to near-infrared light. The relationship between smoke concentration and visibility for diesel fuel is summarised in Table C1.

Table C1 Correlation between visibility and smoke concentration for diesel fuel (Eaton and Young, 1989, adapted)

Smoke	**Visibility (m)**	**Concentration (mg/m^3)**
Diesel Fuel Smoke	10	39
	50	7.9
	200	2.0

Visibility is defined as the path length for a 10% transmission at the concentration determined by the Beer-Lambert law.

C.2.1 Physical and Chemical Properties of Diesel

In general terms the composition of diesel is a complex mixture of aliphatic and aromatic hydrocarbons obtained from the distillation of petroleum, over the carbon range C_9 – C_{28}. Diesels contain a mixture of straight chain alkanes (paraffins), branched chain alkanes, cycloalkanes (naphthenes), alkyl benzenes, alkyl naphthalenes, alkyl phenanthrenes and alkyl dibenzothiophenes. The largest single components are normally n-C_{14}, n-C_{15} and n-C_{16} alkanes.

Typical specifications for diesel used for smoke generation include boiling point, cetane number (a measurement of ignition quality), viscosity and flash point. A range of agents may also be added to road diesel, such as detergents, dispersants, cetane improvers, lubricity aids, corrosion inhibitors and antioxidants.

Diesel fuels are categorised as the middle distillates from crude oil and are denser than petrol. Reference values are given to diesel fuel depending on their application; EU type A is for vehicles, B for industries, and C for heating. In the USA the classification is as follows: No.1 distillate (DF1) (kerosene) and No.2 distillate (DF2) (diesel). Kerosene is not described as a diesel in the EU, but the other types are all 'middle distillates'. Generally diesel in the EU is defined by EN 590:1999. Table C2 defines the maximum and minimum values.

Table C2 Properties of diesel as defined by EN 590: 1999

Property	Unit	Limits	
		Minimum	**Maximum**
Cetane Number		51.0	-
Cetane Index		46.0	-
Density at 15°C	kg/m^3	820	845
Polycyclic Aromatic Hydrocarbons	% (*m/m*)	-	11
Sulphur Content	mg/kg	-	350
Flash Point	°C	Above 55	-
Carbon Residue (on 10% distillation residue)	% (*m/m*)	-	0.30
Ash Content	% (*m/m*)	-	0.01
Water Content	mg/kg	-	200
Total Contamination	mg/kg		24
Oxidation Stability	g/m^3	-	25
Viscosity at 40°C	mm^2/s	2.00	4.50
Boiling Point	°C	160	400
Distillation % (v/v) recovered at 250° % (v/v) recovered at 350°C 95% (v/v) recovered at	 % (*v/v*) % (*v/v*) °C	 85 	 <65 360

Diesel fuel smoke (technically a fog) is a condensation aerosol, consisting of a suspension of 0.5 to 1 µm fuel droplets in air. The droplets are individually translucent but opaque en masse. Particles in this range are respirable. The generation of the condensation aerosol is for the purpose of making the hot plume visible; if conditions were such that a major proportion of the fuel remained in the vapour form, the system would not achieve its purpose. However, a fraction of the fuel (components with low boiling points) might remain in the vapour form. Combusted fuel might also contribute to the total mass of the smoke, but Callahan *et al*. [C1], found that in vehicles at least, the exhaust contributes only 1% to 2% of the total hydrocarbon concentration of the smoke. All measurements of and recommendations for diesel fuel smoke concentrations are reported as milligrams of total particulates per cubic meter.

C.2.2 **Toxicokinetics**

In contrast to the amount of literature dealing with the toxicological effects of diesel engine exhaust, no toxicokinetic studies have been conducted with diesel fuel smoke. However, there is some evidence with respect to deposition and clearance patterns of diesel smoke [C2], [C3], and [C4]. In these studies, details of which will be discussed in Sections C.2.3 and C.2.4, the lung was the primary target organ, with several indicators of an inflammatory response. The material appears to deposit and accumulate in the lung, remaining there long enough to induce an inflammatory response. Within a two-week period, neutrophil levels are back to control levels, suggesting that most of the particles are cleared. However, the macrophage levels were still elevated after that time period, indicating that some inhaled particles might still be in the lung. Dalbey *et al* [C2] and [C3], and Dalbey and Lock [C5] made use of dodecachlorobiphenyl as a dosimetric tracer for aerosols of diesel fuel [C6]. The fraction of inhaled diesel fuel aerosols retained at the end of exposure was 4% to 8%.

C.2.3 Effects in Humans

As stated in Section C.2.2, very little information is available on the health effects of uncombusted diesel fuel smoke in humans. Volunteers who were exposed to concentrations of 170 and 330 mg/m^3 for ten minutes reported no irritant effects [C7]. No other studies involving inhalation exposure of humans have been reported.

Repeated exposure to diesel fuel was reported to cause contact dermatitis in sensitive individuals [C8], but inadequate personal hygiene was indicated as a contributing factor. The literature regarding gastritis from ingested diesel fuel and pneumonia from aspiration of diesel fuels has also been reviewed [C9].

More recent studies on the effects of diesel fuel in humans have identified other conditions, such as olfactory fatigue [C10], acne and folliculitis [C11], hyperkeratosis [C12], abdominal cramps, nausea, vomiting, acute renal failure with anaemia and thrombocytopenia [C13], eye irritation, coordination and concentration difficulties, and fatigue [C14]. Limited research has also suggested an increased risk of developing lung carcinoma and prostatic cancer [C15].

C.2.4 Related Studies

Non-human studies have observed severe toxic signs that have included weight loss, anorexia, and severe dermal irritation, as well as congested kidneys and livers. Commercial diesel fuel did not induce eye irritation or skin sensitisation during a 30-second application [C16]. However, the fuel was extremely irritating to the skin when applied for 24 hr.

The US diesel fuel, DF2 was found to be positive when tested as a tumour promoter in the SENCAR mouse-skin tumorigenesis bioassay but was negative as a complete carcinogen in the same assay [C17].

Two major sets of studies on the toxicity of inhaled diesel fuel smokes have been produced; one was conducted at Aberdeen Proving Ground [C1] [C18] and one at Oak Ridge National Laboratory [C2] [C3] C4] [C5]. These studies were the result of the need for diesel fuel smoke exposure concentration data, as this kind of smoke is used by the military as an obscurant [C19]. The studies cover both one-time and repeated exposures for up to 13 weeks.

In the early stages of continuous exposure, lethargy was observed with increased toxic effects as exposure time was increased. Intermittent exposure caused some hyperactivity, but no acute exposure-related illness was observed.

C.2.5 Existing Recommended Exposure Limits

Exposure limits have not been derived for diesel fuel smoke or its components. The ACGIH TLV-TWA value of 350 mg/m^3 for diesel fuel refers to total hydrocarbons as vapour, not as an aerosol of the total fuel [C20]. Given this limitation and in order to evaluate the risk of human exposure during the modelling study (Section C.3), it was necessary to apply the nearest equivalent occupational exposure limits. These standards are for mineral oil mist, as detailed in Section C.3.6.

