Fire Fighting Systems for Autonomous Vessels

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1 Synopsis

This paper considers the nuances of fire protection requirements and functional solutions for the new generation of Naval Autonomous Surface Vessels (NASV). Their likely value, financial, to mission, and engineering knowledge, will drive a need for them to be resilient to internal and external fire challenges and this paper describes how data integration from disparate systems can be used to make-up the shortfall in situational awareness that the uncrewed situation creates. The application of novel sensors to the marine environment that provide immense data capital from minimal devices is proposed as part of the solution together with consideration of technologies hitherto neglected because of their incompatibility with personnel exposure. Whilst presenting challenges, the NASV environment also creates many opportunities for efficiencies, cost savings, and improvement in performance of fire management systems. The ideal fire and damage control systems will act pre-emptively to avoid fire, supporting the platform to be resilient in its delivery of mission, and once defeated play its role in limiting damage enabling it to return for recovery.

KEYWORDS: Autonomy, Unmanned, Uncrewed, Firefighting, Damage Control

2 Biography

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3 Introduction

The military opportunities presented by autonomous hardware on land, sea, and air, in association with advancements in artificial intelligence (AI) and quantum computing, have the potential to precipitate a revolution in military affairs that could reshape the balance of global power [Starling, Wetxel, Trotti, 2021].

In removing the exposure of personnel from direct harm platform logistics are drastically reduced and new freedoms are afforded to critical strategic decision making. Historically used in ‘disposable form’, the inevitable and essential future reliance upon autonomous platforms with greatly enhanced capability and military/financial value will require similar innovation to ensure their survivability from typical operational challenges associated with the engineering, and from the impact of externally caused damage.

This paper considers the nuances of fire protection requirements and functional solutions for the new generation of Naval Autonomous Surface Vessels (NASV) and will consider some of the opportunities presented by the uncrewed situation and challenges still to be overcome in the implementation of solutions.

4 Why do we need a different approach to NASV fire protection?

Adapting fire and damage control methods to meet the requirements of NASVs is the most recent iteration of historical efforts to address the ever-changing crewing requirements of naval platforms [Chilcott, Kenny, 2018]. QEC has the highest displacement to crew ratio of any previous RN platform and the challenges this poses for fire and damage control have been managed by the adoption of systems that support greatly improved command situational awareness, prevention, automation, and integration with other systems.

Whilst the research supporting these recent innovations can be drawn upon as a starting point [Glockling, Edwards, 2007], a complete re-evaluation is required for the uncrewed scenario. Such a re-evaluation exposes both stress points and opportunities.

It is certainly true that crew are currently fundamental to the resolution of fires and damage on-board with the majority being both detected and suppressed by their actions, but it is also a fact that many potentially beneficial technologies cannot be used because of the presence of people and their needs for a lifesustaining atmosphere which coincide with those of a fire. The enhanced sensor suite that will accompany autonomous control will also afford opportunities for the pre-emptive management of fire [Salhi, Silverston, Yamazaki, Miyoshi, 2019] within a communication and control network more advanced than any previous allowing the prevention of 'transition-to-fire' from internal threats to be considered an achievable primary goal.

Whilst it might seem obvious that automation of fire and damage control will have a very significant role to play, in the absence of persons to confirm the appropriateness of the automatic action, or to deal with the consequences of inappropriate action, the timelines, quality, and accuracy of information gathered prior to automatic action being taken (that might in itself cause consequential damage), will need to be improved over current levels before this can be done. Consideration also needs to be given to the scope in terms of communication of real-time data to a command facility, their ability to interact in the response process including veto of actions, and how the loss of communications to the NASV must be managed – a multi-mode approach.

In summary, fire and damage control systems for NASVs must support the ability of the platform to be resilient in its delivery of mission, and if damaged play their role in limiting damage to the vessel enabling safe recovery. Ideally, with the enhanced native systems available in association with the fire protection systems and advancements in computing [Wu, Chen, Hao, 2021], all actions would be taken pre-emptively. There is also a considerable role for them to play during the development of autonomous technology advancement platforms, that can present as a higher-than-normal risk as teething problems are overcome. On balance, the dual purposing of monitoring and control instrumentation, in association with the extended freedoms afforded to fire and damage control system design, brought about by the uncrewed situation, may offer the potential for cost savings in the assurance of resilience.

