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US Army Research Laboratory

Fire Protection Informational Exchange

by Barrie Homan, J Kevin Boyd, and Steve McCormick

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14. ABSTRACT
US Department of Defense platforms have many components other than stored munitions that are the source of, and vulnerable to, fires caused by a wide variety of threats. Vulnerabilities resulting from a fire can turn a survivable event into a catastrophic loss of crew and equipment. This report documents the results of an information exchange meeting held at the US Army Research Laboratory during 14–15 October 2015, the purpose of which was to bring together the various interested parties across the services to outline, as a community, the current state of the art in fire protection research and engineering and determine where future efforts would be most advantageous. The forum provided the opportunity to strengthen old collaborations, begin new partnerships, and serve as a resource to highlight to potential customers and/or management the importance of continuing efforts in this field.

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Executive Summary

The presentations at the fire protection information exchange meeting held at the US Army Research Laboratory during 14–15 October 2015 ranged in scope from broad summaries of efforts occurring in various agencies to more-focused reports on technical results. Different aspects of the overall vehicle fire problem including the tradeoffs of mitigating technologies were discussed. In general, the discussions centered on the effort to extinguish or mitigate the fire event and on minimizing subsequent adverse consequences rather than technologies or tactics to avoid the initial threat interaction or initiation event. Efforts are underway to understand how the threat interaction disrupts the vehicle's fuel integrity and initiates the fire event. Solutions are being pursued in an attempt to minimize the severity of the damage from ballistic threat, some of which have shown some promise at least with the lower-energy threats.

Once a fire event is underway, the most prevalent and most talked about technology employed is a fire extinguishment system (FES). This broad category encompasses systems that seek to disrupt some critical aspect of the combustion cycle. Materials that interact chemically with the combustion process are the most prevalent type of agent used. Others can act as thermal or even oxygen barriers to the flame. These systems can range from manually deployed, portable extinguishers to sophisticated automatic FESs that can react faster than a human, thereby reducing the event severity and/or deploy when the crew is incapacitated. The consequences of FES use is not without its tradeoffs. Identified risks include the deployment safety of the system, toxicology of the agent itself plus health issues of the pyrolysis products produced by the interaction, and future health and capabilities of the crew and equipment. In addition, there is a new push to address the global warming potential of extinguishing agents.

Current battery technologies with increased stored energy densities are making them more attractive as a power source in vehicles of all types, military and civilian. Lithium (Li)-ion chemistry–based batteries are currently favored as a viable replacement for existing lead-acid types or for new applications. The tradeoffs for the alternate chemistry were a topic of discussion at the meeting. The high-energy density achievable with the new materials can also be a source of, or contribute to, vehicle combustion events. Some of the electrolytes used in the construction of modern Li batteries can themselves be quite flammable. Conventional FES agents can also prove problematic.

Other incorporated materials including composites, tires, and tracks, as well as the uniforms and other garments worn by the crew, are being investigated. If, for example, Soldiers' uniforms can become part of the personal protective equipment by increasing the crew's tolerance to thermal injuries, the requirements placed on the FES may be loosened, allowing for a wider design space.

Discussions centered on the pertinent threats of current interest and the pursuit of solutions that can be easily implemented for current fielded systems while laying the groundwork for new technologies applicable in the longer term that are more effective, less toxic, and environmentally friendly.

The overall conclusions arrived at during this meeting were similar to those elucidated in the previous workshop[1] and are worth paraphrasing here. Effective strategies to combat the threat of vehicle fires in military and civilian vehicles will require a holistic approach; no one prevention/mitigation technology will work for all fires and in all scenarios. Intelligent energy storage designs, improved extinguishment materials and deployment strategies, and advanced materials should all be considered as part of the multitiered approach. The immediate health effects along with the long-term well-being of the crew and the environment will need to be considered in any solutions pursued.

Other general concerns espoused during this meeting also referenced those from the previous workshop. Fire protection is still a secondary consideration early in the design phase of a new vehicle system. This usually leads to lack of definitive requirements at the stage when solutions are easiest to adopt. Health effects are of concern to everyone but lack the proper emphasis. Environmental issues are becoming a greater concern. Lack of end-user feedback, including live-fire data and system limitations, hampers technology development. There also was a consensus that efforts that will strengthen our understanding of the underlying phenomena should be pursued. This knowledge will prove critical to the development of new fire protection technologies and strategies to combat this serious issue.

