LARGE-SCALE TESTS OF PYROTECHNICALLY GENERATED AEROSOL FIRE EXTINGUISHING SYSTEMS FOR THE PROTECTION OF MACHINERY SPACES AND GAS TURBINE ENCLOSURES IN ROYAL NAVY WARSHIPS

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[*]NB – The views expressed in this paper are those of the authors and not necessarily those of the UK Ministry of Defence

1. Introduction

Current Royal Navy (RN) fire management systems and procedures have evolved over time from a combination of research and highly valuable in-use experiences seldom seen in any other applications. The resulting protection procedures are well thought out; the specification of equipment is to a high standard; maintenance regimes are rigid; and activities are executed by very well trained personnel. These factors together ensure that a very high level of operational robustness is consistently achieved. Inevitably any changes to these procedures need to be done carefully and cautiously so as not to jeopardise current performance levels.

The complexities specific to machinery space protection have given rise to research worldwide with the current favoured option being water mist. Although water mist is undergoing extensive trials with the RN, the benefits of a non-water based first attack system, which will not necessitate isolation or extensive Ingress Protection (IP) of electrical systems, is obvious.

The T45 Destroyer (see Figure 1) is the first RN vessels to have an Integrated Electric Propulsion (IEP) system and the benefits of a non-water based first attack system cannot be argued.

Figure 1. The T45 Destroyer

The first attack system for the T45 Destroyer for main machinery space and gas turbine enclosure protection is currently CO_2 which raises other issues. Carbon dioxide is a very effective at extinguishing fires but in the environment of a warship gives an additional weight penalty for cylinder stowage and incurs high through life to maintenance costs. Also careful management of CO_2 systems is a necessity to prevent accidental release of the potentially lethal agent into manned areas.

Fixed aerosol fire extinguishing systems evolved from the Soyuz space programme to satisfy the need for a lightweight, non-pressurised extinguishing medium. Aerosol generating systems have a proven track record of tackling fires in small enclosures and 'open' local application scenarios and on paper fulfil many RN design requirements. Since their development a number of variations have been developed to fulfil a range of fire fighting roles. Principal differences between systems include: the discharge rate of the extinguisher unit (typically between 10 seconds and 1 minute); the means of cooling the ejected agent (chemically or mechanically); and the potassium compound used as the active fire fighting ingredient. Under the DPA research programme two systems were evaluated with very different operational characteristics which for the purposes of this paper shall be described as follows:

Description	**Active ingredient**	**Discharge time**	**Cooling means**
‘Rapid’ discharge system	Potassium Carbonate	<10 seconds	Chemical
‘Slow’ discharge system	Potassium Nitrate	~ 1 minute	Mechanical

Figure 2 and Figure 3 show the difference in ferocity of discharge of the two system types.

Figure 2. Discharge of a single rapid discharge extinguisher unit

Figure 3. Discharge of a single slow discharge extinguisher unit

For RN applications aerosol systems offer the following potential benefits:

- Low storage requirement
- Low weight
- Ease of installation – no additional pipe work
- Simplicity of activation
- Good environmental properties
- Beneficial unit, and through life costs

If aerosol systems can be demonstrated to be effective at satisfying the principle requirements of extinguishing and sustained inerting, it may be a satisfactory replacement for CO_2, with the benefits it brings. The majority of currently installed aerosol systems are very small when compared to machinery spaces ($<10m^3$) that may be up to 1200 m^3 in volume. The only test data available is for enclosures from 1 to 100 m^3 in volume and little relevant interpolation may be made since the fire-fighting regime may be one of ‘local application’ (preserved high velocities) not ‘total flooding’ as is likely in these large enclosures.

This paper examines and discusses the full scale testing carried out in faithful recreations of RN machinery space and gas turbine (GT) enclosures.

1.1. Machinery space protection

Royal Navy ship machinery spaces vary greatly in size depending upon the class of ship and can be as large as 1200m^3 for an aircraft carrier. The fuels within this space are predominantly liquid (diesel, hydraulic and lubricating oils) and can be presented as pools or high and low pressure sprays depending upon their source. Some solid fuels are also present predominantly in the form of electrical cabling. All machinery spaces are characterised by a high degree of clutter. Testing of the agents was performed in a 500m^3 fire test enclosure that complied with the requirements of IMO MSC/Circ. 1007 applicable for the testing of pyrotechnic aerosol systems.