5 Opportunities and Challenges

The major fire and damage control opportunities presented by NASVs pertain to:

- Having no requirement to accommodate occupants.
- Being able to exploit the enhanced systems monitoring, control, communications, data processing, data integration and analysis inherently present in autonomous vessels.

The major fire and damage control challenges that arise from NASVs pertain to:

- Loss of situational awareness.
- Loss of control capability.
- Loss of ability to adapt on the fly to an unfolding situation.
- Reduction in repair actions post fire.

These are considered further in the following sections.

5.1 Opportunities

The opportunities made possible due to the removal of the crew are addressed in the following sections with the caveat that whilst the use of hazardous materials may be presented as a possibility, their selection should be on the basis of providing significant benefit over safer alternatives. It is also assumed that all extinguishing agents used will not only meet current legal requirements in terms of ozone depletion, greenhouse gas contribution, and environmental persistence, but will remain viable for the foreseeable future.

5.1.1 Fire certification for life-safety

The removal of personnel from a risk environment potentially negates the requirement to meet some life-safety legislation, offering potential benefits due to a reduction in safety certification requirements:

- A number of authorities having jurisdiction (AHJs) in the maritime environment worldwide assess and approve vessels for the protection of life, and the risks posed by fire and flood to crew play a significant role in this undertaking. As uncrewed vessels, NASVs will not be subject to this requirement, but will still be required to prevent harm to other 3rd parties.
- The certification requirements and hence protection requirements for explosives potentially moves focus to reflect the risk to the asset and 3rd parties.

5.1.2 Pre-emptive Fire Management

Exploitation of improved monitoring, control, and communication systems and full exploitations of integration of PMS / MCAS / DSAC associated with specifically developed fire and damage control systems offers several benefits across the vessel, not solely limited to fire protection. These include low consequential damage; rapid speed of response; enhanced survivability; reduced cost of repair; and reduced reliance upon passive and active fire protection systems.

- It is likely that the superior condition-based monitoring systems pertinent to the operation of an uncrewed vessel could provide benefit to anticipatory fire detection when integrated with a similarly enhanced fire detection and damage control system. Preventative action taken prior to the transition-to-fire produces the lowest consequence response possible.
- Set within a Bayesian type decision-making framework, conclusion of an imminent adverse event may be determined, communicated, and appropriate preventative action taken on a timescale faster than any single system could determine [Xie, Lin, Chi, Yang, 2016]. Examples of data aggregation in a Bayesian framework might include data informing on extraordinary fuel use or low pressure in fuel lines to indicate a potential leak; raised bearing temperatures or sound and vibration analysis to indicate imminent mechanical failure; mist detection indicating high pressure fuel or hydraulic oil release, all of which may be prevented from manifesting as fire if managed appropriately.
- An enhanced data exchange network could enable further improvement with the introduction of equipment trend data on deterioration of performance, signatures of stress, and routes to failure, that could serve to accelerate the pre-emptive decision-making process.
- Upon identification of imminent failure, preventative actions might include the isolation of electrical equipment (90% of electric fires stop on powering down of the equipment), shutdown of the equipment at risk and startup of alternative option, control of ignition sources, and inerting of the atmosphere etc.

5.1.3 Use of fire preventative materials that are hazardous to health

The removal of personnel from a risk environment potentially negates the requirement to consider material toxicity under fire conditions. This has the potential to offer a greater range of high-performance material options; cost savings; improved performance; improved passive fire protection; and reduced reliance upon extinguishing systems. The freedom to do this and the controls required might be a function of NASV size and their launch requirements and all will need to be considered as part of the overall operational safety case. Larger NASVs might require access controls to protect those entering, and smaller ones, likely launched from a parent platform, will need local management controls.

- Some materials that can form capable barriers to fire can be hazardous to health from skin exposure, ingestion, and inhalation. The toxicity may be attributable to their native chemistry, chemistry in fire, or physical (i.e., fibrous) structure. If sufficient benefit exists to warrant their use, they could be considered for inclusion in a design solution for uncrewed vessels.
- Many additives used in the modification of the fire resisting capability of materials can be very effective but toxic. By way of example the specification of Low Smoke Zero Halogen (LSZH) cabling is a common requirement for many occupied protection applications but may be unnecessary for NASVs and allow for improved performance at a lower cost.