As part of the discussion section, a listing of the types of systems of concerns, possible threats involved, current status, limitation of current technologies, and future directions were discussed. The 4 categories of systems were liquids, solids, electrical, and FES. These subjects were sufficiently covered at the previous workshop[1] with general agreement of its continued validity and will not be reiterated here.

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[1]Homan BE, Boyd KJ, McCormick S. Systems fire protection workshop Report. Aberdeen Proving Ground (MD): Army Research Laboratory (US); 2013 Apr. Report No.: ARL-TR-6398.

1. Introduction

Military vehicles can be vulnerable to devastating fires arising from the combustion of a variety of materials that are normal components of mobile platforms. Although explosives and propellants that are part of the munition system are typically the first thing that comes to mind as a source of uncontrolled combustion, there is a variety of other materials that can also contribute. Most contemporary mobile vehicle systems rely on some type of liquid fuel source for self-propulsion. The energy contained in the fuel for propulsion can greatly exceed the total energy that a vehicle carries from all the other energetic materials. New energy-dense components like lithium (Li)-ion batteries are becoming more prevalent in these systems due to their increased performance potential. Along with the promising capabilities, Li-ion battery technology carries greater risk than the lead-acid batteries it replaces, as the materials used in its construction can be flammable and emit toxic fumes when combusted. Tires, plastics, composites, and other combustible materials can contribute to the severity of a vehicle fire event.

The US Army Research Laboratory (ARL) and the Tank Automotive Research, Development and Engineering Center (TARDEC) jointly organized the Fire Protection Information Exchange meeting to provide a forum for the community to assemble and discuss the efforts being conducted on this topic. The planned outcome of the meeting was the generation of this report. The longer term goal was to provide a mechanism to establish collaborative avenues with the various US entities as well as to explore future foreign involvement through The Technical Cooperation Program and Defense Exchange Agreement mechanisms.

The topics chosen for this meeting were sufficiently broad to appeal to the widest audience. A similar approach was used for the original workshop held in May 2012.[1] Because of the broad travel restrictions that came into play after that last meeting, little follow-up activity was possible. Therefore, it was deemed important to allow for a wide variety of subjects to reconnect the community.

Over 100 people attended the meeting, which included presentations from the following:

- Government presenters
    - ARL
    - TARDEC
    - Office of the Assistant Secretary of the Army for Acquisition, Logistics and Technology (ASA-ALT)

    - US Environmental Protection Agency (EPA)
    - US Federal Aviation Agency (FAA)
    - US Naval Research Laboratory (NRL)
    - Sandia National Laboratories
    - US Naval Air Systems Command (NAVAIR)
    - Natick Soldier Research, Development and Engineering Center (NSRDEC)
    - US Army Public Health Center
    - US Army Aviation and Missile Command
- Industry and academia presenters
    - Alion Science and Technology
    - Amerex
    - Jensen Hughes
    - Kidde
    - Meggitt
    - Polyhalon Technology
    - Robertson
    - Southwest Research Institute (SwRI)
    - Spectrex
    - Tecate Group
    - University of Maryland
    - University of Cincinnati
- Foreign contributors
    - Ministère de la Défense
    - Bundeswehr
- Other participants
    - Army Test Center

- Research, Development, and Engineering Command
- Naval Sea Systems Command
- Program Executive Office (PEO)
  - ✓ Aviation
  - ✓ Land Systems
  - ✓ Soldier
- Industry
  - ✓ A-Gas Americas
  - ✓ AMPAC-Halotron
  - ✓ Chemours
  - ✓ FireTrace
  - ✓ General Motors
  - ✓ Halon Alternatives Research Corporation
  - ✓ Hazard Protection Systems
  - ✓ High Impact Technologies
  - ✓ Pacific Scientific Energetic Materials
  - ✓ Presidio Defense
  - ✓ Rodgard
  - ✓ SEVO Systems
  - ✓ SURVICE Engineering
  - ✓ VTEC Laboratories
  - ✓ WSP Group

