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Submission to ECHA

High Temperature Effectiveness Issues to verify firefighting foam competency under realistic operational summer conditions.

Prepared for:

ECHA, RAC and SEAC Committees

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Note: *Reference documents are listed in numerical order at the end of this submission. Numbers are shown in the text relating to these specific reference documents, highlighted in red superscript, for easier visibility.*

High Temperature Effectiveness Issues

Questions about competency of our firefighting foams under high temperature conditions are increasingly being raised with Aviation Regulators globally - it has become a critical life safety issue, particularly around PFAS-free or Fluorine Free Foams (F3s). The adverse effects of more onerous high temperatures is gaining increased attention from repeated severe heat waves sweeping our planet over the last 5 years. The US

National Oceanographic and Atmospheric Administration (NOAA) declared "*July 2021 was the Earth's warmest month in recorded history* [since 1880]. *…July 2021 was 0.01°C*[0.018°F] *hotter than July in 2016, 2019 and 2020*". This submission is intended to provide the scientific evidence which provides justification for high temperature ICAO Level B and C certification for fire testing of firefighting foams in use at all Australian airports to become a regulatory requirement. It also raises important life safety questions which should encourage ECAH to reject this current PFAS Firefighting Foam Restriction proposal, and re-visit SEAC's final opinion, as it clearly suggests that FAA's public safety concerns are not limited to USA and should be considered b EU regulators as a life safety issue. 2022 is shaping up to be as hot as 2021, so action needs to be considered before a major catastrophe occurs in hot summer conditions. It also provides a sufficient evidence base for European Union Aviation Safety Agency(EASA) to raise these important issues directly with ICAO requesting a technical review and overhaul of the current ICAO fire test standard to better protect life safety and demonstrate best practice, as a matter of urgency. Particularly since EASA's 2022 stated mission[5] is: "*Your safety is our mission. EASA is the centre-piece of the European Union's strategy for aviation safety. Its objectives are:*

- *to promote and achieve the highest common standards of safety and environmental protection in civil aviation*
- *to ensure you have the safest possible flight*

We ensure that your flight is safe in all phases: beginning with the rules the airlines and crew need to follow through to the certification of the aircraft you are sitting in.
We regularly revise the risks and improve the common regulations applied among EU countries and airlines so they are always of the highest standard." Time to implement these objectives regarding firefighting foam safety.

Executive Summary

This Submission summarises evidence from the literature, much of it from peer-reviewed scientific research, confirming that firefighting foam performance is adversely impacted by higher temperatures (ambient, foam solution, substrate and fuel temperatures) and the effectiveness of the foam blanket is exponentially affected by the temperature of the foam, ambient temperature conditions, vapour pressure of the fuel, type of fuel and foam solution temperature. These issues do not seem to have been considered by ECHA, RAC or SEAC adequately, and could affect ECHA's decisions regarding PFHxA and high purity C6 foams, as they may be critical to saving lives in Aviation but also a broad range of other high risk industries with large volumes of flammable liquid fire hazards, where alternative PFAS-free or Fluorine Free Foams (F3s) may be inadequate in prevailing hot summer conditions.

Cooler conditions increase foam effectiveness

Research by Conroy and Ananth in 2015[14] confirmed that the cooler the foam blanket the more effective the fire control and cooling effect on the fuel, which was considered a new mechanism of fire extinguishment not previously understood. They investigated "***fuel surface cooling by the foam and the resulting reduction in fuel vapor pressure,*** ***which depends exponentially on the surface***

temperature*. We develop a model to* ***examine the surface cooling that occurs when a room-temperature foam layer comes in contact with a hot heptane liquid surface****.*" "***As a result of large temperature gradient between the foam and fuel layers, heat conducts very quickly from the fuel to the foam, which reduces the surface temperature of the fuel.***"
They established the cooler the foam applied, the more dramatic the fuel temperature cooling effect and the greater the assistance provided by that foam with rapid, effective extinguishment of the fire. This is also suggested as a reason why manufacturers always preferentially test foams at the lowest temperatures possible to maximise this rapid cooling effect to gain easier fire extinguishment. This paper[14] concludes "***In this work, we predict quantitatively that foam absorbs heat from the surface of a burning liquid pool immediately upon direct contact. The foam cools the hot fuel surface, reducing fuel vapor pressure and mass transport into the fire. Based on this principle, we propose a new fire-suppression mechanism that acts in conjunction with the well-known mechanism wherein the foam forms a physical barrier to the transport of vapor from the fuel surface into the fire***."

Further work by Ananth and Conroy in 2017[22] verified their modelling and concluded "***We propose that the very fast and significant vapor pressure reduction caused by cooling with foam could contribute strongly to suppression of pool fires by rapidly decreasing the fuel evaporation rate. The rapid effect of surface cooling could play an important role in knockdown of the flames in the initial stages of fighting a pool fire.***" Consequently, hotter foam solution temperatures will have an exponentially reduced effect, making fire extinguishment significantly harder and slower under hotter conditions. This research[22] also found that "***Flame extinction is impacted by other mechanisms, such as fuel transport through the foam, which would be reduced by surface cooling of the fuel. Reduced fuel transport through foam tends to enhance flame extinction***." This finding is particularly relevant to PFAS-free foams (F3) as they have no specific fuel repelling or vapour sealing additives, so may suffer greater disadvantages at higher ambient and foam solution temperatures.

Heat radiation effects increase foam destruction
Research by Persson in 1992[23] studied foam layer behavior when subjected to heat radiation. He found that "***Rates of evaporation from all foams were similar at 15g/min, kW, representing 65-75% of the incoming radiation was used in the evaporation of the foam.***" …"***Rate of drainage increased 2-3 times when subjected to heat radiation***."… "***The foam destruction increases rapidly from almost zero to approx. 0.5-1.5cm/min at 5kW/m^2.***" His findings continued "***With 'no radiation' all foams prevented ignition from a small pilot flame just above the foam layer for more than 30 mins. At 5kW/m^2 time to ignition for FP*** [FluoroProtein] ***foam was around 20mins while the D*** [Synthetic Detergent F3] ***and AFFF foams only reached 10-15mins. …At 35kW/m^2 time to ignition was reduced to only 5-6.5 mins across these foams.***" This research provides clear evidence that increased heat radiation produces premature destruction of all foam blankets, with limited variations.

Under the evaluation of heat effects on personnel the UK Health and Safety Executive (2022)[26] confirmed "***Escape is assumed at 5 kW m^{-2} but fatalities within minutes assumed at 12.5 kW m^{-2} and instantaneous death at 37.5 kW m^{-2}.***"

A recent 2022 study by Youjie et al.[27] on thermal stability of firefighting foams at Xian university investigated adding silica nanoparticles (NPs) as a super stabilizer to improve resistance to heat breakdown compared to regular AFFF. This work confirmed that "***At 45°C, the bubbles of A-0#*** [regular AFFF] ***have been changed from an elliptical three-dimensional structure to a polygonal two-dimensional structure at 6 min, and the bubbles largely disappear at 8 min.***" It goes on "***The foam coarsening process at 85°C is similar to that at 45°C. The higher temperature results in the faster increase in bubble size and disappearance.*** *These results indicate that the addition of NPs significantly delays the foam coarsening under heat.*" It then explains ..."*Moreover, the foam lasting time during coarsening process is reduced.* ***This is because the higher the temperature is, the faster the evaporation of water vapor, and the corresponding bubbles quickly become thicker, larger, and quickly broken. The results show that NPs have a significant deceleration on the foam-coarsening rate under heat."***

2017 saw Hinnant et al.[29] also study the influence of fuel and its heating on foam degradation, confirming "***…heat from a fire can dramatically increase the rate of foam degradation through water evaporation***." ***…"Our results showed RF6 degraded faster than AFFF (by factor of 3 at room temperature*** [20°C] ***and 12 at elevated temperatures over fuel*** [50°C]***), which may contribute to differences in their firefighting performance." …"For all experiments F3 degraded much faster than AFFF."***

This was supported by earlier 1979 research by Geyer and his team[30], finding that "*since no aqueous film is produced by the protein-base* [PFAS-free] *agents,* ***the predominant factor defining firefighting effectiveness is foam quality, which is indicated in Figure 9 to rapidly deteriorate through the loss of liquid as it drains from the foam body at elevated solution temperatures***. … ***As the foam viscosity increases, the fluidity decreases, and the foam may become more difficult and time-consuming to distribute uniformly over a burning fuel surface***. ***Therefore, excessively high or low water temperatures are to be avoided***."

US Naval Research Laboratory's (NRL) 2017[29] foam degradation study found that "***As the fuel temperature is raised, there is a higher concentration of fuel vapors beneath the foam than at lower temperatures. This increased concentration at the foam interface can increase the amount of fuel transport through the foam, increasing the rate of foam degradation***."… "***The fuel temperature effect is by far the largest compared to the effect of different fuels*** *and surfactant formulations (including the additives). The effect of surfactant formulation is a close second relative to the temperature effect."* The surfactant formulation is presumably also important because the addition of specific fuel repelling additives assist with resisting fuel transport into and through the foam blanket, making it more durable and less vulnerable to attack. This was confirmed by a different NRL 2017 paper[76] measuring fuel transport in foams (break-through times are in seconds [s]) ***"**The fuel vapor break-through times are 276 s and 820 s for RF6 and AFFF respectively and are indicated by the "break-through flux" in Fig. 3 at a flux of 1.21e-10 mol /cm^{2}s* ***corresponding to 10 ppm of fuel vapor. …The large difference in the measured fuel flux between AFFF and RF6 shown in Fig. 3 can be due to differences in the composition of surfactant solution and in properties of the foams."*** Other research included confirms these room temperature results would be significantly worse under hot summer conditions.

The hotter the fuel the greater the concentration of fuel vapours which intensifies the fire. Hotter ambient temperatures can exceed a fuel's flashpoint temperature (Jet A1≥ 38°C) generating more fuel vapour creating more easily flammable conditions, ignitable or re-ignitable from a spark, burning ember or incandescent composite material. A 2012 FAA Report by Scheffey et al.[16] cautioned "***The exterior fire threat scenario must also be considered, involving exterior burning, which may require suppression by the initial ARFF response. There is also potential for re-ignition of a fuel fire from smoldering fuselage composites*."** Reference was made in this report[16] to a 2004 US AirForce fire test study conducted on two composite (AS4/3501-6 graphite/epoxy) wing boxes. "***After the second test fire was initially extinguished, the composite material flared up three times, requiring additional agent to extinguish the fire.***." It[16] also confirmed the US Navy had conducted fire tests on composite materials using *"3501-6/AS graphite epoxy carbon fiber used for F-8 fighter aircraft wings. As expected, the composite wing was much more resistant to burnthrough than an aluminum wing.* ***It was found that this composite would self-sustain combustion in as little as 2.5 minutes of exposure to an external pool-type fire****."* It continued *" The pool fire was easily extinguished in all tests. However,* ***extinguishment of the composite combustion was not as easy. The surface flames were readily extinguished, but smoldering composite combustion was already established. To extinguish the smoldering composite combustion, the fire fighters applied a continuous stream of AFFF directly on the composite material*. *After applying AFFF for 3 minutes or more, the smoldering composite combustion was extinguished****."*

A 1988 study by Briggs and Webb at UK Fire Research Station[31] made modifications of UK Defence specification 42-24 using different fuels and increasing the impact velocity to approx. 6m/sec to better mimic reality in major fires. They shrewdly observed "***Our concern relates to the possibility that foam agents formulated to meet existing specifications may show disturbing weaknesses in difficult firefighting conditions****."* Consequently, their future testing included previously missing criteria to provide*"… a representation of the more severe type of firefighting conditions.* ***While these conditions are not met every day, a severe test provides reassurance for 'difficult' fires and a margin of safety for less demanding usage***." This testing also raised concerns regarding **"*The effect of weather variations which can prevent meaningful comparison of outdoor fire tests*"**. Suggesting 'Convenient' test temperatures can fail to adequately represent realistic operational firefighting conditions, unless specifically required to be conducted to verify adequacy and effectiveness under prevailing operational weather conditions. *"The most striking pair of results related to a well-established AFFF.* ***When applied to heptane fire under these conditions control and extinction***

times were best of series. When applied to Avgas fire under same conditions, no extinction was obtained*, the foam blanket continued to burn and when foam application ceased, the blanket burned away*. ***<u>A further significant discovery was this result could be reproduced with initial fuel temp at 18ºC, but with fresh avgas from cold overnight storage (8ºC) extinction was obtained.</u>***" Clear evidence that higher ambient fuel temperatures can have a significant impact on reducing a foam's firefighting performance.

Further research in 2018 by Lu, Wang and team[32] from Hunan University also adds relevance from their studies of high temperature resistance. They studied the influence of temperature on foam morphology, stability and viscosity. The experimental results were shown in Fig. 5 which confirmed that 'super stabilised' aqueous foam can be stable at 25ºC and 80ºC with the foaming height basically unchanged. But "***When the temperature rises to 135ºC it began to have a small amount of water evaporation and the foaming height began to decline; When the temperature is 190ºC the foaming height decreases slowly. When the temperature is 245ºC the moisture inside the foam begins to evaporate and the foaming height began to show an accelerated downward trend. When the temperature is 300ºC the internal structure of the foam system is destroyed, loads of water is evaporated, and the foaming height starts to decrease rapidly***." So even though 'super-stabilised', foam degradation occurs 'in slow motion' as higher temperatures occur. A critical point still arrives at which foam degradation occurs rapidly. They confirm with regular foams this degradation occurs at much lower temperatures.

<u>Key aromatics attack PFAS-free foams</u>

Land-mark 2019 NRL research by Snow, Hinnant et al.[33], found that **four leading commercial F3s fire tested on gasoline, required between 2.5 times more and over 6 times more F3 than the benchmark C6AFFF, when required to extinguish gasoline fires in 60 secs**. "*These differences widened as extinction speeds became faster*." Further investigation showed "***Individual major components of gasoline were tested, and the aromatic components were determined to be the source of this difficulty in gasoline fire suppression. This effect substantially increased with the number of methyl substituents (TriMethyl Benzene > Xylene > Toluene > Benzene). This aromatic gasoline component effect correlated with extraction of surfactants across the water-fuel interface*** [into the fuel] ***and in the same order of aromatic compound effectiveness***." Essentially these aromatics prematurely attacked the F3 foam blanket, unprotected by fuel repelling additives. These aromatics are absent in the widely used fire approval test fuel heptane (eg. EN1568-3, ISO7203-1, UL162, Lastfire, FM 5130, IMO), which seem to provide a distorted 'better than reality' impression of F3s ability on flammable fuels like gasoline, than actually exists. Interestingly compositional analysis for Jet A1 fuel[35] confirms these same key aromatics are also present in Jet A /Jet A1 (and its military equivalent JP-8), but at lower concentrations than gasoline. This may help to explain why F3s often struggle with Jet A1 fires under ICAO Level B and C, to the extent that the previous 60second extinguishment time has to be extended to 120secs to allow for persistent edge flickers frequently found when F3s were tested. This NRL testing[33] also found with F3s that "***A plot***

of foam height vs time depicts significant foam degradation differences between the heptane and gasoline fuels."

Flashpoint significance

Flashpoint is not always well understood. Encyclopedia Britannica[34] defines it as: *"the lowest temperature at which a liquid (usually a petroleum product) will form vapour in the air near its surface that will 'flash' or briefly ignite, on exposure to an open flame."* Jet A1 has a flash point temperature of ≥38˚C, so when fuel is exposed above 38ºC ambient temperature conditions (as experienced widely across Australia as BOM data[12] verifies), vapours are increasingly given off making it more volatile, so sufficient vapours are present immediately for ignition to occur and be sustained in response to a spark, match, incandescent cigarette end or composite glowing ember. Once vapourised, JetA1 is extremely flammable and reportedly burns at a much higher temperature than some other fuels. When foam is introduced, Hinnant et al. 2017 NRL research[29] confirmed that as the temperature and vapour concentrations above the liquid fuel increase, more of the fuel vapour will tend to dissolve into the foam blanket. High ambient temperatures are known to prematurely dry out foam blankets impeding fluidity and increasing protective foam blanket breakdown.

A 2011 Hughes Associates Report for US Department of Justice[36] confirmed "*results demonstrated that it is not the depth of fuel that impacts the peak mass burning rate but the quantity of fuel available to burn (ie. burn long enough to achieve a steady state)*" …"*Typically, when discussing the impact of a substrate on the mass burning rate of a fuel, it is assumed that the substrate is acting as a heat sink (i.e., removing heat from the fuel layer), thus reducing the peak burning rate.* ***However, a small subset of tests in which the fuel substrate was heated to temperatures greater than ambient conditions demonstrates that an opposite affect can occur and have significant impact***. ***These tests, while limited, showed that an elevated substrate temperature can increase the peak mass burning achieved during a spill fire scenario***."

This confirms hot tarmac, concrete or metal surfaces under hot summer conditions can increase the intensity and severity of a spill fire, making it harder and therefore also slower for foams to control and extinguish the fire. It may also make sudden unpredictable flashbacks more likely to occur.

Disturbing weaknesses with current approval tests draw misleading asumptions

Concerns recently raised over inadequacies of ICAO Level B and C fire tests at Australian Civil Aviation Safety Authority's regulatory review of its Aviation Rescue and FireFighting Services (ARFFS), has highlighted that requirements are missing to ensure firefighting foams in use are verified competent under hot summer temperature conditions at or above 40ºC, because ICAO Level B and C fire tests are conducted at close to 15ºC, which does not adequately cover firefighting foam effectiveness at 40ºC or above during hot summer conditions, increasingly being experienced across Europe, USA as well as Australia, parts of Asia in recent years, alongside historically the Middle East, where fluorinated foams have dominated Aviation firefighting over decades, until quite recently.

We rely on key fire test approvals to verify acceptable fire performance, like ICAO Level B and C fire tests conducted close to 15°C (59°F) and US MilSpec qualification testing requires around 18-20°C (64-68°F), so how do we know these approved foams will be equally effective at 40°C(104°F), or above? Short answer is: we don't, without specific verification testing to ensure competency. It raises similar questions for all other approval test standards, none of which have specific high temperature verification requirements, including EN-1568-3, Lastfire, ISO-7201-3, UL-162, FM-5130 etc, which also seem deficient and should be addressing this important issue. Some evidence of competency for effectiveness under their duty of care seems essential, to adequately safeguard life safety, not just by Aviation regulators, but other regulators and major firefighting foam users, including ECHA, EASA, and European Commission, to ensure lives, including firefighters, operational plant personnel, flight crews, nearby communities and the travelling public are all safeguarded from increased risk of harm. It seems imperative to ensure their lives are not being compromised during major aircraft, military, offshore platforms, or major industrial, or port/shipboard fires during hot summers, …potentially spreading to cover large parts of our planet?

These concerns are not new, but growing in importance. Briggs and Webb's 1988[31] research highlighted "***Our concern relates to the possibility that foam agents formulated to meet existing specifications may show disturbing weaknesses in difficult firefighting conditions***. *Specifically, we are concerned that* ***a foam may "saturate" with fuel, and a would-be protective foam blanket would sustain combustion and be destroyed***. *Because of this concern, the investigation has been biased to a representation of the more severe type of firefighting conditions. While these conditions are not met every day, a severe test provides reassurance for "difficult" fires and a margin of safety for less demanding usage*."
Fuel variability was also tested confirming *"**heptane is undesirable as a general purpose test fuel as it shows no differences of behaviour where they are known to exist in commonplace incidents**. Uniquely among low flashpoint fuels heptane was extinguished by a simple protein* [fluorine free] *foam*." Findings concluded "***Real-life situations and large-scale trials have shown that some foams offer poor security to the extent that burnback has been known to occur while application is still taking place; i.e., fire control has been lost."***

These findings regarding heptane were clearly re-inforced by NFPA Research Foundation's 2020 comparative fire testing Report[38] where five UL listed F3s were studied "***To summarize the results, the baseline C6 AR-AFFF demonstrated consistent/superior firefighting capabilities through the entire test program under all test conditions***. ***For the FFFs*** [F3s] ***in general, the firefighting capabilities of the foams varied from manufacturer to manufacturer making it difficult to develop "generic" design requirements***." …"***The FFFs did well against heptane but struggled against some of the scenarios conducted with IPA and gasoline (both MILSPEC and E10*** [gasoline with 10% ethanol added]***), especially when the foam was discharged with a lower foam quality/aspiration***." … *"**During the Type III*** [forceful] ***tests, the FFFs required between 3-4 times the extinguishment density of the AR-AFFF for the tests conducted with MILSPEC gasoline*** [standard unleaded] ***and between 6-7 times the density of the AR-AFFF for the tests conducted with E10 gasoline***." Report findings confirmed ***"The results also show that the legacy fuel (heptane) used to list/approve foams, may not be a good surrogate for all hydrocarbon-based fuels."***

Disturbingly similar results from FAA's (US Federal Aviation Administration) 400 comparative F3 fire tests in Sept. 2021[57] led to FAA's Oct. 2021 Cert Alert 21-05[58] raising public safety concerns with F3s stating "*While FAA and DoD* [Department of Defense] *testing continues,* ***interim research has already identified safety concerns with candidate fluorine-free products*** [F3s] ***that must be fully evaluated, mitigated, and/or improved before FAA can adopt an alternative foam that adequately protects the flying public****.* ***The safety concerns FAA has documented include:***

- ***Notable increase in extinguishment time;***
- ***Issues with fire reigniting (failure to maintain fire suppression); and***
- ***Possible incompatibility with other firefighting agents, existing firefighting equipment, and aircraft rescue training and firefighting strategy that exists today at Part 139 air carrier airports*.**

While FAA and DoD continue the national testing effort, the ***FAA reminds all Part 139 airport operators that while fluorinated foams are no longer required, the existing performance standard for firefighting foam remains unchanged (whether that foam is fluorinated or not)****."*

FAA extensively tested**[57]** 19 x PFAS-free foams (F3s – 9 commercially available and 10 developmental) concluding; "***Approx. 400 fire tests have been conducted; NONE passed MilSpec or ICAO Level C***" consequently they "***Conducted ICAO Level C tests both outside and inside because of test results***" So ALL F3s tested failed to pass either ICAO Level C or MilSPec fire tests indoors in FAA's latest $5m 'state-of-the-art' fire test facility. They also all failed ICAO Level C protocol when re-tested outdoors, which may have been slightly easier to pass. 13 of the 21 (62%) F3s tested against ICAO Level C protocol did not extinguish within 2 mins. On MilSpec's 30sec extinguishment requirement, F3 results ranged from a 38sec result to 2mins 23secs, two agents did not extinguish and 6 of 9 (66%) F3s failed the burnback testing,

Recent 2022 Swedish testing of eleven F3s by Dahlbom et al.[59] found *"****None of the products in the study met the fire test performance requirements in all the referenced standards*** *(cf. Table 11). Instead,* ***the products seem to have different niches where they perform best*** *eg. types of fuel and water.* ***This highlights the importance of testing in an environment as close to reality as possible****."* Concluding "***All in all, this means that the expansion ratio and the drainage time measured at ambient*** [room temperature] ***conditions should not be used alone to predict the fire performance of a firefighting foam****."*

The NFPA Research Foundation's May 2022 Fire Service Roadmap[60] to an F3 transition confirmed ***"The new fluorine-free foams are similar to the legacy protein foams in that they rely solely on the foam blanket to contain the fuel vapors to extinguish the fire (i.e., fluorine-free foams do not produce a surfactant film on the fuel surface like AFFF). As a result, air-aspirating discharge***

devices may be required to optimize the capabilities of these products." The 'Roadmap' goes on "***Foams have been developed almost entirely from experimental work. Although many of the technologies are rather mature, no fundamental explanations of foam extinguishment performance have been developed based on first principles. As a result, the fire protection industry relies heavily on the approval tests for defining the capabilities of the foam as well as the extrapolation of these test results to actual applications by applying factors of safety to the test results***." The evidence provided in this document covers at least some relevant 'first principles testing'. The implication from this roadmap being that safety factors have principally been developed based on foams widely in use over the last 50 years eg. AFFFs and FPs, not current F3s, and at cooler 'room' temperatures. Existing safety factors may not be adequate for current FPAS-free foams (F3s) which behave more like those traditional basic Protein foams (confirmed above), which generally require higher application rates and larger safety factors, which may not be included for use of F3s against current standard test protocols like ICAO, when designed with AFFFs in mind – but neglecting required effectiveness during hot summer conditions. It also addresses concerns that "***In addition, fuel type is a significant variable and needs to be considered during testing and foam selection***. *It needs to be noted that these approval tests are not designed to simulate actual full-scale fire scenarios but rather to provide a means to assess the capabilities of these products on an affordable and reproducible scale using many of the parameters/conditions that makeup the industries' Maximum Credible Event (MCE)*." …" ***For the DoD, the design fire includes an aircraft rescue and firefighting (ARFF) scenario that includes a fuel spill under the aircraft that exposes the weapons to fire. This fire needs to be quickly controlled and extinguished to prevent ordnance cookoff. The aviation industry has a similar scenario except the hazards are associated with the burn-through of the fuselage that jeopardizes the occupants of the aircraft. Both the DoD and aviation industry scenarios have well defined fire scenarios (i.e., fuel types and minimal depth spill fires)***." For both DoD and the aviation industry **'time is of the essence'** in providing rapid fire control, extinguishment and life-saving evacuation and rescue. Therefore, ANY delays to expected firefighting effectiveness could cost lives. Potentially many lives in a credible wide-bodied civil aircraft major credible fire event could be 'sacrificed' by such delays in fire control and extinguishment.

This 'Roadmap'[60] provides some important cautions "*There are many very effective FFFs on the market and in use today.* ***However, it is incorrect to assume that these new FFFs are a "drop in" replacement for AFFF even though they may have a specific listing or approval. At this time, there is too much difference between specific FFF's in properties and performance to suggest that the class can be a drop in replacement for the AFFF class of foams. Specific FFF foams maybe used in place of existing specific AFFF foams in fixed systems or portable application, but a detailed evaluation must be completed prior to making that transition*** *as described in this document.* ***Ultimately, end users will need to design and install within the listed parameters in order to ensure a high probability of success during an actual event. This applies to both the discharge devices and proportioning system***." It also includes elevated summer temperature conditions in Australia and elsewhere.

A list of 19 specific weaknesses are raised (Section 9.3) with the current ICAO fire test standard, providing evidence and comparison against current rigorous industry leading US MilSpec requirements. These same safety factor considerations also apply to, but seem missing from most other test standards like EN-1568-3, Lastfire, ISO-7203-1, UL-162, FM-5130, IMO etc.

Additional important evidence is derived from actual major fire incident reports[37,39-50]. Few exist where it has been reliably verified that PFAS-free foams (F3s) were extensively used, so our experience with these alternative agents is still limited, but give cause for significant concerns Two such F3 fires: a Boeing 777 in Dubai[37] and a major chemical fire in Melbourne[40-48] show disturbing effects, when compared to broadly 'similar' fires (a Boeing 777 fire in Singapore[39] and chemical fire in UK[49.50]) where F3s were not used. Additional evidential consideration of response times, composite materials and Practical Critical Areas (PCA) are also included, further raising concerns about the efficacy of F3s in hot summer conditions.

This extensive scientific evidence base provides sufficient justification for ECHA to reconsider a high temperature verification requirement in its PFHxA and PFAS firefighting foam restriction proposals. It also justifies ECHA/EASA raising these issues directly with ICAO, requesting their review and overhaul of current Level B and C approval standards, as well as EN1568-3, ISO7203-1, Lastfire, IMO etc. This should ensure that best practice is achieved and these currently exposed life safety issues for the travelling public and nearby communities can be swiftly addressed by improved fire testing and safeguarding protocols, which this evidence confirms are currently exposed to a series of potential catastrophes.

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1. Background

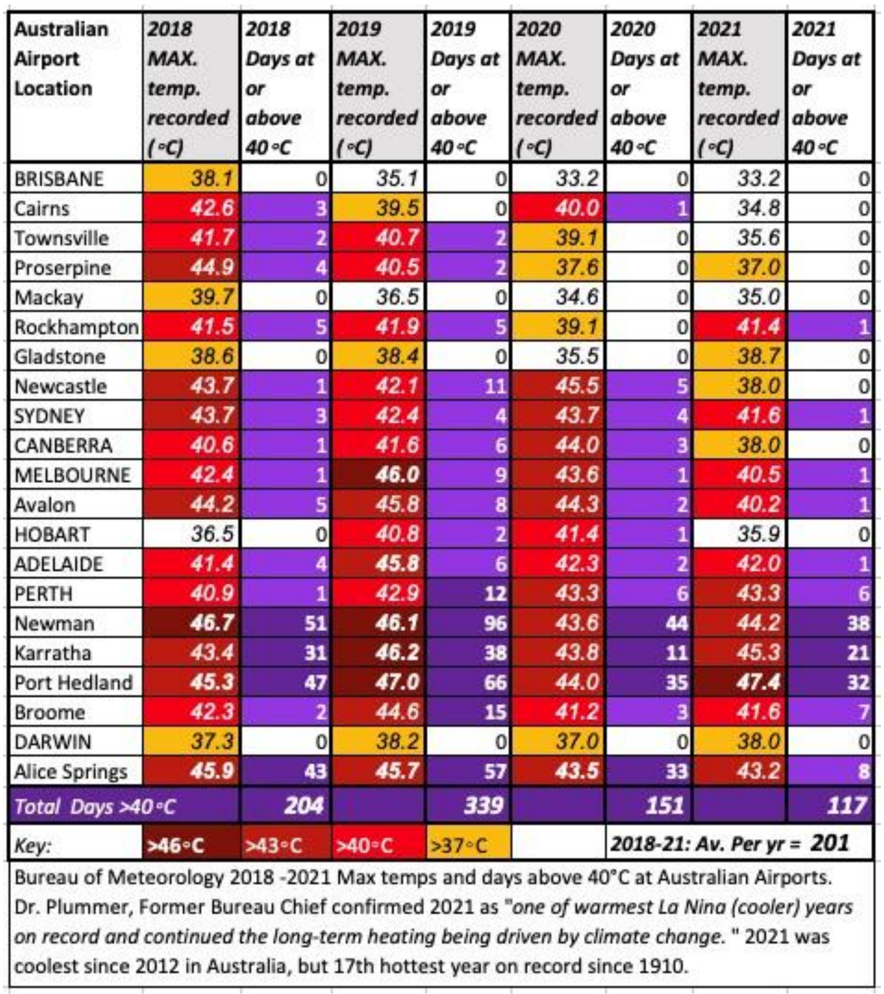
Increasing questions about competency of our firefighting foams under high temperature conditions are being raised with Aviation Regulators globally - it has become a critical life safety issue. The adverse effects of more onerous high summer temperatures is gaining increased attention from repeated severe heat waves sweeping our planet over the last 5 years, and affects all sectors using firefighting foams for volatile and flammable fuels including:

- Refineries and Chemical/Pharmaceutical Plants.
- Storage and Distribution Facilities, Tank Farms & Terminals, including jetties/marine terminals.
- Flammable liquids in transit by rail, pipeline or road/ship tankers.
- Airports, helipads, helidecks, offshore platforms, production vessels, and major transportation hubs.
- All military applications.
- Continued Use in existing Fixed Foam systems (*where alternatives could compromise life safety and critical infrastructure protections relied upon by the system design*).

These high temperature impacts do not seem to have been given adequate consideration by RAC and SEAC in the recent PFHxA firefighting foam restriction proposal, nor in the current PFAS firefighting foam restriction (ban) proposal, so ECHA is urged to take these matters seriously and re-consider their position before lives are lost in potentially avoidable catastrophic disasters.