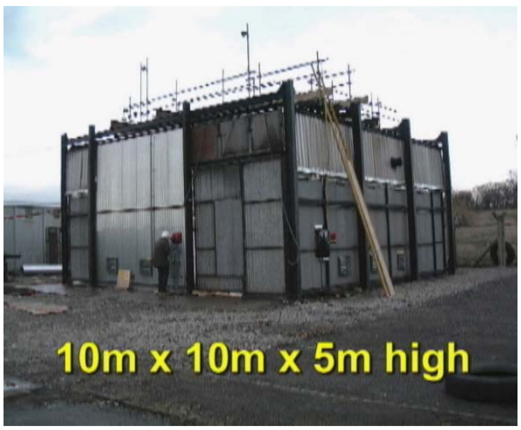

Figure 4. IMO Building

The rig was sealed to a high degree (Integrity test measured 0.26m^2 leakage in total surface area) and the rig was protected against over pressures by system manufacturer installed venting devices.

A series of 9 tests were conducted on each agent that evaluated the system's performance with respect to extinguishment of the fire, prevention of re-ignition, and re-entry capability, for the design period.

A number of other non-conformities were allowed:

a) To increase realism - Spray fires of diesel instead of heptane

b) To account for sensible installation practice - Use of non-symmetrical ceiling mounting positions to avoid pointless discharge onto near surfaces (agent disposition) and allowing the location of the units in the bilge area where no other dedicated extinguishing system exists

1.2. Gas turbine protection

Without any mitigating actions there is the potential to produce very severe fire conditions within the GT enclosure instantaneously. In a worst case scenario 4 tonnes/hour of diesel may be emitted from the fuel manifold and the resulting fire be fed with air at a rate of 9m^3/s. Traditionally such spaces have been protected with Halon systems and more recently, carbon dioxide.

Figure 5. The GT simulation

To adequately test and develop alternative technologies for use in these spaces DPA commissioned a faithful replica of the in-service gas turbine design modelling the geometry, internal surface temperatures and air flow rates at the expected time of fire fighting system actuation. Eight tests were conducted on a range of likely fire scenarios and a further benchmark test using carbon dioxide was also performed.

2. Machinery space fire protection with pyrotechnically generated aerosol systems

A focus group was formed and included experts from the Ministry of Defence (MoD), FPA and industry to establish a realistic test programme for typical fire scenarios in the main machinery spaces. From this the following test programme was agreed:

1. Multiple spray fire test (2 pool and 2 spray)
2. Cold discharge test
3. Fuel manifold spray fire test
4. Cable tray at deckhead fire test
5. Engine spray fire test
6. Deep seated fire test
7. Local application fire
8. Bilge fire test

For all fire tests reported small tell-tale fires were located in the eight corners of the enclosure to confirm the mixing capability of the agent.

2.1. Rapid discharge system evaluation

The rapid discharge system comprised 8 units whose active ingredients of potassium carbonate were chemically cooled with potassium carbonate pellets. 6 x 11 kilogram units were mounted at ceiling level and 2 x 6 kilogram units were mounted under the bilge as shown in Figure 6 and Figure 7 to give a nominal design concentration of 128 g/m^3.

Figure 6. 6 kg unit under bilge

Figure 7. 11 kg units mounted on ceiling

Early on in the rapid discharge test programme it became clear that historic small scale testing of this type of system around which the design rules were based was not appropriate to a much larger enclosure. To this end, although significant modifications were made to the installation and the operational process during testing, it is probably fair to say that no test was conducted with the system fully optimised.

Alterations to the system design were made with the aim of increasing ‘retained’ concentrations within the enclosure by:

- Increasing the amount of agent used
- Encouraging direct access of agent to the fire
- Greater sealing of the IMO building
- Insertion of additional sealing ventilation
- Effective slowing of discharge time by staggering unit activation

With the exception of staggering of the unit firing sequence which produced limited improvements, none of the other measures solved the performance problems.