2. Other Topics Discussed

The community concluded that workshops continue to be useful and should become a regular occurrence. It was suggested that a general workshop similar to this one be held on an annual or bi-annual basis. More-targeted workshops with more-limited interests could be held more often. Although it was agreed that the larger workshop worked well at the unclassified level, potential participants felt they could not present their work at this open level. Future general or targeted workshops should have more-restricted portions so that all in the community can present. Talk of hosting of the general workshop was discussed, and a rotation among the various interested agencies was suggested in an attempt to share the burden and, more importantly, for the different perspectives that each organizer could provide. Although the focus of this workshop was to provide a big picture perspective of the current status of fire protection science and technologies, suggestions for more technical venues that the community may exploit were discussed. Previously, the Ground Vehicle Survivability Symposium hosted by TARDEC was such a venue, and there was talk of reviving that conference. Other possible conferences included the Joint Army, Navy, NASA, Air Force (JANNAF) organization. In particular, the JANNAF Combustion Subcommittee meeting held every 18 months may provide an interface between this community and the broader US Department of Defense (DOD) research community. The authors are pursuing the development of a regular session within this conference. The International Association for Fire Safety Science was proposed as another venue that may prove fruitful to the fire protection community. Suggestions of other possible venues are encouraged.

3. Presented Talks Summary

The agenda for the meeting is in Appendix A, and a list of the participants and their contact information is in Appendix B.

3.1 US Army TARDEC

Steve McCormick provided some background on the history of vehicle fire protection. A large number of vehicles have been lost as the result of vehicle fires in theater, and this vulnerability vector threat remains a significant threat to both vehicles and Soldiers. Approximately 1.5% of all attacks on vehicles from 2007 to 2012 led to fires, producing 220 casualties. Accidentally caused fires are also a concern, with 40 casualties resulting from 2002 through 2012. The fact that highly energetic and highly flammable materials are critical to the functioning of military vehicles makes the threat of fire a continuing problem for the foreseeable future. A multilayer hierarchical approach is being taken by the Army that begins with striking first, minimizing the ability of the enemy to attack, and minimizing the damage of a successful attack, the latter being part of the protection spectrum of concern to this community. Prevention of the fires is the first step with vehicle engineering solutions that attempt to minimize fuel spillage, incorporation of fire resistant materials such as tires and tracks, less flammable fuels, and better personal protection equipment. By far the biggest effort is development of fire suppression systems to fight the fires that do start.

3.2 Ministère De La Défense

Camille Viallon presented her efforts on Li-ion batteries vulnerabilities and the development of a water mist system for crew compartments. The Li-ion battery study evaluated the reactivities of the various battery technologies resulting from low-energy ballistic threats of interest to the French military. It looked at single element configurations and compared the severity of the reaction to an assembled unit having multiple connected cells in close proximity. A water mist system was evaluated for low-speed-growth pan-fire-type application. The results were compared with a typical gaseous-based agent. The water mist system worked reasonably well in comparison but will have integration challenges.

3.3 Bundeswehr Research Institute for Protective Technologies

Felix Kummerlen from the fire protection engineering section provided an overview of Germany's military vehicle fire protection efforts. His division is tasked with managing all technical issues concerning firefighting equipment, both fielded and future. In addition to handheld extinguishers, the thermal resistance of Soldier's clothing can be evaluated. An engine compartment fire relaxes the criteria of an acceptable agent compared with one that must operate within an occupied space. Crew compartment systems must provide lower temperatures, pressures, and toxic gas concentrations and happen within a narrow time frame to minimize injury. Even accidental activation of the system will be constrained by the agent-only effects on the crew. Felix posited that aqueous film-forming foam (AFFF) is currently the most effective agent again pool fires. However, the foaming agent currently in use has environmental issues, and therefore research is being conducted to replace that ingredient.