The US National Oceanographic and Atmospheric Administration (NOAA)[1] declared "*July 2021 was the Earth's warmest month in recorded history* [since 1880]. …*July 2021 was 0.01°C*[0.018°F] *hotter than July in 2016, 2019 and 2020*". Reports confirmed Death Valley, California recorded 54.4°C(130°F), Lytton in Canada 49.6°C(121°F), Syracuse, Italy 48.8°C(120°F), Spain 47°C(116°F), Turkey 49.1°C(120°F), and Taiwan 40.6°C(105°F). This heat wave lasted two to three weeks across parts of Italy, Greece and Turkey with devastating wildfires burning 800,000ha. (3,089 square miles). Other areas experienced $53billion flood damage across Germany, Belgium, China, India and East Asia, killing 240 people in Europe, with 325 lives lost in China. Can our Airport Rescue and Firefighting Services (ARFFS), plus other firefighting responders to different sectors, still rapidly extinguish aviation (and other flammable liquid) fires under these hot conditions? …and how do we know? There is no adequate verification, particularly for the more vulnerable F3s to adequately safeguard lives.

2022 is shaping up to be similarly hot, with heat waves reported across Europe and US in June and July. Phoenix Arizona recorded 46^{o}C(114^{o}F), Nebraska 42^{o}C(108^{o}F), Spain experienced 45^{o}C(113^{o}F), Portugal 47^{o}C(116^{o}F), Japan 40^{o}C(104^{o}F), Italy 41^{o}C(106^{o}F), Croatia 40.4^{o}C(105^{o}F), even arctic Norway glowed in 30.8^{o}C(87.4^{o}F). London's Heathrow airport hit a record 40^{o}C(104^{o}F), France saw 39^{o}C(102^{o}F) with worries of a possible repeat of the 2003 heatwave when 15,000 people were estimated to have died.



Australian Airport Location	*2018 MAX. temp. recorded (◦C)*	*2018 Days at or above 40◦C*	*2019 MAX. temp. recorded (◦C)*	*2019 Days at or above 40◦C*	*2020 MAX. temp. recorded (◦C)*	*2020 Days at or above 40◦C*	*2021 MAX. temp. recorded (◦C)*	*2021 Days at or above 40◦C*
BRISBANE	38.1	0	35.1	0	33.2	0	33.2	0
Cairns	42.6	3	39.5	0	40.0	1	34.8	0
Townsville	41.7	2	40.7	2	39.1	0	35.6	0
Proserpine	44.9	4	40.5	2	37.6	0	37.0	0
Mackay	39.7	0	36.5	0	34.6	0	35.0	0
Rockhampton	41.5	5	41.9	5	39.1	0	41.4	1
Gladstone	38.6	0	38.4	0	35.5	0	38.7	0
Newcastle	43.7	1	42.1	11	45.5	5	38.0	0
SYDNEY	43.7	3	42.4	4	43.7	4	41.6	1
CANBERRA	40.6	1	41.6	6	44.0	3	38.0	0
MELBOURNE	42.4	1	46.0	9	43.6	1	40.5	1
Avalon	44.2	5	45.8	8	44.3	2	40.2	1
HOBART	36.5	0	40.8	2	41.4	1	35.9	0
ADELAIDE	41.4	4	45.8	6	42.3	2	42.0	1
PERTH	40.9	1	42.9	12	43.3	6	43.3	6
Newman	46.7	51	46.1	96	43.6	44	44.2	38
Karratha	43.4	31	46.2	38	43.8	11	45.3	21
Port Hedland	45.3	47	47.0	66	44.0	35	47.4	32
Broome	42.3	2	44.6	15	41.2	3	41.6	7
DARWIN	37.3	0	38.2	0	37.0	0	38.0	0
Alice Springs	45.9	43	45.7	57	43.5	33	43.2	8
Total Days >40◦C		**204**		**339**		**151**		**117**
Key:	>46◦C	>43◦C	>40◦C	>37◦C		*2018-21: Av. Per yr = 201*		

Bureau of Meteorology 2018 -2021 Max temps and days above 40°C at Australian Airports. Dr. Plummer, Former Bureau Chief confirmed 2021 as "*one of warmest La Nina (cooler) years on record and continued the long-term heating being driven by climate change.* " 2021 was coolest since 2012 in Australia, but 17th hottest year on record since 1910.

2019 was hotter in the Southern Hemisphere, where 21 Australian airports recorded 339 days at 40-47^{o}C(104-116^{o}F), some across 6 months (based on Government Bureau of Meterology data). Eight of those airports recorded >44^{o}C(111^{o}F), Including 46^{o}C(114^{o}F) in Melbourne. It raises a critical question: **Are Airport firefighting foams proven fit for purpose under such prevailing hot summer conditions? …how do we know?**

We rely on key fire test approvals to verify acceptable fire performance, like ICAO Level B and C fire tests conducted close to 15^{o}C (59^{o}F) and US MilSpec qualification testing requires around 18-20^{o}C (64-68^{o}F), so how do we know these approved foams will be equally effective at 40^{o}C(104^{o}F), or above? Short answer is: we don't, without specific verification testing to ensure competency.

Australian regulatory requirements and those of EASA and ICAO do not currently seem to adequately address critical fire performance verification requirements which were raised by the 2019 Senate inquiry[2], and cannot be met by "*an optional high temperature foam fire test*", as proposed to meet these recommendations.

The function of ARFFS for aerodromes are widely recognised as being defined as being to: "

a) ***Rescue persons and property from an aircraft that has crashed or caught fire during landing or take-off; and***

b) to control and extinguish, and to protect persons and property threatened by, a fire on the aerodrome, whether or not in an aircraft. "

Yet there is no current, or proposed, regulatory requirement to verify ***clauses a and b*** *above* are being met, which can be provided by ARFFS during prevailing hot summer conditions across Europe, or indeed Australia.

Therefore, maintaining alignment with the ICAO Annex 14 SARPS, wherever possible, should remain a key priority. For aviation regulators.

Under Section 9.2 Rescue and Firefighting, ICAO Annex 14[3] confirms "***The most important factors bearing on effective rescue in a survivable aircraft accident are: the training received, the effectiveness of the equipment and the speed with which personnel and equipment designated for rescue and firefighting purposes can be put into use***." This suggests some verification is required regarding the effectiveness and competency of the equipment or 'tools' used in ARFF and response times, which critically includes the firefighting foam agent.

ICAO's website 'About ICAO'[4] confirms this is not controlled by ICAO as many misleadingly assume, clearly stating "***The stipulations ICAO standards contain never supersede the primacy of national regulatory requirements. It is always the local, national regulations which are enforced in, and by, sovereign states, and which must be legally adhered to by air operators making use of applicable airspace and airports.***

Contrary to many dramatic and media portrayals of UN agencies [ICAO is operated under United Nations], *they do not have any authority over national governments in the areas of international priority they are established for.* ***…ICAO is therefore not an international aviation regulator,*** *just as INTERPOL is not an international police force*."

Therefore, there is no restriction from ICAO's viewpoint in Aviation regulators going beyond ICAO's minimum requirements to meet necessary verification of fire performance competency under more onerous prevailing summer temperature conditions being experienced in Europe, Australia and elsewhere.

The Australian 2019 Senate Inquiry **Recommendation #3**[2] was amongst the first to recognise the importance of this issue by calling for: "*Instituting a testing program* [or certificated requirement] *for firefighting foams in use at Australian airports, utilising the ICAO testing framework as a starting point,* ***to determine the efficacy of the foams under Australia's unique conditions, particularly high ambient temperatures,*** ***<u>to establish whether the foams operate effectively to extinguish aviation fires.</u>***"

The Australian Government's response in its Nov.2019 Report[6] fully accepted Senate Inquiry Recommendation #3, requiring: *"**The updated ARFFS regulatory framework will require ARFFS providers to undertake a strengthened testing regime of operational foam,** noting it is not CASA's role to implement a testing program, but rather regulate the testing process.* ***This will include a full range of performance tests <u>which will better simulate Australian conditions, due to the varied environmental conditions that may exceed the minimum test criteria specified by ICAO</u>.****"*

This wording is very clear and unambiguous. Government (CASA's employer) requires that CASA's updated ARFFS regulatory framework **<u>WILL</u>** require ARFFS providers to undertake a **strengthened testing regime** of operational foam which **<u>WIL</u>L better simulate Australian conditions that may <u>exceed the MINIMUM</u> test criteria specified by ICAO.** Other regulators may also need to consider strengthening their own regulations to provide adequate passenger life safety during hot summer conditions.

So going beyond current ICAO Level B and C minimal requirements is NOT optional, and is not stated as an obstacle by ICAO who are not the civil aviation regulator. Government expects this to become a regulatory requirement, **which requires implementation in these revised regulations to protect public safety**. So why is CASA objecting so strongly to this without clear operational safety justifications? Especially when this is so **clearly an important LIFE SAFETY issue**.

Airport operators like Airservices Australia have confirmed quite reasonably that ***"Airservices only conduct the mandatory foam testing required by the regulations."*** Why would they, or any other operator, conduct extra testwork that is not required by the regulations?

Consequently, there is no confirmation from the Australian operator (and presumably EASA) that this high temperature competency requirement has been currently verified, …***<u>so it remains unclear</u>*** **whether current foams *<u>can or cannot</u>* extinguish fires effectively under these prevailing hot summer conditions?**

<u>Evidence this can be achieved (by regulatory requirement) is a critical life safety objective for Aviation Regulators, in discharging their duty of care to the travelling public, flight crews, firefighters and other emergency responders, involved in major fires during summer at these 21 Australian airports (possibly more in future). Similarly ECHA should consider these implications, before they</u>

accept a complete ban on PFAS in firefighting foams, as they seem instrumental in providing adequate security for saving lives under prevailing hot summer conditions. It is probably the only way **to verify that existing operational foams (especially F3s) do meet these realistic fire conditions, ensuring effectiveness, reliability and competency - now and into the future** – ***hence it's consideration in this proposal seems imperative.***

It is therefore strongly suggested that regulators should be required to: "***Introduce specific requirements for foam testing, including foam proportioning accuracy, expansion, drainage and high operating temperature characteristics relating to foam quality affecting fire performance, with manufacturer's independent verification that the foam operates effectively and reliably to extinguish ICAO Level B or C aviation fires when conducted under ≥40°C prevailing temperatures, representing Australian summer conditions, to provide continued safety for passengers, crew and firefighters at all Australian airports***." …or words to this effect.

This requires minimal input from regulators, as it doesn't require them to conduct any testing (as the Australian Government also suggested was unnecessary), **preferring the requirement of foam manufacturers to provide verification that the foam being provided meet regulatory requirements by also passing ICAO Level B or C fire test under prevailing ≥ 40°C summer conditions, as a pre-condition to its use at European Airports**.

This suggests peer-reviewed scientific evidence of the facts is required to justify that firefighting foams do suffer fire performance issues during high temperature operations, and this is not just 'opinion', which is a key objective of this submission. ECHA and EASA are urged to provide their support for recommending to ICAO that its firefighting foam fire test standards are upgraded accordingly to ensure travellers life safety is adequately protected under increasingly severe prevailing summer temperatures.

Aviation safety regulators are moving towards 'outcome-based regulations' allowing service providers more flexibility in providing their services. Such '**outcome-based regulations' do not lead to a less safe situation**.

2. Rationale Objectives

The Rationale for this submission delivers a summary of significant additional peer-reviewed scientific literature evidence, further justifying the requirement for high temperature fire performance testing, and continued use of C6firefighting foams to safely deal with major aircraft incidents under prevailing hot summer conditions being experienced across Europe. The evidence base increasingly shows F3s are unlikely to be adequately reliable and effective in saving lives under such onerous conditions now being experienced in EU.

It also justifies regulators recommending inclusion of this important high temperature fire performance testing requirement to ICAO directly, in a revision of ICAO's Airport Services Manual[11] (Clause 8.1.8) firefighting foam fire test method for performance Level B and C fire test standards, along with other weaknesses clearly identified in Section 9 below.

3. No regulatory mechanism exists to verify ARFFS foam competency during summer

A regulatory mechanism to ensure fire performance competency by firefighting foams in Australia is NOT currently provided, but is clearly essential to verify year round effectiveness at all Australian airports.

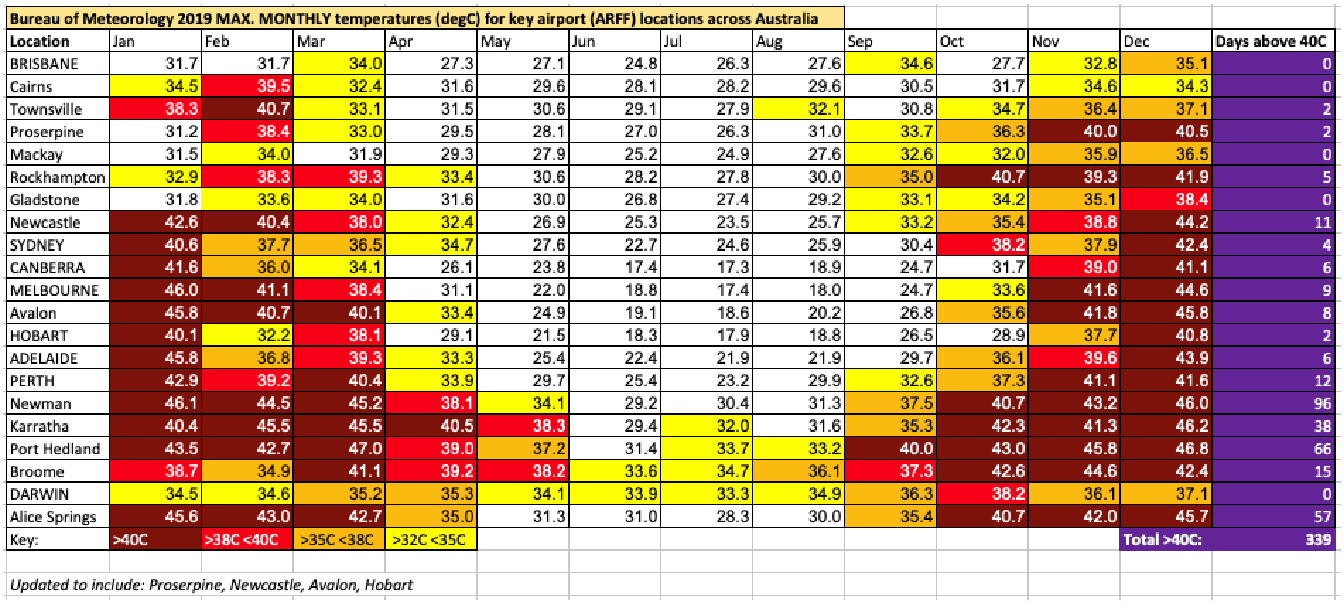
Airport Operators, Regulators, ARFFS personnel and the travelling public currently have no way of confirming whether existing foams can achieve or demonstrate effectiveness across the prevailing conditions experienced at Australian airports by ARFFS, year round at all Australian airports. Such a requirement is currently missing from CASA regulations. Therefore verification of firefighting foam competency under prevailing conditions at Australian airports year round, is not being adequately regulated, exposing lives to unnecessarily increased danger, particularly under severe summer conditions. This can be simply remedied by inclusion of a fire performance test conducted under such 40^{o}C or above conditions, in these revised regulations. A regulatory requirement for certification by foam manufacturers to verify high temperature fire test performance of any foam used by ARFFS at airports globally (where ICAO standards are adopted – incl. EU), to meet ICAO Level B and/or C under ambient and foam temperature conditions ≥40^{o}C, should form a key part of addressing this inadequacy by its inclusion in revised Aviation regulations, also requiring acceptance from the chemicals regulator – ECHA that effective foams can still be responsibly used for major aviation emergencies. This could easily be achieved by requiring foam manufacturers to provide a second independently witnessed high temperature ICAO Level B fire test certificate alongside the existing 15^{o}C ICAO Level B certification, as evidence of this extra fire test requirement, conducted under ambient conditions and foam solution temperatures at or above 40^{o}C using the ICAO Level B or C protocol with Jet A1 fuel with full details recorded on the independent test certificate provided by the foam manufacturer to verify compliance. This would be a minor extra regulatory requirement, beyond the minimum current ICAO certification (where certification testing is inadequate - usually at or close to 15^{o}C), accepted by ICAO (confirmed in its statements under 'About ICAO'[4]) as necessary to adequately reflect operational conditions in Australia. Using Jet A1 fuel under the ICAO fire testing conditions clause 8.1.8.3[11] would require air and foam solution temperatures to be ≥ 40^{o}C (with fuel and water base temperatures also recorded close to 40^{o}C) to ensure adequate reflection of summer operational conditions across much of Europe.

Otherwise regulatory requirements for due diligence by operators seem compromised, and lives of flight crew, firefighters and the travelling public are being unnecessarily exposed to potential increased risk of loss during a major summer emergency fire - simply because existing firefighting foams (fluorinated and non-fluorinated) are currently not verified as effective under these prevailing hot summer conditions.

The US National Oceanographic and Atmospheric Administration (NOAA)[1] declared "*July 2021 was the Earth's warmest month in recorded history* [since 1880]. …*July 2021 was 0.01°C*[0.018°F] *hotter than July in 2016, 2019 and 2020*". Reports confirmed Death Valley, California recorded 54.4°C(130°F), Lytton in Canada 49.6°C(121°F), Syracuse, Italy 48.8°C(120°F), Spain 47°C(116°F), Turkey 49.1°C(120°F), and Taiwan 40.6°C(105°F). This heat wave lasted two to three weeks across parts of Italy, Greece and Turkey with devastating wildfires burning 800,000ha. (3,089 square miles). Other areas experienced $53billion flood damage across Germany, Belgium, China, India and East Asia, killing 240 people in Europe, with 325 lives lost in China. Can our Airport Rescue and Firefighting Services (ARFFS), plus other firefighting responders to different sectors, still rapidly extinguish aviation (and other flammable liquid) fires under these hot conditions? …and how do we know? There is no adequate verification, particularly for the more vulnerable F3s to adequately safeguard lives.

2022 is shaping up to be similarly hot, with heat waves reported across Europe and US in June and July. Phoenix Arizona recorded 46°C(114°F), Nebraska 42°C(108°F), Spain experienced 45°C(113°F), Portugal 47°C(116°F), Japan 40°C(104°F), Italy 41°C(106°F), Croatia 40.4°C(105°F), even arctic Norway glowed in 30.8°C(87.4°F). London's Heathrow airport hit a record 40°C(104°F), France saw 39°C(102°F) with worries of a possible repeat of the 2003 heatwave when 15,000 people were estimated to have died.

It is also particularly relevant at each of these 21 Australian airports where temperatures reach or exceed 40°C, sometimes across several months of the year, according to Bureau of Meteorology (BOM)[12] airport weather and climate data records for 2019 and the 2018-2021 summary, provided below:



Bureau of Meteorology 2019 MAX. MONTHLY temperatures (degC) for key airport (ARFF) locations across Australia

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Days above 40C
BRISBANE	31.7	31.7	34.0	27.3	27.1	24.8	26.3	27.6	34.6	27.7	32.8	35.1	0
Cairns	34.5	39.5	32.4	31.6	29.6	28.1	28.2	29.6	30.5	31.7	34.6	34.3	0
Townsville	38.3	40.7	33.1	31.5	30.6	29.1	27.9	32.1	30.8	34.7	36.4	37.1	2
Proserpine	31.2	38.4	33.0	29.5	28.1	27.0	26.3	31.0	33.7	36.3	40.0	40.5	2
Mackay	31.5	34.0	31.9	29.3	27.9	25.2	24.9	27.6	32.6	32.0	35.9	36.5	0
Rockhampton	32.9	38.3	39.3	33.4	30.6	28.2	27.8	30.0	35.0	40.7	39.3	41.9	5
Gladstone	31.8	33.6	34.0	31.6	30.0	26.8	27.4	29.2	33.1	34.2	35.1	38.4	0
Newcastle	42.6	40.4	38.0	32.4	26.9	25.3	23.5	25.7	33.2	35.4	38.8	44.2	11
SYDNEY	40.6	37.7	36.5	34.7	27.6	22.7	24.6	25.9	30.4	38.2	37.9	42.4	4
CANBERRA	41.6	36.0	34.1	26.1	23.8	17.4	17.3	18.9	24.7	31.7	39.0	41.1	6
MELBOURNE	46.0	41.1	38.4	31.1	22.0	18.8	17.4	18.0	24.7	33.6	41.6	44.6	9
Avalon	45.8	40.7	40.1	33.4	24.9	19.1	18.6	20.2	26.8	35.6	41.8	45.8	8
HOBART	40.1	32.2	38.1	29.1	21.5	18.3	17.9	18.8	26.5	28.9	37.7	40.8	2
ADELAIDE	45.8	36.8	39.3	33.3	25.4	22.4	21.9	21.9	29.7	36.1	39.6	43.9	6
PERTH	42.9	39.2	40.4	33.9	29.7	25.4	23.2	29.9	32.6	37.3	41.1	41.6	12
Newman	46.1	44.5	45.2	38.1	34.1	29.2	30.4	31.3	37.5	40.7	43.2	46.0	96
Karratha	40.4	45.5	45.5	40.5	38.3	29.4	32.0	31.6	35.3	42.3	41.3	46.2	38
Port Hedland	43.5	42.7	47.0	39.0	37.2	31.4	33.7	33.2	40.0	43.0	45.8	46.8	66
Broome	38.7	34.9	41.1	39.2	38.2	33.6	34.7	36.1	37.3	42.6	44.6	42.4	15
DARWIN	34.5	34.6	35.2	35.3	34.1	33.9	33.3	34.9	36.3	38.2	36.1	37.1	0
Alice Springs	45.6	43.0	42.7	35.0	31.3	31.0	28.3	30.0	35.4	40.7	42.0	45.7	57
Key:	>40C	>38C <40C	>35C <38C	>32C <35C								Total >40C:	339

Updated to include: Proserpine, Newcastle, Avalon, Hobart

Currently, there is no ARFFS regulatory requirement to provide verification of firefighting foam's fire performance capability, beyond the certification requirement for foams to meet ICAO Level B fire test criteria[11], requiring a single fire test using fresh water on Jet A1 (Flashpoint 38°C) [*or Kerosene [Flashpoint 38-60°C – a combustible not flammable liquid like Jet A1*] at air and foam solution temperatures of ≥15°C. This cannot and does not adequately verify effective use of firefighting foams at elevated temperatures above the flashpoint of Jet A1 experienced in EU, Australia and elsewhere, nor does it suggest the foam used may be effective against multiple car fires involving gasoline in sun-exposed, or even shaded multi-storey, car parks adjacent or near runways and/or terminal complexes at many airports across EU, where shade temperatures are increasingly reaching or exceeding 40°C. This current situation is only likely to get worse into the future.

The 2019 paper[13] by a multinational team of researchers led by Sun et al., studied the global heat stress issues faced by our warming climate with just a small increase above the 2015 UN Paris Agreement aims, and the sobering criticality of keeping our climate to a maximum 1.5°C increase above pre-industrial levels (which globally we are still trending to substantially overshoot!). It found "*An additional 0.5°C increase* [up] *to the 2°C warming target leads to* ***>15% of global land area becoming exposed to levels of heat stress that affect human health****;* ***almost all countries in Europe will be subject to increased fire danger,*** *with the duration of the fire season lasting 3.3 days longer; 106 countries are projected to experience an increase in the wheat production-damage index.* ***Globally, about 38%, 50%,*** *46%, 36%, and 48%* ***of the increases in exposure to health threats, wildfire****, crop heat stress for soybeans, wheat, and maize* ***could be avoided by constraining global warming to 1.5 °C rather than 2 °C. With high emissions, these impacts will continue to intensify over time, extending to almost all countries by the end of the 21st century: <u>>95% of countries will face exposure to health-related heat stress</u>, with India and Brazil ranked highest for integrated heat-stress exposure. <u>The magnitude of the changes in fire season length and wildfire frequency are projected to increase substantially over 74% global land, with particularly strong effects in the United States, Canada, Brazil, China, Australia, and Russia."</u>***

On health effects, Sun's findings[13] continue: "*In our study, we calculated the total number of days with an HHI > 105 °F (****equivalent to 40.6 °C, hereafter referred to as AT105F****)* [They used the Health Heat Index (HHI) as a measure of apparent temperature (AT). This index is calculated from daily temperatures and relative humidity (RH) values obtained from the five internationally recognized climate models in the ISI-MIP datasets]. ***Above this threshold, heat conditions become dangerous or extremely dangerous for at-risk groups*** *(https://www.weather.gov/safety/heat-index)* ***and heat disorders such as heat stroke and heat exhaustion become likely*** *(NOAA, 1985; Fischer and Schar, 2010). AT105F is the threshold at which the United States National Weather Service issues heat advisories, (https://www.weather.gov/dmx/dssheat). We used the threshold of AT105F for the entire land area.*" This could mean vulnerable passengers are suffering heat stroke and heat exhaustion above 40°C which may delay their ability to evacuate an aircraft under such conditions, potentially making a disaster more likely, particularly if fire control and extinguishment are delayed.

Under their Results section[13], the comments are similarly sobering: “***Extreme high temperature is one of the greatest global natural hazards to human health. The risk of human illness and mortality increases on hot days, compounded by attendant increases in humidity, which restricts people's ability to dissipate heat***.” …”*Increases in the AT105F are also projected for eastern China, Southeast Asia,* ***Australia,*** *and the southeastern United States (Fig. 2).* ***In these regions, relative humidity tends to decrease, but the elevated temperatures nevertheless cause increased heat stress.*** *Compared with the changes under 1.5 °C warming, global warming at the 2.0 °C limit set by the Paris agreement* ***results in a further rise in the frequency of danger heat conditions and expansion of affected areas****.* ***The total area affected under 2.0 °C warming is predicted to be about 15.6% larger than that under 1.5 °C warming. AT105F over the affected areas is 1.6 times and 2.3 times higher under 1.5 °C and 2.0 °C than under the current climate***.” …”*Future projections under 1.5 °C and 2.0 °C warming show that* ***the number of countries exposed to heat stress will increase to 129 and 135 respectively, compared with the 109 heat stressed countries in the baseline period. Newly affected regions will arise in the United States, Indonesia, and Australia***.” …”***Considering both the population and the areas exposed to heat stress, about 26 countries will be subjected to more than double the health-related heat integrated exposure under 1.5°C global warming relative to the baseline period,*** *and this increases to 54 countries under 2^{o}C warming*.” …”***Under global warming, the increased daily temperature and associated changes to other weather variables will lead to more frequent, intense, and widespread heat-related extremes***.”

Australia particularly, is singled out as an early sufferer of increased human heat stress conditions from rising ambient temperatures, so the longer duration of high temperatures currently seen at Newman, Port Hedland and Karratha airports will increase further and inevitably more places will experience extended or more regular high temperature conditions. Several of these locations may also be experiencing severe heat stress in vulnerable people (or are increasingly likely to do so quite soon as Sun et al (2019)[13] confirms), so evacuation of passengers may be further impeded and delayed by passengers suffering heat stress effects. Higher foam application temperatures also deliver a reduced differential with the fuel and therefore a reduced cooling effect as evidenced by Conroy and Ananth (2015)[14] below (in Section 4), with likely extended extinguishment times. Both factors are working against the objective of achieving safe evacuation of all survivors before the atmosphere inside the aircraft is no longer survivable, exposing lives to increased danger of loss in major incidents during summer conditions in Australia. Scheffey & Bagot (2008)[15] estimated survivable atmospheres exist for within 3 minutes, which further research by 2012’s FAA Report[16] by Scheffey and team had extended to 4 mins based on additional insulation and composite materials (see Section 10 below).

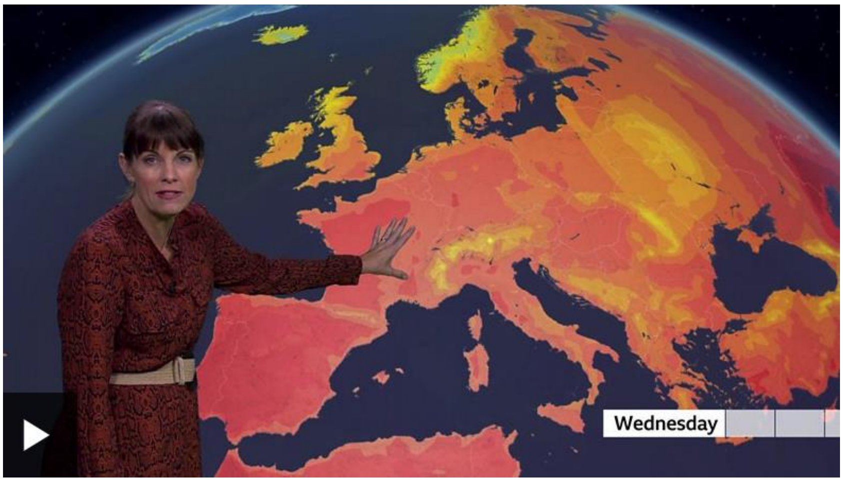
Australia is not unique in experiencing heat waves. Climate change is heating up our planet and USA and EU are similarly suffering hot summer prevailing conditions. The US National Oceanic and Atmospheric Administration (NOAA)[17] on 13th Aug 2021 confirmed “***July 2021 was Earth’s warmest month in recorded history***.” and “***July*** [2021] ***featured two $25 billion flood disasters and Earth’s hottest reliably measured temperature on record: 54.4°C (130°F) at Death Valley, California***.”

NOAA's National Centers for Environmental Information, NCEI[17] also confirmed *"**July 2021 was Earth's hottest July since global record-keeping began in 1880, 0.93 degrees Celsius (1.67°F) above the 20th-century average**,*]. *Since July is also the hottest month of the seasonal cycle, that meant that July 2021 was **more likely than not the warmest month on record for the globe since 1880**,"*

EU's Copernicus Climate Change Services[18] confirmed "***July 2021 joined July 2020 as the third warmest July on record globally, less than 0.1°C cooler than July 2019 and July 2016. It*** [2021] ***was the second warmest July on record for Europe. Heatwaves occurred from the Baltic to eastern Mediterranean***." Copernicus also confirmed "***During the*** **[2021]** ***summer heatwave, many temperature records were broken, including a provisional national record for Spain at 47.0°C and a provisional European record of 48.8°C in Italy****. In parts of Italy, Greece and Turkey, the **heatwave lasted for two to three weeks**. … The **total area burnt*** **[in wildfires]** ***during July and August in the Mediterranean region exceeded 800,000 ha****.*"

Europe experienced further heatwaves with records again broken in June 2022. The Washington Post[19] (28th June 2022) confirmed "***Scorching temperatures have again swept across parts of Europe****, with many locations in Italy among those setting June or all-time records for heat. **Temperatures surpassed 104 degrees Fahrenheit (40 Celsius) across much of Italy this week**. On Tuesday, downtown Rome hit its warmest temperature on record at 105 degrees Fahrenheit (40.8 Celsius), while several other cities set monthly records. **Record-warm temperatures persisted overnight across a large chunk of Eastern Europe**.*"

BBC News (14th July 2022)[20] confirmed "***Soaring temperatures have gripped parts of Europe, which has barely recovered from its last*** [June 2022] ***heatwave."*** It continued ***"Heatwaves have become more frequent, more intense, and longer-lasting because of climate change. The world has already warmed by about 1.1C since the industrial era began****. … The heat sweeping across Spain is unusual in that it is affecting almost the whole of the country*." It also extended across much of Portugal and France as the BBC's reporter Susan Powell shows on this weather map of the sustained heatwave across most of Europe to southern Russia and Kazakhstan around the northern Caspian Sea (far right on map), on Weds.13th July 2022.



The Guardian headline also reported on 19th July 2022[21] that "***UK reaches hottest ever temperature as 40.2C recorded at Heathrow*** [London airport]***.***" with this current heatwave continuing in Europe.