In conclusion the rapid discharge agent failed to put out the majority of the fires except where direct access of the agent to the seat of the fire was allowed and agent velocities were high. Due to the number of extinguishing failures little dedicated information was collected on its inerting ability, but by definition much can be inferred. The aerosol has no cooling capability and produces large amounts of carbon monoxide (11,000 ppm) and carbon dioxide, suspended fine particles, and incurs total loss of visibility. Purging of the enclosure or the provision of suitable protective clothing before re-entry should be considered.

Although not an ideal set of tests results indications were that there was scope for development. All of the problems experienced during the test programme may be attributed to not achieving the correct held concentration level within the enclosure. The most rewarding development was considered to be in further slowing the discharge, which would require the use of an alternative system.

Figure 8 and Figure 9 shows the operation of the ventilation system during system operation.

Figure 8. External view of rig during cold discharge test

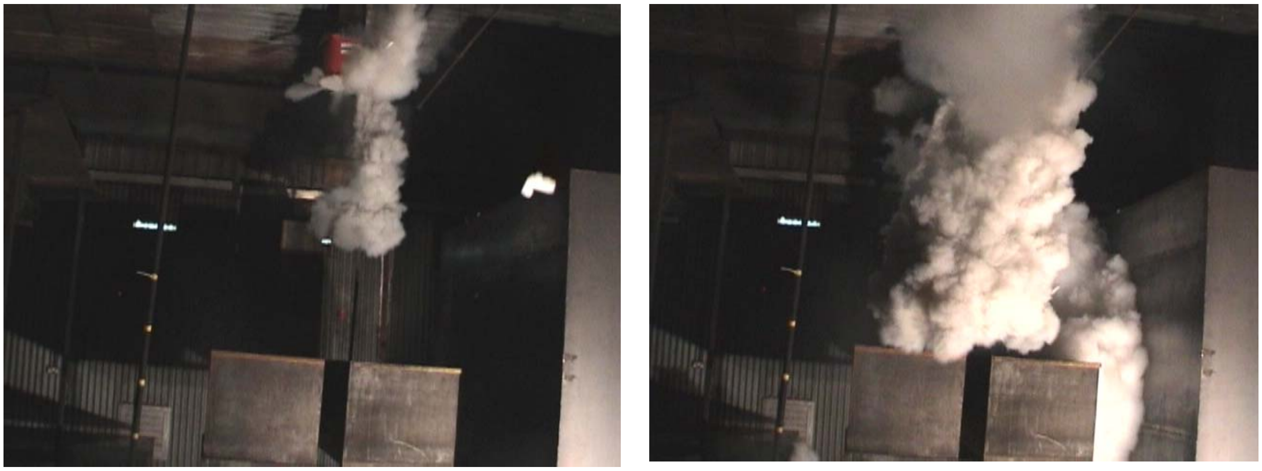

Figure 9. Internal view of rig during cold discharge test

2.2. Slow discharge system evaluation

From the rapid release system tests it was evident that a slow release time may be beneficial in ensuring that agent concentrations are achieved and maintained correctly distributed within the enclosure. An alternative product was found that claimed to address all of the issues raised.

To further challenge the system it was considered that unit location would not be permitted as a function of performance since in the main machinery space of a destroyer it may not be possible to mount the units on a regular grid in the deck head. To this end the units were mounted vertically in clusters symmetrically placed around the walls of the enclosure as shown in Figure 10. Discharging towards the ceiling, this configuration ensured that the units do not discharge directly onto any test fire and thereby correctly addresses 'total-flooding' performance.

Each unit contains 1.1 kilograms of active fire fighting medium and 56 were used to achieve the desired concentration (123.2 g/m^3) in the IMO test enclosure.

Figure 10. Location of unit 'clusters' around the IMO enclosure

The results from the test are as follows.