C.3 Atmospheric Emission Modelling

C.3.1 Description of Method

Atmospheric dispersion modelling is used to predict how pollutants are dispersed in the atmosphere from different pollution sources, taking into account the effects of local buildings, topography, meteorology and a number of other factors. In general, all models require two types of data:

- Information about the source being modelled, including location, pollutant emission rate, exit velocity and temperature.
- Information about the dispersing characteristics of the meteorology surrounding the source, including wind speed and direction, and atmospheric stability.

Dispersion models use this information to mathematically simulate the dispersion of the atmospheric emission in order to derive estimates of concentration at specified locations. Some models even simulate the chemical transformations and removal processes that can occur in the atmosphere.

The study presented here was undertaken using the atmospheric dispersion model ADMS 3 (version 3.1) [C21] which is a state-of-the-art Gaussian plume dispersion model [C22] used widely in the UK by industry, consultancy, local authorities and regulators such as the Scottish Environment Protection Agency (SEPA) and the Environment Agency (EA).

C.3.2 Model Set-Up

Emissions were considered from one principal source, namely a gas turbine stack located on an offshore platform. A review of offshore platform structures based on previous projects provided information on the typical geometry of a platform in the central North Sea. The geometry used in the modelling study is presented in Table C3 and a plan of a typical offshore platform used in the modelling study is given in Figure C1.

Table C3 Geometry of surface features used in the modelling study

Input parameters	Offshore Platform	Rig Buildings
Area (m^2)	76 × 52 = 3,952	50.7 × 34.7 = 1,759
Height above sea level (m)	24	50

The modelling exercise was carried out in order to determine the maximum impact of the emissions of diesel vapour in a range of meteorological conditions and, in particular, the concentrations predicted to occur at the nearest receptor. In this case the nearest receptor is the platform, where there is a risk of human exposure to the emissions.

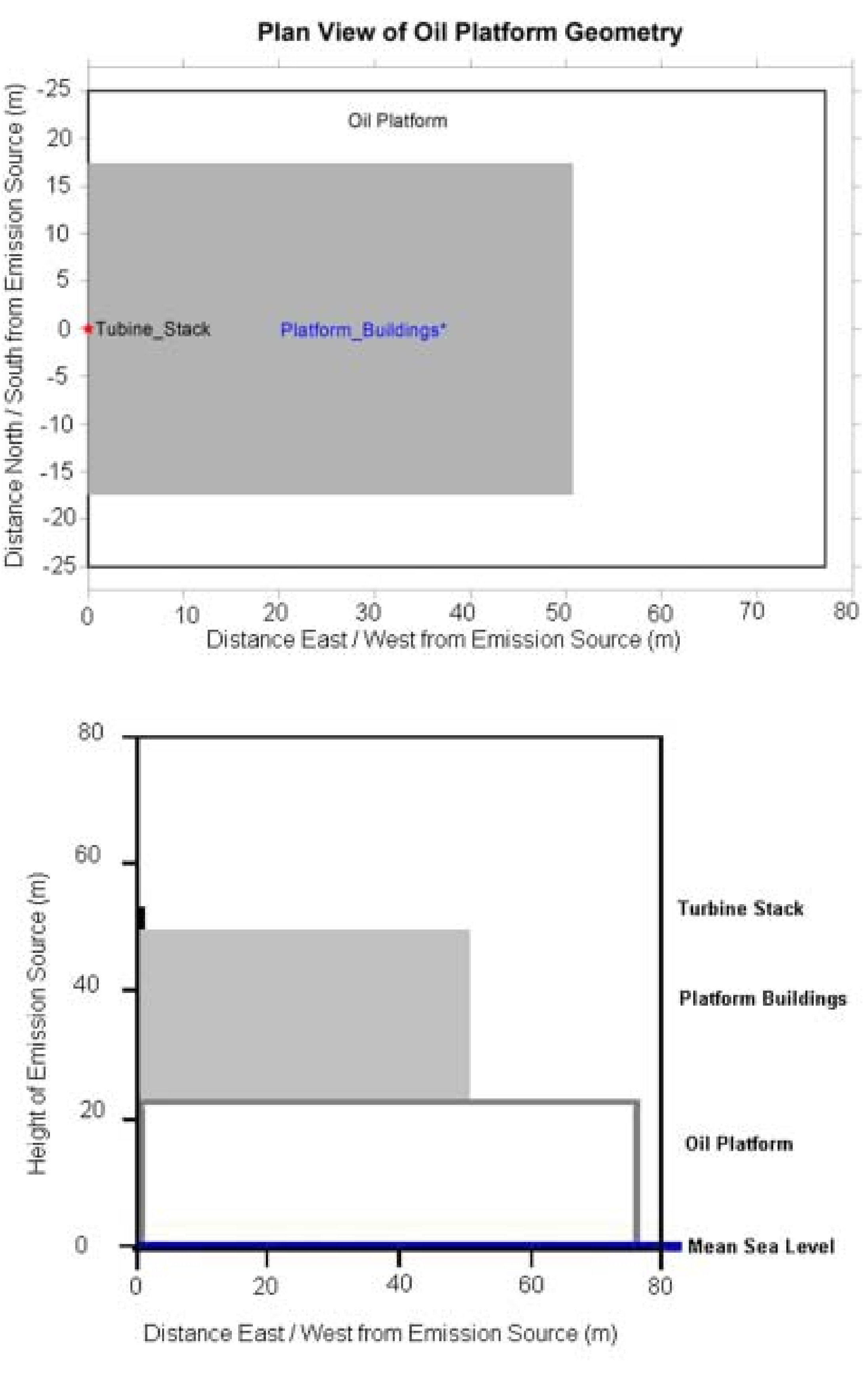

Figure C1 Plan and elevation view of offshore platform geometry

C.3.3 Emissions and Source data

Information about emissions from the gas turbine stack was provided from the feasibility study (Section 3 of the main report). The aim of this study was to determine the type of plume with the greatest visibility, with the intention of using short release plumes of 30 minutes duration to aid offshore helicopter landing safety. A review of the topography and emission sources was conducted for typical North Sea platforms based on previous studies.

Two approaches were considered for modelling a 30-minute plume release, which included a continuous release, and a 30-minute duration ‘puff’. When using ADMS 3 it is not possible to model a puff and platform topsides effects simultaneously. This means that the building downwash and containment effects would not affect the modelling of a plume in the form of a short-lived puff and its subsequent dispersion. For this reason, and to ensure a realistic representation of the fate of the plume on and around the platform, a continuous plume was modelled instead and averaged for a 15-minute period for each one-hour meteorological dataset. This gives the expected diesel concentration for each meteorological scenario for the given emission rate. A 15-minute averaging period was chosen in order that the concentrations could be compared with the 15-minute HSE Short Term Exposure Limit (STEL).