Why Europe is becoming a heat wave hot spot was explained in a New York Times article on 18th July 2022[9]. It confirmed "***Scientists say the persistent extreme heat already this year is in keeping with a trend. Heat waves in Europe, they say, are increasing in frequency and intensity at a faster rate than almost any other part of the planet, including the Western United States***." This article reviewed research explaining the cause[9] as "*Low-pressure zones tend to draw air toward them. In this case, the low-pressure zone has been steadily drawing air from North Africa toward it and into Europe. 'It's pumping hot air northward,' said Kai Kornhuber, a researcher at Lamont-Doherty Earth Observatory, part of Columbia University.*
Dr. Kornhuber contributed to a study published this month that found that ***heat waves in Europe had increased in frequency and intensity over the past four decades, and linked the increase at least in part to changes in the jet stream.*** *The researchers found that many European heat waves occurred when the jet stream had temporarily split in two, leaving an area of weak winds and high pressure air between the two branches that is conducive to the buildup of extreme heat*."

Everyone can expect more frequent and more intense heat waves, **so the issues around life safety verification of firefighting foam's competency and effectiveness at saving lives during aircraft fires has become increasingly urgent for ECHA and EASA locally in EU, and for ICAO to action globally. This should be carefully considered before acceptance of this proposed PFAS ban in firefighting foams, as it is unclear whether F3s can deliver adequate safety under such increasingly severe summer temperature conditions.**

4. Fire performance tests easier to pass under cool 15°C conditions

Inspection of most ICAO Level B[11] fire test certificates will indicate manufacturers gain a competitive advantage by testing as close to (or sometimes even below) this 15°C minimum criteria, as the fire is easier to extinguish under such cool conditions.

Research by Conroy and Ananth in 2015[14] confirms that rapid cooling of the fuel is achieved at typical 'room temperatures'. It investigated "***fuel surface cooling by the foam and the resulting reduction in fuel vapor pressure, which depends exponentially on the surface temperature****. We develop a model to* ***examine the surface cooling that occurs when a room-temperature foam layer comes in contact with a hot heptane liquid surface***." **This important finding confirms it is not a linear relationship where 1degree of temperature difference generates 1degree of fuel cooling, it clearly states this is an exponential relationship, where 1 degree of temperature difference delivers more than 1 degree of fuel cooling. So the cooler the foam applied, the more dramatic the fuel temperature cooling effect and the greater the assistance provided by that foam with extinguishing the fire.** **Clearly indicating this effect is a major contribution to effective firefighting and faster extinguishment**, hence why manufacturers always test at the lowest temperatures possible to maximise this rapid cooling effect.

“***As a result of large temperature gradient between the foam and fuel layers, heat conducts very quickly from the fuel to the foam, which reduces the surface temperature of the fuel.”*** These tests provided evidence that ‘room-temperature’ foam dramatically cooled the burning heptane fuel. If the foam solution was closer in temperature to the fuel surface temperature (ie higher foam solution and therefore foam blanket temperature), a significantly smaller gradient would exist (due to the exponential relationship) and therefore a less dramatic cooling effect. This would make the surface cooling harder to achieve, delaying vapour pressure reduction and making it significantly less, thereby delivering significantly less impact on the fire making it considerably harder to extinguish.

“***Both numerical and analytical models show that the fuel surface temperature decreases almost instantaneously from the heptane boiling point (98.6^{o}C prior to foam application) to*** **54^{o}C** [not the 78.6^{o}C expected from 20^{o}C foam, if it were a linear relationship]***, which corresponds to a 75% reduction in the vapor pressure. We have also predicted the effects of foam thermal conductivity and expansion ratio on surface cooling, where the predictions indicate that the foam thermal conductivity is a relatively sensitive parameter that could lead to greater cooling when*** [the differential is] ***increased***.” …” ***The temperature gradient is initially very large at the interface, transitioning from the boiling temperature of heptane (98.6^{o}C) [8] to room temperature (20^{o}C) in the foam. As a result of the large temperature gradient between the foam and fuel layers, heat conducts very quickly from the fuel to the foam, which reduces the surface temperature of the fuel.*** *As shown in Figure 5a, the interface temperature drops significantly between t = 0 and t = 1 s.* ***With time, the heat conducted from the fuel surface raises the temperature of the adjacent foam, and the temperature gradient reduces (reducing the magnitude of heat conduction)***.”

Figure 5 (a) shows this very rapid, almost instantaneous fuel temperature reduction by the addition of a 20^{o}C foam layer and consequent rise in foam temperature after 5 seconds. Figure 5b shows these temperature profiles ‘zoomed in’ at the interface during the first second.

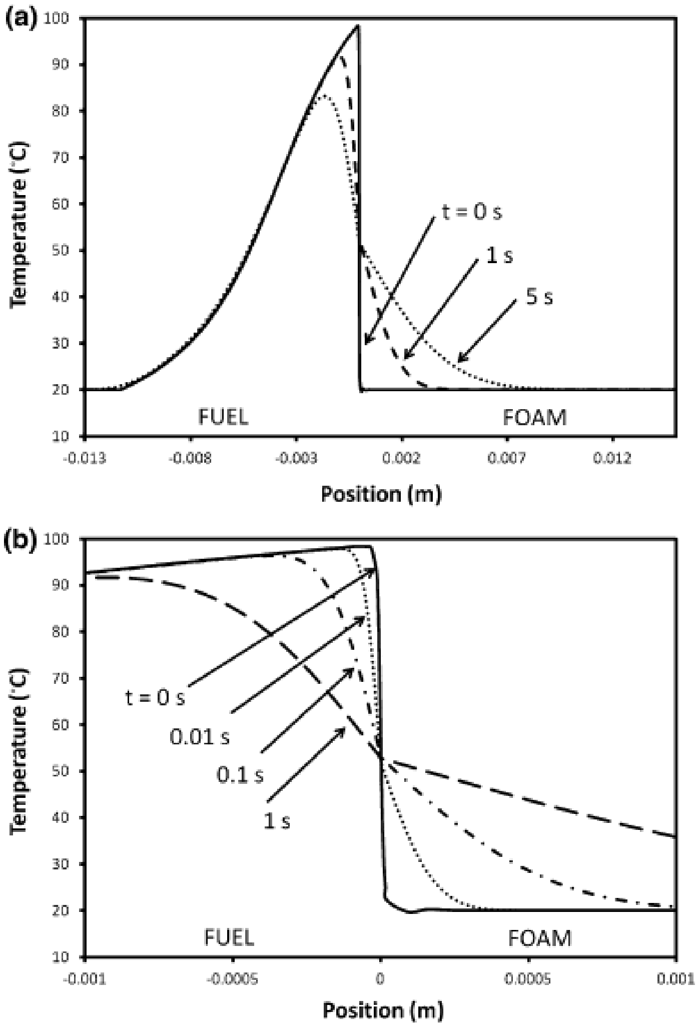


Figure 5. Temperature as a function of position in the fuel and foam at various times. (a) Temperature profiles in the fuel and foam at longer times (up to *t* = 5 s). The interface position is 0 m. (b) Temperature profiles near the interface at short times.

This effect is dramatic and clearly contributes significantly to rapid fire extinguishment. This effect would be far less effective, if the foam temperature were at 40°C instead of 20°C, with the expectation of providing significantly less than half the cooling effect as it is stated this is an exponential relationship, not a linear one. This means the cooling effect dramatically increases as the temperature difference across the fuel-foam interface increases, so the wider the differential the significantly greater the cooling effect.

It was also found by Conroy and Anath (2015)[14] that "***direct cooling is caused by heat conduction from the fuel to the foam due to direct contact****. Indirect cooling is calculated without the foam and heat feedback from the flame.* ***Indirect cooling is caused by heat loss from the fuel surface to the cooler liquid underneath****.* ***Figure 8 shows that the decrease in surface temperature due to both direct and indirect cooling is over 40°C after 1 s, whereas the temperature decreases by only a few °C with indirect cooling alone. These results support that direct cooling drives the rapid, significant decrease in fuel surface temperature and that indirect cooling is relatively***

unimportant." This testing provides further evidence that it is the direct contact of cool foam onto hot fuel which drives rapid vapour pressure reduction and a strong extinguishing effect.

Testing also considered the effect of foam expansion ratio: "*Figure 10 shows that* ***the interface temperature increases by 5°C when the foam expansion ratio is varied from 5 to 10, and the vapor pressure changes by 32%.*** *We vary the foam expansion ratio from 5 to 10 because the MilSpec test sets a minimum value of 5 for the expansion ratio [12] and the expansion ratio in Mil-Spec tests is typically less than 10.*" However, "***The thermal conductivity is assumed to be independent of expansion ratio. The model predicts that the surface cooling effect is insensitive to the foam expansion ratio for the range of expansion ratios typically used in liquid pool fire suppression***."

This paper[14] also recognises that "*In actual fire-fighting applications, the fuel can be high or low boiling liquids, such as jet fuels or gasoline, and the heat from the fire could penetrate deep into the pool before foam is applied [8]. Also, the foam may be applied non-uniformly to the surface and allowed to spread across the pool [12].* ***During this initial period of foam application, foam may degrade rapidly and delay the formation of a thick foam layer on top of the pool. However, surface cooling can occur due to foam evaporation and by the drainage of relatively cool liquid from the foam into the hot pool surface during the initial period of foam layer build-up*****.** ***Also, foam degradation produces liquid water or its vapor that can cause some slow cooling. Our analysis is applicable when the pool surface has cooled enough to form a layer of foam on top of the pool.***"

In Conclusion it is thought this work has identified a new mechanism of foam fire suppression increasing effectiveness, but it is strongly reliant upon cool foam delivering a large differential temperature between foam solution and fuel surface temperature for maximised results. "*In this work, we predict quantitatively that foam absorbs heat from the surface of a burning liquid pool immediately upon direct contact.* ***The foam cools the hot fuel surface, reducing fuel vapor pressure and mass transport into the fire. Based on this principle, we propose a new fire-suppression mechanism that acts in conjunction with the well-known mechanism wherein the foam forms a physical barrier to the transport of vapor from the fuel surface into the fire***."

Following this important work, Conroy and Ananth conducted further research in 2017[22] as a follow-up study to these 2015 findings[14], which validated their earlier conclusions and modelling with extensive lab experiments. Fuel cooling model calculations for interfacial temperature were validated against experimental data using a laboratory modeling 28ft^2 (2.6m^2)-pool fire test (based on US Mil-spec) with:

Pan size: 19cm diameter
Fuel: Heptane
Fuel depth: 1.0cm vs 1.5cm (28ft^2 Mil-spec)
Pre-burn time: 60sec vs 10sec (Mil-spec)
Samples: RF6 (Solberg) & Buckeye 3% Mil-spec AFFF
Foam solution/Fuel temperatures: room temperature (20°C)

2.0 cm foam thickness/ 1cm fuel depth (vs. previous model: 1.5cm foam thickness/1.3cm fuel depth).

Major conclusions from this further 2017 research[22] confirmed that:

- ***“The measurements showed rapid (<10s) and significant (25°C) cooling of the fuel close to the foam-fuel interface in good agreement with the model predictions***.”
- Right after pre-burn (60s) and immediately after foam application, the fuel temperature at the foam-fuel interface decreases rapidly: “***Measurements show that the fuel temperature near the foam-fuel interface (~1mm deep) decreases from about 85°C to less than 60°C in less than 10s***.”
- ***“Cooling of liquid fuel surface has a strong effect on the fuel vapor pressure which drives the evaporation of flammable gas away from the liquid fuel surface.***” (<10sec, >70% reduction).
- “***We propose that the very fast and significant vapor pressure reduction caused by cooling with foam could contribute strongly to suppression of pool fires by rapidly decreasing the fuel evaporation rate. The rapid effect of surface cooling could play an important role in knockdown of the flames in the initial stages of fighting a pool fire***. *However, **the surface cooling mechanism alone will not completely extinguish a flame because it will not suppress evaporation enough to prevent the formation of a combustible fuel-air mixture.** Flame extinction is impacted by other mechanisms, such as fuel transport through the foam, which would be reduced by surface cooling of the fuel. **Reduced fuel transport through foam tends to enhance flame extinction**.”*
- “***More importantly, the measurements and predictions unanimously support the idea that rapid, significant interfacial cooling occurs when a room-temperature foam is applied to a hot heptane surface, supporting our claim that surface cooling could have a rapid, significant effect on pool-fire suppression***.”
- “***This rapid cooling of the fuel surface can result in rapid reduction in fuel vapor pressure. Therefore, cooling the fuel surface with foam could quickly reduce the fire size and the heat release rate because of the reduced combustion rate, which depends directly on the fuel vapor concentration***.” Strongly suggesting foam temperature is important in maximising this effect.
- “***During the preburn time, the fuel receives heat from the flame. The thickness of the heated region beneath the fuel surface (i.e., thermal boundary layer) therefore increases with preburn time. Benchscale experiments by Ananth et al (2013) have shown for RF6 foam applied to heptane pool fires, that increasing the preburn time can also increase the time and amount of foam required to extinguish a pool fire***.”
- “*Note that the MILSPEC tests are conducted **with a preburn time of 10 s; our measurements suggest that the foam could have a slightly greater cooling effect in these tests because of the relatively short preburn time.***”

So the longer the fire burns and the hotter the conditions, the harder and slower it is to extinguish –

whatever foam type is being used. It begs the important question of firefighting competency around any foam agent being used under these more challenging, onerous and demanding high temperature conditions that BOM data confirms are being experienced at up to 21 Australian airports during summer.

Concluding the surface cooling effects section, Ananth and Conroy (2017) confirm "***<u>We propose that the very fast and significant vapor pressure reduction caused by cooling with foam could contribute strongly to suppression of pool fires by rapidly decreasing the fuel evaporation rate. The rapid effect of surface cooling could play an important role in knockdown of the flames in the initial stages of fighting a pool fire</u>***. *However,* ***the surface-cooling mechanism alone will not completely extinguish a flame because it will not suppress evaporation enough to prevent the formation of a combustible fuel-air mixture. Flame extinction is impacted by other mechanisms, such as fuel transport through the foam, which would be reduced by surface cooling of the fuel. Reduced fuel transport through foam tends to enhance flame extinction***." This finding is particularly relevant to PFAS-free foams (F3) as they have no specific fuel repelling or vapour sealing additives.

Under convection effects, these findings confirm "*The natural convection within the heptane layer is caused by the cooling effect of the foam on the pool surface. During burning and before foam application, the temperature within the heptane layer decreases monotonically with depth; thus, density increases monotonically with depth and forms a stationary, hydrodynamically stable[4] heptane layer. When the foam is applied, the fuel near the interface cools below the temperature of the underlying fuel. This situation, wherein a heavier fluid is positioned above lighter fluid, is unstable and drives natural convection near the foam-fuel interface.* ***The rising of hotter fuel to the interface will cause its temperature to increase. Therefore, convection counteracts the interfacial cooling initially caused by the foam, which could lower the effectiveness of the surface-cooling mechanism***." This suggests that higher ambient and foam solution temperatures will also counter-act the interfacial cooling, reducing the effectiveness of any surface cooling effects, thereby also making the fire harder and slower to extinguish.

This study[22] recognizes large-pool firefighting is generally more complicated "*There are important differences between our idealized case and a real pool-fire scenario.* ***Phenomena not considered here include: (1) rapid destruction of foam by evaporation of water when applied to the surface of burning hydrocarbons (with high boiling point), (2) rapid evolution of foam properties due to drainage and coarsening (both are affected by temperature), and (3) heating-induced expansion of foam that changes specific heat and thermal conductivity.*** *We emphasize that we considered surface cooling mechanism on fuels with boiling points less than the boiling point of water.* ***For high-boiling-point fuels, the surface cooling effect on fire suppression is more complicated because (1) evaporation of water contained in the foam introduces significant cooling*** [and premature foam collapse] ***and (2) water vaporization can affect flame behavior (for example, by spreading fuel vapor upon expansion of water vapor as well as increasing sensible enthalpy of the gases surrounding the flames). We are primarily interested in fuels with lower boiling points because they are more volatile and typically more difficult to extinguish when ignited. Additionally, the***

preburn time in a real pool fire depends on the response time of firefighting personnel and may extend significantly beyond the preburn times used in this work (<60 s). Further, liquid fuels may spill onto solid surfaces that could affect heat transfer in the liquid pool during a long preburn, which could affect the natural convection within the fuel pool.” Consideration should also be given to significantly increased surface temperatures of concrete/tarmac runways, taxiways and aprons, in summer well above the high ambient temperature conditions (always given as shaded temperatures), which could add significant heating and vapour pressure to thin fuel spills, increasing volatility, encouraging rapid ignition and potentially prolonging burning durations, especially where adequate fuel supply exists.

Modelling and measurements from this 2017 study[22] also showed that AFFF aqueous films have a very small effect in this cooling mechanism. “*The initial temperature profile within the heptane layer corresponds to our measurements following a 60-s preburn and a brief delay (~15 s) for the application of foam.* ***The predictions agree well with the experimental data for fuel temperature***. *The model shows that heat conduction from the hot fuel into the foam layer dominates over convective heat transfer in the liquid for the rapid, significant drop in fuel surface temperature*. ***Free convection is predicted to raise the interface temperature after a few seconds following foam application, but the temperature increase is relatively small (~6°C). For our experimental conditions, a heptane fuel surface temperature is predicted to decrease by over 30°C in less than 0.1 s, corresponding to a reduction in vapor pressure of nearly 70% on the same time scale.*** *Fluorinated foams may form aqueous films on top of the fuel surface and could affect surface cooling due to the high specific heat of water; however*, ***temperature measurements are very similar between fluorinated and non-fluorinated foams***. *Model predictions with a 60-micron thick aqueous foam placed between the foam and fuel showed a negligible difference in the fuel cooling (including the fuel surface).* ***The measurements and predictions suggest that an aqueous film has a very small effect on the surface-cooling fire suppression mechanism***.”

Combining these research findings[14,22] strongly confirms that **cooler foam temperatures have an important effect in cooling the fuel surface and extinguishing the fire more rapidly. Consequently, hotter foam solution temperatures will have an exponentially reduced effect, making fire extinguishment significantly harder and slower under hotter conditions. It is therefore reasonable to envisage a point will be reached, at which the fire cannot be extinguished and continues to burn, unless perhaps significantly higher application rates (or much cooler foams) are rapidly delivered**. CASA nor Airservices seems to understand how their existing foams behave under such circumstances. Nor do they seem willing to include a regulatory requirement to verify any foam usage in future is capable of effectively extinguishing aviation fires under such prevailing high temperature conditions. A reconsideration of that position is surely justified.

A major concern is that this may explain why the Dubai 2016 Boeing 777 fire continued burning for 16 hours to destruction, despite several concerted attempts being reported in the

Investigation reports to achieve extinguishment, when using Fluorine Free Foam (F3) from the early stages of ignition.

These findings[14,22] **also confirm that fires with longer pre-burns (or even burnback re-ignitions) are also generally harder to extinguish, requiring more foam solution and taking longer to extinguish.** This should require regulatory testing to verify current application rates are sufficient to achieve effective extinguishment under summer conditions, and effectively verify current foam's competency to deal with major aviation fires during summer across Australia. **Without clear evidence from a regulatory fire test certification requirement under high (≥ 40°C) temperature conditions, life safety and cabin survivability are being exposed to unnecessary, but significantly increased, danger in major incidents during summer across Australia. Without this regulatory requirement, CASA are failing their duty of care to provide adequate safety for flight crews, firefighters, the travelling public and other emergency responders likely to be involved in such incidents.**

4.1 *Heat radiation effects increase foam destruction*

A 1992 study in Sweden by Henry Persson[23] studied foam layer behaviour (7 & 10cm) when subjected to heat radiation using levels from 0kW/m^2 to 35kW/m^2. Tests were conducted using D (Synthetic detergent [F3]), AFFF, FP, AFFF-AR and FFFP-AR foam types. "***Rates of evaporation from all foams were similar at 15g/min, kW, representing 65-75% of the incoming radiation was used in the evaporation of the foam.*** *The highest rate of evaporation, 18g/min, KW was recorded with D* [F3) *foam generated by mixing*." The remainder confirmed as being reflected or absorbed by the foam solution, but not investigated. "***Rate of drainage increased 2-3 times when subjected to heat radiation***."… "***The foam destruction increases rapidly from almost zero to approx. 0.5-1.5cm/min at 5kW/m²***. *The destruction rate then seems to increase more slowly, proportionally to the radiation, to approx. 1,5-2.5cm/min at 35kW/m2*." It continued "***With 'no radiation' all foams prevented ignition from a small pilot flame just above the foam layer for more than 30 mins. At 5kW/m² time to ignition for FP foam was around 20mins while the D and AFFF foams only reached 10-15mins***." …**At 35kW/m² time to ignition was reduced to only 5-6.5 mins across these foams."** The research confirms "*35kW/m² does not reflect the situation for foam at the flame front. Radiation levels of approx. 150kW/m² are more relevant and in this case the rate of evaporation would be slightly more than 2,000g/min ,m², in other words, in the same order of magnitude as the rate of drainage*."

This research provides clear evidence of increased heat radiation produces premature destruction of all foam blankets.

Chen et al's 2011 team[24] researching into the initial fuel temperature effects on burning rate of pool fire in 2011 found that "*The burning rate during the steady burning stage was observed to be relatively independent of the initial fuel temperature.* ***In contrast, the burning rate of the bulk***

boiling burning stage increases with increased initial fuel temperature". Suggesting higher initial fuel temperatures increased the bulk burning boiling rate, and thereby fire intensity.

Chen, Kang and his team continued this work in 2011[25], finding that "***By analyzing the temperature differences between the fuel surface and wall, it is concluded that the convective heat is transferred from the liquid to the wall at the early stage, but this trend is reversed during the latter stages. During the bulk boiling stage, the wall temperature is higher than fuel surface temperature and the heat transfers from the wall to the liquid fuel***." Chen's team confirmed previous studies observations that "***the burning rate increases with increasing pool diameter****. However, it can be seen that* ***for the same diameter, the burning rate is not always constant but can vary to be sometime two times greater****. As mentioned earlier,* ***many initial parameters play important roles in determining the burning rate, such as the environmental conditions (ambient temperature, wind) and lip height.*** *In this study,* ***a variation in fuel burning rate is observed because of the bulk boiling behavior. Thus, the initial fuel thickness is a factor that should be considered in pool fire research****.*"

These important findings help to explain why we experience edge flickers and poor edge sealing around fire test trays, because the metal wall temperatures become higher than the boiling fuel surface temperature, transferring heat back into the fuel from the edges increasing vapourisation and fire intensity at the edges. The significance of lip height also indicates that the metal above the fuel is radiating extra heat down onto the fuel surface around the tray edges, increasing the destructive radiant heat forces preferentially drying out the foam blanket, collapsing the bubbles and causing premature foam destruction around the edge interfaces with the metal tray. This can be seen with the higher walls in the Lastfire test, with a larger metal area radiating heat down onto the fuel surface, making it harder to seal against the metal edges of the container, intended to be a 'simulated storage tank' type of environment. This confirms that hot metal and debris can increase localized foam destruction at exactly the places where re-ignition is most likely to occur. Without fuel repelling additives, the resulting foam blanket becomes significantly more vulnerable to heat attack as vaopurs are diffused into the foam bubbles, so as they break they may deliver 'puffs' of vapour around these higher temperature points, which is more likely to ignite, sustain ignition and caused accelerated burnback. This may help to explain several commonly observed phenomena around sudden flashbacks and sudden re-involvement of F3 blankets.

UK's Health and Safety Executive[26] website (2022) addressing Fire Effects for UK Offshore oil and gas installations, confirms that "***Objects with temperatures above 45°C may cause pain if in contact with skin for more than 10s … At skin temperatures above 44°C, pain is felt and injury continues whilst the temperature remains above this point. The rate of injury increases by a factor of 3 for every degree above 44°C, such that at 50°C, the injury rate is ~100 times that at 44°C****. In addition, for heat fluxes greater than 12.5 kW m-^{2}, 33% of the final burn occurs during cooling*." Under a section 'Industry practice in assessing fire effects' it confirms "*Heat effects on personnel are evaluated using simple and pessimistic Rule Sets based on human response to 5, 12.5 and 37.5 kW* *m^{-2}*. ***Escape is assumed at 5 kW m^{-2} but fatalities within minutes assumed at 12.5 kW m^{-2} and instantaneous death at 37.5 kW m^{-2}.*** *”*

A recent Feb. 2022 Yougie et al. study[27] on thermal stability of firefighting foams at Xian University (China), investigated adding silica nanoparticles (NPs) compared to a regular AFFF, to improve resistance to heat breakdown. It confirms that "***At 45°C, the bubbles of A-0#*** [regular AFFF] ***have been changed from an elliptical three-dimensional structure to a polygonal two-dimensional structure at 6 min, and the bubbles largely disappear at 8 min.*** " A-0# is fluorinated AFFF without any nanoparticles, A-1# to A-4# have increasing amounts of silica nanoparticles (NPs) added, A-4# being quite viscous. "*The surface tension and conductivity of the dispersions decrease but the viscosity increases with the increase in NP concentration. The foaming ability of APG0810/FS-50 solution is reduced by the addition of NPs and decreases with the increase in NP concentration. The coarsening, drainage, and decay of the gel foams under thermal action slow down significantly with increasing NP concentration. T**he thermal stability of the gel foams increases with the addition of NPs and further increases with the increase in NP concentration."***
It goes on "***The foam coarsening process at 85°C is similar to that at 45°C. The higher temperature results in the faster increase in bubble size and disappearance.*** *These results indicate that the addition of NPs significantly delays the foam coarsening under heat.*" It then explains ..."*Moreover, the foam lasting time during coarsening process is reduced.* ***This is because the higher the temperature is, the faster the evaporation of water vapor, and the corresponding bubbles quickly become thicker, larger, and quickly broken. The results show that NPs have a significant deceleration on the foam-coarsening rate under heat. The higher the concentration of NPs in gel foams is, the stronger the deceleration effect***." This confirms that without stabilizing NPs to slow down foam degradation, the hotter the foam bubble temperature the faster it degrades and collapses.

5. Higher foam solution and fuel temperatures adversely affect fire performance

Ananth was separately asked an important clarifying question about his 2015 research with Conroy (Section 4 above) by private e-mail 26th May 2021[28]. **Q: Based on your modeling studies and your lab experiments, which has the most impact on the foam quality and fire test performance? Is it temperature, air, premix or fuel? Can you rank the importance? This Q was referring to the fire test temperature conditions specified in various foam standards, such as Mil-spec, UL 162, etc. asking did he have any answers or opinion to this question?**

Ananth answered by e-mail 27th May 2021[28]. **A:** ***“In the model, both fuel and foam temperatures are important because they affect fuel vapor pressure and degree of vapor generation. But, after the preburn, the fuel temperature is near boiling point where the vapor pressure is 1 atm. The foam temperature is determined by the premix solution temperature rather than air, which has very small thermal mass. So, I expect premix solution temperature to be the #1 factor. “***

Ananth's response confirms that without consideration of ambient temperatures and likely resulting foam solution and fuel temperatures during testing, foam solutions and fuel could be significantly lowered to the minimum temperatures allowed, which would thus provide a greater cooling effect with quicker fire control and extinguishment, while also making burnback testing easier to gain a Pass. Similarly, fuel could be 'chilled' prior to ignition to reduce vaporisation rates providing an unfair advantage in passing specific tests over other similarly listed foams, but unrealistic of more likely real operational fire conditions. In order to provide more consistent and verified fire test results, the ambient, fuel and foam solution temperature conditions need to be clearly specified and recorded, as representative of potential realistic 'major credible event' (MCE) scenarios under operational summer conditions. Without such beneficial cooling effects of the foam blanket, fuel transport through the foam is expected to increase, making flame extinguishment harder to achieve under more intense fire conditions.

This was similarly established during 2017 US Naval Research by Hinnant et al.[29] into the influence of fuel and its heating on foam degradation. **Experiments quantified unignited fuel induced foam degradation** by applying foams onto varying temperature fuels and water (for comparison) using F3 (RF6 - ICAO) and AFFF (Buckeye 3%-MilSpec) on n-heptane, Iso-Octane and MethylCycloHexane (MCH). "***Water evaporation from the foam bubbles can also contribute to degradation. …heat from a fire can dramatically increase the rate of foam degradation through water evaporation***." It is similarly expected that high ambient temperatures would also dry out the foam blanket, increasing its degradation rate, while also reducing its fire performance effectiveness.

This graph below (Fig 16 of their paper[29]) clearly shows this dramatic reduction in foam stability as unignited fuel temperature rises.

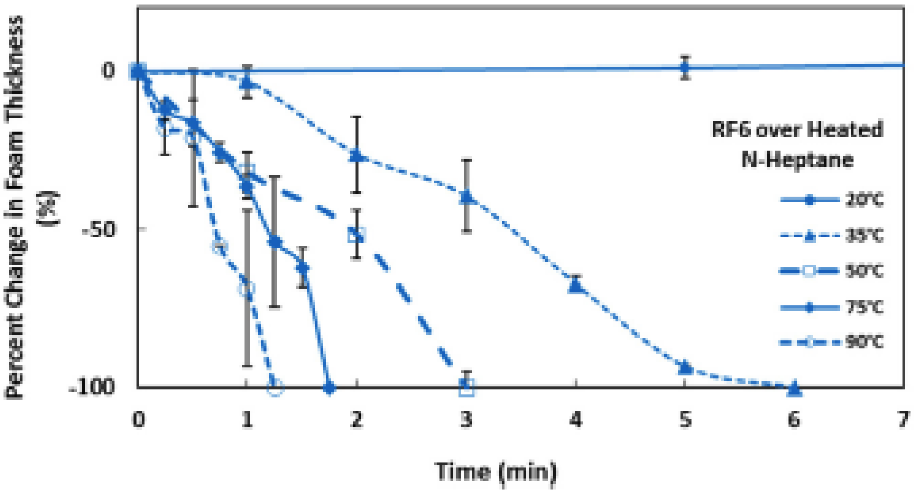


Fig. 16. RF6 foam degradation versus time over *n*-heptane at room temperature, 35, 50, 75, and 90 °C. Initial foam thickness was 1.8–2 cm.