3.4 ASA-ALT/Jensen Hughes

Daniel Verdonik spoke on the environmental issues concerning fire suppressant agent use. He provided a history of the treaties and international agreements that are driving the current concern of ozone depletion and global warming trends being exacerbated by the use of current agents. The 1988 Vienna Convention was the first treaty and entered into force in 197 countries including the United States. This convention focused on the ozone depletion potential (ODP) of substances like halogenated hydrocarbon (halon) fire extinguishment agents. The Vienna Convention laid the groundwork for the 1989 Montreal Protocol, which regulated the production and distribution but not the use of, ozone-depleting substances (ODSs). The most destructive substance was identified as halon. Unfortunately, halons are currently some of the most effective fire suppressants. Some use was authorized under the agreement for critical applications. Military vehicles were one example targeted for this exception. The agreement specifies dates for which military vehicles and systems should be halon-free. As the focus shifted from ozone depletion to climate change, the United Nations Framework Convention on Climate Change, ratified in 1992, provided a mechanism to develop a new (Kyoto) protocol for addressing the use of global warming potential (GWP)–classified substances. Some of the materials listed are used as replacements for ODSs. The US administration recently issued a fact sheet concerning greenhouse gases in which the informational meeting that is the subject of this report was mentioned.[2]

3.5 US Environmental Protection Agency

Margaret Sheppard from the Stratospheric Protection Division of the EPA spoke on its Significant New Alternatives Policy criteria for evaluation of alternatives for commercial propellants and fire agents. The EPA considers other factors in addition to ODP and GWP, including flammability, toxicity, and other occupational and consumer health/safety elements that are also of interest to military systems. For fire suppression agents, there are currently 59 "acceptable" substitutes and 5 "unacceptable" substitutes for a total of 64 listed substances. However, some of the acceptable substitute agents are being reconsidered while new substances are being evaluated for use.

3.6 TARDEC/Alion Science and Technology

Steve Hodges spoke of the US Army's current effort to modernize legacy vehicle platforms. Part of that effort includes updating fire suppression agents with more environmentally friendly substitutes, as current workhorse agents have high ODP and GWP. Of course, the agents must also be effective. TARDEC conducted multiple tests to determine effectiveness by comparing current agents (baseline) with other replacement candidates using a set of criteria that included performance and safety factors. Results were mixed, with some of the candidates failing while others show promise but are not easily implemented.

3.7 KIDDE, Inc.

John Porterfield talked about the use of alternate fire suppression agents for military ground vehicles; in particular, new agents for crew compartments. Fielded agents suffer from high ODP and/or GWP, can be affected by environmental conditions, and can carry toxicology risks. Aqueous solutions (e.g., water and potassium acetate) have the potential to overcome some of the risks associated with other agent choices. However, aqueous-based agents have drawbacks that will have to be overcome before this technology can be fully utilized.

3.8 US Federal Aviation Agency

Doug Ingerson presented an overview of the activity the FAA is currently supporting with an emphasis on pursuing minimum performance standards for the replacement of halons within the power plants of aircraft. Each candidate must be reasonably far along in its development to be considered ready for implementation and perform at least as well as the legacy agent (Halon 1301). A representative test bed has been developed to mimic conditions typical in real-world applications. Two early candidates, HFC-125 and CF3I, are being recommended as possible replacements although each have their challenges and have not been pursued by the civilian sector. Later candidate development efforts have also suffered from significant problems and have been either abandoned by the applicant, FAA support having ended, or, for the latest applicant, ongoing.

3.9 Polyhalon Technologies

Casey Chapman presented his company's suppression agent technology. By using polymerized halon-like materials, a solid is formed that can be applied in novel ways (e.g, coatings and additives).

3.10 Blazetech

Albert Moussa presented Blazetech's work on a breathable foam for thermal and fire protection of passengers in a military vehicle. His presentation could not be included here, but if interested contact the author (Appendix B).

3.11 US Naval Research Laboratory

Katherine Hinnant presented NRL's work on the performance of fire agent foam used mainly for fighting pool fires. Current fluorinated foams have proven effective but have the potential for long-term harm to biological systems. Alternate foams have been developed for the civilian market but have failed to meet military standards. Fuel transport and foam degradation are considered the key mechanisms controlling the performance of a particular foam. The legacy foams' orders of magnitude longer lifetime is the main attribute that contributed to the difference in performance. Further efforts to understand why are in the works.