The model calculations were based on a 41 x 41 point grid encompassing 1 km^2, making each grid square 625 m^2. The model was set up to calculate the dry deposition rate of the vapour (µg/m^2/s) and the atmospheric concentrations (µg/m^3) at an offshore platform height for each grid square.

In Section 4.4.2 of the main report the worst-case scenario environmentally, and the best plume visibility, was exhibited at a diesel vapour emission rate of 261.5 g/s. The diesel plume was therefore modelled as a continuous release of nebulised oil droplets with an emission rate of 261.5 g/s.

Two wind directions were used in the model: southwest and west. The west wind represents the maximum potential for human exposure with the plume blowing across the platform before dispersing out at sea, and south west is the prevailing wind direction for the North Sea. Details of the emission source are given in Table C4.

Table C4 Parameters of the emission source used in the modelling study

Input Parameters	Gas Turbine Stack
Diameter (m)	2.5
Height above sea level (m)	54
Exit Velocity (m/s)	23
Average Temperature (^{o}C)	200
Diesel injection rate (g/s)	261.5
Droplet Size (µm)	1
Droplet Density (Kg/m^3)	844

C.3.4 Meteorology

When carrying out air quality impact assessments of emissions, a number of operating scenarios are considered to simulate real-life conditions. It would be uneconomical to undertake detailed dispersion modelling calculations for each option, so it is common practice to undertake screening assessments of a range of options or worst-case scenarios using a standard range of meteorological conditions that are common for the UK climate.

The seven meteorological conditions range from very convective, i.e. lots of atmospheric turbulence, through to very stable, i.e. very still conditions often associated with a temperature inversion and little or no atmospheric turbulence. These roughly correspond to the old Pasquill Stability Categories A-G that were used prior to the development of 'new generation' dispersion models such as ADMS 3.

Wind speed and direction have a major influence on the trajectory of a plume or release of pollution but, fundamentally, it is atmospheric turbulence that determines how the plume is spread and where the maximum impact occurs at ground level.

The seven meteorological conditions are listed in Table C5, and include the following parameters:

- wind speed (m/s);
- surface heat flux (balance between incoming and outgoing solar radiation in W/m^2);
- atmospheric boundary layer height (m).

These are the minimum parameters required by ADMS 3 in order to characterise the dispersion climate in the vicinity of the source.

There are three stability D conditions with different wind speeds in the range 5–15 m/s (D1–D3), in order to reflect the higher wind speeds in neutral conditions which are commonly found over the North Sea.

Table C5 Summary of meteorological parameters used in the modelling study

Wind Speed (m/s)	Net Solar Heat Flux (W/m^2)	Boundary Layer Height (m)	Approximate Pasquill Stability Equivalent
1	113	1300	A
2	84	900	B
5	74	850	C
5	0	800	D_1
10	0	800	D_2
15	0	800	D_3
3	-10	400	E
2	-6	100	F
1	-0.6	100	G

C.3.5 Atmospheric Emission Modelling Results

The screening analysis provided data on the maximum predicted downwind concentration of diesel vapour for a range of meteorological conditions, as well as the predicted concentration at platform level.

C.3.5.1 Model Results for West Wind

The results of the model for the west wind, shown in Table C6, show the maximum predicted 15-minute concentration of diesel vapour at platform height considering all nine meteorological stabilities. The maximum predicted deposition rates of diesel vapour at platform height considering all nine meteorological stabilities are displayed in Table C7.

Table C6 Maximum 15-minute mean atmospheric concentrations for a continuous diesel plume for a west wind

Stability	Maximum Predicted Concentration on Rig ($\mu g/m^3$)	Maximum Predicted Downwind Concentration ($\mu g/m^3$)	Location of Maximum Predicted Downwind Concentration (distance in m east and north of the source)	
A	1073	640	250 m east	0 m north
B	1152	619	375 m east	0 m north
C	2022	1041	300 m east	0 m north
D1	1545	2201	200 m east	0 m north
D2	2684	2341	175 m east	0 m north
D3	3683	2326	150 m east	0 m north
E	684	809	350 m east	0 m north
F	184	16	100 m east	0 m north
G	154	44	1000 m east	0 m north

Table C7 Maximum 15-minute mean dry deposition rates for a continuous diesel plume for a west wind

Stability	Maximum Predicted Deposition on Rig ($\mu g/m^2/s$)	Maximum Predicted Downwind Deposition ($\mu g/m^2/s$)	Location of Maximum Predicted Downwind Deposition (distance in m east and north of the source)	
A	177	106	250 m east	0 m north
B	251	135	375 m east	0 m north
C	883	455	300 m east	0 m north
D1	657	936	200 m east	0 m north
D2	2226	1941	175 m east	0 m north
D3	4494	2838	150 m east	0 m north
E	173	204	350 m east	0 m north
F	30	3	100 m east	0 m north
G	13	4	1000 m east	0 m north

Figure C2 shows that, for all meteorological stabilities, the diesel plume is entrained within the wake caused by the topography of the platform, resulting in the maximum diesel vapour concentration occurring on the platform and forming the first downwind peak concentration. The fraction of the plume which is unaffected by the turbulence that the platform creates forms a second peak in diesel vapour concentration downwind where it rejoins the turbulent flow. The second peak occurs between 170 and 400 m downwind of the gas turbine for stability conditions A–E and at about 1000 m downwind for stability conditions F and G.