Hinnant's team testing[29] confirmed ***"Our results showed RF6 degraded faster than AFFF (by factor of 3 at room temperature [20°C] and 12 at elevated temperatures over fuel [50°C]), which may contribute***

to differences in their firefighting performance.” **AFFF lasted nearly 8 hrs on n-heptane at 20°C, but reduced to 35 mins when fuel temperature was raised to 50°C and around 8 mins at 90°C. In contrast RF6 lasted nearly 4 hrs on n-heptane at 20°C but only 3 mins at 50°C and just over 1min at 90°C**. “***For all experiments F3 degraded much faster than AFFF.”***

Geyer’s team in their 1979 FAA Report[30] studied a comparative evaluation of firefighting foam agents on 100ft^2 (9.3m^2) Jet A fuel fires. **Results confirmed two leading AFFFs delivered around 25% faster fire control times on Jet A with 125°F (51.7°C) foam solution temperatures when compared to 35°F (1.7°C) solution temperature, Conversely, two FluoroProteins (one almost same) and both basic protein foams (F3) experienced slower fire control times (by around 35% up to 46%) at the higher 125°F foam solution temperature**, as this extracted Fig. 10 graph below confirms:

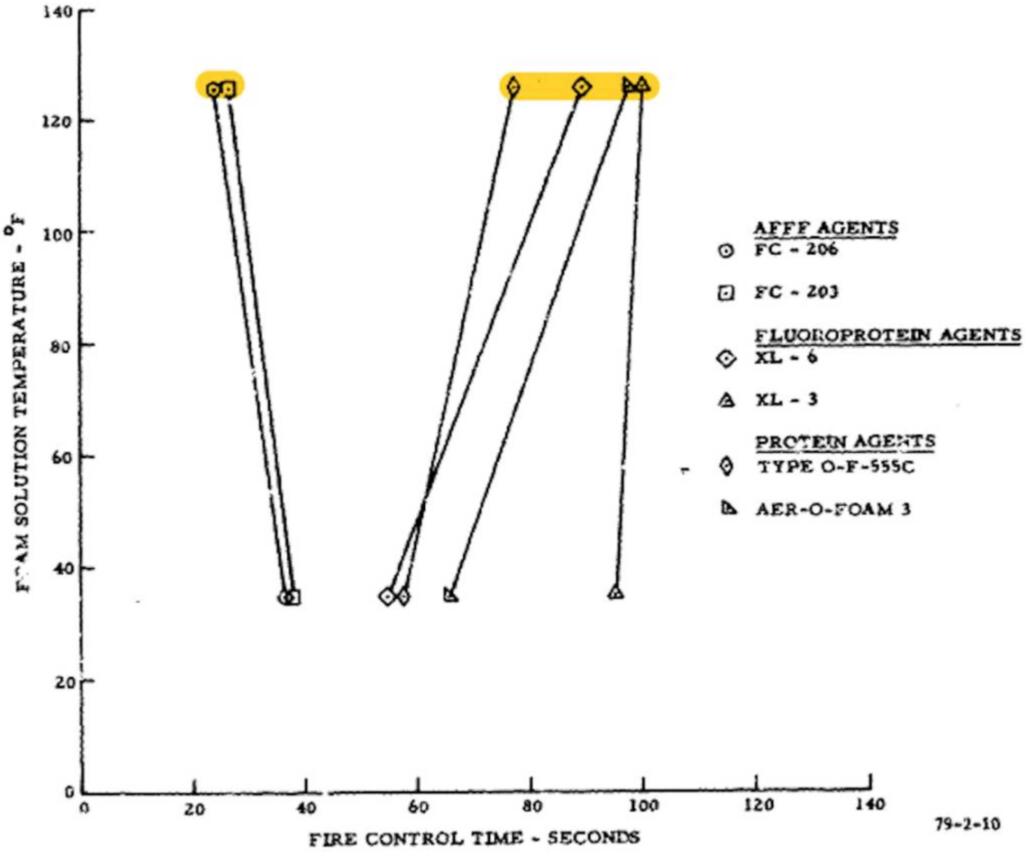


FIGURE 10. EFFECT OF FOAM SOLUTION TEMPERATURE ON FIRE CONTROL TIME

Geyer found[30] that “***The general trend among all foams was for the expansion ratio to increase (figure 8) and the 25-percent solution drainage time to decrease (figure 9*** [below]***) as the solution temperature was increased from 35°F (1.7°C) to 125°F (51.7°C).*** *The effect of these diverse trends in foam quality upon fire control time is indicted in figure 10* [above] *for the different classes of agents*.”

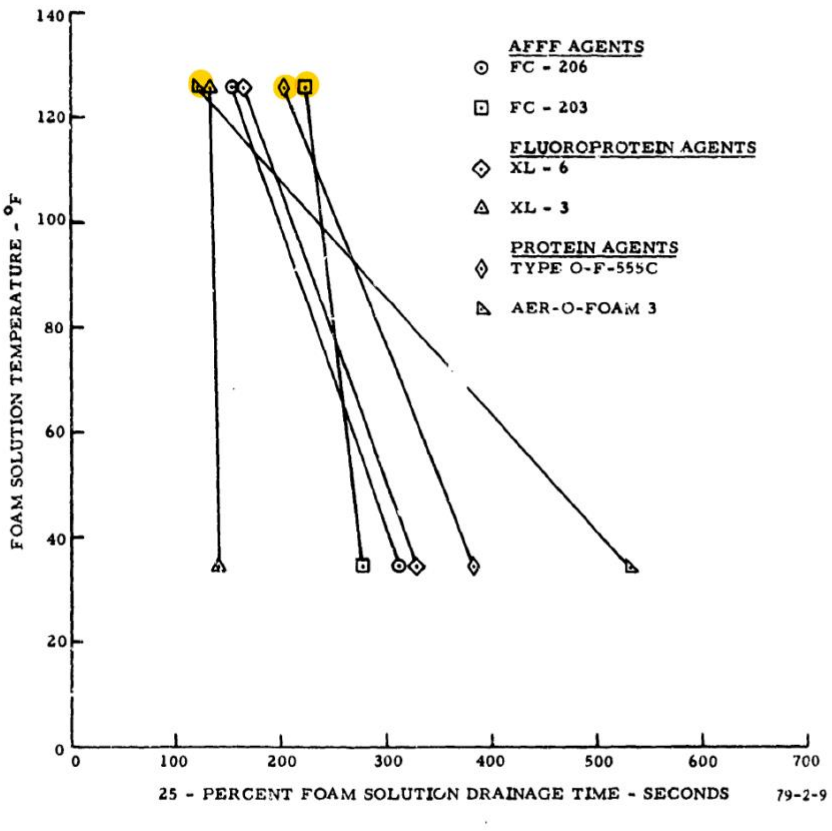


FIGURE 9. EFFECT OF FOAM SOLUTION TEMPERATURE ON THE 25-PERCENT SOLUTION DRAINAGE TIME

Findings continued[30] "*since no aqueous film is produced by the protein-base* [PFAS-free] *agents,* ***the predominant factor defining firefighting effectiveness is foam quality, which is indicated in Figure 9 to rapidly deteriorate through the loss of liquid as it drains from the foam body at elevated solution temperatures****. The extended fire control time is further augmented by an increase in the foam expansion ratio, which in the case of low-expansion protein-type foam agents, is accompanied by a rise in foam viscosity.* ***As the foam viscosity increases, the fluidity decreases, and the foam may become more difficult and time-consuming to distribute uniformly over a burning fuel surface****.* ***Therefore, excessively high or low water temperatures are to be avoided***."
Geyer also established that "*In general****, the temperature of the water and foam liquid was determined to be*** [even] ***more influential than the ambient air temperature in establishing the foam quality*** *produced by any particularly foam-dispensing system*." Under hot conditions though, warmer ambient air temperatures usually also warms the water and foam solution used in foam production to higher than otherwise temperatures, contributing to less effective outcomes.

NRL's 2017 foam degradation study[29] found that "***As the fuel temperature is raised, there is a higher concentration of fuel vapors beneath the foam than at lower temperatures. This increased concentration at the foam interface can increase the amount of fuel transport through the foam, increasing the rate of foam degradation***."… "***The fuel temperature effect is by far the largest***

compared to the effect of different fuels *and surfactant formulations (including the additives). The effect of surfactant formulation is a close second relative to the temperature effect;"* …This study concluded "***our findings show faster fuel-induced degradation of RF6 foam may contribute significantly to its inferior fire suppression performance relative to AFFF foam***."

A different 2017 study by Hinnant's team[76] measured fuel transport through foams, which explained these surfactant differences more clearly, finding that "***Fig. 3 shows that AFFF has a lower fuel flux than RF6 by an order of magnitude over 2000 s for the same foam layer thickness over the same room temperature n-heptane fuel."***

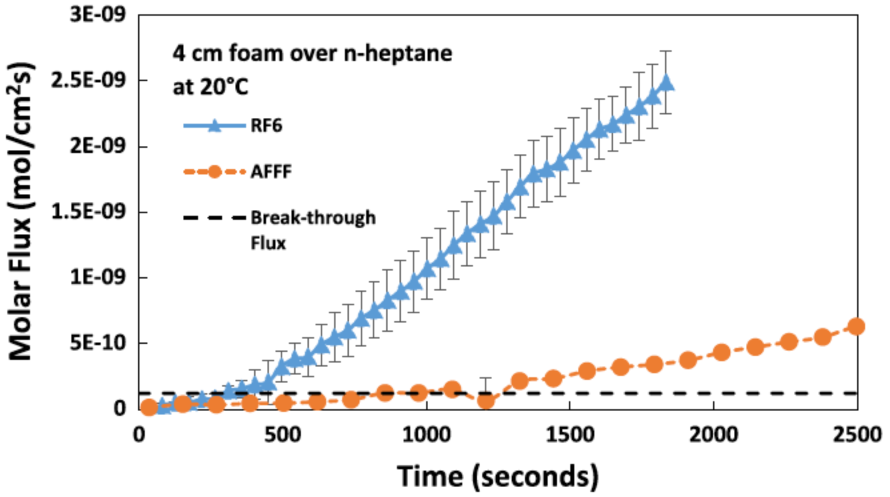


Fig. 3. Measured fuel flux with time through 4 cm thick foam layers covering an n-heptane pool at 20 °C.

It continued[76] *"The fuel vapor break-through times are 276 s and 820 s for RF6 and AFFF respectively and are indicated by the "break-through flux" in Fig. 3 at a flux of 1.21e-10 mol /cm^2s* ***corresponding to 10 ppm of fuel vapor. …The large difference in the measured fuel flux between AFFF and RF6 shown in Fig. 3 can be due to differences in the composition of surfactant solution and in properties of the foams*** *listed in Table 3."* This was graphically represented in Fig 5 showing more and less fuel transport, through F3 and AFFF foam blankets respectively.

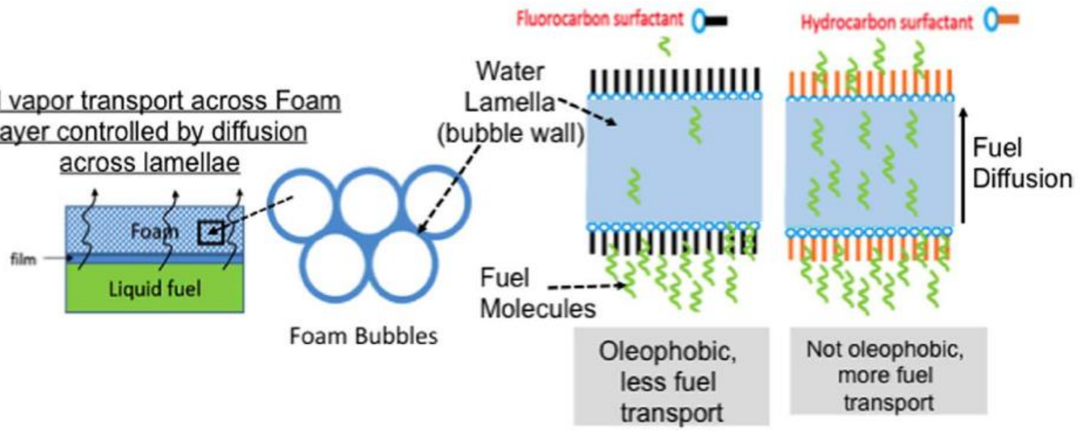


Fig. 5. Fuel transport within the bubble structure and the lamellae, and the role of fluorocarbon and hydrocarbon surfactants in the transport across a lamella.

This was explained further[76] as “*Fuel vapors can easily dissolve into the liquid lamella and move unimpeded by the hydrocarbon surfactant of RF6 through the foam layer resulting in faster transport in RF6 foam compared to AFFF as shown in Fig. 5. In addition to repulsion towards fuel, foam stability and lamella thickness are also important to reduce fuel flux through the lamellae.* ***Surfactants can affect the thinning dynamics of lamellae, thereby affecting foam degradation directly [25]. A synergy between the fluorocarbon and hydrocarbon surfactants contained in AFFF was shown to be important for forming stable foams, despite reduced repulsion towards fuel by the presence of hydrocarbon surfactants in the AFFF formulation*** *[27]. Therefore, a balance between foam stability and oleophobicity appears to exist and affects fuel transport through AFFF*.”

This study[76] concluded *“****Fuel vapors absorbed into the liquid lamella may be impeded by the surfactant adsorbed at the lamella interface. AFFF contains fluorocarbon surfactants that are hydrophobic and strongly oleophobic. RF6 contains hydrocarbon surfactants, which have hydrocarbon tails similar to fuels, which are less oleophobic than fluorocarbon surfactants. Furthermore, solubility of the fuel in the foam solution was found to be less with fluorocarbon surfactants than with hydrocarbon surfactants alone resulting in its faster fuel flux through the fluorine-free foam***.” Other research presented shows this important distinguishing factor increases in severity under hot summer conditions when the fuel’s vapour pressure rises, reducing the firefighting effectiveness of F3s under these more onerous conditions.

Briggs & Webb at UK Fire Research Station[31] in 1988 also made a major test modification to UK Def 42-24 on different fuels by increasing foam impact velocity with 5L/min nozzle (on 0.25m^2 tray) directed downwards with application rate reduced to 1.5L/min/m^2 (*just below ICAO Level C’s 1.56L/min/m^2*) delivering a more severe output velocity of approx. 6m/sec.**to better mimic reality in major fires**. Their testing also raised **“*The effect of weather variations which can prevent meaningful comparison of outdoor fire tests*”**. Suggesting ‘Convenient’ test temperatures can fail to adequately represent realistic operational firefighting conditions, unless specifically required to be conducted to reflect varying operational weather conditions. *“The most striking pair of results related to a well-established AFFF.* ***When applied to heptane fire under these conditions control and extinction times were best of series. When applied to Avgas fire under same conditions, no extinction was obtained****, the foam blanket continued to burn and when foam application ceased, the blanket burned away.* ***A further significant discovery was this result could be reproduced with initial fuel temp at 18°C, but with fresh avgas from cold overnight storage (8°C) extinction was obtained.***” Clear evidence that higher ambient fuel temperatures can have a significant impact on reducing a foam’s fire performance. Test fuel temperature was subsequently set at 20°C+-2°C. More findings from this work are discussed in later sections.

Further 2018 research by Lu, Wang et al. from Hunan University (China)[32] is also relevant, from their study of high temperature resistance of novel aqueous foam performance for fire extinguishing. **They recognized deficiencies in regular Class B foams, especially when the fire temperature is high**, as the water does not reach the burning area when the water in the prepared aqueous foam is further evaporated and has vaporised so the fire extinguishing performance has been lost, which they suggested can happen below 55°C. Their research studied different foaming and stabilising agents, modified by a super absorbent polymer for high temperature fire suppression performance. **They found it was important to maintain stable foam morphology at elevated temperatures.** They studied the influence of temperature on foam morphology and viscosity. The experimental results were shown in Fig. 5 below. This shows the prepared 'super stabilised' aqueous foam can be stable at 25°C and 80°C with the foaming height basically unchanged. "***When the temperature rises to 135°C it began to have a small amount of water evaporation and the foaming height began to decline; When the temperature is 190°C the foaming height decreases slowly. When the temperature is 245°C the moisture inside the foam begins to evaporate and the foaming height began to show an accelerated downward trend. When the temperature is 300°C the internal structure of the foam system is destroyed, loads of water is evaporated, and the foaming height starts to decrease rapidly***."

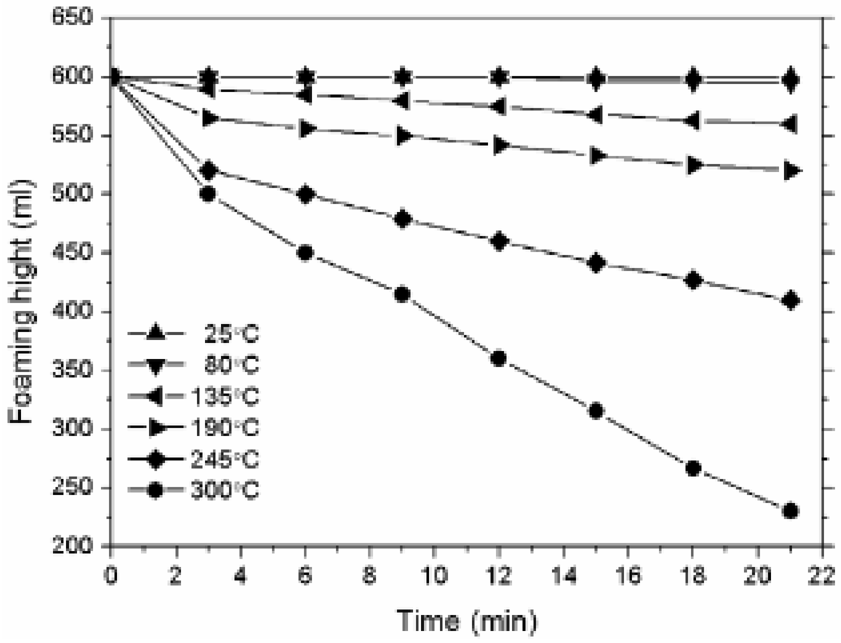


Fig. 5. The foaming height varies with time at different temperatures

Their research[32] found foam viscosity also increased up to 5,032Pa-S at 190°C, when the viscosity starts to decrease dropping to 3,100Pa-S at 300°C. "*Through the change in viscosity, it is concluded that the prepared aqueous foam can still maintain the foam form at 220°C**, which is much larger than that of common chemical foam extinguishing agent (5°C~55°C)**."* **This research clearly shows high temperatures evaporate and dry out the foam blanket reducing firefighting effectiveness.** This happens at low temperatures of around 55oC with conventional foams, but even adding super stabilisers to foams also adversely affects them, but they withstand much higher temperatures before quickly degrading and breaking down under high temperatures. So the same effects occur at much lower temperatures with existing commercially available AFFF and F3 foams.

6. Key aromatics can attack foams

Maintaining effective fire control and extinguishment generally becomes harder under high temperature conditions, particularly on lower flashpoint fuels and when the foam has no fuel repelling additives to prevent it mixing into the foam, potentially attacking the protective foam blanket, as subsequent US Naval Research Laboratory's (NRL) June 2019 research[32] by Snow, Hinnant, Farley and Ananth confirmed with gasoline. We shouldn't forget that several major Australian Airports have sun exposed car parks often full of gasoline fueled vehicles or in shaded multi-storey car parks as a significant ARFFS fire hazard, often adjacent to runways or airport terminals like Melbourne and Sydney, where shade temperatures can also exceed 40°C.

Importantly in this 2019 NRL research[33] Snow's team also found that **four leading commercial F3s fire tested on gasoline, required between 2.5 times more and over 6 times more F3 than the benchmark C6AFFF, when required to extinguish gasoline fires in 60 secs**. "*These differences widened as extinction speeds became faster*." Further investigation showed "***Individual major components of gasoline were tested, and the aromatic components were determined to be the source of this difficulty in gasoline fire suppression. This effect substantially increased with the number of methyl substituents (TriMethyl Benzene > Xylene > Toluene > Benzene). This aromatic gasoline component effect correlated with extraction of surfactants across the water-fuel interface*** [into the fuel] ***and in the same order of aromatic compound effectiveness***." Essentially the aromatics extracted surfactants from the F3, prematurely attacking the foam blanket, but these aromatics are absent in the widely used fire approval test fuel heptane, so most current international approval ratings (eg. EN1568-3, ISO7203-1, UL162, Lastfire, FM 5130, IMO) seem to provide a distorted 'better than reality' impression of F3s ability on flammable fuels like gasoline, because they are tested on the easier fuel heptane. Interestingly SDS for Jet A1 fuel confirms these same 4 aromatics are also present in Jet A1, but at lower quantities than gasoline. This may help to explain why F3s often struggle with Jet A1 fires under ICAO Level B and C, to the extent that the previous 60second extinguishment time has to be extended to 120secs to allow for persistent edge flickers frequently found when F3s were tested. This also suggests that at higher ambient temperatures these aromatics would be more volatile and actively vaporizing from the fuel, making the fire more intense and difficulty to extinguish. NRL suggested a well-defined "*TMB-heptane mixture could be developed for **gasoline sensitivity testing of F3 formulations to diagnose extinction shortfalls that heptane pool fires will not detect***."

NRL[33] also found "*Two diagnostics that relate valuable information about foam-fuel interaction are a foam degradation test and a fuel-vapor transport test. Foam degradation was evaluated by monitoring the disappearance of a 4 cm thick layer of laboratory generated foam deposited over 60 ml of 35°C heptane or gasoline in a 100 ml beaker. There is an increase in bubble size followed by a shrinking of the foam volume**. A plot of foam height vs time depicts significant foam degradation differences between the heptane and gasoline fuels"***

7. Flash point significance

Encyclopedia Britannica[34] defines Flashpoint as "**Flash point**: *the lowest temperature at which a liquid (usually a petroleum product)* ***will form a vapour in the air near its surface that will "flash," or briefly ignite, on exposure to an open flame****. The flash point is a general indication of the flammability or combustibility of a liquid.* ***Below the flash point, insufficient vapour is available to support combustion. At some temperature above the flash point, the liquid will produce enough vapour to support combustion.*** *(This temperature is known as the fire point.)"*

As temperature increases, so the vapour pressure of any fuel will also increase, resulting in higher concentrations driven into the gas phase, with more of the fuel vapour potentially dissolving into the foam blanket. As the vapour pressure increases there will become enough gas or vapour above the liquid surface for it to ignite from a spark (or match) - called the 'flash point' temperature, and at a slightly higher temperature there will be sufficient vapour given off to sustain ignition as fire, the 'fire point'. At normal room temperature, Jet A1 aviation fuel gives off very little vapour, so doesn't ignite easily or form dangerous fuel-air mixtures – it cannot be ignited by a match and usually needs to be warmed by a flaming torch at one spot for a while to give off enough vapour for it to sustain ignition (or spike with a little gasoline). In cooler temperatures, once a small area is ignited the heat from that area spreads, releasing more vapour sustaining more fire until the whole fuel surface in the fire tray is engulfed in flame which may take several seconds. The warmer the ambient and therefore fuel temperature, the faster this occurs until it reaches the flashpoint temperature or fractionally above when ignition occurs almost instantly from a spark or small ignition source (like a match) and is sustained as fire.

Jet A/JetA1 (and its military equivalent JP-8) aviation fuel are flammable (not combustible like most kerosenes), contain the same 4 aromatics as gasoline (identified by NRL in 2019[33] as attacking foam) but at lower quantities and a much higher flash point temperature of ≥38˚C[35], so when fuel is exposed above that temperature in ambient conditions (as experienced widely across Australia as BOM data verifies), vapours are increasingly given off making it more volatile, so sufficient vapours are present immediately for ignition to occur and be sustained in response to a spark, match, incandescent cigarette end or glowing ember. Once vapourised, JetA1 is extremely flammable and reportedly burns at a much higher temperature than some other fuels.

When foam is introduced, Hinnant et al, 2017[29] confirmed that as the temperature and vapour concentrations above the liquid fuel increase, more of the fuel vapour will tend to dissolve into the foam blanket. More fuel arriving in the foam blanket reduces its stability causing quicker drainage of the foam with a less robust foam blanket, delivering less good fire performance and shorter duration of protection against re-ignition. Viscosity and solubility of the foam will also be changing with rising temperatures, so there could be a number of dynamic effects happening at the fire interface, which may reduce overall effectiveness.

High ambient temperatures are known to prematurely dry out foam blankets impeding fluidity and increasing protective foam blanket degradation.

A 2011 Hughes Associates Report for US Department of Justice[36] 'Fire Dynamics and Forensic Analysis of flammable fuel fires' confirmed their research "*results demonstrated that it is not the depth of fuel that impacts the peak mass burning rate but the quantity of fuel available to burn (ie. burn long enough to achieve a steady state)*" …"*In general, less thermally conductive materials (i.e., vinyl and water) produced mass burning rates higher than those achieved in tests with more thermally conductive substrates (i.e., steel and concrete). … Typically, when discussing the impact of a substrate on the mass burning rate of a fuel, it is assumed that the substrate is acting as a heat sink (i.e., removing heat from the fuel layer), thus reducing the peak burning rate.* ***However, a small subset of tests in which the fuel substrate was heated to temperatures greater than ambient conditions demonstrates that an opposite affect can occur and have significant impact****.* ***These tests, while limited, showed that an elevated substrate temperature can increase the peak mass burning achieved during a spill fire scenario****. This increase is attributed to the heated substrate pre-heating the fuel layer prior to ignition, reducing heat loss from the fuel to the substrate and reducing the amount of energy required to volatize the fuel, thus more fuel can be evaporated." (See pE-3 & E4)*. This study also showed in general, ignition delays of 5 mins (300 sec compared to 30secs) resulted in larger areas with reduced peak mass burning rates per unit area, due to substrate cooling and evaporative fuel losses which were shown to account for some of the changes in peak mass burning rate, unless fuel supply was continuous, as is often the case in major incidents where leaking fuel from large aircraft fuel tanks is likely. *"0.5L gasoline spills on impermeable coated concrete with 300 second ignition delays … showed that tests with higher initial temperatures of 27-28^{o}C had higher heat release rates (~300kW) compared to the tests with slightly lower pad temperatures of 22-24^{o}C* [ambient] *that had heat release rates of about 200kW." (See* p79). This research clearly indicates fuel volatility often increases on high temperature substrates, increasing heat intensity which could be significantly adversely affecting a firefighting foam's effectiveness under summer ambient conditions exceeding 40^{o}C in Australia.

The FAA 2012 Report[16] into Methodologies for calculating firefighting agent quantities in aircraft fires confirmed that spilled liquid fuel can be ignited by numerous ignition sources present in an aircraft crash, including misting fuel and incandescent/difficult to extinguish composite materials. It suggested "*If the spilled fuel is above its flashpoint, the fire then propagates through the vapor-air mixture over the surface of the fuel at a rate of 700 to 800 ft/min* [213-244m/min] *low-flashpoint liquids (aviation gasoline (AvGas)). Both AvGas and JP-4 have flashpoints well below zero, and in almost all accidents the fire may spread in this manner.* ***However, kerosene (Jet A) and JP-5 fuels, with flashpoints of 110°*** [43^{o}C, although Jet A Flashpoint confirmed as ≥38oC or 100.4oF in most SDS] ***and 140ºF*** [60^{o}C] ***respectively, are frequently below their flashpoints when spilled****. The ignition source must then heat the liquid sufficiently to evaporate some liquid and then ignite the resultant vapor-air mixture. Once ignited, the flame heats adjacent layers of the liquid fuel and increases its evaporation rate to produce a combustible fuel-air mixture above the surface of the*

fuel. ***In this manner, the flame propagates slowly over the fuel surface at a rate of only 30 to 40 ft/min*** [9-12m/min]. *Once the fire is ignited, radiant heat from the fire plume warms and evaporates the liquid fuel in the pool. The vaporized fuel and air diffuse into the combustion zone above the surface of the liquid pool, where the burning reaction occurs.*
Gasoline almost immediately attains a combustion rate of 0.15 in./min [3.8mm/min] *of liquid depth per minute;* ***kerosene fuels will burn more slowly at first but reach a combustion rate of 0.13 in./min*** [3.3mm/min] ***in a period of 2 to 3 minutes. The temperature of the plume ranges from about 1100°F [593oC] at the edge to l500° to 2000°F*** [815- 1,093oC] ***in center; intermittent peak temperatures as high as 2200°F*** [1204°C] ***may occur****. The height of the plume is on the order of 1.5 to 2.0 times the diameter of the fire*." It went on to identify 5 *"basic stages of a crash fire as consisting of*
. an enveloping mist fire that persists for 15 to 20 sec.
. a residual fire involving spilled or/and spilling fuel that gradually increases in intensity.
This developing fire may ignite other combustibles, such as magnesium components,
tires, oil, hydraulic fluid, and cargo.
. ***a developing fire that reaches a level of maximum intensity in about 2 to 5 minutes.***
. a gradual decrease of the maximum-intensity fire when the spilling and spilled fuel is
exhausted. ***This may not occur for a considerable time and may be quite slow****. "*

However, **once the Jet A/Jet A1 fuel's flash point is exceeded in hot summer conditions, vapourisation occurs virtually instantly, with fire propagating through the vapour-air mixture over the fuel surface at a much faster rate than indicated above, involving the whole fuel pool in fire almost immediately. This is rarely considered adequately during prevailing hot summer conditions, particularly when PFAS-free foams are being used.**

8. Evidence from major fire events where F3s were used

Additional important evidence is derived from actual major fire incident reports. Few exist where it has been reliably verified that modern PFAS-free foams (F3s) were extensively used, so our experience with these alternative agents is still limited. Two such fires in Dubai and Melbourne show disturbing effects, when compared to similar fires where F3s were not used.

Clearly no two fires are alike, but there are some broad similarities between these pairs of fires being compared, which permit some generalised comparisons to be made. It also raises questions about why such stark contrasts are clearly evident. It leads to concerns whether in some way the choice of foam agent may have contributed in some part to the severity of the adverse outcomes experienced in these two incidents, which were not evident in similar fires where different foams were used. The scientific research contained within this document may also contribute towards a clearer understanding of the limitations foams may face when under increased pressure far beyond the small-scale fire test approvals we assume are adequate in protecting us form major credible fire events.

8.1 Boeing 777 aircraft fire – Dubai, 3rd Aug. 2016

It took 3.5 years before the Feb. 2020 Gulf Civil Aviation Authority (GCAA) final investigation report[37] into this Dubai crash was published, and it still left many important questions unanswered.

This major 2016 Boeing 777 engine detachment fire in Dubai resulted from an attempted 'go-around manoeuvre' under severe 48°C wind shear conditions.

The final GCAA Dubai investigation report[37] confirmed "*Eighteen seconds after the initiation of the go-around the Aircraft impacted the runway at 0837:38 UTC and slid on its lower fuselage along the runway surface for approximately 32 seconds covering a distance of approximately 800 meters before coming to rest adjacent to taxiway Mike 13.* ***The Aircraft remained intact during its movement along the runway protecting the occupants however, several fuselage mounted components and the No.2 engine/pylon assembly separated from the Aircraft****. During the evacuation, several passenger door escape slides became unusable. Many passengers evacuated the Aircraft taking their carry-on baggage with them. Except for the Commander and the senior cabin crewmember who evacuated after the center wing tank explosion,* ***all of the other occupants evacuated via the operational escape slides in approximately 6 minutes and 40 seconds****. Twenty-one passengers, one flight crewmember, and six cabin crewmembers sustained minor injuries.* ***Four cabin crewmembers sustained serious injuries.***


Boeing 777 fire in Dubai, 3rd Aug.2016

Approximately 9 minutes and 40 seconds after the Aircraft came to rest, the center wing tank exploded which caused a large section of the right wing upper skin to be liberated. As the panel fell to the ground, it struck and fatally injured a firefighter. The Aircraft sustained substantial structural damage as a result of the impact and its movement along the runway and it was eventually destroyed by fire."

“*The commander initiated evacuation approx. one minute after the aircraft came to rest.*” …“***The evacuation of 282 passengers, including 67 children and infants, presented a significant task for the crewmembers, particularly in the aft cabin, from where 86 percent of the passengers evacuated***.” …” ***During the evacuation, smoke filled the center cabin****, separating the forward evacuation process from the evacuation in the aft cabin*.” Fast and effective evacuation by the crew saving those 180 seconds certainly contributed greatly to saving 282 passenger lives, 16 cabin crew and 2 flight (total 300) on board. Suppose infirm or disabled passengers, parents with infants or vulnerable people experiencing heat stress or panic attacks, delayed evacuation beyond that 180 seconds; there would have been a major ‘multiple lives lost’ tragedy unfolding that day, beyond the bad enough tragedy of a brave firefighter losing his life.