Additionally, the ability to use traditionally hazardous materials offers the potential to use signature coatings to enhance early detection of fire precursors.

- In certain scenarios where specific identification of an emerging critical situation can be difficult to detect within the limited pallet of fire indicators, materials that are easily detected, but alien to the environment can be applied as coatings to key assets. At elevated temperatures, or when on fire, the involvement of these key assets can be determined with high reliability.

5.1.4 Use of methods of fire extinguishing/prevention that are hazardous to health

Removal of personnel from a risk environment negates the requirement to maintain a breathable atmosphere offering opportunities for fire protection methods that provide robust ignition protection and reduce material participation in a fire.

- A challenge for all occupied fire protection situations has been the common demand for oxygen by the fire and those trying to survive the event. The greater demand for oxygen by humans (minimum 15%) than fire (variable, but typically 12%) means that fire extinguishing concentrations are never coherent with human occupation. Unoccupied spaces allow for great freedom in approach to the temporary or permanent depression of oxygen levels such as:

- Permanent depression of the oxygen within the protected space to below 12% O_2 v/v (or that required by the most hazardous fuel present)
- Evacuation of air from the protected space
- Permanent replacement of air with an alternative atmosphere (i.e., depleted oxygen exhaust gases, non-conducting liquids etc.).

Additionally, removal of personnel from a risk environment negates the requirement to maintain a breathable atmosphere, offering further options on extinguishing agent, improved media efficiency, and reduced storage volume and weight requirements. Some of the most effective gaseous extinguishing agents, in terms of their capability and storage footprint (weight), are limited in their application due to their inherent toxicity. In the uncrewed environment of NASVs the benefits of these could be more fully exploited (subject to sufficient controls when persons are present). They include:

- Carbon dioxide, a liquifiable gas in common use but at extinguishing concentrations is lethal to those exposed to it. It requires half the storage volume of competing non-liquifiable inert gases such as Inergen™ and is reliable and effective.
- Triodide (CF3I), once proffered as a drop in alternative to Halon 1301 and Halon 1211 such is its efficiency, but use is currently limited to unoccupied applications such as aircraft engine nacelles.
- Condensed Aerosol systems, a small format powder extinguishing system that can be effective in smaller compartments, but to date its use is limited to unoccupied areas [Connel, Glockling, 2003].
- Exhaust gases, dependent on propulsion solutions an opportunity to use the oxygen depleted exhaust gases of the propulsion system for fire management. This is already an option used for tank inerting.

5.1.5 Efficiencies in extinguishing agent use and number of systems required

Removing personnel from the risk environment offers simplification of fire extinguishing systems with potential cost savings. It is traditional practice to encapsulate risks into sub enclosures for the protection of crew from i.e., electrocution and noise, and the equipment from accidental physical damage. To protect these myriad of compartment sub-enclosures requires many fire systems with differing capabilities.

If the requirement for sub-enclosures can be removed on the basis of the compartment being uncrewed, then the compartment and its contents could be protected by a single system if the constraints on free gas movement are removed, and a suitable all-purpose extinguishing agent is found.

5.1.6 Reduction of free-volume oxygen

Fire requires oxygen, and the quantities available within the compartment spaces demanded for crew occupation can be significant. If the free volume can be reduced by design, or actively when a fire occurs, a fire may self-suffocate earlier, and the quantities of gaseous extinguishing agent required will be greatly reduced.

- In the civil construction environment, voids are often packed with non-combustible mineral fibre to reduce fire spread and oxygen contribution. This approach could be applied with due consideration given to survey and access requirements.
- Active methods of free volume reduction could be considered, such as the inflation of fire resisting bags with an inert gas.

5.1.7 Freedom to use fuels that might present health challenges

With personnel removed from the vessel the use of future fuels that present higher native toxicities should be easier and protection options should be similarly simplified. Risks to the parent vessel from NASV fuel systems would require a specific safety and environmental analysis to be conducted.