Test 1 - Multiple spray test

- The agent successfully managed to extinguish the four primary fires and eight tell-tales
- Spray fires easier to extinguish than pool fires
- Distribution of agent around the enclosure was good but some buoyant behaviour reduced performance at low level
- Prolonged inerting of the enclosure is possible with this agent
- Loss of agent through pressure excursions is minimal

Test 2 - Cold discharge test

- To simulate accidental discharge of the unit
- Max. mean temperature rise within the enclosure of approx. 40°C was recorded
- Peak pressure spike of 47 Pa
- Agent fills enclosure from the top down. The rate at which this happens is a function of the size of the enclosure, particularly height
- After discharge has finished, the cooling agent mixes and stratification is likewise reduced

Test 3 - Fuel manifold spray test

- The agent successfully managed to extinguish the primary fire and all of the high level tell-tales and two of the low level tell-tales
- Good spray fire performance (within 30 seconds of end of discharge)
- Failure of extinguishing the two floor level tell-tales would suggest that the increase buoyancy produced by the heat of the spray fires left low level parts of the enclosure concentrations below extinguishing value.
- Given the comment above it is possible that not enough agent is being used to adequately protect the enclosure

Test 4 – Cable tray at deckhead

- The agent successfully extinguished the primary fire, all of the high level tell-tales that were ignited, but none of the four low level tell-tale fires. A high level tell-tale was successfully re-ignited after a relatively short period of time.
- Good 'solid fuel' Class A spray fire performance
- Not tackling the low level tell-tale fires suggest that the low level areas of the enclosure remained at agent concentrations below extinguishing levels. The cable fire is very low heat output source and may not drive the agent around the enclosure on convective currents
- Again given the comment above it is possible that not enough agent is being used to adequately protect the enclosure

Test 5 - Engine spray fire test

- The agent successfully extinguished the primary fire, all of the high level tell-tales that were ignited, but none of the four low level tell-tale fires
- Good spray performance
- Not tackling the low level tell-tale fires is in keeping with the fuel spray fire test given the similarity of configurations
- This time four rather than two of the tell-tales were extinguished. This reduction in performance might be attributed to a single unit that failed to operate.
- Again given the comment above it is possible that not enough agent is being used to adequately protect the enclosure

Test - 6 Deep seated fire test

- The agent successfully extinguished one of the primary fires, all of the high level tell-tales and three of the four low level tell-tale fires
- Inadequate agent concentrations at floor level
- Perhaps the deep seated fire needs more agent than pure class B fires since three of the four low level tell tales were extinguished
- Again it is possible that not enough agent is being used to adequately protect the enclosure

Test 7 - Local application fire test

- The agent failed to extinguish the pool fire. This was expected given the low momentum possessed by the system

Test 8 - Bilge fire test

- The agent failed to extinguish the bilge fire but all high and low level tell-tales were extinguished before oxygen levels were at extinguishing values.
- In keeping with the previous seven tests agent concentration levels at low level are insufficient.
- Larger fires may be more difficult to extinguish than smaller fires
- Again it is possible that not enough agent is being used to adequately protect the enclosure

The slow discharge system appeared to confirm the theories pertaining to the shortcomings of the rapid discharge system for large enclosure protection and successfully extinguished four of the six set total flooding fire scenarios. The fires not extinguished were the floor level deep seated Class B fire and the bilge fire which infers that not enough agent was injected to achieve an extinguishing concentration in all areas of the enclosure. Being lighter than air, floor level fires will be most greatly affected by inadequate agent quantities. This was neatly confirmed by the ratio of tell-tell fires successfully extinguished at the high and low locations as follows:

- 21 of 21 high level tell-tales fires were extinguished
- 12 of 23 low level tell-tale fires were extinguished

The results suggest that extinguishing performance is a function of fire location, fuel type, fire type, and fire class, and to this end the final system should be designed to the most onerous configuration.

Evaluation of the true potential effectiveness of the agent is difficult since the results suggest that the implementation of the system was not optimised and higher concentration of agents should be used.

3. Gas Turbine protection with the slow discharge aerosol system

The slow discharge agent was the only test medium used for the GT enclosure test. Once again a focus group was formed and included experts from the Ministry of Defence (MoD), FPA and industry to establish a realistic test programme for the GT enclosure. The following fire tests were agreed:

1. Large pool fire (bilge)
2. Cold discharge test

3. High pressure spray fire test
4. High pressure spray and pool fire test
5. Deep seated fire test (diesel soaked insulation)
6. Repeat of test 5 without insulation
7. High pressure spray fire test
8. Sustained inerting test

The protection of gas turbines is complicated by the wide variation in surface temperatures within the enclosure (70-800^oC), the fact that the contents are continuously purged with cooling air, and that during shut down in the event of a fire, these parameters may be rapidly changing.