The fire could evidently not be extinguished. This was Emirates Airline’s first full aircraft hull loss, **estimated to be valued at around US$ 100 million.**

Under rescue and firefighting, the final report[37] confirms “***The fire commander and the first two ARFFS major foam vehicles (MFVs) arrived at the Accident site within 90 seconds of the Aircraft coming to rest and immediately started to apply fire extinguishing agent****. Additional firefighting vehicles arrived shortly after.*
After the Aircraft came to rest, the fire continued on the separated No.2 engine. Video footage recorded by a passenger showed the aft lower portion of the No.1 engine on fire. Other video footage showed black smoke, without visible flames, issuing from the lower fuselage in the vicinity of the right wing root area and the right main landing gear bay. This smoke continued to increase in density from the time the Aircraft came to rest until the center wing tank explosion.
When Fire 6 and Fire 10 were positioned close to the R4 door, ***they narrowed the escape path of the passengers, slowed down the evacuation of the Accident site, and limited the ability of the ARFFS crew to observe the movement of the evacuated passengers on the ground and take necessary actions to preserve their safety****. Fire 6 continued to use its main and bumper monitors to apply extinguishing agent.” …*
“*When the firefighters exited Fire 10, they deployed a sideline and commenced fighting the right main landing gear fire from a closer position.* ***One of these firefighters was later fatally injured by the explosion of the center wing fuel tank. Other firefighters from Fire 10 approached the detached No.2 engine inlet with a sideline but were unable to extinguish the fire****. The No.2 engine exhaust fire was eventually extinguished when Fire 5 arrived and applied extinguishing agent*.”
“***The initial firefighting tactics prevented the potential of any fire spreading from underneath the lower fuselage adjacent to the right main landing gear bay. This provided a safe path for the evacuating passengers on the right side of the Aircraft. At that time, and when the cabin doors were opened after firefighting had commenced, there were no signs of interior fire that would require immediate attention***”
“***The Investigation concludes that during the offensive mode, there was no clear firefighting tactical plan. The major foam vehicles were positioned from where the smoke was issuing, no clear sectors had been established or sector commanders appointed, and at no time during the firefighting was high reach extendable turret (HRET), or secondary media (dry powder) considered***.
After the explosion, the fire commander decided to change the firefighting tactic to defensive mode where, in theory, the identified risks outweighed the potential benefits. His

attention was towards the safety of the ARFFS personnel over saving the Aircraft, because he believed that there was no expectation that the Aircraft could be saved*.*
The fire commander did not consider the hazard of the remaining fuel in the left wing tank, which had the potential to cause another explosion. Firefighters with sidelines were moving in close proximity to the left wing without awareness of the explosion hazard*.*

ICAO Doc 9137 Airport Services Manual Part 1 – Rescue and Fighting – chapter 12.1 Features Common to All Emergencies states:

> ***"If the source of heat and fire cannot be controlled, fuel tanks exposed but not involved should be protected by appropriate agents to prevent involvement or explosion****."*

During this period of defensive mode, large volumes of water were used in an uncoordinated tactic, which prolonged the time until the Aircraft fire was brought under control. The Investigation concludes that the lack of communication, and the inability of the fire commander, crew managers, or firefighters to identify the landing gear fire as the source of smoke, prevented the fire commander from exercising proper decision-making in vehicle positioning and from developing optimum firefighting tactics*." …*

*"****Given that approximately eight minutes was available from when the fire commander and two MFVs arrived at the Aircraft until the wing explosion, identifying the main landing gear fire and taking appropriate firefighting actions, may have provided an opportunity to prevent the tank explosion****.*

The Investigation recommends that the Airport enhance training for the ARFFS personnel to enable them to identify confined heat sources based on indicators and smoke traces. This training should enable the fire commander to understand the fire dynamic and determine the appropriate tactics, depending on the site circumstances and considering utilization of unique capabilities of the fire vehicles. This should be supported by sufficient training in incident command*."*

Regarding the 'fire extinguishing agent' the Investigation report[37] confirmed "*The fire extinguishing agent was supplied to the Airport ARFFS fire vehicles from five batches. Two batches were granted a certificate of conformity issued on 9 September 2014, and three were certified on 27 March 2015. According to the certificate of conformity,* ***the agent's performance complied with the requirements of the European Norm EN 1568:2008, part 3 and 4 specification and the ICAO level B standard at 3% and 6% concentration. At 6% concentration, the agent complied with the ICAO level C standard****.*
Foam conformity certification was available at the Airport for all batches of foam concentrate for both operational stock and stock in storage. According to the extinguishing agent data sheet, it is a concentrated fire extinguishing agent supplied by Solberg Scandinavian AS, Norway. ***The agent was suitable for jet fuel fire types.***

The agent storage temperature ranges between minus 30 to 65 degrees centigrade with no limitations on storage quantity or shelf life." Perhaps surprisingly its use under the most demanding and prevailing hot conditions regularly experienced at Dubai seems not to have been adequately verified in advance, under realistic emergency fire conditions. One wonders why not?…but also why does ICAO not address this important issue in its approval standard, to provide assurance to regulators and operators that foams are adequate for most foreseeable emergency incident prevailing conditions to improve life safety for everyone.

"On 13 September 2016, tests were carried out at the supplier's facilities on samples taken from the same batches that were used during the Accident. The tests were performed in accordance with ICAO level B[39] *standards, and concluded that the foam performance and the re-ignition resistance met the specifications of the test standards.*
A report was also issued by the supplier on the quality testing of samples taken from the MFV 5 and MFV 7 tanks. The report concluded that all samples were in a satisfactory condition*."* It is believed this covered laboratory analysis of Solberg RF3x6 ATC concentrate samples to EN1568-3 in Norway, and not a full ICAO Level B fire test in Dubai under prevailing 40-48°C conditions representative of the fire conditions experienced during this incident, which should reasonably be expected. A key Q: Why not?

No explanation was given in the report about why the plane burned for 16 hours, what constituted fire control and why subsequent progression to extinguishment was not achieved. **This is particularly concerning when six Airport crash trucks were in attendance plus two domestic fire vehicles, as recorded in the Investigation Report.**

Also no consideration of whether there was anything that could/should have been done differently to try and save the firefighter's life and prevent the fuel tank explosion.

Many would expect most aviation fires to be extinguished within 9 minutes. Why was this not the case in Dubai? Non-aspirated jet application of F3 and water breaking down the foam blanket were identified as potential contributory causes in the Investigation report.

No rigorous fire test attempting to re-create conditions during this fire – even at a laboratory scale, seems to have been conducted as part of the investigation to try and understand why the plane continued to burn for 16 hours, unimpeded. Why also was an ICAO Level B fire test not conducted later on this same foam in Dubai under similar ambient temperature conditions as part of the investigation? This could have verified whether the foam was deficient in some way? or whether some other causes prevented the fire from being extinguished by ARFF crews over those long 16 hours, before destruction became inevitable?

However under 'Fire extinguishing agent' the report[37] confirmed that "***Video evidence as well as statements from attending firefighting personnel indicated that the finished quality of the foam applied to the Aircraft was not of the required standard and appeared to be lacking the characteristics of a secure foam blanket***. ***The Investigation concluded that this was because of the application method utilized by the firefighters. The firefighting agent was applied from non-aspirating (jets) main and bumper monitors against the Aircraft structure at near right angles causing the foam bubbles to breakdown on impact***. ***Additionally, some firefighters were applying foam, while other firefighters in a different section of the Accident site were applying water. This had the effect of breaking down the foam blanket and washing it into the airport drainage system***."

This indicates the foam was forcefully applied as if it were a more forgiving leading quality AFFF with fuel repelling and vapour sealing additives delivering superior burnback resistance, but this was evidently not the case. AFFF are equally effective when delivered from non-aspirating jets, but F3s generally require a well aspirated foam blanket of 7-10:1 expansion ratio to be most effective.

NFPA Research Foundation testing in 2020[38] showed significant variation between low expansion (3-4:1) and higher expansion foam (7-10:1) with F3 performing significantly better at higher expansions. “***There was some variation in capabilities between the two hydrocarbon FFFs*** [F3s] ***with H-FFF2 requiring between 25%-50% more agent (application rate) than the AR-AFFF for the lower aspirated foams and about 15%-30% more agent (application rate) than the AR-AFFF for the higher aspirated foams. H-FFF1 required between 50%-100% more agent (application rate) than the AR-AFFF for the lower aspirated foams and about 30-40% more agent (application rate) than the AR-AFFF for the higher aspirated foams***.” …”***FFFs are not a “drop in” replacement for AFFF. However, some can be made to perform effectively as an AFFF alternative with proper testing and design (i.e., with higher application rates/densities).***”

This report[38] continues “***Due to its oleophobic properties, AFFF has two separate mechanisms that combine to aid in the extinguishment of a flammable liquid fire; a water/surfactant film that forms on the fuel surface and a foam blanket (i.e., matrix of bubbles) which both serve to seal-in the flammable vapors resulting in extinguishment*** *(i.e., shutting off the fuel vapors that are burning above the fuel surface*)***. FFFs have only the foam blanket to seal-in the vapors. As a result, the capabilities of FFFs will be highly dependent on the characteristics of the foam blanket (which depend on the associated discharge devices as well as the foam type itself)***. ***The film produced by AFFF has provided an additional level of protection for systems and discharge devices that do not produce aspirated foam***.” Concluding “***Ultimately, end users will need to design and install within the listed parameters in order to ensure a high probability of success during an actual event***. *This applies not only to the discharge devices but also to the proportioning systems as well (due to the highly viscous nature of some of the FFF concentrates).”*

“***Firefighting tactics should be developed from the moment of arriving at the accident site and should be continuously re-evaluated depending on their outcomes, or based on fire dynamic changes***.”

Aviation fires are intended to be controlled and extinguished very quickly to retain a survivable atmosphere in the cabin to protect lives. 9 minutes seems quite a long time - perhaps usually sufficient for ARFF crews to achieve extinguishment and safe evacuation?

Why was that not achievable in Dubai? Has the absence of PFAS in the foam contributed to the inability of fire crews to prevent aircraft destruction and significant PFAS escaping into the environment from seating, carpets, screens, computer systems, wiring etc. as the plane slowly burnt out over 16 hours. Why are ICAO fire test approvals not better constructed to provide verification of competency under a realistic range of likely prevailing conditions, including forceful use of aspirated and non-aspirated foam nozzles, plus high and low temperature conditions to better simulate summer and winter fire responses.

8.2 Boeing 777 aircraft fire – Singapore, 27th June 2016

A dramatic contrast to the Dubai fire was evident in Singapore six weeks earlier where **another Boeing 777 with major right engine and wing fire, landed in tropical 32°C heat and was fully**

extinguished by ARFF Service within five minutes – not 16 hours. **All 241 passengers and crew disembarked the aircraft 15 minutes after the fire was extinguished.** The plane was repairable and not destroyed. Only fluorinated FFFP and AFFF foams were used.

The Transport Safety Investigation Bureau of Singapore Final Report[39] dated 27th Feb. 2017 confirmed "***Shortly after landing in Changi Airport, a fire was observed to have occurred in the vicinity of the aircraft's right engine. After the aircraft came to a stop on the runway, a fire developed under the right wing. The airport rescue and firefighting service, which was already on standby, responded promptly and the fire was extinguished. All persons on board the aircraft disembarked via a mobile stairs. There was no injury to any person in this occurrence***."

The investigation report[39] confirmed: "***The ARFF which was on standby with four foam tenders and one water tender, entered the runway as soon as clearance to enter the runway was given by the Control Tower. The first foam tender arrived on scene after 57 seconds and started discharging foam at the right engine***." "***As the fire developed, it propagated towards the forward section of the engine and entered the core of the engine through the fan booster inlet***."
" ***The entire fire event lasted for about five minutes before the fire was extinguished by the ARFF. Throughout this period of fire, there was no EICAS indication in the cockpit that a fire was detected***."
"*The right wing and engine area of the aircraft sustained extensive damage.* ***There was no damage to the fuselage and the left wing, nor to the windows in the area of fuselage closest to the fire***."
The report[39] confirmed "***Disembarkation commenced at 0710 hrs via a mobile stairs positioned at the front left door of the aircraft. All occupants, including the flight crew, vacated the aircraft by 0731 hrs.***"

Disembarkation of all 241 people on board reportedly took 21 minutes, and started approx. 15 minutes after the fire was extinguished. Imagine the carnage if evacuation had been similarly delayed in the Aug. 2016 Dubai Boeing 777 fire, discussed in Section 8.1 above.

8.3 Chemical Factory fire – Footscray, Melbourne Aug. 2018

A second major F3 emergency was witnessed in Melbourne on 30th Aug 2018. Although not an aviation fire, this was the largest industrial fire Melbourne's had experienced in over 25 years since the Coode Island Methanol fire in 1991. This fire occurred in the West footscray - Tottenham residential suburbs of Melbourne, forcing 20 suburbs[40] into lockdown and 50 schools and child-care centre closures[41] due to toxic smoke. ABC News[41] confirmed *"The Metropolitan Fire Brigade (MFB) said the West Footscray fire began early Thursday morning and about 140 firefighters were fighting the fire, with 30 trucks and cherry picker aerial appliances on the scene."* EPA Victoria confirmed[43] the foam used "*did not contain PFAS*" ie F3, and reports confirming Alcohol Resistant Fluorine Free Foam was used, and were appropriate for this mix of chemicals[42]confirmed by EPA VIC[43] as including ***BTEX – Benzene, Toluene, Ethylbenzene, Xylene, Phenol, Polyaromatic hydrocarbons, detergents. Acetone, oxygen and acetylene***[41] ***plus other solvents*** were reported present by an MFB officer***. BTEX includes the same aromatics shown to attack F3s during US Naval Research Laboratory testing in 2019***[33]. The Inspector General of Emergency Management's (IGEM) Incident Report also confirmed that the incident was first reported at 05:02 on 30th Aug. 2018, fire control was achieved almost 17 hours later at 21:52 that day[42], fire operations were completed 6 days later on 4th Sept. 2018, with site hand-over back to the owner on 14th Sept.16 days after the fire started[42].


Footscray Chemical Factory Fire –Aug.2018

30 firefighters following multi-day attendances at this major chemical factory fire, were reportedly still suffering debilitating illnesses 15 months later[44]: including sudden fainting, headaches, nausea, nose-bleeds, fatigue, dizzyness etc. – a major cause for concern, quite possibly resulting from toxins, excessive chemical or smoke exposure; likely due in part to the relatively slow fire control, as reported.

This was Melbourne's biggest fire in decades, leaving a destroyed facility. The IGEM report[42] confirmed there were extensive long-term polluting consequences following this fire. EPA Victoria[45] confirmed over 2,000 fish were killed, excessive runoff destroyed the local creek, with remediation still on-going 18months later. 55 million litres of contaminated runoff water had been pumped out of the creek by 3rd day[46], into chemical waste facilities and WWTPs (Waste Water Treatment Plants). IGEM's Report confirmed[42] *"Over 70 million litres of water and 170 cubic metres of sediment have been removed from the area with plans to remove more contaminated material. Support agencies advised IGEM that the waste removal will take at least 12 months and the land itself will have restricted use due to soil damage*." This IGEM Report[42] also confirmed *"The control agency* [MFB] *requested support from ARFFS who arrived at the scene at 12.00pm"* ARFFS trucks commonly use non-aspirating nozzles, which have been shown by NFPA-RF comparative fire testing[38] to be less effective when F3s are being used, often requiring higher application rates to achieve fire control. ARFFS trucks using F3 for hydrocarbon fuels, with likely low aspiration delivery equipment would have been ineffective on the polar solvent chemicals involved in this fire, but should have bene effective on areas where hydrocarbon fuels were involved, as normally experienced during airport firefighting. Unfortunately, the IGEM Report[42] focused on broader issues of incident command and inter-agency communications, not detailed issues regarding firefighting. Despite there being no fatalities, a Coronial investigation is underway into this fire and there are criminal proceedings underway, but the Coroner's Court[47] has confirmed these matters are not expected to be concluded until 2023, until which time the Fire Investigation report, Coroners findings and hearing transcripts are unavailable.

8.4 Chemical factory fire – Avonmouth, UK Oct. 1996

Contrasting this Footscray fire response with a similar 1996 **Chemical factory fire at Avonmouth in UK** confirmed major differences in firefighting performance. The Avon Fire Brigade Incident Report[49] confirmed this major chemical fire and explosion was controlled in 2 hours and extinguished in just 4 hours using fluorinated AR-FFFP foam, despite water restriction issues delaying the initial foam attack. 134 appliances and their crews responded to the fire. The site was reported as safely handed over to the Health and Safety Executive, within 10 hours of the fire starting. Monitoring continued for 34hrs on site to ensure no re-ignition or chemical reactions occurred. The Institute of Fire Engineers (IFE) Incident Directory Report[50] and Avon Fire Brigade Report[49] confirmed fuels involved included: Propylene Oxide, Epichlorhydrin, Methanol, MonoChloroBenzene, Kerosene, Methylene DiBromide, Diethyl ethylphosphonate, Sodium thiocyanate.

Avonmouth major chemical factory fire, UK 1996, controlled in 2 hours and extinguished in 4 hours using AR-FFFP foam[49].

Avon Fire Brigade's Report[49] also confirmed the site was surrounded by another chemical complex, fuel depots, major port, industrial units and congested residential areas, but neither incident escalation, nor severe runoff, nor environmental off-site hazards were reported issues.

If not well managed and quickly controlled, overall incident impacts can create unrecognized hazards and increased environmental harm: from slow fire control; excessive smoke; greater breakdown product releases and excess firewater run-off; following prolonged burning. Such major incidents responses can adversely affect adjacent residents, firefighters, the broader public's safety, water courses, our environment, all of which may not be adequately considered by legislators; **thereby failing Society's expectations.** This is widely recognized as requiring avoidance and mitigation by Fire Protection Association Australia's 2020 latest Best practice guide[51] covering The Selection and Use of Firefighting Foams, (Information Bulletin IB-06 v3).

Where F3s have experienced major fire emergency use, evidence is sounding warning bells of potentially increased risks[37,40-47]. These include lockdowns from excessive smoke; slow fire control/extinguishment; run-off overflows causing increased environmental harm (potentially disasters); aircraft/facility destruction; adverse health effects on firefighters; prolonged recovery and in one case no business continuity[52]. **Are unnecessary F3 risks already being taken with public safety, particularly where high ambient temperatures and non-aspirated forceful applications are involved, placing extra stress on more vulnerable and less forgiving F3 agents?**

These four major fires and their contrary outcomes require further consideration by regulators, as they represent an important part of the justification for review of current fire test standards like ICAO Level B and C fire test protocols. The European Chemicals Agency Committee for Socio-Economic Assessment (SEAC) in their 2021 draft opinion on PFHxA restriction[53] warned (bottom p85) "***Costs of large fires that cannot be stopped could be enormous both in terms of economics, environment and potentially human suffering*.**"

9. Disturbing weaknesses with current approval tests

Concerns recently raised over inadequacies of ICAO Level B and C fire tests at TWG regarding the Part 176 ARFFS regulatory proposals[1] review are not new.

Briggs and Webb of the UK Fire Research Station (FRS) highlighted similar concerns in their 1988 paper[31] "Gasoline Fires and Foams". These issues confirmed "***Our concern relates to the possibility that foam agents formulated to meet existing specifications may show disturbing weaknesses in difficult firefighting conditions****. Specifically, we are concerned that* ***a foam may "saturate" with fuel, and a would-be protective foam blanket would sustain combustion and be destroyed****. Because of this concern, the investigation has been biased to a representation of the more severe* *type of firefighting conditions. While these conditions are not met every day, a severe test provides reassurance for "difficult" fires and a margin of safety for less demanding usage*.” A worthy and logical position, often assumed -but rarely evidenced - by existing fire approval tests like ICAO Level B and C (but also EN1568-3, UL162, ISO 7203-1, Lastfire, FM5130, IMO), particularly when PFAS-free foams (and not AFFFs) are increasingly being used, without adequate consideration of incumbent weaknesses (being discussed and identified in this document) with these alternative PFAS-free agents.

Fuel variability was also discussed in this paper[31], “***heptane consistency should be good, severity and realism are open to question***.” **Gasoline was the most severe fuel tested. Hexane was more severe than heptane. Pentane/toluene appeared to mimic gasoline. Toluene-hexane mixtures were more difficult to extinguish with difficulty increasing with toluene content up to 40%v/v**. Testing also raised **“*The effect of weather variations which can prevent meaningful comparison of outdoor fire tests*”**. ‘Convenient’ test temperatures can fail to adequately represent realistic operational firefighting conditions, unless specifically required to be conducted to reflect varying operational weather conditions. Authors recognised “***toluene as a ‘difficult’ fuel despite relatively low volatility. Its lower interfacial tension implies a greater readiness of aromatic hydrocarbons to emulsify in water or aqueous solutions.”*** This coincided with NRL’s 2019 findings on aromatics.

37 further fire tests were conducted[31] at 2L/min/m^2 and foam velocity of 7-8m/sec on 0.25m2 fire using modified FRS 5L/min nozzle and 4.5m2 fires at 2.4L/min/m^2 with UNI84 nozzle (Expansion 8:1, output velocity 7.2m/s). *“**heptane is undesirable as a general purpose test fuel as it shows no differences of behaviour where they are known to exist in commonplace incidents**. Uniquely among low flashpoint fuels heptane was extinguished by a simple protein* [fluorine free] *foam*.” **Foams self-extinguishing Mogas under these tough and forceful conditions incl. both FPs, the FFFP and one AFFF (most AFFFs failed). All foams (including Protein) self-extinguished heptane contamination.**

Heptane is currently used as the test fuel for many widely used fire test standard approvals including: EN1568-3; ISO 7203-1; UL162, FM5130; Lastfire; IMO. Whilst it does mimic gasoline fire performance quite well for fluorinated foams it does not do so for PFAS-free foams (F3).

This was clearly evidenced by NFPA Research Foundation (Back and Farley) 2020 comparative fire test Report[38] ”Evaluation of Fire Protection effectiveness of Fluorine Free Firefighting Foams (F3s)”. Five UL listed F3s were studied, two hydrocarbon based F3s and three Alcohol Resistant versions (AR-F3s) were tested against a baseline C6 AR-AFFF using the UL162 fire test on a range of fuels; IsoPropyl Alcohol(IPA), heptane, MilSpec gasoline and E10 (gasoline with 10% ethanol added). It confirmed “***To summarize the results, the baseline C6 AR-AFFF demonstrated consistent/superior firefighting capabilities through the entire test program under all test conditions**. **For the FFFs in general, the firefighting capabilities of the foams varied from manufacturer to manufacturer making it difficult to develop “generic” design requirements***.” …”***The FFFs did well against heptane***

but struggled against some of the scenarios conducted with IPA and gasoline (both MILSPEC and E10), especially when the foam was discharged with a lower foam quality/aspiration. *The FFFs required between 2-4 times both the rates and the densities of the AR-AFFF to produce similar results against the IPA fires conducted in with the Type II* [gentle] *test configuration.* ***During the Type III*** [forceful] ***tests, the FFFs required between 3-4 times the extinguishment density of the AR-AFFF for the tests conducted with MILSPEC gasoline and between 6-7 times the density of the AR-AFFF for the tests conducted with E10 gasoline***. *From an application rate perspective,* ***the FFFs typically required between 1.5 to 3 times the application rates to produce comparable performance as the baseline AFFF for the range of parameters included in this assessment***."

This report[38] also confirmed ***"The results also show that the legacy fuel (heptane) used to list/approve foams, may not be a good surrogate for all hydrocarbon-based fuels."***

Could Briggs & Webb's findings[31] be another reason why test approvals are reluctant to make tests 'harder' by moving away from common heptane test fuel use, when test factors have seemed historically adequate – but when based on fluorinated foams. This may no longer be the case in the light of growing F3 usage? F3s generally seem to work well on heptane at lower temperatures, but not so well on other flammable volatile fuels particularly gasoline, E10, hexane, benzene, toluene, avgas, some also struggling with avtur - Jet A/JetA1. Current MilSpec is widely recognized as probably the hardest approval test, yet US Department of Defence are under pressure to create a 'diluted' version to allow F3s to pass seemingly without addressing likely compromises that could result for life safety of front-line personnel and without due consideration of national security issue vulnerabilities it may also expose.

Briggs & Webb[31] confirmed "*The procedure adopted for both fire sizes was vigorous application of foam (at approximately 7 m/s) until 80% control was obtained.* ***This level of control was likely to represent the near-worst case for "difficult" application; by the time this stage is reached fire fighters are likely to find scope for less forceful application***. *The nozzles were then rotated through the vertical plane to give indirect 'gentle' application."* It concluded "***Real-life situations and large-scale trials have shown that some foams offer poor security to the extent that burnback has been known to occur while application is still taking place; i.e., fire control has been lost***. *…By the same token* ***heptane is undesirable as a general purpose test fuel insofar as it shows no differences of behavior where they are known to exist in commonplace incidents***. *… Consequently, there is a need for a more searching standard test method than any of those currently familiar."* **There still is!**

FAA's 1994 Technical Report (Scheffey and Wright)[54] conducted an 'Analysis of test criteria for specifying foam firefighting agents for aircraft rescue and firefighting'. They found **"***It was shown that the [US] MIL SPEC using a low flashpoint fuel [gasoline] and the lowest application rate of any test standard reviewed* [1.64L/min/m2 v more recent ICAO Level C using 1.56L/min/m2 but with other concerns – see Section 9.3 below]*, requires the least amount of agent for extinguishment***."** Their review also highlighted that "*The limited data available suggest that agents that fail to meet* *the MIL SPEC criteria may not provide this same factor of safety.* ***Given the basis of the FAA criteria (tests with QPL agents) and the critical time frames involved in ARFF operations (1-3minutes to respond, 60 seconds to control the spill fire), this safety factor is entirely appropriate as a basis for minimum FAA Certification."*** **…** MilSpec is ***"to date, the method with the best data to correlate results between small and large-scale for the application of interest, FAA certification of primary agents at critical application rates*** [used by FAA at 0.13gpm/ft^2 or 5.5L/min/m^2 operational application rate]**."**

FAA's 1994 results[54] of their 'modelling' experiments showed that *"…for a control time of 60 seconds, the application rate for AFFF was on the order of 0.04 - 0.06 gpm/ft^2 (1.6 - 2.4 Lpm/m^2) while the application rate for protein foam* [F3] *was 0.08 - 0.10 gpm/ft2 (3.3 - 4.1 Lprn/m^2). The data indicate that the application rate curves become asymptomatic at rates of approximately 0.1 gpm/ft^2 (4.1 Lpm/m^2} and 0.2 gpm/ft^2 (8.2 Lpm/m^2) for AFFF and protein foam respectively* [including 70% and 100% respective safety factors]. ***Above these rates, fire control times would not appreciably improve. Likewise, critical application rates for fire control are indicated when control times increase dramatically***." It goes on *"**The Montreal ICAO Panel[9] pointed out that quantities of agent required to extinguish actual aircraft fires are normally greater than those for test and training fires for a variety of reasons. They identified the problems of scaling from small to large scale, the training of the firefighting personnel, inaccessibility of some fire areas, initial overuse of foam, the three-dimensional nature of aircraft fires, and difficulties in deployment and control. Geyer has also identified wind as a factor. It is appropriate then, that any standard specifying foam products have a factor of safety. This is usually accomplished by having tests meet fire performance and bumback requirements at critical application rates, i.e., at rates below the rate at which increases provide insignificant benefits**. For AFFF, rates above 0, 10 gpm/ft2 (4.1 Lpm/m^2) may not provide any significant benefit in terms of substantially decreased control times. Critical rates for AFFF are on the order of 0.03 - 0.05 gpm/ft2 (1.2 - 1.6 Lpin/m^2."*

FAA's 1994 study[54] also covered large scale fire tests. Expansion ratio data for air aspirated and non-aspirated nozzles is given in Table 14. Appendix C confirms "*large pool fires of 16,000ft^2 (1,486m^2) were conducted using AFFF on Jet A at an application rate of 0.05gpm/ft2 (2.05L/min/m^2) with fire control times of 28secs for aspirated foam (expansion 6.7:1) with a control application density of 0.023gpm/ft^2 (0.94L/min/m^2). Non aspirated AFFF (expansion 4.9:1) achieved a control time of 24secs and control application density of just 0.020gpm/ft^2 (0.81L/min/m^2)*. ***A smaller 8,000ft^2 (748m^2) Avgas fire using AFFF at 0.05gpm/ft2 application rate with aspirated foam (expansion?) achieved fire control time of 56secs and control application density of 0.047gpm/ft^2 (1.92L/min/m^2). Another AFFF test by Tuve on Avgas with fire area 4,400ft^2 (408m^2) using a slightly higher application rate of 0.06gpm/ft^2 (2.46L/min/m^2) and aspirated foam*** [expansion unconfirmed] ***achieved a faster control time of 19secs and control application density of 0.019gpm/ft^2 (0.61L/m^2)***.*"*

No evidence of similarly large scale fire tests using modern F3 agents have been found in the literature or public domain, to provide evidence that F3s represent an effective comparison.

The largest known to date was in Dallas 2018, where a 40m long 300m^2 fire test was conducted and reported by Lastfire[55,56] on Jet A1 using AR-F3 as CAF (Compressed Air Foam) in a strange test configuration where the metal sides seemed suspended in water, acting like a huge heat sink, with short preburn time and application rate of 2L/min/m^2 achieving full extinguishment in around 3mins 27sec from time of actuation, an effective application density of 7L/min/m^2. (7 times higher application density on a 5 times smaller fire area than FAA reported in 1994).

FAA's (US Federal Aviation Administration – Bagot K Presentation Sept. 2021) summarizing FAA's ARFF Research program[57] into alternative PFAS-free (F3) foams which conducted 400 fire tests. Results were summarised to FAA's REDAC (Research, Engineering, Development Advisory Committee). FAA's extensive testing[57] of 19 x PFAS-free foams (F3s – 9 commercially available and 10 developmental) concluded: "***Approx. 400 fire tests have been conducted; NONE passed MilSpec or ICAO Level C***" consequently they "***Conducted ICAO Level C tests both outside and inside because of test results.***"
So ALL F3s tested failed to pass either ICAO Level C or MilSPec fire tests indoors in FAA's latest $5m 'state-of-the-art' fire test facility. They also all failed ICAO Level C protocol **when re-tested outdoors**, which may have been considered slightly easier to pass.
13 of the 21 ICAO Level C F3 tests did not extinguish within 2 mins, ie. 62%. On MilSpec's 30sec extinguishment requirement, F3 results ranged from a 38sec result to 2mins 23secs extinguishment. Two F3 agents did not extinguish and 6 of 9 F3s failed the burnback testing, ie 66%.

These stark and quite shocking test results provided the evidence base for **FAA's October 2021 Cert Alert 21-05[58] which raised public safety concerns over F3s, based on slower extinguishment, re-ignition, lack of compatibility** with other agents (Dry chemical and other F3 agents), lacking compatibility with existing equipment and existing training protocols. This Cert Alert[58] stated "*While FAA and DoD* [Department of Defense] *testing continues, **interim research has already identified safety concerns with candidate fluorine-free products that must be fully evaluated, mitigated, and/or improved before FAA can adopt an alternative foam that adequately protects the flying public. The safety concerns FAA has documented include:***

- ***Notable increase in extinguishment time;***
- ***Issues with fire reigniting (failure to maintain fire suppression); and***
- ***Possible incompatibility with other firefighting agents, existing firefighting equipment, and aircraft rescue training and firefighting strategy that exists today at Part 139 air carrier airports.***

While FAA and DoD continue the national testing effort, the ***FAA reminds all Part 139 airport operators that while fluorinated foams are no longer required, the existing performance standard for firefighting foam remains unchanged (whether that foam is fluorinated or not)****. Airports that are currently certificated under Part 139 will remain in compliance through use of an approved firefighting foam that satisfies the performance requirements of MIL-PRF-24385F(SH)* [which now includes F3s if they pass – Amendment 4, Apr.2020].” FAA made this strong stand to avoid compromising the travelling public’s safety with this Cert Alert.