- As alternative propulsion systems are considered such as methanol, ammonia, LNG, LPG, and hydrogen (fuel cells), the native toxicity and fire and explosion risks associated with each will need review. Management of the direct fuel risks, and those of the agents that might be needed to control them (see previous), will be afforded greater freedoms in the uncrewed environment.
- As lithium-ion battery technologies become more prevalent, their modes of failure and toxic potential are becoming more evident and of increasing concern. The uncrewed situation of NASVs will enable

greater freedoms, such as arrangement and compartmentalisation, for managing the consequential damage associated with their involvement in fire.

5.1.8 Smoke Management

Smoke is major contributor to poor situational awareness and injury during fire and can act to greatly reduce the efficiency of response. As such, great effort is put into the containment and control of smoke. In the uncrewed situation, and by selection of sensor suites that are not impacted by the presence of smoke there is potential for it to be ignored from a fire detection and control perspective (harm from equipment contamination would need addressing), simplifying fire management.

5.2 Challenges

Changing to an uncrewed vessel brings with it a number of challenges, these are primarily around the ability to provide situational awareness under all scenarios and to be able to provide a proportional response to fire incidents, be they due to mechanical failure, accidental damage or hostile damage. There are also a number of challenges related to the technology required to achieve the required levels of protection. The following sections outline some of these challenges and postulates some of the resolutions to these challenges.

5.2.1 Determination of every risk scenario permutation

Most current protection systems operate to simple logic of the form ‘if-this-then-that’. In crewed vessels the protection is afforded to fire scenarios that are most likely, and/or have the most damaging outcome. The less probable, easily managed (low risk), or slower timeframe events are often left to manual intervention which will not be available in the uncrewed situation.

The management of unconsidered scenarios is most normally dealt with by having intelligent ‘boots on the ground’ to assess the situation, and reconfigure the resources to hand, often in novel ways, to resolve the event. Removing the personnel therefore reduces situational awareness and the ability to respond to novel events and increases the risk of escalation.

In the event that any of the assumptions made in respect of, the fire scenarios considered, the availability of the sensors to report, or ability to control the systems required to respond to the event, turn out to be incorrect through damage, malfunction or missed analysis, there will be a need to determine the next best option with the remaining available systems and information. These can be pre-determined and preprogrammed through a process of ‘what if’ impairment assessments.

A much greater level of effort will be required in hazard identification (HAZID) and hazard operability (HAZOP), to identify all ‘normal’ risk event paths, together with ‘abnormal’ paths to failure. This will also need to consider whether an inappropriate action of a fire safety system could cause harm to the asset or a 3rd party and will need to be cognisant of system sensitivities to potential alternative fire-fighting responses and media.

5.2.2 Measurement of every parameter important to the prosecution of an optimised response

Failure to measure every parameter important to the prosecution of an optimised response, be that by design or abnormal event, will lead to a loss of situational awareness. However, sensor weight must be balanced against the ability to remotely build a situational damage picture and the cost practicalities associated with that.

The interpretation of an event occurring in a NASV can only be as good as the available sensors allow. Too few sensors, or measurement of too few parameters can result in multiple potential causes being assessed as viable, that might demand conflicting actions to be taken, or an inability to efficiently exploit the resources available, resulting in increased consequential damage and loss of mission. The ability to adapt in terms of detection and action will depend on the flexibility and omnipresence of sensor equipment available, and the level of control available over responding systems. The correct balance of sensors to capability will be determined from a fault tree analysis of threat likelihood.

Sensing systems that have wide area coverage and can glean many parameters can assist greatly in the determination and resolution of unconsidered challenges, but it will not always be obvious where detection is required, or where extinguishing systems might need to act. To account for this systems design should be based on a ’black-box’ scenario test for likely and unlikely events (blind testing).

More (unusual) parameters may need to be measured that describe i.e., extents of damage to equipment and compartment boundaries; whether compartmentation has been breached / door and hatches are open or closed etc., and there will be requirements to reconfigure the response to take in to account which systems are still available for use in the event of damage and malfunction.

5.2.3 Health monitoring and control of every system important to the prosecution of an optimised response

The use of monitored parameters as action stimuli across the vessel is reliant on the monitoring systems and field elements health. This has a direct relationship with the ability to maintain situational awareness, control response and to adapt to developing situations, and requires fallbacks to be considered to degradation in this capability.

Subject to the sensor suite describing correctly the action required, the response may be provided automatically (without external intervention), or with reference to an external operator dependent on the scenario and ramifications of the response; noting that the response may be multi-faceted requiring the shutting down of equipment, startup of alternative equipment, control of ventilation systems, release of an extinguishing agent etc.