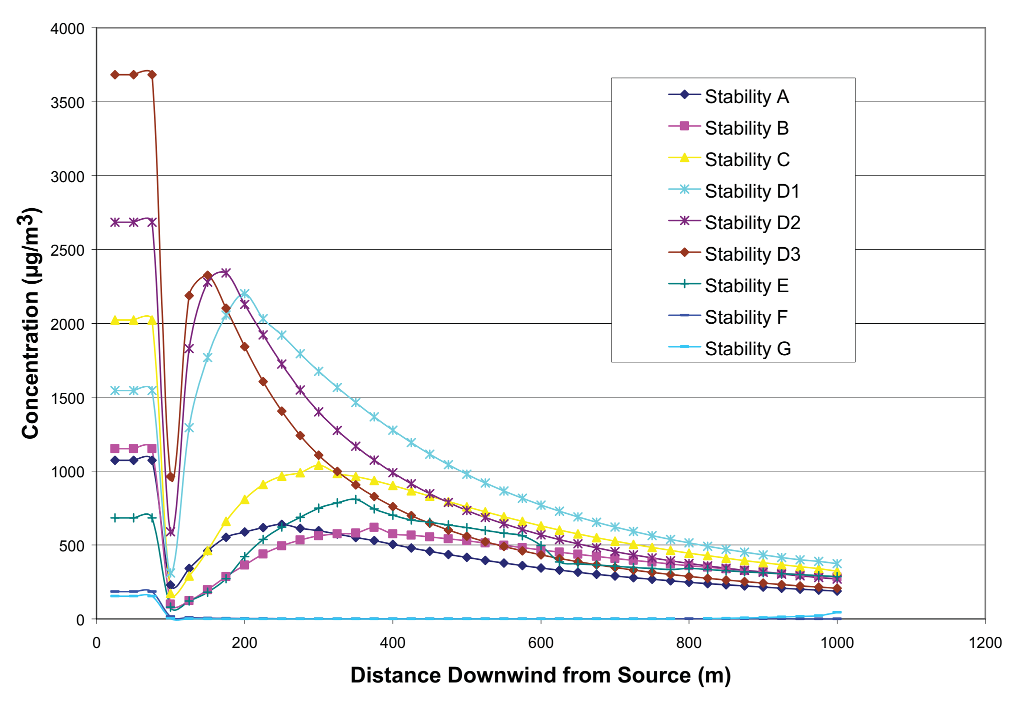

Figure C2 15-minute mean diesel vapour concentrations for a west wind

Figure C3 shows that the areas affected by atmospheric pollution from the diesel plume are confined to the east of the platform and depict the worst-case scenario occurring during stability D3. The maximum diesel vapour concentration of 3,683 μg/m^3 occurs at 75 m east of the gas turbine exhaust stack. This location is on the eastern edge of the platform. For all stabilities except stability G the maximum diesel vapour concentration off the platform occurs between 100 and 375 m east of the emission source.

Figure C4 shows the worst-case scenario of diesel vapour deposition for stability D3. The plan indicates that the maximum dry deposition of diesel vapour occurs close to the platform for a west wind. The greatest deposition occurs on the east edge of the platform with a deposition rate of 4,494 μg/m^2/s at a distance of 75 m east from the gas turbine exhaust stack. For all stabilities except stability G, the peak deposition rate off the platform occurs between 100 m and 375 m east of the emission source.