Primary issues with respect to gas turbine protection include:

- the time at which the inlet damper supplying air to the enclosure is shut down
- the time at which the 1st shot of extinguishing agent is applied
- the time for which the GT may operate (at a given output) without cooling air
- the time that it takes for an alternative GT unit to be brought on line
- the time for which inerting of the enclosure is required

relative to the time of automatic detection of the fire.

Current operating procedures require manual confirmation prior to any fire-fighting actions being taken; a process that can take up to 2 minutes. Given the potential level of fuel and oxygen delivery to the fire scene it is likely that significant (catastrophic) damage may be endured by the turbine in this period. To release extinguishing agent during this time is also likely to be of limited benefit as the residence time of the agent at these air flow rates is minimal and indeed may never actually achieve an extinguishing concentration due to dilution.

This study assumed the operating procedures for fire management to be as follows:

- events controlled by an automatic fire detection system
- the inlet damper is shut immediately upon detection of a fire[1]
- the extinguishing agent shall be released once the inlet damper is seated and confirmed (15-30 seconds)
- an inerting time of 15 minutes is required during which the 'worst-case' leakage rate through the damper is applicable

To assume anything different may well be asking too much from current Halon replacement technologies.

A modified version of the slow discharge system was used so that the units could be mounted on the outside of the enclosure with the agent 'piped' in. This was more for experimental convenience rather than any other reason and final designs may incorporate the units within the gas turbine enclosure.

The GT enclosure differs from many fire protection applications in that it is continuously purged. The agent lost over time will have to be replaced if extinguishing concentrations are to be maintained and with it the level of protection. The GT enclosure ventilation rate (damper leakage) will influence greatly the agent concentration within the enclosure. Figure 11 shows the

[1] An allowance is made for a residual air flow rate through the inlet damper of 0.15m^3/s. This residual air flow rate is likely to be one of the greatest factors affecting extinguishant performance.

theoretical concentration profile for a range of ventilation rates for an initial 5 unit shot followed by single unit top-up shots every 60 seconds.

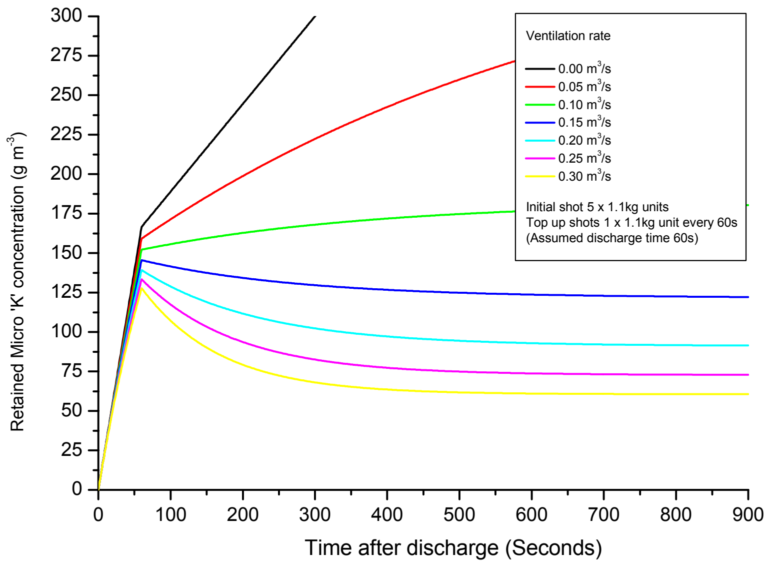

Figure 11. Concentration modelling of a single shot discharge of 5 slow discharge units followed by top-up shots at 60 second intervals for a range of ventilation rates

At a ventilation rate of 0.15m^3/s the design concentration is satisfactorily achieved for the duration for which top-up units are available.

All tests were successfully extinguished apart from test 5. Test 6 was performed to understand the reason for test 5 failures by removing the fibre insulation. The result showed that higher concentrations may be appropriate for deep seated fires.