3.12 US Army Public Health Center

Matthew Bazar discussed the health aspects of using fire suppression agents in Army vehicles. Suppression agents can have adverse effects by being directly toxic or producing toxic byproducts, posing an inhalation hazard (powder), creating a low-level oxygen environment, or having thermal exposure issues from the discharge of the agent. The criteria used by the military to judge hazards lie between civilian standards and lethal limits to avoid incapacitation. Recent animal studies have been conducted to study the toxicity arising from agent use due to agent or agent byproducts interaction.

3.13 Southwest Research Institute

Donald Grosch presented SwRI's work on hydrodynamic ram (HDRam) experiments. This effort was undertaken to understand the transfer of kinetic energy from ballistic impacts into the fuel. The momentum transfer from the impacted liquid to the tank structure is the main cause of tank failure. Visualization of the interaction of a Viper shaped charge jet (SCJ) and the fuel surrogate (water) was presented. The exit hole from these events was always large and petaled despite several attempts to minimize the damage using stripper plates upstream of the exit plate. The use of a SCJ proved to be too violent, and a lower-energy threat was deemed more appropriate to start. The spray characterization became the focus for the work, as this information is critical to study the flame spread within a dry-bay fire event. Fragment simulation projectiles and small-caliber bullets were chosen as a more appropriate energy level threat for this work. Particle image analysis was used to characterize the droplet size and morphology distribution and velocities.

3.14 ARL

Barrie Homan spoke next on ARL's mission program in fuel fire. The efforts have also focused on the HDRam phenomena. Data on the forces resulting from HDRam on a surrogate tank were obtained by using digital image correlation techniques. This technique was also used in an experimental fixture that allowed for a more amenable approach to the characterization of the HDRam process. In an attempt to mitigate the HDRam-generated shock wave damaging the tank, a baffle design was tested experimentally and modelled using the ALE3D hydrocode. Both the model and experiments showed some promise. ARL also plans to study the generation of fuel spray characterization resulting from ballistic impacts.

3.15 Sandia National Laboratories

Dan Guildenbecher presented his talk on digital in-line holography and its application to liquid sprays. This technique promises the ability to resolve 3-D liquid droplet patterns with a single camera setup. The advantage to the system is that the optical configuration is relatively simple while capturing transient events. The large depth of field inherent in the technique can lead to large positional (out of image plane) uncertainties. The technique currently requires a small field of view and dilutes sprays, which might limit it to smaller systems. In addition to validation studies, Dan has used this system to investigate the combustion of aluminum drops formed from burning propellants.

3.16 TARDEC

Julie Klima summarized her work on energy-absorbing materials that have high fire resistance. She concentrated on materials that have good absorption properties for protection of the head and neck areas. In particular, Soldier protection materials to mitigate head-vehicle impact resulting from underbody blast or other events will require significant improvements over current configurations. Developed material solutions, however, will also be required to be fire resistant. Currently, only a limited number of materials can satisfy both requirements.

3.17 University of Maryland

James Quintiere spoke on using engineering test data for predicting fire hazards. Because fire retardancy ratings are organization-specific, little agreement and therefore little usefulness,can be obtained from any particular test. Extrapolating the fire resistance properties to new scenarios become problematic. James proposes a set of flammability parameters that can lead to useful predictions that may span multiple material classes.

3.18 US Army NSRDEC

Thomas Tiano presented information on the development of the next generation of flame-resistant materials for Soldier protection. Current flame-retardant (FR) uniforms are significantly more expensive, require foreign-produced materials, and the production is not environmentally friendly. Efforts are underway to develop technologies to impart fire retardancy to the existing non-FR fielded fabrics that are durable and launderable. A summary of contractor lead efforts to achieve these goals was presented.

3.19 US Naval Air Systems Command

The NAVAIR fire protection program was summarized by Ryan Arthur. Single-engine aircraft fire suppression typically have required engine shutdown. The effort attempts to address the obvious drawback of loss of propulsion during fire extinguishments. As unmanned vehicles continue to increase in complexity and cost, fire protection has become more important. Investigations into the operation and service life of existing fire protection systems are also being pursued.

3.20 Sandia National Laboratories

Alex Brown introduced Sandia's Fire Science Department, outlining capabilities for well-instrumented experiments as well as high-fidelity modeling tools. The goals of the program are incorporating experimental data into understanding fire events and validation and verifying computer models. Fuel fires, propellant fires, and burning of composite materials have all been investigated. Modeling tools under development are coupling various codes developed to address different physics of particular applications but have a role describing the complete fire event.