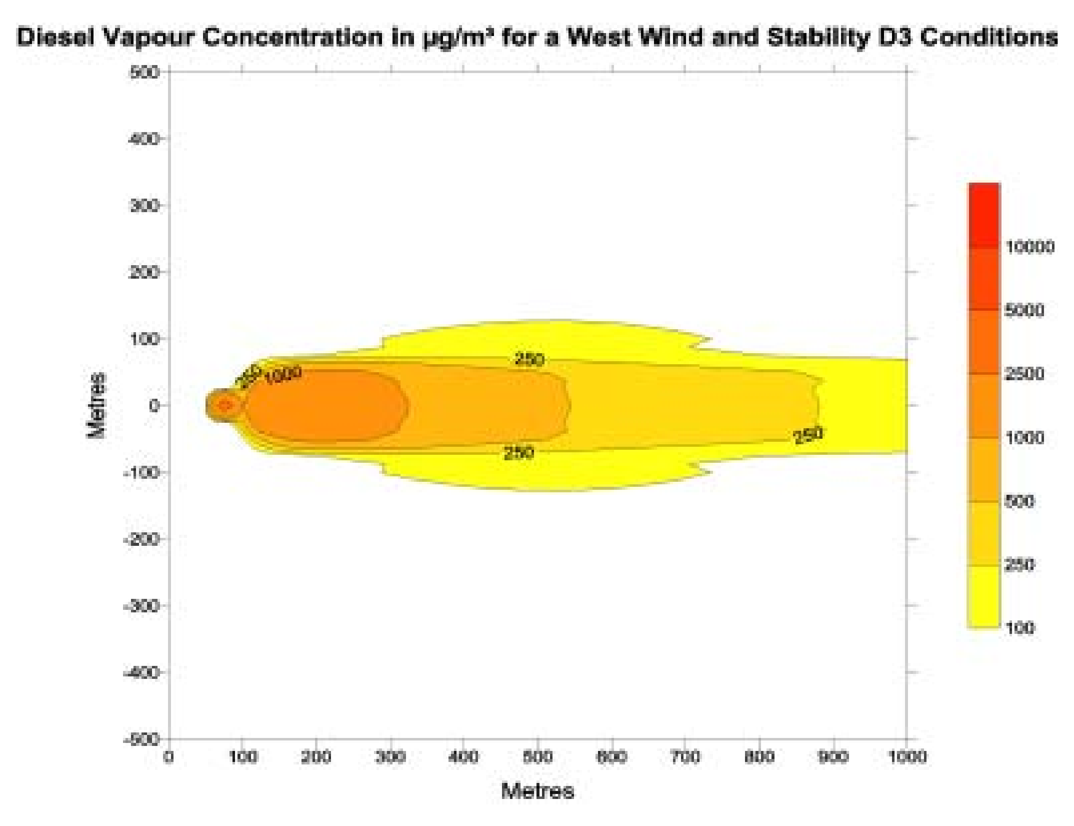

Figure C3 Maximum 15-minute mean vapour concentration for a west wind

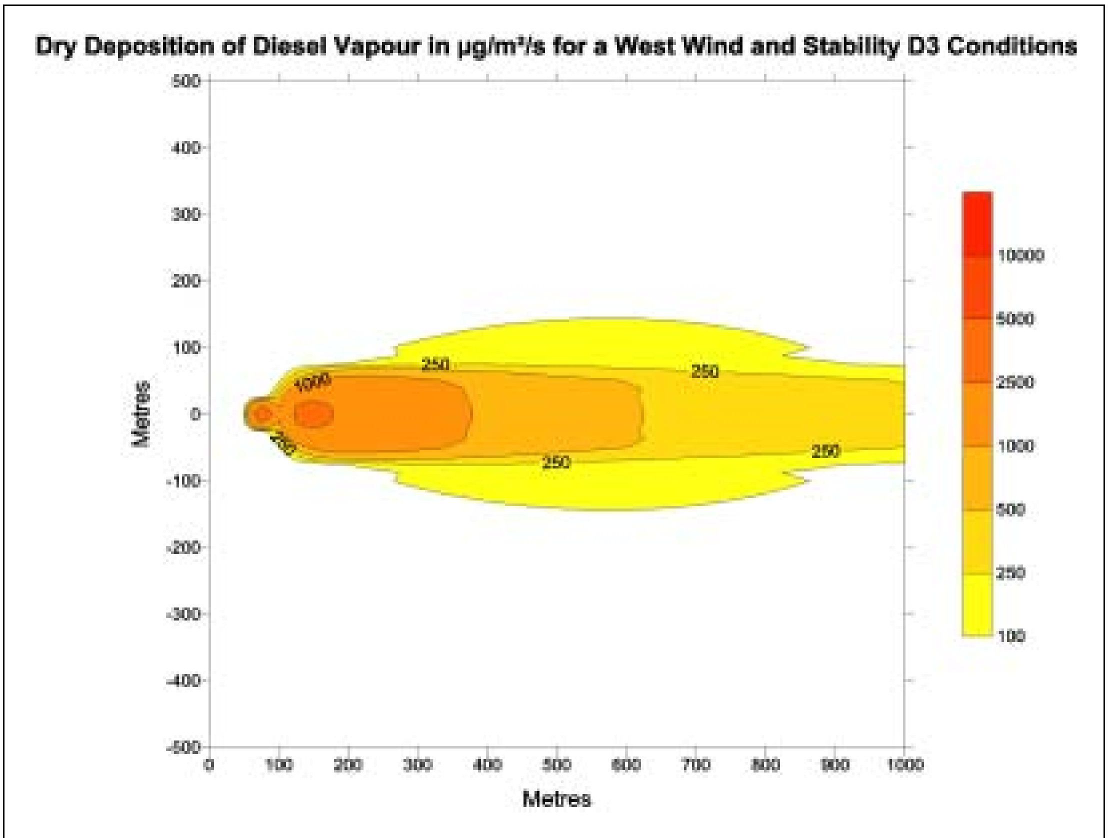

Figure C4 Maximum 15-minute mean dry deposition rate for a west wind

C.3.5.2 Model Results for Southwest Wind

The results of the model for the southwest wind, shown in Table C8, show the maximum predicted 15-minute concentration of diesel vapour at platform height considering all nine meteorological stabilities. The maximum predicted deposition rates of diesel vapour at platform height considering all nine meteorological stabilities are displayed in Table C9.

Table C8 Maximum 15-minute mean atmospheric concentrations for a continuous diesel plume for a southwest wind

Stability	Maximum Predicted Concentration on Rig ($\mu g/m^3$)	Maximum Predicted Downwind Concentration ($\mu g/m^3$)	Location of Maximum Predicted Downwind Concentration (distance in m east and north of the source)	
A	1028	1028	75 m east	50 m north
B	1024	1024	75 m east	50 m north
C	2121	2260	125 m east	125 m north
D1	1643	4188	100 m east	100 m north
D2	3146	7702	75 m east	75 m north
D3	4400	10682	75 m east	75 m north
E	632	1816	125 m east	125 m north
F	153	153	75 m east	50 m north
G	111	111	75 m east	50 m north

Table C9 Maximum 15-minute mean dry deposition rates for a continuous diesel plume for a southwest wind

Stability	Maximum Predicted Deposition on Rig ($\mu g/m^2/s$)	Maximum Predicted Downwind Deposition ($\mu g/m^2/s$)	Location of Maximum Predicted Downwind Deposition (distance in m east and north of the source)	
A	170	170	75 m east	50 m north
B	223	223	75 m east	50 m north
C	926	987	125 m east	125 m north
D1	699	1781	100 m east	100 m north
D2	2609	6389	75 m east	75 m north
D3	5368	13033	75 m east	75 m north
E	159	458	125 m east	125 m north
F	25	25	75 m east	50 m north
G	9	9	75 m east	50 m north

Figure C5 shows that for all meteorological stabilities there is a significantly increased turbulence effect due to the platform topography for a southwest wind. The atmospheric concentrations of diesel vapour in the immediate vicinity of the platform are uniform for each stability category. This represents the portion of the plume entrained in the building wake region. The maximum diesel vapour concentrations off the platform occur between 100 and 350 m of the emission source where the plume entrained by the buildings and the plume bypassing the platform come together.

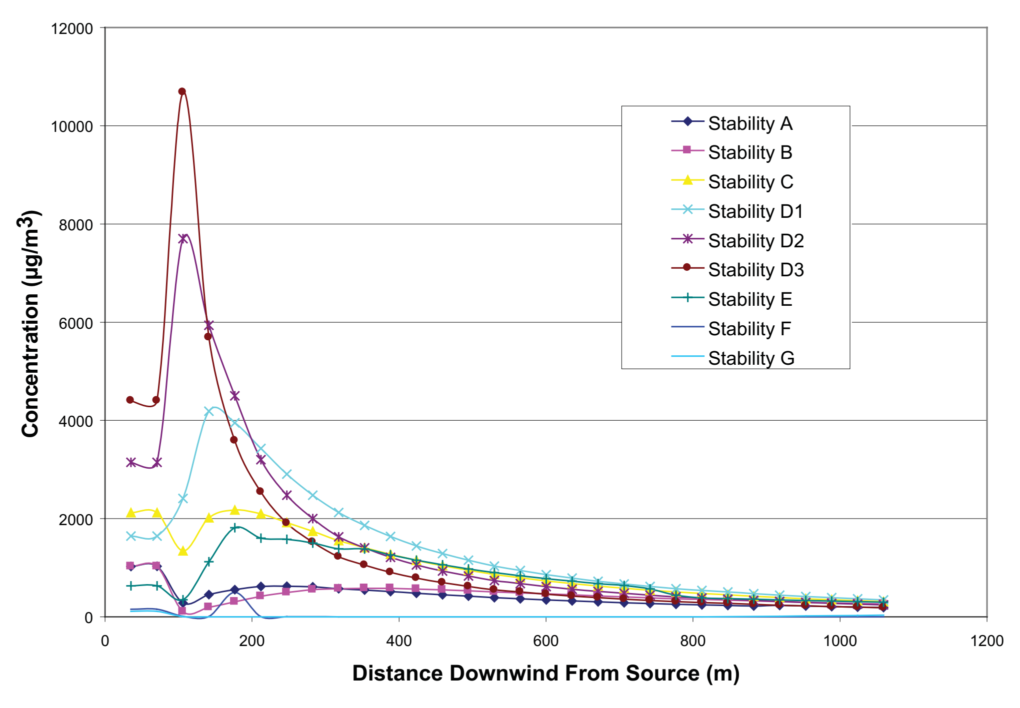

Figure C5 15-minute mean diesel vapour concentrations for a southwest wind

Figure C6 indicates the dispersion of the diesel plume at platform level for the worst-case scenario represented by stability D3 for a southwest wind. The concentrations of diesel vapour are significantly greater than those exhibited for a west wind. The maximum concentration of diesel vapour is 10,682 µg/m^3, located 75 m east and 75 m north of the emission source. This maximum diesel vapour concentration therefore occurs off the northeast edge of the platform. For all stabilities, the peak concentration occurs between 25 and 200 m north east of the gas turbine exhaust stack. For stabilities F and G, the maximum-modelled concentration is reported in several grid squares ranging from 25 m south to 50 m north, and from 25 to 75 m east of the emission source. Therefore, the peak concentration is evident over a wider area and occurs both on and off the platform for these stability conditions. This is due to the entrained fraction maintained at ground level due to the lower turbulence associated with these two stability conditions.