4. Discussion

4.1. Machinery space protection

Stark performance differences were observed in the test results obtained for the rapid and slow discharge systems despite being classified as similar systems. This is a particularly worrying aspect from a potential user's viewpoint which needs further explanation.

These systems differ from alternative technologies in that they generate heat, and are therefore lighter than air. There is therefore the potential for:

- loss of agent from the enclosure during discharge due to the amount of gas injected during combustion of the unit's contents (as is the case for all gas-type systems)
- loss of agent from the enclosure due to expansion of the gases of the enclosure as they are heated by the agent. During cold discharge testing (no fire) the mean temperature within the enclosure was raised by around 66^{o}C and 40^{o}C for the rapid and slow discharge systems, respectively. This represents an isobaric volume change of 113m^3 and 68m^3, respectively, which must act to force agent out of the enclosure during the critical discharge period.
- Ingress of fresh oxygen rich air after discharge as the enclosure's contents cools

- Stratification of the agent in the enclosure to leave low level areas under protected.

Even with significant venting applied to the enclosure the rapid discharge system consistently recognised pressures of around 600 Pa and failed to extinguish the design fires. With very little ventilation (no flaps were ever observed to operate) pressures of 40 Pa were more common with the slow discharge system which achieved much greater levels of performance.

A number of reasons why the amount of agent supplied to the protected space might be insufficient for robust fire management are given below. It is particularly important for this type of system to be correctly designed since there may be no 'half measures' in performance. If an oxygen depleting gaseous system is under-designed there will probably still be a residual benefit from the agent injected and the fire may burn at a much reduced rate accordingly. It is not clear whether this is the case for aerosol systems: it is possible that injecting too little agent is the same as injecting no agent at all, especially if it is consumed in the fire.

Surprisingly, the criteria selected for determination of the design concentration for pyrotechnically produced extinguishing aerosols does not follow the same approach as for gaseous systems: perhaps they should.

Gaseous system design concentrations are derived as follows:

I. Small scale testing in the cup burner apparatus determines the **extinguishing concentration** of the agent (followed by larger scale [$100m^3$] confirmation)

II. On to this value is added a safety factor which is currently typical 30%. The **extinguishing concentration** multiple by 1.3 give the operational **design concentration**. The concentration that should be achieved in the enclosure to robustly tackle the fire.

III. To achieve the **design concentration** in the enclosure requires the multiplication of this value by a 'flooding-factor' that includes an amount of agent that must leave the enclosure during the discharge process (air and some agent must obviously be displaced). For example to achieve the extinguishing concentration of 20% within the enclosure might actually require the injection of 1.4 x the estimated amount of agent.

IV. Container numbers are then selected to supply the requirements of III, and rounded up to a whole number adding a further safety factor.

In the design process of pyrotechnically generated aerosol it would appear that Step III is not addressed. Therefore any loss of agent from the enclosure (which is inevitable due to thermal expansion and gas injection) must be drawn from the safety factor quantities which is clearly not what these factors are design to do.

The above approach also assumes that agent is not 'consumed' by the fire. If it is then an additional quantity might be included to account for this based on the type of fire expected.

These tests might suggest that the additional quantities of agent required for complete protection are 'significant', but not great.

4.2. Gas turbine enclosure protection

The primary fire protection mechanism for a Gas Turbine enclosure was observed to be the passive protection afforded by the enclosure itself. If actual enclosures offer the same level of fire resistance as the test simulation, large fires will quickly self-extinguish through oxygen starvation. Re-ignition may well occur and cycling is possible and the slow-discharge system using top-up units to account for purging was observed to mange these events well.

5. Conclusions

As a result of the reasonably successful work on the slow discharge agent consideration is now being given by the designer's of the T45 Destroyer to use this media on Diesel Generator enclosures and HV/LV switchboards within the vessel.

In parallel with the fire-testing programme both agents have received approval from the Institute of Naval Medicine for use in unmanned compartments on RN vessels. The limiting factor being the amount of CO produced under release. There is approximately a two-minute time period for personnel to vacate a compartment before the levels of CO become prohibitive.

The commercial slow discharge unit has been fully shock tested and meets the military capability for RN surface vessels.

There is still an ongoing assessment on the concentration levels required to achieve optimum fire extinguishment.

Note:

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