The recent 2022 Dahlbom et al. paper from RISE[59] (Research Institute of Sweden), produced a range of very interesting findings of relevance to these issues. It conducted fire tests using 11x PFAS-free foams (F3s) on Jet A1, heptane and diesel pool fires (diesel being the easiest to extinguish), with quite cool foam solutions used in the range 15-20°C. CAFS (Compressed Air Foam Systems) and UNI86 low expansion foam nozzles were used with fresh and seawater, generally following ICAO Level B (freshwater only), EN1568-3 and IMO (Marine) fire test protocols. 9 of these foams were commercially available, 2 were in late stages of product development. The authors confirmed “*The focus* [of these tests] *has been widened to include impact from different types of fuels and waters, usage concentrations, and firefighting foam generation techniques and application methods*.” However, despite such minor differences to these test protocols “*The authors argue, however, that the results presented in this study are nonetheless comparable with results of a test performed without any deviations from the standard test methods and may be utilized as a baseline for comparison of different PFAS-free firefighting foams*.” Testing showed “*A firefighting foam works by preventing fuel vaporization, separating oxygen from the fuel* ***and cooling the fuel surface and surroundings***.” But …“***No correlation between fire control times and expansion ratio nor drainage time was found***.”

“***None of the products in the study met the fire test performance requirements in all the referenced standards*** *(cf. Table 11). Instead,* ***the products seem to have different niches where they perform best*** *eg. types of fuel and water.* ***<u>This highlights the importance of testing in an environment as close to reality as possible</u>****.”* Confirmation of effective capability under prevailing conditions and specific fuels is therefore critical to adequately representing the hazards being faced during emergency firefighting.

Findings[59] showed one foam never achieved 90% fire control on ICAO Level B nor EN1568-3, with Jet A1 or heptane respectively, using the specified UNI86 test nozzle. “*With the firefighting foam designated A, 90%* [fire] *control (cf. Table 4) was never achieved in two of the tests (F1.0 and F2.0);”* …*”In test F1.0 [ICAO Level B] the heat flux was significantly reduced to approximately 0.2kW/m^2* (as shown in Fig. 2); ***however, almost the entire fuel surface was still involved in the fire,*** *cf. Figure* ***4. This may be due to fuel pick-up and poor foam stability****. During test F1.0, a steady state was achieved; foam was applied at the same rate as it was consumed (as indicated by the constant heat flux after 50 s, cf. Figure 2).* ***With the current set up and application rate it would therefore be possible to control the fire, but not extinguish it****.”* This suggests Increasing the application beyond the test rate may have achieved successful extinguishment, but would erode the safety factor built-into the test rate to deal with the more onerous conditions usually experienced during real fire conditions.

Only 3 of the 11 F3s tested[59] passed ICAO Level B’s 120sec extinguishment time. The same 3 also passed using CAFs only shaving a few seconds off UNI86 extinguishment times. Only 2 of the 11 F3s tested passed the EN1568-3 extinguishment time (3 mins) for Class I using forceful UNI86 nozzle application, only 1 also achieving a ≥10 minute burnback test pass. 3 different foams improved extinguishment times sufficiently to pass this EN1568-3 fire test using Compressed Air Foam (CAF). *“A flare-up occurred for some of the firefighting foams, which typically lasted for some seconds. In those cases, the time to the first occurrence of a flare-up covering more than 25% of the surface has been reported.* ***This is in line with the definition by Schaefer et al. [11], who argued that the first failure of a foam blanket indicates a loss of adequate protection. Two factors indicating a low transport of fuel vapours through the blanket and the robustness of the firefighting foam when generated as CAF (B1.1, B2.1) can be pointed out: no flare-ups occurred and the burn-back times were significantly improved (longer)***.”

Dahlbom’s team[59] also found "*results indicate that the time to fire knockdown decreases with decreasing foam viscosity. The heat flux was shown to be small, although the entire fuel surface was involved in the fire.* ***The tests showed a dependence on fuel type; different products performed differently depending on the fuel.*** *Tests using sea water showed that addition of salt to the foam solution generally prolonged the extinction time, although for one of the firefighting foams a shorter extinction time was observed.* ***Out of the eleven evaluated PFAS-free products there was no product that outperformed the rest. None of the products in the study met the fire test performance requirements in all the referenced standards***."
These findings confirmed earlier 2020 results from NFPA Research Foundation[38] and Snow’s 2019 US Naval Research Laboratory findings[33].

Dahlbom’s tests[59] with CAFs generally made a more significant improvement on EN1588-3 results than ICAO Level B, and 50% higher proportioning rates generally extended fire extinguishment times. “Where increased proportioning delivered improved results they were generally small, but where performed worse, the impairment was generally large (up to 2 mins). …***A potential explanation is that the foam produced with a higher admixture was stiffer and did not spread as well as the foam with lower admixture****.”*

This Swedish discussion section[59] also confirmed that this study "***highlights the importance of testing in an environment as close to reality as possible***." and "***None of these products managed to reach 99% control of the fire in F2.0. This is assumed to be due to interactions with the fuel causing rapid breakdown of the firefighting foam***." …“***It may be concluded that the properties of the firefighting foam must be such that the firefighting foam can rapidly spread over the surface and thereby supress the fire but retain enough stability to prevent foam degradation caused by***

the fuel's vapour and radiation from the fire. *As demonstrated,* ***CAF shortens the extinction times, but does not reduce the heat flux as quickly as the foam generated using the UNI 86 nozzle. The investigation has also shown a significant dependence on fuel type; different products perform differently depending on the fuel. Also, a foam solution prepared from sea water most often showed longer extinction times***.”

NFPA Research Foundation's May 2022 Firefighting Foams: Fire Service Roadmap[60] (assistance when transitioning to PFAS-free foams), also expresses caution that F3s behave differently from the AFFFs they may be replacing. It begins with a section confirming how foams work: “*The* [foam] *solution is then aerated to form a bubble structure. Because the aerated foam is lighter than flammable or combustible liquids, it floats on the fuel surface. The floating foam produces a layer of aqueous agent, which suppresses and prevents combustion by containing the fuel vapor at the fuel surface and preventing air from reaching the fuel vapor. If the entire surface is covered with an adequate amount of foam, the fuel vapor will be completely separated from air, and the fire will be extinguished.* ***Low-expansion foams are quite effective on two-dimensional (pool) flammable and combustible liquid fires, but not particularly effective on three-dimensional flowing fuel fires. This is particularly true of three-dimensional fires involving low flashpoint fuels. Typically, an auxiliary agent, such as dry chemical, is used with foam where a three-dimensional fire (running fuel or pressurized spray) is anticipated***.” This verifies that approval verification of F3 compatibility with Dry Chemical agents is critical to avoid unexpected degradation of the foam blanket by the dry chemical, which can occur in foams without fuel repelling and/or film forming additives.

This 'NFPA-RF Roadmap'[60] continues” *Some legacy non-fluorinated foams, notably those that are protein-based, form thick, viscous foam blankets on liquid hydrocarbon fuel surfaces. These foams are typically referred to as mechanical foams. These foams extinguished fires using strong bubble structure to smother the fire as opposed to the film and bubble structure of the AFFF.*
The new fluorine-free foams are similar to the legacy protein foams in that they rely solely on the foam blanket to contain the fuel vapors to extinguish the fire (i.e., fluorine-free foams do not produce a surfactant film of the fuel surface like AFFF). As a result, air-aspirating discharge devices may be required to optimize the capabilities of these products.”

The 'Roadmap'[60] goes on “***Foams have been developed almost entirely from experimental work. Although many of the technologies are rather mature, no fundamental explanations of foam extinguishment performance have been developed based on first principles. As a result, the fire protection industry relies heavily on the approval tests for defining the capabilities of the foam as well as the extrapolation of these test results to actual applications by applying factors of safety to the test results***.” The evidence provided in this document does cover relevant 'first principles testing'. The implication from this roadmap being that safety factors have principally been developed based on foams widely in use over the last 50 years eg. AFFFs and FPs. This may no longer be adequate for current FPAS-free foams (F3s) which behave more like the traditional basic Protein foams as confirmed above, which generally require higher application rates and larger safety factors, which may not be adequate for increasing use of F3s against current standard test protocols designed with AFFFs in mind -like Aviation hazards in hot summer conditions.

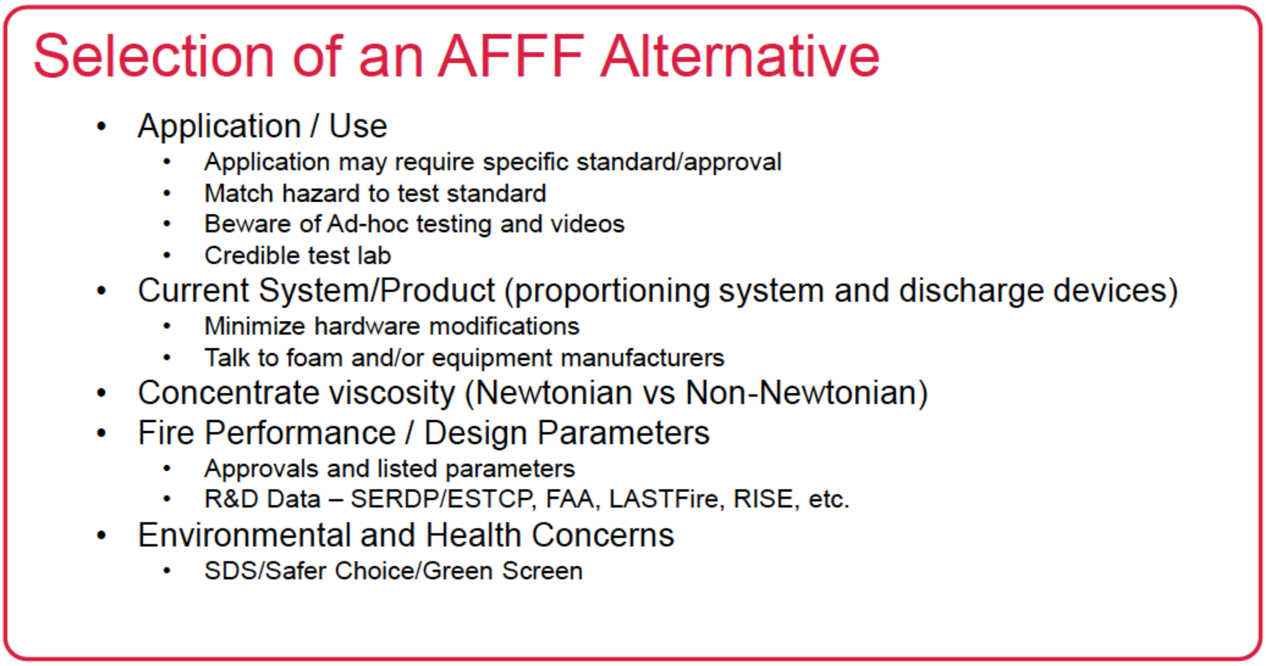
Dahlbom's 2022 Swedish research[59] confirms ". ***The tests showed a dependence on fuel type; different products performed differently depending on the fuel."*** which provoked a recommendation which "***highlights the importance of testing in an environment as close to reality as possible***." …including prevailing high ambient temperature conditions.

A 'foam tutorial' section of the 'Roadmap'[60] provides a useful reminder that "*Some discussion is also provided on products being marketed as 'universal agents'* [Class A Wetting Agents] *that can be used to extinguish both Class A fires (ordinary combustibles) as well as Class B fires (liquid fuel)* [but this may require high application rates, depending on fuel]. *But in general, since all Class B foam solutions are comprised of over 90% water, they all work well in extinguishing Class A fire*s." It goes on to clarify that existing test protocols *"the protocols are designed to verify specific capabilities and vary in difficulty depending on the scenario in which it was intended to mitigate. As a result, a foam designed and approved for DoD/Aviation applications may not perform well against a large petroleum industry fire (and vise-a-versa).* ***In addition, fuel type is a significant variable and needs to be considered during testing and foam selection****. It needs to be noted that these approval tests are not designed to simulate actual full-scale fire scenarios but rather to provide a means to assess the capabilities of these products on an affordable and reproducible scale using many of the parameters/conditions that makeup the industries' Maximum Credible Event (MCE)*." …" ***For the DoD, the design fire includes an aircraft rescue and firefighting (ARFF) scenario that includes a fuel spill under the aircraft that exposes the weapons to fire. This fire needs to be quickly controlled and extinguished to prevent ordnance cookoff. The aviation industry has a similar scenario except the hazards are associated with the burn-through of the fuselage that jeopardizes the occupants of the aircraft. Both the DoD and aviation industry scenarios have well defined fire scenarios (i.e., fuel types and minimal depth spill fires)***." For both DoD and the aviation industry '**time is of the essence' in providing rapid fire control and extinguishment. Therefore ANY delays in effectiveness could cost lives, potentially many lives in a wide-bodied aircraft major credible fire event**.

Warnings in this 'Roadmap'[60] are also usefully added "As a high-level overview of the state of the industry, ***a recent literature search identified between 60-70 commercially available products that were being marketed as "environmentally friendly" AFFF alternatives. A deeper dive into this information revealed that about one-half of these products did not have legitimate approvals and/or listings and were being marketed strictly on limited ad-hoc testing and associated videos. The remaining products have been tested to, and/or listed/approved to the legacy test protocols*** *shown in Table 3.0-1. Many of which have been successfully fielded and are in use today for a range of applications. The use of products tested and approved by credible testing and approval authorities is highly recommended (i.e., be skeptical of products being marketed solely on adhoc testing and videos)*." However, it does not alert users to those legacy test protocols being based on easier to pass heptane, rather than frequently used gasoline or E10 which may require higher application rates to be effective, nor does it point out that those legacy test protocols are predominantly designed around fluorinated foam performances like AFFFs, FFFPs and FPs, not PFAs-free agents which behave more like basic protein foams as confirmed earlier in the Roadmap document. Care evidently needs to be taken, re-inforcing Dahlbom's 2022 recommendation which "***highlights the importance of testing in an environment as close to reality as possible***."

Important cautions continue in this 'Roadmap'[60] with "*There are many very effective FFFs on the market and in use today.* ***However, it is incorrect to assume that these new FFFs are a "drop in" replacement for AFFF even though they may have a specific listing or approval. At this time, there is too much difference between specific FFF's in properties and performance to suggest that the class can be a drop in replacement for the AFFF class of foams. Specific FFF foams maybe used in place of existing specific AFFF foams in fixed systems or portable application, but a detailed evaluation must be completed prior to making that transition*** *as described in this document.* ***Ultimately, end users will need to design and install within the listed parameters in order to ensure a high probability of success during an actual event. This applies to both the discharge devices and proportioning system***."

Guidance is given by this 'Roadmap'[60] under 'Selection of an acceptable AFFF alternative' that "*The foam selection framework described in Annex C provides a couple of different approaches for identifying and selecting a fluorine-free foam. In short, the first focuses on compatibility with current hardware and/or a comfort level associated with a specific foam manufacturer and the second which revisits the basics and hazards and focuses on best performers independent of previous experience. The framework is outlined in Figure 4.0-1 below.*



Selection of an AFFF Alternative

- Application / Use
  - Application may require specific standard/approval
  - Match hazard to test standard
  - Beware of Ad-hoc testing and videos
  - Credible test lab
- Current System/Product (proportioning system and discharge devices)
  - Minimize hardware modifications
  - Talk to foam and/or equipment manufacturers
- Concentrate viscosity (Newtonian vs Non-Newtonian)
- Fire Performance / Design Parameters
  - Approvals and listed parameters
  - R&D Data – SERDP/ESTCP, FAA, LASTFire, RISE, etc.
- Environmental and Health Concerns
  - SDS/Safer Choice/Green Screen

Figure 4.0-1 Foam Selection Framework

Ultimately, there are a range of potential products that should be considered ***and researched prior to final selection. The end users will need to do their homework to ensure the selection of an appropriate AFFF replacement, to minimize the potential for transition regret*** *(i.e., to avoid multiple repeated replacements over time)*."
Transition regret could include inappropriate selection of F3 alternatives when C6AFFF agents have been shown to deliver faster, more reliable, more effective fire control and extinguishment at lower application rates on volatile fuels like gasoline, E10 and even Jet A/Jet1, and minimise harm to passengers, flight crews and firefighters by early reliable fire control, reducing the generation of smoke, reducing production of noxious breakdown products of the fire (including known carcinogens like benzene, formaldehyde, benzo a pyrene etc.), creating less runoff and resulting adverse environmental impacts from C6 AFF concentrates which are not categorized bioaccumulative nor toxic, have a short human half-life averaging 32 days, which is excreted in urine and has not been found to be harmful to human health. It may be the best all-round compromise to deliver life safety without the harmful concerns of legacy C8 AFFFs. Legacy C8 foams have not been manufactured since 2002-3 for Electrochemical Fluorination (ECF) products that were shown to breakdown to PFOS and PFHxS, and late 2015 for fluorotelomer products which could break down to PFOA.

These different C6 characteristics were confirmed by Russell et al's (2013)[61] study into 'Elimination kinetics of PFHxA in humans' , concluding "*The apparent* ***elimination half-life of PFHxA in highly exposed humans ranged between 14 and 49 d with a geo-mean of 32 d*** *[days]. The half-lives of PFHxA in mice, rats, monkeys and humans were proportional to body weight with no differences observed between genders, indicating similar volumes of distribution and similar elimination mechanisms among mammalian species.* ***Compared to long-chain perfluoroalkyl acid analogs, PFHxA is rapidly cleared from biota****.* ***The consistent weight-normalized elimination half-lives for PFHxA in mammalian species indicates that results obtained from animal models are suitable for establishment of PFHxA benchmark dose and reference dose hazard endpoints for use in human risk assessments***." …"***In all mammalian studies, the primary route of elimination was via urine***" … "***PFHxA is cleared from the plasma of humans and male rats 40–80 times faster than PFOA*** [typical legacy C8 human half-lives are 3.8yrs for PFOA; 5.4 yrs for PFOS; and 8.8yrs for PFHxS, as defined by Olsen et al research in 2007[62]]*. The slow rate of PFOA elimination from humans and male rats is due to a renal resorption mechanism which effectively reduces the net secretion rate of this carboxylic acid." …"The observed temporal concentrations of PFHxA in the blood of ski wax technicians showed a consistent pattern of clearly detectable peak concentrations established during the racing season (e.g.0.65–15.01 ng mL*$^{-1}$*) followed by elimination to values near or below the limit of quantitation (e.g. <0.05–0.14 ng mL*$^{-1}$*) in the months immediately following ski season.* ***The cyclic pattern of exposure and uptake during ski season followed by rapid elimination during spring, summer and fall was observed repeatedly with no apparent trend of bioaccumulation after four years of seasonal exposure***."

Also the Australian Industrial Chemicals Introduction Scheme (AICIS - formerly NICNAS), the Australian government's chemicals regulator, has confirmed through its 2015 IMAP (Inventory Multi-tiered Assessment and Prioritisation) Environmental Tier II assessments that legacy long-chain ≥C8s like PFOS[63] & PFOA[64] are categorised PBT. This assessment confirms "***It is not currently possible to derive a safe environmental exposure level for such chemicals and it is therefore not appropriate to characterise the environmental risks for these chemicals in terms of a risk quotient***." These legacy C8 PFAS are therefore widely banned or severely restricted from use and listed as Persistent Organic Pollutants (POPs) under the UN Stockholm Convention.

Short-chain C6 PFAS are significantly different from the concerns of their longer chain 'legacy C8' cousins. AICIS' 2015 IMAP framework's Environmental Tier II assessment of short-chain PerFluoroCarboxylic Acids (PFCAs) and direct precursors (including PFHxA)[65] confirms in its Hazard characterisation summary that ***"Hexanoic acid,*** *undecafluoro-; hexanoic acid, undecafluoro-, ammonium salt; pentanoic acid, nonafluoro-; pentanoic acid, nonafluoro-, ammonium salt; butanoic acid, heptafluoro-; and butanoic acid, heptafluoro-, anhydride are categorised as:*

- ***P*** [Persistent]
- ***Not B*** [Bioaccumulative]
- ***Not T*** [Toxic]"

Further AICIS findings[65] confirmed that ***"The chemicals in this group are not PBT substances according to domestic environmental hazard criteria."*** and ***"The chemicals in this group are not prioritised for further assessment under the IMAP Framework."*** Persistence and mobility alone do not cause harm. Only when inextricably linked to adverse bioaccumulation and toxicity impacts does the potential for harm occur, in which case these bioaccumulation and toxic hazards could then be extended over time and/or potentially spread over wider distances. This does not seem to be the case with C6 PFAS and the main breakdown product PFHxA.

In addition, AICIS' 2016 IMAP Tier II Human Health Assessment's Occupational and Public Risk Characterisation[66] for short-chain PerFluoroCarboxylic Acids (PFCAs) and direct precursors (including PFHxA) concluded: ***"Therefore, the*** [short-chain PFCA] ***chemicals are not considered to pose an unreasonable risk to workers' health."*** and … "***the public risk from direct use of these chemicals is not considered to be unreasonable***.***"***
Clear differentiation is now widely accepted between PBT Legacy Long-chain ≥C8 PFAS chemicals deserving of tight restrictions and bans in place due to POP listing, and the more environmentally benign P, NOT B, NOT T short-chain ≤C6 agents delivering relatively low concerns regarding human health and the environment, particularly when faster fire control and extinguishment using lower applications rates has been demonstrated (FAA[15,16,54,57,58] , NRL[14,22,29,33], NFPA-RF[38,60]), reducing risks of high smoke volumes, excessive firewater runoff and risk of overflows from containment areas, while also saving lives of potential aviation fire survivors.

EUROFEU (the European Committee of the Manufacturers of Fire Protection Equipment and

Firefighting Vehicles) in its May 2020[67] submission to the European Chemicals Agency (ECHA) public consultation on its proposed PFHxA in firefighting foams restriction proposal, **highlighted sections from the Dossier Submitter** [DS = Environmental Agencies from Germany, Netherlands, Denmark, Norway and Sweden] **confirming PFHxA was not harmful or hazardous**. EUROFEU also confirmed that **REACH requires clear evidence of unacceptable risk to human health or the environment**, which is clearly not the case, as EUROFEU confirmed to ECHA.

Eurofeu[67] confirmed: "***The DS*** [Dossier Submitter] ***itself states clearly that no hazards are identified for the substance*** [PFHxA] ***proposed for restriction:***

2.5.2 Human health impacts

The human exposure to PFHxA, its salts and related substances has the potential to cause adverse health effects. The toxicological profile of PFHxA is described in Annex B.5. Studies suggest that PFHxA might cause risks with regard to developmental and reproductive toxicity.

To date no indications of serious human health risks are documented. Human exposure to PFHxA is limited and the studies available suggest a considerable gap between effect levels and measured exposure levels and the current state of research suggests that human exposure to PFHxA is unlikely to increase to levels that cause risks to the human health*. But since PFHxA is extremely persistent and the releases are not reversible the magnitude of future exposure* ***cannot be predicted conclusively*** [yet – but hopefully will be]. *The extreme persistence means that the exposure via environment is intergenerational, and inevitably increasing,* [just unscientifically assuming harm in future] *in case the releases are not minimised. It* ***may thus be possible*** [speculation without evidence] *that serious health concerns related to PFHxA-exposure* ***may be documented in the future*** [a 'wish' not based in fact]. *It is important that releases are reduced to a minimum and possible future uses of the substances are prevented* [without evidence of any harm or benefit derived from such prevention, while ignoring the strong societal benefits of essential uses].

Considering the absence of clear evidence regarding human health impacts from exposure to PFHxA, the Dossier Submitter concludes that there are currently no impacts to be expected.

However, with a rising environmental concentration of PFHxA this may change in the future [but there are currently no facts suggesting this is the case, so it probably would be evident by now if there were to be problems in future]."

NB: Sections in brackets [ ] are this author's addition -not EUROFEU's, …**but seem implied by the general tone of EUROFEU's strong rejection of PFHxA restriction in their submission response**.

EUROFEU[67] also confirmed that *"All health related statements in the dossier point to the future and use conjunctives only"*, an example give was p. 10: *"PFHxA* ***may affect*** *the health of the general population in the future"* and p. 85 *"The* ***possible impacts*** *of continued emissions on the environment and human health are largely unknown* ***but might be*** *extremely severe*." …both being unproven 'assumptions'.

EUROFEU also pointed out that "***The criteria for adding a substance to Annex XVII REACH are stated in REACH, article 68 ff.:***

- ***unacceptable risk to human health or the environment***
- ***meets the criteria for classification in the hazard classes carcinogenicity, germ cell***

mutagenicity or reproductive toxicity, category 1A or 1B *(dossier says this is not fulfilled, p. 31)*

- ***Taking into account the socioeconomic impact of the restriction****, including the availability of alternatives*."

EUROFEU correctly confirmed: "***PFHxA does not meet any of the above*** [REACH]***criteria. This is supported by numerous literature referenced by the DS himself in the restriction dossier***."

Eurofeu also produced a Position Paper[68] on Fluorine Containing (and Fluorine Free) Foams which provides some additional useful advice on the responsible use of AFFF and potential alternatives.

9.1 Other research confirms improved fire testing necessary for Aviation Safety

FAA's 1994[54] conclusions include "***Based on the small- to large-scale correlation, agents which meet the MIL SPEC can meet FAA and NFPA criteria at application rates less than the design application rates of 0.13 gpm/ft² (5.5 Lpm/m²)****. This provides a factor of safety for products used at the lowest foam agent application rate.* ***The limited data available suggest agents that fail to meet the MIL SPEC criteria may not provide this same factor of safety****.*

Given the critical times involved in survivable post-crash fires and the probability that quantities of agent required to extinguish actual aircraft fires may be greater than those for test fires, the factor of safety inherent in MIL SPEC agents is entirely appropriate for FAA certification purposes. The safety factor is needed to address factors such as the level of training of firefighting personnel, inaccessibility of shielded fires, initial overuse of foam, three-dimensional fire scenarios, and difficulties in deployment and control*.*

Many of the performance criteria in the MIL SPEC are relevant to civilian aviation situations, e.g., interagent compatibility, PKP [dry chemical] ***compatibility, and performance of mis-proportioned and old agents****."*

So why are these important additional factors not considered, addressed, or included by ICAO in their current Level B and C fire test requirements? Surely this requires review and consideration of a significant and overdue overhaul?

Particularly when FAA's recent 2021[57] testing of 19 leading F3s, none of which was able to extinguish the ICAO Level C fire test using Jet A, nor MilSpec using gasoline, either in their new $5m purpose built indoor fire test facility, nor when repeated outdoors in case the indoor conditions were too onerous. This lead to FAA's Cert Alert (Oct. 2021)[58] voicing public safety concerns around F3s and re-inforcing that only MilSpec qualified foams were acceptable for use at FAA regulated airports.

Dahlbom's 2022 Swedish paper[59] fire tested 11x PFAS-free foams (F3s) on Jet A1 following ICAO Level B freshwater protocol, with quite cool foam solutions used in the range 15-20ºC. It confirmed *"**None of the products in the study met the fire test performance requirements in all the referenced standards** (cf. Table 11). Instead, **the products seem to have different niches where they perform best** eg. types of fuel and water. **<u>This highlights the importance of testing in an environment as close to reality as possible</u>**. This should better ensure effective capability can be achieved under prevailing conditions and specific fuels, representing the hazards being faced during emergency firefighting*." This requirement, suggested as essential by Dahlbom's research, is not currently the case with CASA's regulations, nor ICAO Level B and C fire test requirements. Both seem satisfied that testing around 15ºC ambient and foam solution temperatures, is an adequate indication of fire performance capabilities under significantly more onerous conditions, without any certification or verification in place. No specified fuel temperature is given and no due consideration of severe summer heat, freezing winter conditions, or whether the fuel is pushed above its flashpoint. **Additional regulatory requirements are therefore critical to ensuring competency of foams when being used under these more onerous prevailing conditions, during aircraft fires in Australia***.*

9.2 Hot and cold Burnback testing

Interestingly when Dahlbom's team[59] burnback tested all foams on cold heptane fuel to simulate an unignited fuel spill, none reached 6min 30sec as a 25% involvement time from the heptane fueled burnback pot placement in the foam blanket using UNI86 nozzle generated foam, but all 4xF3s cold burnback tested with CAFS showed dramatic improvement to exceed the 10mins pass with ease.

This was explained *"As outlined by Persson et al. [1], several differences exist between cold and hot* [burnback] *tests. **To explain the total mass loss of the firefighting foam, this study mentions radiation induced drainage and evaporation as additional parameters to ordinary drainage. From other studies [7, 9] it is also known that the fuel impacts the foam degradation. <u>All in all, this means that the expansion ratio and the drainage time measured at ambient conditions should not be used alone to predict the fire performance of a firefighting foam</u>.**"*

This suggests realistic conditions need to be involved in testing to ensure meaningful results are obtained, which can verify competency of the foam under the circumstances it is expected to face during major incident emergencies. Perhaps many fire approval tests are indicating 'best case conditions' with a 'safety factor' (assumed, not verified) to offset realistic worse case conditions often being faced in major fire emergencies. Are those safety factors usually based on the assumption a more effective and forgiving Fluorinated foam is being used? not a PFAS free alternative agent which indications suggest may give differing results? Hence the need to regulate an adequate verification test under prevailing conditions to demonstrate effectiveness and adequate speed at extinguishing relevant future fires under prevailing summer conditions.

Dahlbom's discussion section also "***highlights the importance of testing in an environment as close to reality as possible***." re-confirming the need for regulation and additional high temperature fire testing to better represent prevailing environmental conditions.

9.3 List of Weaknesses in ICAO Level B & C fire tests requiring rectification

Increasing evidence from comparative fire tests, lack of operationally relevant requirements during real aviation fires including for example; broad 'kerosene' fuel category which spans flammable and combustible fuels; high (and low) temperature operating conditions; high and low expansion foam can affect outcomes and required application rates; compatibility with dry chemical for engine fires etc; potential for seawater usage during emergencies at many coastal airports, often partly surrounded or immediately adjacent to the sea eg. Schipol, Amsterdam; La Guardia, New York; San Francisco; Boston; Kansai, Japan; Sydney; Brisbane; Hobart, etc.

Also in comparison with US MilSpec[69], ICAO fails to include important additional requirements related to maintaining effectiveness during major incidents like reduced and over-rich proportioning rates. These factors all combine and contribute to confirming that the current ICAO fire test standard[11] has not kept up with growing needs to demonstrate that lives can be kept safe, are not compromised by missing criteria, so that safety is demonstrated and maintained as ICAO's highest priority. There is a risk of growing complacency from a very safe industry which experiences very few major fire incidents. Consequently, the relevance of these fire tests are rarely called into question. This becomes particularly and increasingly apparent with the growing adoption and usage of PFAS-free or fluorine free foams (F3s) at major airport hubs like Amsterdam, London Heathrow/ Gatwick, Paris Charles de Gaulle, Copenhagen, Stuttgart, Dubai, Sydney, Melbourne, Auckland and others. The severity of a major 2016 fire involving a Boeing 777 in Dubai which burned for 16 hours to destruction, seemingly could not be extinguished using F3s, yet alarm bells have not been ringing that this could represent a systemic industry failure due to inadequate fire testing approvals.