Figure C7 shows the dry deposition rate of diesel vapour droplets for a southwest wind for the worst case of stability D3. The peak deposition rate of 13,033 µg/m^2/s is found 75 m east and 75 m north of the emission source. For all stabilities the peak deposition rate occurs between 25 and 125 m north and east of the gas turbine exhaust stack. The peak dry deposition rate of diesel vapour droplets occurs in the same region as the peak atmospheric diesel vapour concentration.

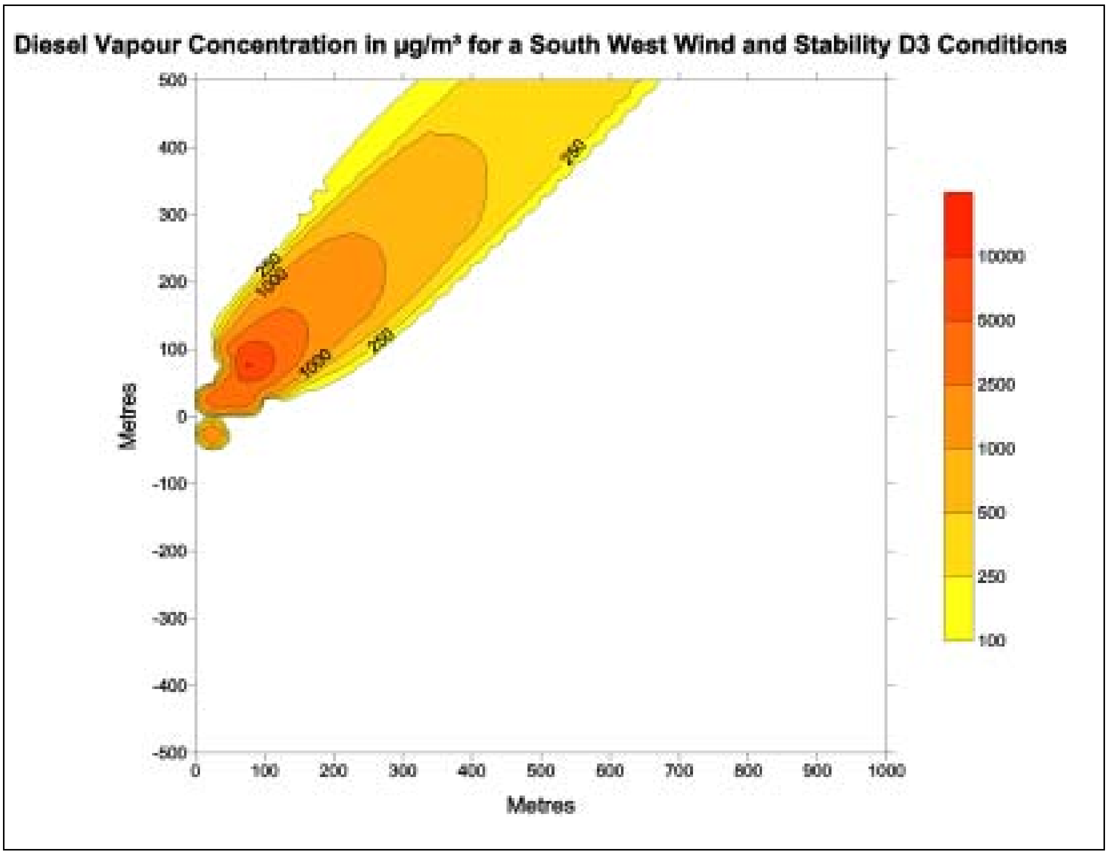

Figure C6 Maximum 15-minute mean diesel concentration for a southwest wind

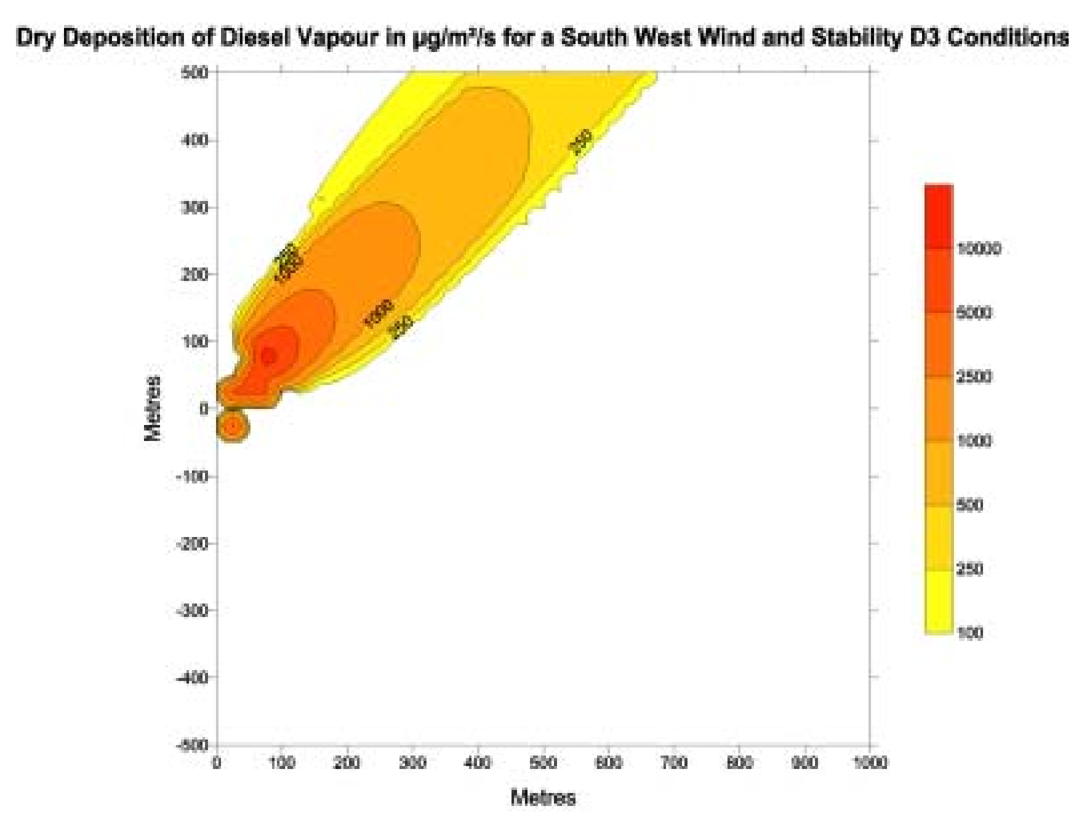

Figure C7 Maximum 15-minute mean dry deposition rate for diesel vapour for a southwest wind

C.3.6 Air Dispersion Modelling Conclusions

Current standards for exposure limits for mineral oil mist, excluding metalworking fluids, are provided in the HSE guidance EH40/2000 [C23], and the EH40/2002 Occupational Exposure Limits supplement 2003 [C24]. There are two current UK OELs applying to refined oil mists which do not include used engine oils or metalworking fluids:

- 5 mg/m^3 (5,000 µg/m^3) Long-Term Exposure Limit (LTEL) based on an 8-hour TWA reference period; and
- 10 mg/m^3 (10,000 µg/m^3) STEL based on a 15-minute reference period.