In some cases, the loss of a single control / monitoring capability (such as ventilation control), may require an alternative approach to be taken in resolving the situation to avoided wasted time, or increased consequential damage.

5.2.4 Replacement of human actioned responses

The crew of any platform plays a major role in the recovery process. Whilst many actions can be automated, such as equipment management, containment, and activation of extinguishing systems, some are more difficult. To counter this design analysis and resolution of all human interventions critical to resolving a fire situation completely will be required.

In the marine environment Class B liquid fuel fire risks are often considered a higher risk than Class A (solid) fuel risks because of their different rates of burning. That said, Class A fuels can be difficult to fully extinguish using traditional firefighting systems and may smoulder for many days – these types of fire are normally ‘damped down’ by human intervention. The ability to suppress, or extinguish a fire, is a combined property of the system deployed and the burning nature of the fuel. In the uncrewed situation, all fires must be completely extinguished.

5.2.5 New sensor technology requirements

As previously discussed without a crew many simple data gathering requirements critical to fire management become more complex, e.g., door’s status or boundary integrity and confirmation that the fire is extinguished. The adoption of technology will be required to account for this loss of situational awareness.

Many systems are also not typically designed to detail the success or failure of the actions taken being principally designed to raise alarm and invoke an action and after that their role is complete. The ideal sensors will perform their task of alerting and triggering a response, continue to report during the firefighting process measuring success or determining the need for a continued or heavier weight response, assist at indicating when the situation has been resolved, and be ready for the next incident.

In many areas innovation in application of sensing technologies to replace manual information gathering will be required together with increased robustness of sensors to withstand fire and with an ability to reset after the event.

5.2.6 System Reset following an event

Following a fire and its satisfactory management there is a need to support the continued mission of the NASV. There should be enough resilience within the sensor network to ensure its survival, and extinguishing systems should be resettable so they may once again perform their function if called up to do so. The level of system resilience required will be determined by introducing the sensor network into the survivability analysis and allocating a target commensurate with the highest priority function associated with it.

This may well impact the architecture of fire protection systems requiring multiple gas charges or appropriate water supplies together with suitably robust distribution networks to allow continued protection.

5.2.7 Lack of published information and research on materials properties and firefighting methods for the uncrewed environment

Particularly in respect to fire extinguishing systems, the majority of research effort has gone into finding agents that are suitable for use in occupied spaces as this is where the greatest application and financial reward exists.

Information of systems pertinent for use in the uncrewed space might be lacking where research on promising advances has stopped upon establishment of toxicity credentials. Policy is required to support selection and therefore development of solutions that specifically consider the boundaries relating to uncrewed vessels.

6 Sensor technology requirements

The necessary innovation in fire management on NASVs demands the integration of all available data to create the best picture of the event as possible, to a resolution and timeliness that enables the provision of the most appropriate response option. The key sources of information and control are Platform Management System (PMS), Machinery Control And Surveillance (MCAS), Damage Surveillance And Control (DSAC) and the dedicated fire protection sensors, dedicated situational awareness sensors, equipment health monitoring systems, and externally delivered input. The contribution that these may make to improving situational awareness are considered below:

Data source	Parameter	Sensor	Application
PMS	All	All	Centralisation of data input, determination and control of response, event monitoring and adjustment of response until resolved. Resetting
MCAS (monitoring)	Equipment temperatures Fuel usage Fuel/oil pressure Operating efficiency Vibration/sound	Thermocouple Flowmeter Pressure sensor Combined sensors Accelerometer	To warn of impending failure. To act as a prompt to investigate further. To diagnose in association with all other available information to draw a conclusion earlier than any single system would allow. To enable actioning of a preventative response.
Deterioration trend data	Trend and threshold data for at-risk equipment	Specific to equipment	To be used in conjunction with MCAS and other data to determine the relevance of readings and likely outcome and timescale to failure.
Fire detection (gas-bourn)	Smoke Heat Carbon monoxide	Particle detector Thermocouple Gas cell	To inform of fire. To locate fire if sensor weight is appropriate (to compartment, to equipment, to component). To report on progress of fire (growth or reduction). To confirm fire is out.
Fire detection (visual) – line-of-sight	UV IR CCTV	Optical Optical Optical	To inform of fire. To locate fire if sensor positioning is appropriate (to compartment, to equipment, to component). To report on progress of fire (growth or reduction). To confirm fire is out.
Fuel release	Oil mist	Particulate detector	To inform of fuel release and potential of imminent fire or explosion.
Dedicated situational awareness sensors	Compartmentation Failure characteristic	Ultrasonic detection Sound	To inform on the extent of compartmentation following damage. To warn of impending damage scenario. To warn of occurrence of an event.
Equipment health monitoring systems	Electronic health	Condition based monitoring	To inform on the ability of systems to perform their function if called upon.
MCAS (control)	All	Equipment & systems	Control of Ventilation / flaps / isolation of equipment / alternative start up etc.
DSAC	All	Equipment & systems	Flood / NBC / Fire Control
Externally delivered input	All	All	To override / confirm other information where pertinent. To authorise response.