A significant number of weaknesses have been identified with ICAO's Fire Test Approval certification at both Level B and Level C, particularly when compared to the more rigorous and real-life incident orientation of the current US MilSpec PRF-24385F (SH) Amendment 4, Apr. 2020 (MilSpec)[69]. These require correction and include:

- **Single pass using freshwater without any repeat testing** qualifies any foam as 'ICAO Certified' - even if this is just 1 out of 100 attempts! This is an unacceptably low bar and encourages poorer performance and inconsistency. MilSpec requires 7 straight fire test passes including a half strength fire test, without any failures to become a qualified listed product.
- **No requirement for re-certification over time**, so once a product is ICAO certified, its always approved - forever! This does not adequately protect users or incident victims against 'cost-cutting' or formulation changes that perhaps unintentionally reduce fire performance over time. There should be an ICAO requirement for a re-test every 3-5 years to verify continued

acceptability, and retain Certified status. MilSpec has an effective 'traffic light' system in place; green for currently qualified and acceptable for continued use; orange for re-testing pending, hold off ordering; red for re-testing period exceeded or did not pass - so no longer qualified. ICAO should consider a similarly robust system of on-going approval/certification which is publicly checkable online, since firefighting foam is such an important life-saving agent/tool which can positively assist, or indeed hamper, ARFF Services efforts during major emergencies.

- **Broad kerosene fuel testing category currently allowed,** which misleadingly allows fire testing on easier *combustible* category fuels with flashpoints 38-60°C, rather than Jet A1 only (required pre-2014) with a more volatile *flammable* fuel category flashpoint of 38°C, which can be exceeded under prevailing summer conditions in Australia, as confirmed by the BOM research[12] presented.
- **Testing only with high quality UNI86 branchpipe delivers better results,** making the fire test easier to pass. Aviation widely uses proprietary non-aspirated nozzles delivering significantly lower expansions which deliver more forceful plunging applications, but these are not tested. Their use may require higher application rates in compensation as confirmed by NFPA Research Foundations (NFPA-RF) Jun.2022 Transition roadmap[60]. "*The research conducted to date suggests that FFFs* [F3s} *tend to lose effectiveness when discharged through non-air aspirating nozzles that produce lower aspirated/aerated foam with expansion ratios less that 4-5."* also *"…reduced foam quality can be compensated for by increased application rate*" … "*The burnback and vapor suppression capabilities* [of F3s] *have also been shown to increase with increased aspiration*." ie. non-aspirated F3 applications are more vulnerable to sudden burnback, and may require higher application rates to be effective.
- **Extinguishment shifted from a 60 second requirement (pre-2014), to a 120sec requirement** post-2014 allowing persistent edge flickers and previously unacceptable AFFFs to now pass. This along with other 2014 changes has 'diluted' the acceptance threshold for this Standard eroding the safety factor previously relied upon to adequately protect life safety. It assumes adequate fire control in the PCA (Practical Critical Area) – as confirmed in Section 11. Without full extinguishment, this PCA is vulnerable to flashbacks and re-ignition during passenger evacuation without prior extinguishment, particularly with increasing use of F3s which do not have fuel repelling or vapour sealing additives, and may suffer decreased burnback capabilities, particularly when applied forcefully, or through non-aspirated nozzles/turrets with lower expansion ratios of 4-5:[38.] Not to mention smouldering of composite airframe materials[16]. This is confirmed by NFPA-RF's recent fire service transition roadmap (p15)[60]: "*The new fluorine-free foams are similar to the basic legacy protein foams in that they rely solely on the foam blanket to contain the fuel vapors and prevent them from mixing with oxygen/air above the fuel surface resulting in fire extinguishment (i.e., fluorine-free foams typically do not produce a surfactant film on the fuel surface like AFFF)*."
- **Fire testing is conducted at cool ambient and foam solution temperatures of 15°C only**, when such cooler temperatures decrease fuel volatility, while increasing foam stability,

making it easier to pass[14-16] – as evidenced in Sections 4 & 5. This is not representative of prevailing summer conditions in Australia, nor Middle East, much of Europe, parts of Africa, S. America nor Central Asia. It also does not adequately test fire performance under cold winter conditions commonly experienced by N. Europe, N. India/Nepal/Pakistan, Japan, Korea and parts of S. America and NZ.

- **No consideration of viscosity changes** with F3s, which tend to be more viscous shear-thinning or pseudo-plastic concentrates than usually Newtonian AFFF concentrates[60]. They are non-Newtonian (not flowing like water}, so they only 'thin down' with increasing shear rates. Minimum use temperatures of F3s are often only around 0°C to -3°C. They may be frozen or unusable below -5°C as their viscosity increases well above the recommended 200mm^2/sec., potentially up to several thousand mm^2/s (check the relevant Safety Data Sheet [SDS]). NFPA-RF's Fire Service Roadmap[60] confirms: "*The fire protection industry tends to refer to these thicker products as either non-Newtonian or pseudo-plastic concentrates. As general a statement, it appears that **concentrates*** **[incl. most F3s]** ***that have maximum viscosities (i.e., the viscosity at the lowest use temperature) of 200mm2/s (as determined using EN ISO 3104), can be proportioned with legacy AFFF hardware with little to no modification** or adjustments*." Otherwise specialised proportioning devices, even trace heating may also be required.
- **No recognition of increasingly hot summer operational temperatures,** as 15°C hardly represents hot summer conditions as summer often experienced ≥35°C in most places. After fire control, the hotter the ambient temperatures the less differential to provide sudden cooling [14,15] greater the drying out effects on the foam blanket[25,26,29,32], encouraging premature collapse and eroding the foam's ability to resist burnback as confirmed in Sections 4 and 5. AFFFs have unique additives, proven to be more resilient and effective against heat from fires and subsequent higher ambient temperatures[16], as fluorochemicals retain better bubble fluidity resisting these drying effects, while also reducing fuel pickup from forceful application and improving the remaining foam blanket's resistance to re-ignition. F3s have no such mechanisms, pick up fuel when forcefully applied, are prone to drying out in hot ambient conditions, and prone to sudden unpredictable flashbacks and re-ignition, exacerbated by premature foam bubble collapse from high ambient temperatures. Cooler conditions increase foam stability, reduce drying effects making the foam blanket more effective at fire control, so it's easier to pass the test at 15°C and provide adequate resistance to re-ignition. **Such ability is eroded under higher ambient conditions, particularly at or above 40°C which exceeds the flashpoint of Jet A1**, as confirmed in Sections 7 and 9. Consequently, the current ICAO Level B test result and Certification does not necessarily represent effectiveness under Australian hot summer real incident conditions – particularly when more vulnerable F3s are being used. Climate change is increasing the severity and frequency of such hot summer periods, and increasing F3 usage at major airports is also increasing the risks to public life safety. ***This problem needs to be urgently addressed by ICAO.***
- **No requirement for compatibility testing verification with Dry Chemical powder**, when

foam is often used alongside Dry Chemical for engine fires and other 3-D fuel fires[16,60,69]. AFFFs are usually compatible with most Dry Chemical, F3s are often attacked by Dry Chemical, collapsing the foam blanket, and exposing fuel to sudden re-ignition. The May 2022 NFPA Research Foundation's Fire Service Roadmap to transition confirms that "*Low-expansion foams are quite effective on two-dimensional (pool) flammable and combustible liquid fires, but not particularly effective on three-dimensional flowing fuel fires. This is particularly true of three-dimensional fires involving low flashpoint fuels.* ***Typically, an auxiliary agent, such as dry chemical, is used with foam where a three-dimensional fire (running fuel or pressurized spray) is anticipated.***" This verifies that approval verification of F3 compatibility with Dry Chemical agents is critical to avoid unexpected degradation of the foam blanket by the dry chemical which can occur in foams without fuel repelling and film forming additives. Consequently, MilSpec requires a compatibility fire test with Dry Chemical, so should ICAO.

- **Airports are often coastal, adjacent or jutting into the sea** (eg. Sydney, Brisbane, Hobart, LaGuardia New York, Osaka etc.), potentially requiring seawater use at airports during major emergencies yet without any proficiency provision. Most AFFFs will work with seawater, even if somewhat less effectively, but F3s often suffer considerable fire performance reduction or foam collapse in seawater- the salt reducing/inhibiting bubble formation, as found by Dahlbom's 2022 research[59]. Some consequently are clearly labelled 'freshwater use only' - as potentially ineffective using seawater, or indeed brackish bore-waters. ICAO has no seawater test requirement, unlike most other fire test protocols eg. US MilSpec, EN1568-3, ISO 7203-1, UL162 etc. With sea levels rising more airports may become adjacent or surrounded by sea, so perhaps its time ICAO included a sweater fire test.
- **Special handmade UNI86 branchpipe is used** (for consistency and repeatability across different concentrates) but delivering unrepresentatively high quality foam onto the fire, which does not match regular (often non-aspirating) nozzles more widely used at airports globally. Even when dedicated proprietary aspirating nozzles are being used, they rarely meet the high foam quality delivered by UNI86 test nozzles, so the test seems to be delivering a 'best case' result for the foams, without representing real nozzle usage during emergencies[16,38,60], and without significant 'reserve capability' in a safety factor necessary during fire emergencies – especially if the 'Pass' is borderline. Using a lower quality nozzle would build a safety factor into the pass results… but ICAO seem to be eroding that safety factor with better test nozzle performance than is likely in most major credible events.
- **No foam concentrate or premix storage at elevated temperatures** (eg. 10 days at 65°C prior to testing as required by MilSpec[69], which ensures no precipitation, stratification or premature deterioration occurs, which could block proportioning devices or cause poor fire performance by the foam. Such a precautionary test would better verify foam suitability under year round storage conditions.
- **No corrosion testing requirements** to ensure Certificated foams will not degrade either storage containers and tanks causing potential leakage, or could potentially attack critical

aircraft parts or unintentionally weaken structural aircraft elements like wheels and undercarriage. MilSpec provides these assurances, but not ICAO.

- **No environmental impact testing requirements** to ensure acceptable toxicity levels to aquatic organisms in waterways on and/or surrounding airports in Australia, or anywhere. Why not?
- **No PFAS testing requirements** to verify foams either contain only high purity C6 fluorosurfactants, or are free from fluorine without other persistent or potentially toxic/harmful ingredients. Some manufacturers have tried to use Fluoropolymers, or Siloxanes in claimed F3 formulations, which are unacceptable as F3s but ICAO has no way of providing assurance this is not occurring. Nor is there any testing required to ensure other chemicals included will not cause harm to human health or our environment. No firefighting foams are 'good' for our environment, but they are a necessary tool in controlling major flammable liquid fires in aviation and industry generally. ***Many foam users are seeking the 'least worst' foam agents when viewed from overall incident outcomes****, arguably delivering more important incident safety than just agent 'environmental credentials' because as the research presented indicates fire performance is key to saving lives and extinguishing aviation fires quickly. It's not just the concentrate criteria that's important – such reliance could be misleading, if higher application rates and slower fire control lead to excessive firewater run-off, excessive smoke production and duration, potentially resulting in loss of life. Also unnecessarily increased damage, potentially resulting in delayed airport re-opening, or causing extended airport closures or aircraft hull losses due to such delayed extinguishment, smoke, persistent re-involvement, fatalities, major injuries, or destruction of the aircraft requiring specialised equipment to move it to a safer place, so the airport can safely resume normal operations*. All these factors make major incidents harder, slower, more dangerous and damaging to resolve.
- **No available 'approved list' of Certificated concentrates** with a 'traffic light' system showing status regarding re-testing due dates, or completion by manufacturers, to ensure formulations have not changed since Certification and a foam's competency remains in place. This product tracking and re-verification process is provided under MilSpec by DoD's Qualified Products database (QPD)[70] and Underwriters Laboratories[71] as best practice, yet nothing is provided by ICAO. Time it was to improve fire and life safety.
- **Testing is conducted with premixed foam solution only**, so no requirement for the concentrate to be accurately proportioned immediately prior to use, as occurs on virtually all ARFF trucks (which do not carry premixed foam solution!) and required by UL162's fire testing protocol at minimum use with specific proportioning devices to achieve UL listing[72]. More viscous products can tend to form globules which can fail to mix properly within the water stream. Induction may occur precisely, but these globules may sink and coalesce along the bottom of pipes, with clear water flowing above, leading to weak foam solution (or virtually water) being delivered onto the fire, unable to effectively extinguish or resist flashbacks and re-involvement of the fire. This can become more prevalent during lower flow requirements eg. handlines, but is not being considered under ICAO fire testing. MilSpec

similarly does not conduct a proportioning test currently, but UL162 leads the way and some similar concentrate testing arrangement at minimum use temperatures should be incorporated by ICAO and MilSpec as best practice to provide confirmation of competency.

- **No consideration of increased vapourisation rates from flammable fuels** (eg. Jet A1, Avgas) likely to occur under hot summer conditions above Jet A1's 38°C flashpoint, making fires more intense and potentially harder to control, increasing life safety risks for passengers, flight crew and firefighters, as confirmed by research findings in Sections 7 and 9.
- **This ICAO test standard complacently relies upon the forgiving and resilient nature of Fluorinated foams** under real life conditions for its credibility, and the relatively few major incidents which have occurred in recent years. It misleadingly does not translate to F3s which are significantly more vulnerable, unforgiving and less resilient when faced with extra pressures usually experienced in major incidents, as NFPA-RF Fire Service roadmap[60] confirms "*the FFFs [F3s] are not as forgiving as AFFF with respect to application technique. Specifically, the first hose stream pass with the FFFs provided good knockdown and control, but it typically took two passes to extinguish all the fires as opposed to one for AFFF.*" Also "*…the FFFs required better application techniques and a little more finesse to be effective. As a result, pre-fire planning and training will be key to successful implementation/deployment of these products going forward*." ICAO seems not to have adequately addressed the implications of increasing use of F3s, beyond extending the extinguishment time from 60 secs to 120secs in 2014 allowing F3s to pass the test. An ICAO Level B or C test result pass, may not translate to effective action in major incidents, especially under high temperature conditions, as already evidenced in Dubai's Boeing 777 crash in Aug 2016, and Melbourne's Footscray Chemical fire in Aug 2018, where Fluorine Free Foam [F3] was extensively used in both incidents.

These weaknesses clearly show the current ICAO Standard is overdue for a major review and overhaul of its fire performance criteria to keep pace with best practice, and the vulnerabilities of F3s, which are not currently being recognized, which could put a large plane load of lives in increased danger unnecessarily.

These weaknesses provide a sufficient evidence base for European Union Aviation Safety Agency(EASA) to raise these important issues directly with ICAO requesting a technical review and overhaul of the current ICAO fire test standard to better protect life safety and demonstrate best practice, as a matter of urgency. Particularly since EASA's 2022 stated mission[5] is: "*Your safety is our mission. EASA is the centre-piece of the European Union's strategy for aviation safety. Its objectives are:*

- *to promote and achieve the highest common standards of safety and environmental protection in civil aviation*
- *to ensure you have the safest possible flight*

We ensure that your flight is safe in all phases: beginning with the rules the airlines and crew need to follow through to the certification of the aircraft you are sitting in.

We regularly revise the risks and improve the common regulations applied among EU countries and airlines so they are always of the highest standard." Time to implement these objectives regarding firefighting foam safety.

Briggs & Webb (1988)[31] summed it up well, when they confirmed "***Our concern relates to the possibility that foam agents formulated to meet existing specifications may show disturbing weaknesses in difficult firefighting conditions***.*"* Consequently, they ensured future testing was improved to include previously 'missing criteria'[31]*"…to a representation of the more severe type of firefighting conditions. While these conditions are not met every day, a severe test provides reassurance for 'difficult' fires and a margin of safety for less demanding usage*." This should surely also be ICAO's objective for a more robust and realistic fire test revision.

Most of these weaknesses and missing criteria highlighted as requiring change to the current ICAO Standard (2015)[11] are summarised in this comparison table against current US MilSpec PRF 24385F (SH) Amendment 4, dated April 2020[69].

Criterion	**US Mil PRF 24385F (SH) Amdmt 4 Apr.2020spec. (3% Foam)**	**ICAO 2014 revision Levels B and C (3% Foam)**
Fire tray shape and area	Circular 28ft^2 (2.6m^2) and Circular 50ft^2* (4.64m^2)	Level **B**: Circular 4.5m^2 **Level C: Circular 7.32m^2**
Fuel type – fire test	**Unleaded gasoline (Flashpoint -40^{o}C)**	Jet A1 (FP38^{o}C) or Kerosene (FP 38-60^{o}C) *(ONLY Jet A1 required pre 2014)*
Fuel type – burnback pot	**Unleaded gasoline (1 Gal, 3.8L)**	Gasoline or Kerosene (2L)
Fuel quantity	**10 gals (37.85L, shallow water base) - 28ft^2; 15 galls (56.77L) - 50ft^2**	Level **B**: 100L fuel Level **C**: 157L fuel (over equal water bases)
Non-aspirated Foam nozzle & flow rate	**Mil spec 2 gal/min (7.5L/min) Modified Std nozzle (typical expansion 3-5:1)**	NR (*NB: More challenging test conditions esp. for F3s*)
Aspirated Foam nozzle & flow rate	**NR *(NB:AFFFs perform equally effectively at 7-10:1, but non-aspirated more forceful = tougher performance test)***	UNI86, 11.4L/min Special high performance nozzle (typical expansion 7-10:1) Not representative of most nozzles being used by ARFFS
Nozzle pressure	100psi (7 bar)	6.3-6.6 bar
Concentrate storage stability (pre-fire test)	**10 days @ 65°C**	NR
Application density (higher)	**0.07g/ft^2 (2.92L/min/m^2) 28ft^2 (fresh and saltwater)**	**Level B**: 2.5L/min/m^2 (single freshwater test only)
Application density (lower)	**0.04g/ft^2 (1.64L/min/m^2) 50ft^2‡ (saltwater only)**	**Level C: 1.56L/min/m^2** (single freshwater test only)
Ambient& foam solution temperatures	**23°C± 5°C (ie.17-28°C)**	≥15°C (*some certs. Show 0°C)*
Fuel & water base temperatures	**NR**	NR
Nozzle movement	Complete freedom of movement	**Fixed position**
F and F-free foams allowed	Yes	Yes

PFOS & PFOA analysis	≤ 800ppb PFOS ≤ 800ppb PFOA	NR
Total Fluorine content	Measured	NR
Foam % tests	3%; 1.5 % (lean) #†; 15% (rich)*†	3% only
Fire pre-burn time	10 secs	60 secs
Foam water quality	Fresh & Sea ‡	Fresh only
Foam application time	90 secs	120secs
Total extinction (pass)	30 secs (3%), 45 secs (1.5%) 55 secs (15%), 50 secs 50ft^2	120 secs
Burnback pot size/fuel (both centre tray)	0.3m dia, 50mm tall, 1 gal ULG (3.785L)	0.3m dia,200mm tall, 2L ULG/Kerosene
Burnback pot ignition time	60secs end foam application	120 secs end foam application
Burnback re-involvement (pass)	≤25% tray in 6 mins (3%)#, 5 mins (1.5%)#, 3.3 mins (15%)* 6 mins (50ft^2)*	≤25% tray in 5 mins (single freshwater test only)
Total fire tests to Qualify/Certify as Passed	7 Fire extinctions & burnbacks, Dry Chem test, fresh and seawater, after ageing 10 days 65°C	1 (fire extinction & burnback – freshwater only)
Film, sealing, corrosion, compatibility, storage etc.	✓	NR
Compatibility with Dry Chemical fire test	≥6 mins burnback	NR
Aquatic toxicity test	LC50 ≥500mg/L	NR
Biodegradability, BOD/COD	20 day Biodeg. 65% COD ≤1,000k mg/L (3%)	NR
Strict drum & label spec.	✓	NR
Qualified Agent Database	✓	NR

Key: 🟩 = Harder; 🟧 = Easier: 🟨 = Equivalent; NR = Not Required; * = seawater test only; #= fresh and seawater tests; †= 28ft^2 test only; ‡ = same as UL162 fire test.

Table 1: Comparison of 3% foam requirements for 2020 MilF Spec. v the latest 2014 ICAO Levels B and C. fire test.

<u>NB</u>: It should be noted that the ***public comment draft US Milspec fire test for PFAS-Free foams***[73] *has weakened the current specification, contains many inconsistencies and raises concerns about mis-representing realism for major credible aviation fire events.*

The evidence contained in this submission Pt.2 document highlights the often unappreciated vulnerability implications of F3 usage during major credible aviation incidents (like the Dubai fire in 2016 discussed in Section 8.1), **<u>intended to ensure compromising life safety in future aviation incidents is avoided</u>.** These risks are only set to increase as our world gets inexorably hotter (discussed in Section 3), if F3s continue to be used without significant revisions to the ICAO Standard to cover critical missing criteria identified above.

ECHA and EASA are urged to take a leadership role in encouraging ICAO to undertake these improvements, as Europe is 'on the 'front-line', as increasing global climate' hotspot' already experiencing these adverse impacts with rising temperatures, increased flooding, severe bushfires and storm events, providing growing likelihood of more challenging fire events. Responding to these fire test weaknesses would seem critical for ICAO to maintain confidence with regulators, airport operators, insurers and ARFF foam users, by confirming necessary modifications to the ICAO fire test protocol so it can remain relevant by providing effective and representative Approval Certification of realistic emergency events, including those where F3s are being used, which are safe and fit for purpose across a wide range of operational conditions increasingly being faced by airports globally. **Currently this still seems NOT to be the case in Australia**. As severe heatwaves in Europe (2021 & 2022), USA, India, spreading globally over recent years are also indicating, such a Standard review by ICAO is now long overdue.

10. Criticality of vehicle response time to survivable atmospheres

An interesting paper by Scheffey & Bagot(FAA) in 2008[15] '**Status Report on an effort to Evaluate and Develop Methodologies for Calculating Firefighting Agent Quantities Needed to Combat Aircraft Fires**' reviewed current methodology for calculating total firefighting agent requirements to combat aircraft fires. A key focus was to improve effectiveness of ARFF resources, with the introduction of larger frame aircraft (eg. Boeing 777, A380 etc) with higher fuel loads, composite materials, higher passenger numbers and potentially increased thermal radiation from larger pool fires. All provided motivation to investigate whether current methodologies remained appropriate – which also seems topically relevant to required objectives of this CASA review of Part 176 ARFFS regulatory requirements.

It[15] considered US Title 14, Code of Federal Regulations Part 139 (14 CFR 139) ARFF requirements, NFPA and ICAO requirements, since "*The specification of firefighting agent quantities and associated crash firefighting and rescue (CFR) vehicles to deliver these agents was developed* ***with the goal of saving lives in a survivable aircraft accident at or in the vicinity of an airport****. The agent quantities are based on cutting a rescue path for occupant self-evacuation, assuming a large jet fuel pool fire has occurred*." Research conducted by FAA (US Federal Aviation Administration) "***indicated that when an aircraft is involved in a fuel spill fire, the aluminium skin will burn through in about one minute. If the fuselage is intact, the sidewall insulation will maintain a survivable temperature inside the cabin until the windows melt in approximately 3 minutes. At that time the cabin temperature rapidly increases beyond a survivable temperature*.**" Severe smoke is also likely to cause a noxious suffocation risk to any passengers still on-board, so the assumption of rapid 2minute response times and 60 second fire extinguishment (within total 3 mins of ARFF action) from the fire starting has a direct effect on the ability of ARFFS crews to save passenger and crew's lives. This research[15] confirmed ARFF vehicles are intended to provide "***adequate amounts of extinguishing agent at appropriate discharge rates so that trained personnel should be able to obtain fire control in one minute. ARFF personnel must reach the accident scene within two minutes in order to prevent life safety consequences of the anticipated fuselage burn-through***." It has been demonstrated this is generally only likely to be possible using leading high purity C6 AFFFs (MilSec listed) as ICAO Level B and C approvals require foams to extinguish the fire (even if sections like PCA) within 120secs not 60secs as previously, *before* current changes in 2014, and without fuel repelling additives which may lead to premature and sudden flashbacks or re-ignition involvement, particularly when used in hot summer conditions where incandescent and smouldering composite materials are likely to provide an ever-present source of re-ignition potential, which could place escaping passenger's, flight crews and firefighter's lives under increased risk of unacceptable harm.

The Scheffey 2008[15] warned "***Currently, there is little latitude in adjusting these critical times without significant technological or regulatory changes. Pool fire extinguishment is based on the best, currently available primary agent, AFFF.*** *Reducing vehicle response time would add significantly to equipment and facility requirements*."

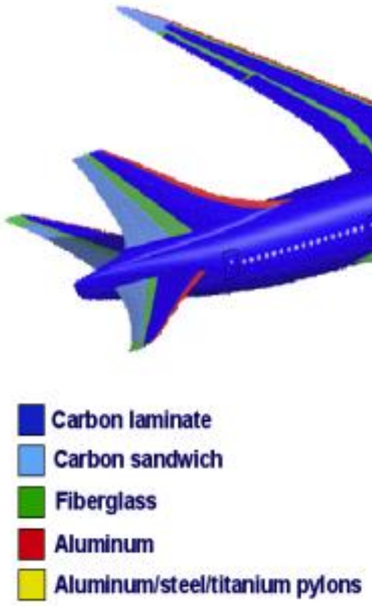
This builds on Scheffey's earlier 1994 Analysis of test criteria research[54], which confirmed that " *If the fuselage is intact, the sidewall insulation will maintain a survivable temperature inside the cabin until the windows melt out in approximately three minutes. At that time the cabin temperature rapidly increases beyond survivable levels."* This 1994 Analysis continues "***ARFF vehicles are designed to reach an accident scene on the airport property in two to three minutes, depending on the standard enforced by the authority having jurisdiction. Having reached the scene in this time frame, the extinguishing agent must be applied to control a fire in one minute or less. The one minute critical time for fire control is recognized by FAA, National Fire Prevention Association (NFPA), and the International Civil Aviation Authority (ICAO.)***" **This is no longer the case with the current ICAO Level B and C fire test, following the latest revision in 2014, where full extinguishment was extended from 60 secs to 120secs.**

A more recent 2012 FAA Report by Scheffey's team[16] confirmed that it was "***noted that quick response and quick knockdown of the fire by airport fire equipment offer the best chance of passenger survivability in an aircraft crash situation.***
They recommended a maximum response time of 3 minutes, recognizing that "this time period is considered by most authorities to be longer than can actually be tolerated to assure survivability of all passengers." They asserted that the effectiveness of an airport crash fire/rescue service diminishes rapidly with response times to the scene of a crash in excess of 2 minutes, based on their thermal analysis as described in section 3.2.2. They indicated that a desirable response time would be 90 seconds *(0-second response time would be the goal, but it is obviously not practical), with a 2-minute response as optimum.* ***Even these response times, they noted, will not be adequate for major crash fires, in which fuselage openings are directly exposed to fire or in which the cabin interior is involved***."

This 2012 report[16] also recognized longer response times were possible with fire offsets further from the fuselage such that "***The initial offset for the 2-minute response is on the order of 10 to 12 m. For fires occurring within 3 m or less of the fuselage, success is predicted only when response time is less than 1.5 minutes. Fortunately, most crash fires have some growth period (e.g., Okinawa, 2007). Immediate fuselage involvement does occur, however (Los Angeles, 1978); in some cases, response time on the order of 1 minute is achieved (Los Angeles, 1978; Toronto, 2005)***."

10.1 Smouldering Composite materials risk re-ignition

This 2012 report[16] also confirms **“*Foam effectiveness was based on a conservative estimate of 0.13 gpm/ft2*** *[5.5L/min/m2]* ***required for suppression using aqueous film-forming foam (AFFF).*** *The agent requirement methodology in NFPA 403 was found to be an acceptable and appropriate method to establish agent quantities.* ***The new FAA 4-minute burn-through criteria dramatically reduced the chances of interior ignition for the intact aircraft crash scenario*****.” This 4 minute burn-through scenario may explain the extended 3 min response time in NFPA 403:2018 from the previous 2 minutes, but still seems to assume “*, the extinguishing agent must be applied to control a fire in one minute or less.”*** This may not be possible with modern F3s, achieving ICAO Level B and C fire tests extinguishment within 2 minutes at 15°C, without taking into account the likely reduced fire control capabilities, when operating under hot summer conditions, likely at or above the flashpoint of JetA1. Are we ignoring realistic credible events during summer? which other research presented seems to suggest may result in such ‘theoretical optimism’ to be misleading?



Composite materials involved in Boeing 787 aircraft (extracted from Report)

Concerns were also expressed in this 2012 report[16] that **“*Data are lacking to fully understand the threat posed by the potential large-surface area involvement of composite material. There is insufficient data to make a clear determination of the agent requirements for advanced composite airframes that are used in new aircraft. Suppression of burning composites requires testing*.** *Additionally, data regarding the potential for combustible materials in a debris field from larger aircraft and the new escape slide locations to add to the agent requirement is also insufficient and requires testing.”* Add to that questions of foam’s effectiveness under high temperature summer conditions in Australia.

This 2012 report[16] confirmed that the requirement for newly installed thermal acoustic insulation to resist flame penetration has extended cabin survivability for intact fuselages exposed to an exterior

fire threat. It also confirms that the growing use of composite materials also provide delayed flame penetration into the fuselage interior.
It goes on to confirm that "*Much of the aircraft interior is constructed from composite material and is subject to toxic fume and flame spread criteria. This argument focuses on the interior fire threat only (e.g., in flight cabin fire).* ***The exterior fire threat scenario must also be considered, involving exterior burning, which may require suppression by the initial ARFF response. There is also potential for re-ignition of a fuel fire from smoldering fuselage composites*.**"
Reference is made in this report[16] to a 2004 US AirForce fire test study conducted on two composite (AS4/3501-6 graphite/epoxy) wing boxes. "*The second scenario simulated a 5-minute delayed extinguishment in which the fire department responded with AFFF.* ***After the second test fire was initially extinguished, the composite material flared up three times, requiring additional agent to extinguish the fire.*** *No data was provided in the test report related to the amount of agent used, duration of foam application, or foam amount required to extinguish the reflashes*."

It[16] also confirmed the US Navy had conducted fire tests on composite materials using *"3501-6/AS graphite epoxy carbon fiber used for F-8 fighter aircraft wings. As expected, the composite wing was much more resistant to burnthrough than an aluminum wing.* ***It was found that this composite would self-sustain combustion in as little as 2.5 minutes of exposure to an external pool-type fire****."*
It continued *" The pool fire was easily extinguished in all tests. However,* ***extinguishment of the composite combustion was not as easy****.* ***The surface flames were readily extinguished, but smoldering composite combustion was already established. To extinguish the smoldering composite combustion, the fire fighters applied a continuous stream of AFFF directly on the composite material****. In the case of the panels on the lower wing surfaces, the fire fighters went in close with the hand line.* ***After applying AFFF for 3 minutes or more, the smoldering composite combustion was extinguished****.*
The smoldering composite combustion produced a visible glow as the graphite fibers burned. It also produced faint smoke or rising heat waves as the epoxy smoldered*. PKP was effective at extinguishing the surface flames on the composite panels,* ***but it did not extinguish the smoldering composite combustion****.* ***Smoldering composite combustion was best extinguished by cooling the composite with direct application of AFFF.***
The presence of JP-5 fuel in the wings seemed to affect the burning composite and helped establish the smoldering composite combustion*.*
***It was concluded that fast response by the fire fighters reduced the chance that smoldering fire will be established. Since fire fighters may have to work in close to the aircraft to control the* composite fire, they must be aware of potential re-ignition of fuel under or around the aircraft**."

This FAA 2012 Report[16] re-affirmed FAA's fire performance objectives:

- to protect ambulatory occupants by preventing heat penetration inside intact aircraft
- prevent thermal threat to evacuating passengers
- Ensure sufficient agent available to establish a safe area for continuous rescue and recovery efforts of survivors, while also affecting final extinguishment of all exterior and interior fires.