The risk of human exposure is on the platform and therefore the maximum predicted concentration on the platform can be compared directly to the 15-minute STEL.

For a west wind the peak diesel vapour concentration occurs on the platform for all stabilities except stabilities D1 and E. For a west wind the maximum diesel vapour concentration on and off the platform is below both the 5,000 µg/m^3 LTEL and the 10,000 µg/m^3 STEL for all stability conditions modelled.

For a southwest wind, the maximum diesel vapour concentration occurs on the platform for all stabilities except stabilities D1, D2 and D3. For a southwest wind, the maximum diesel vapour concentration on the platform is below both the 5,000 µg/m^3 LTEL and the 10,000 µg/m^3 STEL for all stability conditions modelled. The maximum diesel vapour concentrations off the rig for stabilities D2 and D3 are above the 5,000 µg/m^3 LTEL and the concentration for stability D3 is above the 10,000 µg/m^3 STEL. The areas of exceedance of the OELs, predicted to occur for stability D2 and D3 conditions, are located within 50 m of the edge of the platform.

Due to the symmetrical nature of the platform geometry and the emission source configuration assumed in this study, the exceedances predicted for a southwest wind would be reciprocated for a northwest wind with the plume extending away from the platform in a southeasterly direction.

Initial analysis of wind rose data for offshore platforms in the North Sea suggests that strong southwest winds are most frequent. This represents the worst-case scenario for oil vapour concentration. Northwest winds are also frequent in certain areas of the North Sea, which are likely to create exceedances in diesel vapour concentration close to the platform.

C.4 Discussion

C.4.1 Primary Effects

C.4.1.1 Occupational Considerations

A number of potential impacts could be associated with the use of diesel fuel as a smoke generating agent. Section C.2.3 reviews detrimental effects of diesel fuel upon inhalation and dermal contact. In addition to these, the odour threshold for diesel fuels ranges between 0.5 and 0.7 ppm and in the near vicinity of the diesel injection points this threshold could potentially be exceeded and, depending on the final concentration, cause irritation or exacerbate the effects of smoke inhalation. However, entrainment of emissions into the accommodation HVAC systems is unlikely and therefore such health implications would be minimal. It should be noted that designs of topsides account for, and have prevention mechanisms to ensure that ingestion of emissions does not occur. It is also possible that visibility may be affected to some extent, and this might present an additional safety hazard. However, it should be noted that the objective is to provide smoke just dense enough for the helicopter pilot's awareness of the location, rather than obscure visibility to a hazardous degree.

C.4.2 Secondary Effects

C.4.2.1 Operational Considerations

In theory, it would be possible to isolate personnel from the vicinity of the diesel fuel smoke for the duration of the helicopter landings and take-offs. However, in practice this is likely to cause unacceptable disruption to the normal working practices on the platform and associated vessels. Therefore, on the grounds of cost and production efficiency, it is anticipated that personnel would be exposed to diesel fuel smoke for approximately two hours weekly.

C.4.2.2 Effects on Platform Safety

The large temperature gradient between the expelled gas from the turbines and the surrounding atmosphere will inevitably lead to fairly rapid condensation of the nebulised diesel droplets. Though the rate and spread of deposition will depend on the prevailing weather conditions and platform topsides geometry, it is anticipated that a considerable proportion of the diesel fuel smoke may condense and adhere to work surfaces (platform structure, decking, ladders, tools and equipment). It has been calculated that for the worse case scenario (D3 stability in a southwest wind), the deposition of diesel vapour droplets on the rig will be approximately 5,368 $\mu g/m^2/sec$. Over a 30 min period at its location this amounts to approximately 9.67 g/m^2 of diesel, which is the equivalent to approximately 1.005 kg/m^2 per year if two 30 min sessions were completed each week (104 sessions). This could potentially lead to an increased risk of slippery surfaces and consequent personnel injury. Platform surfaces are designed with these risks in mind and therefore have integrated non-slip surfaces to protect against such occurrences, so it is unlikely that the increase in such risks will be significant. Increased contact with skin, via hand rails for example, could potentially induce dermatological irritation and thus pose further risk to health and safety.

C.4.2.3 Effects on Aquatic Organisms

Using the depositional rates from the modelling results it has been calculated that, on a worse case scenario basis, approximately 5.1 g/m^2 may be deposited at sea in a west wind scenario and approximately 23.46 g/m^2 may be deposited in a southwest wind scenario over a 30 minute period. Over a period of 12 months this would amount to approximately 0.530 kg/m^2 and 2.44 kg/m^2, respectively, if 104 sessions were conducted. For the worse case scenario, approximately 0.00244 tonnes will be deposited over $1m^2$ at sea. This is a comparatively large quantity considering it equates to 0.04% (over $1m^2$) of the diesel released into the UKCS in 2001, when a total of 5.97 tonnes was released into the marine environment [C25]. However, based on the modelling results, an area of hundreds of square metres will receive a deposition of diesel in varying concentrations. Such diesel fuel fall-out or condensation has the potential to form localised slicks on the sea surface, though it is anticipated that the mechanical action of waves and surf will prevent these from coalescing readily and form larger, spill-like films. Instead, the fuel will be physically mixed into the water column, forming small droplets that are carried and kept in suspension by the currents, but will not dissolve. The unresolved complex mixture (UCM) in diesel, which comprises structurally more complex molecules, is not readily biodegradable and therefore may remain in the environment for decades. It should be stressed that diesel is acutely toxic to water-column organisms, fish, invertebrates and seaweed, and any that come into direct contact with it may be killed. Exact toxicity values are strongly dependent on the fuel's composition. However, typical LC_{50} values are in the range of 1.0–2.6 mg/l for crustaceans, and 0.1–2.2 mg/l for fish

[C26, C27]. The risk to marine birds is also well documented, although the relatively fast evaporation and dispersion rate of the fuel renders this risk insignificant.

C.4.2.4 Legal Considerations

Until recently, under the Prevention of Oil Pollution Act 1971 (POPA), all releases of oil to the marine environment were to be reported to the DTI, unless subject to a specific exemption. However, the POPA has subsequently been replaced by the Offshore Petroleum Activities (Oil Pollution and Prevention and Control) Regulations 2005. The regulations are designed to encourage operators to continue to reduce the quantities of hydrocarbons discharged during the course of offshore operations and therefore, the release of diesel would be subject to stringent justification and any release should be as minimal as possible.