Table 1 – Contribution of Data Parameters from Sensors to fire protection

The correct solution will require an appropriate balance between sensor weight, situational awareness coverage, and resolution. Ideally sensors will be omnipresent with an ability to perform their function unencumbered by a lack of atmosphere homogeneity or clutter impacting lines-of-sight and gas flow. These factors can be overcome to a degree by detection systems that are easily distributable, and by using the transmission properties of air to sound and pressure.

By way of example newer linear type sensing technologies, not yet common to the marine environment can make a valuable contribution to the uncrewed situation. In these likely cluttered environments, the use of line-of-sight detectors and point detectors can be problematic to accommodate. Fibre-optic cable systems [Glockling, Edwards, 2007] using pulsed laser backscatter methods can now report temperature every metre along 20 km of cable making it immensely efficient. Easily positioned to cover surfaces and equipment alike, the technology is particularly well suited to supporting ‘AI’ learning systems due to the immense amount of data generated. Some fibre optic systems are capable of additionally measuring vibration adding another facet to their potential benefit.

The widespread use of fibre optics for data connectivity onboard modern vessels offers with minimal additional infrastructure the ability to potentially monitor every cable tray, every individually controllable piece of equipment, and thermally map every deckhead and bulkhead, the resolution of fire location identification could be enough to support highly targeted responses [Glocking, Doherty, 2008]. If appropriately positioned the system could also inform on flooding and flood progression from the air/water temperature interface differential.

In a similar vein, ultrasonic devices using a source and detector configuration are already used for the assessment of compartment sealing. It would not be a great technological step to develop these portable devices in fixed installation form that could report on loss of compartmentation from damage and thereby provide valuable input to the resolution of the event (whether more extinguishing agent is required, potential for fire spread etc.

A more detailed look at sensor innovation pertinent to the uncrewed situation will be the subject of a further paper.

7 Conclusions

Historically autonomous vehicles and drones have been used in a capacity where they might be considered disposable, low cost, small in size, and of technological low value, thereby negating the need for protection and resilience. As their development is steered towards undertaking critical front-line roles demanding larger, costlier and more technologically advanced platforms, this perception must change and there is a need to achieve equivalent levels of self-sustaining survivability and protection of sensitive information / engineering knowledge as their crewed predecessors. By their very nature, NASVs will be a sensor and data rich environment. Their value, both in terms of mission and cost, will drive a need for them to be resilient to internal and external challenges of fire. The removal of crew from the equation, whilst presenting challenges, also creates many opportunities for efficiencies, cost savings, and improvement in performance which should result in increased resilience in their ability to deliver their mission.

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9 Glossary

AHJ	Authority Having Jurisdiction
AI	Artificial Intelligence
CCTV	Closed Circuit Television
COMAH	Control of Major Accident Hazards
DSAC	Damage Surveillance and Control
HAZID	Hazard Identification Study
HAZOP	Hazard Operability Study
IR	Infrared
LNG	Liquified Natural Gas
LPG	Liquified Petroleum Gas
LSZH	Low Smoke Zero Halogen
MCAS	Machinery Control and Surveillance
NASV	Naval Autonomous Surface Vessel
NBC	Nuclear Biological Chemical
PMS	Platform Management System
QEC	Queen Elizabeth Carriers
UV	Ultra-Violet