These would appear to coincide with ICAO and CASA’s objectives also. It emphasizes the importance of **rapid response times and fast acting agents which are recognised as key to minimising fatalities in major aircraft fires. This is particularly relevant when uninterrupted fuel leaks or fuel tank penetrations can be achieved by fuel line ruptures, engine failures, engine detachments, landing gear failures and debris punctures from a broad range of aircraft accidents and incidents.**

Amongst its conclusions this 2012 report[16] confirms *“**Understanding the threat posed by the potential, large-surface area involvement of composite material suffers from a lack of data. … When a wing is also involved, the composite has a high heat release rate, and firefighters are inefficient in attacking the fire and applying agent (over 5500 gallons*** **[20,820 litres]** ***might be required****).*

These tests were all conducted with MilSpec AFFFs. Such continued smouldering and incandescence of these composite materials after pool fire extinguishment, increases the risk of flashbacks and re-involvement, while also increasing the danger for escaping passengers, firefighters and flight crews, particularly when PFAS-free foams (F3s) without fuel repelling additives are being used, and especially under prevailing hot summer conditions at or above the flashpoint of JetA/Jet A1 ie ≥38ºC.

Also additional concerns were raised in this 2012 report[16] “***Because of their increased volume, double-deck aircraft could be considered analogous to two aircraft on top of each other.*** *Increasing the height by adding additional decks does not increase the overall length, which would increase the required amount of agent;* ***therefore, a safety factor can be accommodated by considering all double-deck aircraft in the next-higher category until sufficient data is available to adequately characterize the hazard***.” It continues …” *A simple summary has been provided by Tom Lindemann, a past member of the NFPA 403 Technical Committee [17], which states that* ***FAA research indicates that when an aircraft is involved in a fuel spill fire, the aluminum skin will burn through in about 1 minute. If the fuselage is intact, the sidewall insulation will maintain a survivable temperature inside the cabin until the windows melt in approximately 3 minutes. At that time, the cabin temperature rapidly increases beyond a survivable temperature of 400°F*** [204ºC]. ***The ARFF equipment and agents can control a fire in 1 minute. Therefore, ARFF personnel and equipment must reach the scene in 2 minutes to meet the anticipated burn-through scenario.***” This statement relies on, and assumes, the use of AFFF to provide fire control in 1 minute. It probably does not anticipate likely delays from slower F3 usage and particularly not under severe high summer temperatures >40ºC being regularly experienced at several European airports and more widely in other regions eg. Australia, USA, Asia etc.. This 2012 Report also confirms that “*NFPA 403 implicitly requires agents for these requirements in the* Q_1*,* Q_2*, and* Q_3 *approach, and explicitly in the ICAO Annex 14 rationale. The FAA and* ***ICAO do not explicitly recognize the*** Q_3 ***(interior firefighting) requirement***.”

There does not appear to be a similarly rigorous series of fire tests conducted to verify that F3s behave similarly effective under these very varied conditions as the US LilSpec AFFFs tested in this 2012 Report. Why not? Surely this is required before full confidence can be gained in F3 alternative foams for Aviation use. The real-life major fires described (Dubai's Boeing 777 in 2016 and Footscray's 2018 chemical fire in Melbourne) do not give confidence that this may be the case, which should justify more rigorous testing before adoption by major airport hubs and locations where high summer temperatures are involved.

Extending response times to 3 minutes as NFPA 403:2018[74] suggests (from previously 2 minutes – presumably based on FAA revised 4 minute burn-through criteria), while providing slower acting foam agents (which ICAO requires to extinguish Level B or C fires in 2 minutes [from 1 minute previous to 2014 changes]) without allowance for impaired fire performance by F3s as other research suggests[14-16,22,27,29,32,60] during hot summer temperature conditions could result in exceeding the 4 minute window by up to 1 minute or more. **This could be unintentionally creating a significant response problem, whereby survivors may be doomed to perish within un-survivable atmospheres in the cabin as a 'death warrant' for otherwise potential crash survivors. A situation most Coroner's would probably find inexcusable and untenable.**

Such a scenario was raised by this 2012 Report[16] confirming "*The Gage report [6] cited* ***a detailed survey of aircraft accidents up to 1963, which indicated that the conventional rescue concept was applicable to crew-only aircraft. In passenger transports, the occupants either escaped themselves or, unless the fire was extinguished, they perished. This escape, however, may have been aided or made possible by fire suppression activities. An updated survey by the Gage report of accidents did not indicate any significant variation from this conclusion****."* Surely in this modern age such an approach is widely considered unethical, without every effort being made to save lives wherever possible by using the most effective tools possible.

Why are these continuing legitimate concerns regarding prevailing high temperature conditions during summer, not being taken sufficiently seriously by Regulators like ECHA, EASA, or indeed ICAO?

Further testing was confirmed by this 2012 Report[16] into response times and conditions necessary for cabin ignition to occur, and presumed resultant fatalities. *"****It was found that a heat flux of 9.59 kW/m2 was the threshold value for causing the aircraft interior to ignite****. This is called the isoflux in this analysis. The isoflux distance is the maximum distance from an aircraft where a fire could cause interior ignition due to thermal radiation.* ***The distance from the edge of the fire at which this flux occurs varies with the scenario, but ranges from about 3 m for an aircraft located downwind of a fire to 33 m for an aircraft located upwind of a fire.***"

It was found that over the parameter range considered, there are basically five ARFF response time fuel spill offset regions. These regions are as follows*:*

- ***Time Region I: ARFF needs to extinguish the fire to the 9.59-kW/m isoflux distance to prevent aircraft ignition.***

- ***Time Region II: ARFF needs to extinguish the fire beyond the maximum distance that the fire could produce an incident heat flux of 9.59 kW/m (the isoflux) at the aircraft outer surface to prevent interior aircraft ignition. This occurs in situations where the fuselage is heated to such an extent that an incident heat flux less than 9.59 kW/m may still result in interior ignition.***

- ***Time Region III: ARFF arrives before the aircraft ignites, but suppressing some or all of the spill fire does not prevent ignition. In other words, ARFF has arrived too late or the fire is too close to the aircraft to prevent interior ignition.***

- ***Time Region IV: ARFF arrives after the aircraft interior has ignited.***

- ***Time Region V: the maximum incident heat flux at the aircraft is less than 9.59 kW/m , thus, ignition is not predicted regardless of the ARFF suppression actions.***

Figure 9 shows example Scenario 1 wherein the time regions for a 240-ft-long aircraft with a 0.02-in.-thick aluminum skin is exposed to a spill fire without wind.” Figure 9 is shown below.

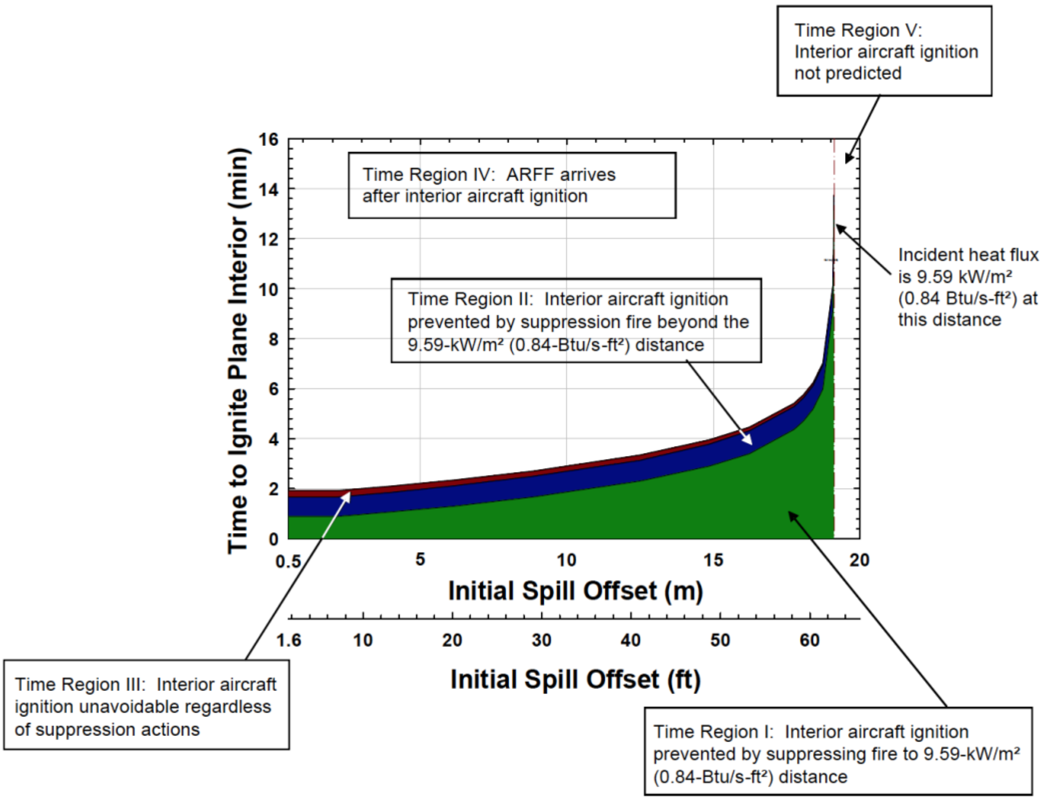


Figure 9. Example Response Time Regions, Scenario 1

This Figure 9 graph above (from FAA 2012 Report[16]), clearly predicts that cabin ignition can occur within 2 mins where the fire is less than 1m offset from the fuselage, but only extends up to 4mins response when the fire offset is 15m …and without wind. This 2012 Report also confirmed that "***For fires occurring within 3 m or less of the fuselage, success is predicted only when response time is less than 1.5 minutes***." Extending response times from 2 minutes to 3 mins seems counter-productive to the key ARFFS objective of saving as many lives whenever and wherever possible in the vicinity of an airport during aircraft fires and other related emergency fires.

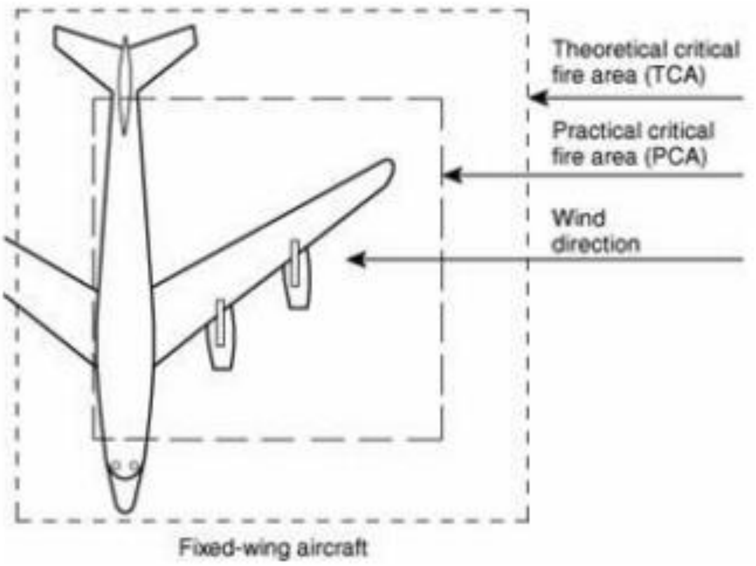
Again this questions the speed and efficacy of PFAS-free (F3) foams under less than ideal conditions which are shown to dominate most Australian airports for most of the year. It increasingly affects many other areas including much of Europe, Middle East, USA, parts of S. and C. America, Africa and Asia, so should also be brought to the attention of ICAO directly.

11. Relevance of TCAs (Theoretical Critical Areas) and PCAs (Practical Critical Areas) to F3 usage

The Scheffey & Bagot (2008) study[15] also investigated *"**Data analysis of actual incidents and spill sizes which indicated that a PCA OF APPROX. 2/3RD (66%) of the TCA is consistent with the objective of preventing the fire from melting through the fuselage or causing an explosion of fuel tanks**. **The equipment and techniques used to discharge agent should be capable of controlling the fire in the critical area in 1 minute and of extinguishing the fire within another minute. Using available fire extinguishment test data, a single agent attack at an application rate of 0.13, 0.18 and 0.20 gpm/ft^2*** **[5.33, 7.38 and 8.2L/min/m2]** ***for AFFF, fluoroprotein, and protein foams*** **[Fluorine Free]*****, respectively, was established***."

Scheffey's later FAA 2012 Report[16] also confirmed that "***The Gage report was accepted, which advocated that the fire area*** [TCA] ***should be the length of the fuselage times the wingspan. A one-third reduction*** [for PCA] ***was applied based on historical loss data***." ie PCA is 66% of TCA.

*"**The ICAO RFFP II decided that the TCA served only as a means for categorizing aircraft in terms of the magnitude of the potential fire hazard in which they might become involved**. It was not intended to represent the average, maximum, or minimum spill fire size associated with a particular aircraft."* That was assumed to be the PCA.



This 2012 report[16] also confirmed that there was no quantitative way to predict the spill size and its growth during incidents. Historical data from 26 incidents showed fuel spills were generally <53% of length x width TCA measurement. It was therefore assumed an unlimited spill size potential in their analyses.

That Report[16] clarified "*Agent extinguishing application rates were developed for firefighting foam (protein, fluoroprotein, and aqueous film-forming foams (AFFF)).* ***By multiplying the PCA times the rate of application and the required fire suppression time, the total agent quantity can be determined. The required foam/water solution required for control in the PCA, designated as Q_1, is***

$$Q_1 = PCA \times R \times T$$

Where: PCA = Practical critical area; R = Rate of application for a specific foam; T = Time of application (1 minute for control in the PCA).

Additional foam agent was necessary to affect total fire extinguishment, designated as Q_2. *There has been no agreement on a quantitative method to determine Q_2; quantities have been developed for Q_2 as a function of the aircraft PCA based on expert judgment.* ***A third agent component for potential post-crash interior firefighting, designated as Q_3, has recently*** [relative to 2012] ***been established in NFPA 403.***" Confirming Total Quantity $Q_T = Q_1 + Q_2 + Q_3$. It does not seem that ICAO includes recommended extra water/foam quantity (Q_3) required for fighting fires inside the cabin to assist rescue and saving passenger/crew lives.

Scheffey's team in this 2012 FAA Report[16] also confirmed that ARFF assisted accidents are infrequent, but do occur. 73 ARFF responses to actual incidents were reviewed (out of 1,230 incidents from 1992 to 2012). Of these, 11 were non-survivable; in 33 the occupants self-evacuated with assistance; and 29 incidents were ARFF assisted. Where the passengers could walk

(ambulatory) most evacuated before ARFF arrival. In incidents where fatalities occurred, ARFF were able to assist in evacuating some surviving occupants.
Rapid response times and fast acting foam agents would undoubtedly have contributed to saving more lives. Is this still possible with PFAS-free foams (F3s)? Where is the evidence to confirm or deny this?

This 2012 report[16] went on to consider the effectiveness of anticipated 'escape paths', "*Geyer considered protection of the occupants within the aircraft (i.e., by preventing hazardous conditions from occurring within the cabin), but the Gage report* ***considered the thermal threat to occupants who have already evacuated the aircraft. For this threat, the fire had to be kept sufficiently clear of the escape path to enable the occupants to reach safety. The Gage report stated that the version of NFPA 403 current at the time of the study was based on fire suppression activities*** [in the PCA] ***to provide a clear area the full length of the fuselage and 100 ft*** [30m] ***wide****. The Gage report assumed a no-wind condition of a clear space 40 ft* [12m] *wide on each side of the aircraft, with a 20-ft* [6m] *allowance for the fuselage width, as equivalent to the wind-aided fire threat analyzed by Geyer. Thus, the no-wind and wind scenarios resulted in the same critical areas.*" A fire model was produced to test this theory, assuming "*The exposing fire was assumed to be represented (as viewed by the occupant) by a rectangular plume. The length of the plume was 80% of the fuselage length and its height was 1.20 times the fuselage height. The width of the fire was assumed sufficient; the plume had an emissivity of 1 and a radiant intensity of 10 Btu/ft2 sec.[113.6kW/m2]. This was analyzed for an occupant who exited from the aircraft opposite the center of the plume and escaped along the fuselage until the occupant was beyond the plume by 25% of its length. At that time, escape was assumed to be complete. This fire model and the escape path (total length = 0.6 L) is shown in figure 1. The radiant exposure was computed for a clear path of widths equal to 20%, 40%, and 60% of the fuselage length (0.2, 0.4, and 0.6 L). The analysis did not consider the fire on the opposite side of the aircraft since the individual would be partially shielded by the fuselage.* "

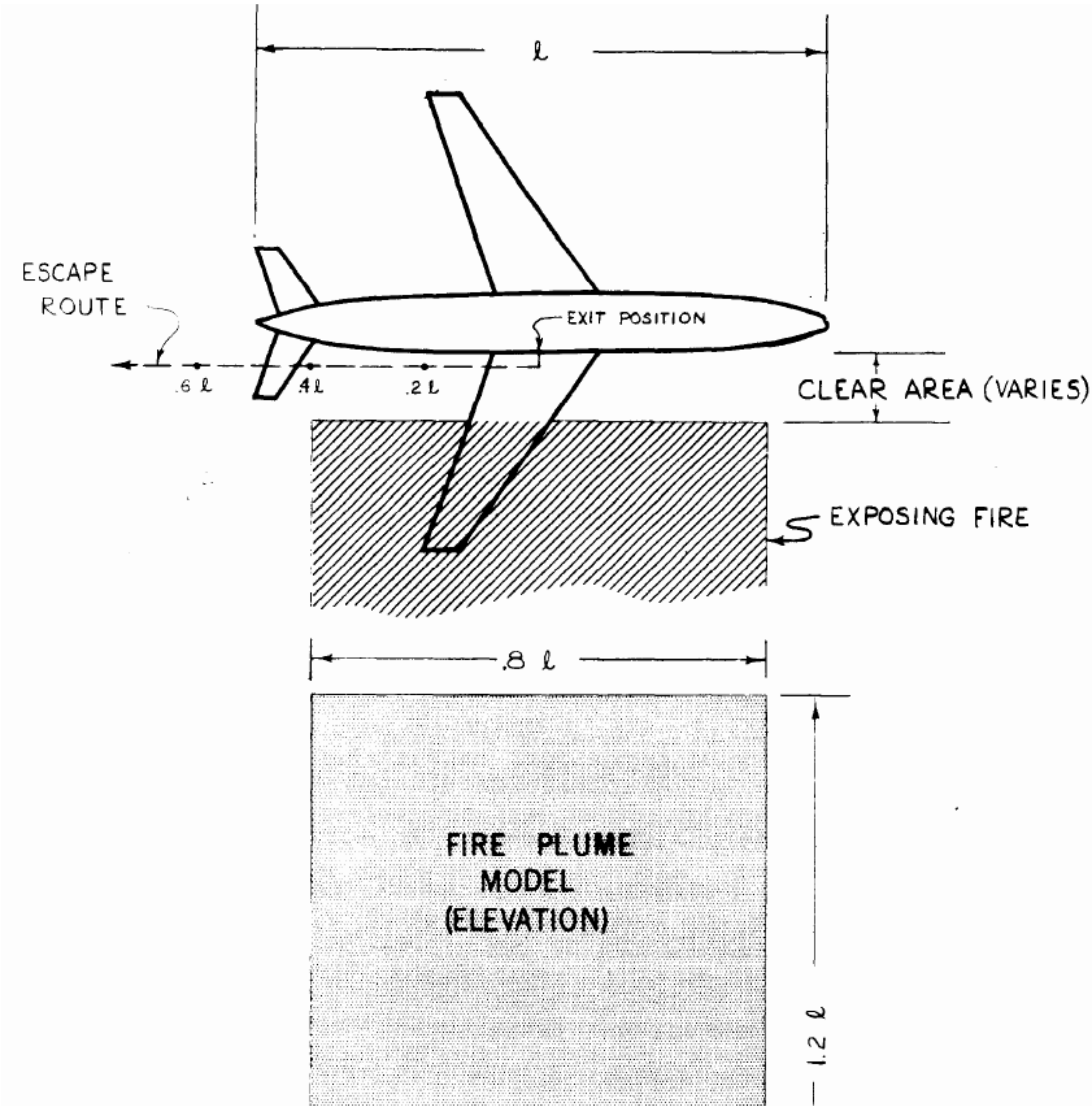


Figure 1. Fire Model Used for Escape Analysis [6]

“***It was found that an escaping passenger from a small aircraft would be subject to unbearable pain while exiting the aircraft, and the exposed flesh would have third-degree burns prior to reaching a safe distance from the fire***. ***With a larger aircraft, the situation becomes even worse. When applied to a B-747 aircraft, the model predicted that at clear path occupant fire separations of 46 and 92 ft (0.2 and 0.4 L*** [ie. 14 and 28m]***), the escapee would suffer third-degree burns while exiting the aircraft. At a separation of 128 ft*** [39m] ***(0.6 L) from the fire, the occupant would be able to traverse a short distance along the escape path before receiving third-degree burns***.” …“*In other words,* ***the TCA/PCA, where the fire area is intended to be controlled very quickly (60 seconds) by the first arriving vehicles, is not necessarily a clear rescue path for ambulatory occupants***.” This problem is compounded when slower acting F3s and high summer temperatures are both involved, as a realistic credible fire event likely to occur in Australia.

This could relate to Jet A1 and gasoline fuels, whether in runway incidents or terminal/runway adjacent carparks, which is not adequately considered when alternative PFAS-free or Fluorine Free

Foams (F3) are increasingly being used at major airports in Australia, Europe and elsewhere, as extensive comparative testing by NFPA Research Foundation[38,60], US Naval Research[14,22,29,33], FAA[15,16,,54,57,58] and Swedish testing[23,59], has confirmed. Historically Europe, at least northern Europe has not suffered extreme summer temperatures, but reported extended heatwaves in 2021 and recently in June and July 2022 across much of southern and Eastern Europe reaching temperatures of 40°C and even 47°C in Spain, Italy and Greece both years (with unprecedented 40°C recorded at London's Heathrow airport on 19th July 2022). These heatwaves have delivered severe conditions to Europe which are very similar to much of the Middle East and 21 airports in Australia. This is not being adequately reflected by ICAO in its current Level B and C approval fire tests.

D**oubts clearly remain whether effective and rapid fire control is possible when using F3s under realistic summer temperatures exceeding 40°C, particularly when ICAO Level B or C approval testing requires a pass to achieve extinguishment within 120seconds when tested under relatively cool and easier conditions of just 15°C, not 40°C.** *Yet CASA and Airservices still stubbornly refuse to conduct such testing or include this life safety requirement in revised regulations during discusssions this far. It is hoped this Evidence Rationale will change that.*

The Scheffey 2008 study[15] also acknowledges "***The differences in aircraft fuel load are substantial,"*** with larger frame aircraft, while confirming *"Using the existing NFPA 403 requirements, the A380 would be a Category 10 aircraft, which would require 14,260 gallons of AFFF discharged from vehicles totaling about 3,200 gpm* [23% increase] *(plus 500 gpm for handlines) based on the current PCA calculation. This compares to the B747, a Category 9 aircraft, which requires 9,570 gallons of AFFF protection, discharged at a total of about 2,600 gpm (plus 250 gpm for handlines)."* It recognises *"**The safe evacuation of passengers occurs when the incident flux from the adjacent (unextinguished) pool fire along the exit path does not exceed the threshold of pain (2.5–5kW/m^2)**."* Part of the plausibility assessment for increased heat flux, larger pool fires, more passengers to evacuate – potentially taking longer although extra evacuation slides are provided in larger aircraft (but with potentially greater obstructions and difficulty from wind effects, larger numbers of infirm or disabled passengers and parents with infants, delaying evacuation efficiency), is consideration of the safety factor inherent with current agent requirements, and whether that can be maintained when generally recognized inferior F3 agents are exclusively being used.
It also considers "Q1: the quantity of foam required to obtain a 1-minute control time in the PCA, and Q2: the foam and water quantity required for continued control of the fire after the first minute, or for complete extinguishment of the fire or both. Over time, changes in aircraft size have required revisions to the values of both Q1 and Q2 and introduction of a third component Q3: the total quantity of water requirement for interior firefighting. It defines Q2 =***f*** x Q1 confirming "***the values of f for Q2 currently range from 0% for Category 1 airports through 190% for Category 10.***" …"*The large number of exit chutes* [16] *from the A380 **may create an obstructed pool fire. If the plastic material melts and becomes involved in the pool fire, the burning fuel may be more persistent than fires on flat surfaces. This should probably be investigated, with an eye toward possible adjustment of the Q2 agent quantity***." …"*Burnback resistance of foam agents should be*

quantified for a 'debris' field" which is also requiring further consideration in the light of increasing F3 usage.

Several new technologies have also been tested and acknowledged by this 2008 study[15] and Batelle Department of Energy2019 research[75] eg. compressed air foam systems (CAFS), ultra high pressure, combined agents etc. some of which resulted in lower control/extinguishment application densities which may be appropriate in future, notably UHP. Batelle's research[75] found that although significant improvements were achieved in extinguishment times (47%) and burnback capability (34%) using CAFS, it was still insufficient to enable F3s to pass MilSpec. One out of the 12xF3s tested achieved extinguishment time below 60 secs against the MilSpec pass requirement of 30secs. A different F3 also achieved a burnback result that passed MilSpec but failed extinguishment. Batelle also found **substantial reductions in stream reach resulted, remaining a significant concern for both CAFS and UHP.** Scheffey in 2008[15] confirmed *"Analysis has shown that the 0.13 gpm/ ft*^{2} [5.33L/min/m^2] *provides a substantial factor of safety for extinguishment of two-dimensional aviation fuel fires. The MIL SPEC test is performed at a rate as low as 0.04 gpm/ft*^{2} [1.64L/min/m^2] *on gasoline* [10sec preburn]*, with an extinguishment density of 0.033 gal/ft*^{2}*. Analysis of data for AFFF that does not meet the MIL SPEC* [which also includes all current F3s] ***suggests that these agents may not provide a similar safety factor. It has been shown that the current ICAO*** **[Level B]** ***foam test method is not equivalent to the MIL SPEC requirements**."* It also confirmed ICAO developments were underway, implemented in 2014 with a higher ICAO Level C fire test, using a similar application rate to MilSpec, but requiring a single freshwater fire test only on Jet A1 not gasoline fuel **and with many other important test requirements still missing**.

In conclusion this Scheffey & Bagot (2008) study[15] warns *"The regulatory requirements and current methodology for calculating firefighting agent quantities needed to combat aircraft fires have been described.* ***These requirements and methodology may require revision based on newer, larger aircraft being introduced into commercial passenger service. The newer aircraft have more passengers, a greater fuel load, and more composite materials****. Analytical techniques can be used to quantitatively evaluate the TCA/PCA methodology.* ***Composites and large egress chutes may create debris in the crash area which might extend extinguishment times or require a greater degree of burnback resistance. The existing fire safety objective (cut an egress path around a burning aircraft for self-evacuating passengers) may merit revision to more formally address on-board firefighting and physical rescue of passengers in a survivable post-crash environment****."*

This becomes particularly relevant when a greater reliance is being placed by Aviation regulators and operators (incl. EASA) on proven to be less effective PFAS-free alternative foams, based on claimed 'environmental benefits' and fire testing at 15°C, which may not be substantiated as competent in major emergencies when slower fire control, particularly under challenging summer conditions would seem to be placing lives under increased danger, which unintentionally are not being adequately protected by ICAO's current Level B and C fire test approval standards. It also does not currently take account of the extended smoke emissions, delayed fire control and likely increased firewater run-off from such incidents which are likely to deliver increased environmental harms, not decreasing them as intended.

Summarising findings of the 2012 FAA Report[16] confirmed that "***For most situations, involvement of the entire length of the aircraft was assumed. Historically, this is a rare event. Additionally, the loss history of firefighting activities (section 4.10) confirms that, historically, agent quantities*** [defined in NFPA 403] ***are sufficient for the exterior fire scenario***." Although it should be remembered that all the assumptions and testing in this report were based on and conducted with MilSpec qualified AFFF; not PFAS-free foams now being considered to replace them or already replacing them at some major airports worldwide, including Australia-wide, without any clear evidence of equivalent, equally successful firefighting outcomes.

The 2012 Report[16] also concludes that **"*For most situations, involvement of the entire length of the aircraft was assumed. Historically, this is a rare event. Additionally, the loss history of firefighting activities (section 4.10) confirms that, historically, agent quantities are sufficient for the exterior fire scenario*." It is unclear whether this would necessarily be the case when PFAS-free F3s are involved, particularly under high temperature conditions.**

It is therefore possible, particularly when F3s without fuel repelling and vapour sealing additives are being used, that full extinguishment of the fire may be the only reliable way to reduce the risk of sudden flashbacks and re-involvement from incandescent materials (including modern composite materials) such that cabin occupants or escaping passengers could suffer quite severe burns or death as a result.
This probability significantly increases when F3s are being used during hot summer conditions for which there does not seem to be any/sufficient evidence of competency from CASA, Airservices Australia, ICAO or other scientific test data currently available that could be found, in the public domain.

Three major incidents in Dubai (Boeing 777 fire in Aug. 2016)[37], Singapore (Boeing 777 fire in Jun. 2016)[39] and Melbourne's Footscray chemical factory fire in Aug. 2018)[40-48] provide evidence of significant concerns regarding PFAS-free foam (F3) effectiveness during use in major fire outcomes, supported by extensive comparative fire testing by National Fire Protection Association –Research Foundation[38,60], US Naval Research Laboratory[14,22,29,33], US Federal Aviation Administration[15,16,54,57,58] and the Swedish Research Institute (RI:SE)[23,59], referenced accordingly.

12. Issues require urgent regulation by EU, and ICAO to improve life safety

The issues raised in this submission Pt. 2 require urgent attention to prevent the avoidable loss of lives in future aircraft fires – which could be as soon as tomorrow. EASA and ICAO claim to place life safety as their 'highest priority' **which should justify strong regulatory recommendations to**

ensure current firefighting foams are verified as effective during hot summer conditions being increasingly experienced across EU.

It should also justify EASA raising these important life safety issues with ICAO directly, urging them to review and overhaul their current ICAO Level B and C fire test standard up to current best practice, rectifying the current weaknesses demonstrated to adequately protect and improve life safety globally.

ECHA and EASA are urged to review the referenced papers below to verify the summary findings presented above, and use this submission document Pt. 2 (incl. references), along with the previous Submission (Pt. 1) in May 2022, to include regulatory requirements for high temperature fire test certification across EU, before imposing a PFAS ban on firefighting foams as it may expose the travelling public to unacceptably increased risk of life loss.

ECHA & EASA are therefore strongly urged to take these concerns up directly with ICAO, through their normal channels, but should also perhaps consider raising this with the Council of ICAO, President of Air Navigation Commission (Mr. Padhraic Kelleher), which it is understood represents ICAO's main Technical Review body, to gain more urgent attention to this life safety matter. E-mail: pkelleher@icao.int A copy could also be sent to ICAO's Secretary General Mr. Juan Carlos Salazar, and the new Deputy Director of Aviation Safety (replacement office holder to Mr Catalin Radu, believed not yet announced) **to raise awareness at the highest level that ICAO's duty of care may potentially be compromised**. Informing ICAO's Operational Safety Section ops@icao.int while also copying ICAO's Office of Internal Oversight (formerly the EAO, Evaluation and Audit Office) at oio@icao.int as it relates to responsibility for the systematic evaluation and internal audit of ICAO's programmes, projects and activities to assess whether the organisation's stated objectives and impacts have been achieved, which is in question regarding Aviation safety when alternative PFAS-free foams are increasingly being used. **This may have reputational implications for ICAO and may be placing the travelling public under unintentionally increased life safety risks** under the current Airport Services Manual Doc 9137-AN/898 Part 1 – Rescue and Firefighting, 4th edition 2015. **Chapter 8 and its Fire test approval specifications exhibit significant weaknesses as defined, requiring urgent attention and revision to avoid compromising life safety of flight crews, emergency responders (incl. firefighters) and the travelling public** (incl. you, me, ICAO and ECHA staff and Directors).

Mike Willson 3rd Sept. 2022
Director and Technical Specialist – Firefighting Foams and Foam Systems.

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