C.5 Conclusions

The present study has evaluated the occupational and environmental effects of using diesel fuel smoke as a means of improving hot plume visibility from gas turbine exhausts offshore. Parameters such as physicochemical properties of diesel, toxicity data on humans and animals, and air dispersion modelling of the possible spatial distribution of the smoke for a number of meteorological conditions for a typical offshore installation, have been examined.

Overall, the air dispersion modelling indicated that the maximum diesel vapour concentration on the platform would be below the relevant UK OELs (Section C.3.6) under the majority of atmospheric conditions. However, a worst-case scenario is predicted to occur for northwest or southwest winds for stability categories D1, D2 and D3, where the OEL would be exceeded in close proximity to the platform. There is the possibility, therefore, of a risk to personnel on the platform or on adjacent vessels (e.g. standby vessels) under these conditions.

Due to the proximity of areas of exceedance to the platform, it is recommended that a more detailed study of the atmospheric dispersion of the intended diesel plume is carried out to determine the full risk to human health. Detailed modelling should include more precise platform geometry, stack dimensions and location (Section C.3.2).

In addition to possible health risks, there are likely to be significant operational considerations. For example, there may be a requirement to disrupt normal working practices on the platform and associated vessels when diesel vapour is being released. In a worst-case scenario, deposition on the platform could potentially amount to 9.67g/m^2 in 30 minutes, which is the equivalent to 1.005kg/m^2 per year if there were two 30 minute sessions per week (104 sessions). Deposition of condensed diesel droplets on work surfaces may potentially create slippery conditions that could be hazardous, but the increased risk of this is generally thought to be minimal due to existing platform non-slip surface measures. Though not acutely detrimental when examining individual receptors (platform personnel, marine flora and fauna, safety issues with respect to slippery surfaces, etc), the confluence of these factors may render the use of diesel as a smoke generating chemical a rather problematic candidate, especially considering the potential quantity of fuel vapour droplets that would be released into the marine environment.

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MSDS of diesel fuel (various).

C.7 Glossary of Terms

Alveola	An air-cell of the lungs.
Beer-Lambert law	(Optics): law stating that the degree of absorption of light varies exponentially with the thickness of the layer of absorbing medium, its molar concentration and extinction coefficient.
Density	Ratio of the mass of a material to its volume.
Flash point	The lowest temperature at which a flame will propagate through the vapour of a combustible material to the liquid surface. It is determined by the vapour pressure of the liquid, since only when a sufficiently high vapour pressure concentration is reached, can it support combustion.
HSE	Health and Safety Executive
Lavage	A washing (med.), a cleansing of the stomach by means of emetics administered in large quantities of water.
LC_{50}	Lethal concentration that kills 50%
LD_{50}	Lethal dosage that kills 50%
LTEL	Long-Term Exposure Limit
Macrophages	Type of white blood cell (or leukocyte) found in all vertebrate animals, specialising in the removal of bacteria and other micro-organisms, or of cell debris after injury. They are found throughout the body, but mainly in the lymph and connective tissues, and especially the lungs where they ingest dust, fibres, and other inhaled particles.

Neutrophils	Type of white blood cell. Neutrophils are granulocytes that are filled with microscopic granules, i.e. little sacs containing enzymes that digest micro-organisms like bacteria.
OEL	Occupational Exposure Limit
PM	Particulate Matter
Refractive index	Measure of the refraction of a ray of light as it passes from one transparent medium to another.
STEL	Short-term Exposure Limit
TLV	Threshold Limit Value
Tumorigenic	Capable of causing tumours.
TWA	Time-Weighted Average
UCM	The chromatographic 'hump' that remains after an oil/fuel sample has been substantially biodegraded. UCMs are therefore relatively inert to biodegradation.
Viscosity	(Physics): the resistance of a fluid to flow, caused by its internal friction, which makes it resist flowing past a solid surface or other layers of the fluid. It applies to the motion of an object moving through a fluid as well as the motion of a fluid passing by an object.
%v/v	Percentage by volume
%w/w	Percentage by weight

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Appendix D Small-Scale Experiment Run Logs

Table D1 Run matrix for experiments 1 and 2

Experiment 1	Photo	Pump	T1	T2	Heat no.
50% sol	1	500	566	420	15
	2		534	355	14
	3		501	341	13
	4		463	317	11
	5		421	298	10
	6		370	270	10
	7		325	248	9
	8		290	224	8
Refresh glycerol and turn heat gun up to max. to clear out tube					
Experiment 2	**Photo**	**Pump**	**T1**	**T2**	**Heat no.**
50% sol	9	1000	560	339	15
	10		533	327	14
	11		483	310	13
	12		435	291	12
	13		407	272	11
	14		370	249	10
	15		320	228	9
	16		300	212	8

Table D2 Run matrix for experiments 3 and 4

Experiment 3	Photo	Pump	T1	T2	Heat no.
50% sol	17	750	550	360	15
	18		526	348	14
	19		482	329	13
	20		452	310	12
	21		445	301	11
	22		402	280	10
	23		369	261	9
	24		307	233	8
	25		246	198	7
Refresh glycerol and turn heat gun up to max. to clear out tube					
Experiment 4	**Photo**	**Pump**	**T1**	**T2**	**Heat no.**
50% sol	26	625	554	347	15
	27		527	337	14
	28		489	320	13
	29		446	300	12
	30		403	281	11
	31		366	261	10
	32		335	242	9
	33		291	218	8
	34		256	200	7
	35		209	178	6
	36		186	157	5

Table D3 Run matrix for experiment 5

Experiment 5	Photo	Pump	T1	T2	Heat no.
70% sol	37	500	549	370	15
	38		492	347	13
	39		452	327	12
	40		402	304	11
	41		365	284	10
	42		330	264	9
	43		299	242	8
	44		252	214	7
	45		227	191	6
	46		191	174	5
	47		144	137	4

Table D4 Run matrix for experiments 6 and 7

Experiment 6	Photo	Pump	T1	T2	Heat no.
80% sol	1	500	425	338	15
	2		400	333	14
	3		380	323	12
	4		350	305	10
	5		315	282	8
	6		265	254	6
	7		208	208	4
Refresh glycerol and turn heat gun up to max. to clear out tube					
Experiment 7	**Photo**	**Pump**	**T1**	**T2**	**Heat no.**
80% sol	8	1000	421	338	15
	9		375	311	13
	10		310	279	11
	11		260	245	9
	12		203	202	7
Refresh glycerol and turn heat gun up to max. to clear out tube					

Table D5 Run matrix for experiments 8 and 9

Experiment 8	**Photo**	**Pump**	**T1**	**T2**	**Heat no.**
80% sol	13	500	395	346	15
	14		347	325	13
	15		280	270	11
	16		260	259	10
	17		210	220	8
Refresh glycerol and turn heat gun up to max. to clear out tube					
Experiment 9	**Photo**	**Pump**	**T1**	**T2**	**Heat no.**
80% sol	18	1000	458	340	15
	19		423	329	14
	20		391	315	13
	21		332	285	11