3.21 Southwest Research Institute

Matt Blais described the capabilities of SwRI's Fire Technology Department. He outlined the ability to measure such flammability characteristics as energy release, ignitability, flame spreading, and smoke production. SwRI facilities can work with a wide variety of shapes, sizes, and forms (liquid, solids, and gases) and has modeling capabilities in the form of thermal finite-element codes and computational fluid dynamics (CFD) tools.

3.22 US Army Aviation and Missile Command

Tim Helton talked about the fire threat to Army aviation systems. Although most events recorded were the results of crashes, system failures, or leakage of flammables onto ignition sources, few official reports record the specifics of how the event was ultimately handled. When documented, the usefulness of a halon-based system is indisputable. However, current halon-based systems are being phased out. Army aviation subject matter experts have been and will continue to work with national and international committees and consortiums like the FAA's halon aviation rulemaking committee integrated product team, Halon Alternatives for Aircraft Propulsion Systems, and the International Aviation Systems Fire Protection Working Group.

3.23 TARDEC

TARDEC's fire suppression modeling effort was presented by Vamshi Korivi. A CFD capability is under development that will incorporate the required physics and chemistry to significantly reduce the costly experiment-driven design process. Multiple configurations can be evaluated while providing insights into the flame spread within vehicle compartments including the interaction of the suppression agent. Current chemical mechanisms (~800 reactions) are still too large for systems more extensive than small laboratory experiments. The use of a smaller global reaction mechanism allowed for simulation of vehicle-size fires and the introduction of suppressants to evaluate the design of suppressant delivery systems, concentration of toxic byproducts, and pressure.

3.24 ARL

The current status of the Fire Prediction Model (FPM) was presented by Jamie Edwards. This model addresses 3 damage pathways: dry-bay fires, spray fires, and ullage fuel-air explosions. These fires can be caused by a variety of threats ranging from traditional ballistic impacts to high-power laser ignition. Special attention was given to the IGNITE module development, which begins the process of modeling the fire event. ARL is also evaluating the documentation that accompanies the FPM. Further work is being conducted to compare the code with the reference materials that inspired it.

3.25 Sandia National Laboratories

The next few talks, led off by John Hewson of Sandia National Laboratories, concerned the subject of batteries. As potential energy densities of battery technologies increase dramatically, so do potential safety concerns. Thermal runaway is a major concern that has hindered incorporation of battery technologies. Investigations into the mechanisms of runaway energy release were discussed. The reactivity of any pathway heavily depends on the materials used to construct the battery, though some promising cathode materials are being developed. Modeling tools to study this problem have been mostly developed under the Stockpile Stewardship program, which has addressed some of the same physics required to understand the battery runaway problem. Several real-world cases were shown to showcase the current status of these sophisticated models.

3.26 Jensen Hughes

Gerard Back presented the company's efforts in Li-ion battery fire testing it is performing for the US Navy. The large number of electrolytes used in Li-ion batteries all have different internal energies and volatilities. These different chemistries are packaged into a wide array of form factors. The battery cells can then be agglomerated into an even wider array of packs that can have thousands of individual cells connected into series (higher voltage) or parallel (higher current) combinations of both forms. Some initiation events were suggested, including shorts, physical damage, overcharging, and/or ambient overheating. The Navy has tested over 30 different types including 5 specific to the military. Modeling tools are being developed to attempt to quantify the hazards and predict propagation and mitigation characteristics.

3.27 ARL

Kevin Boyd presented his work on Li-ion battery vulnerability due to over-charging scenarios. Two chemistries were overcharged while monitoring for signs of thermal runaway. Visible data as well as thermocouple measurements provided a measure of the violence of the event. Both chemistries produced copious amounts of smoke/combustion byproducts with one of the chemistries (NiCoMax) also producing external flames. A proof-of-principle suppression system was evaluated in which a candidate agent flooded the battery compartment at the first sign of runaway. For both chemistries, there was a significant reduction in the overall severity of the event, although there was still a large amount of combustion products apparent.

3.28 Tecate Group

Other energy storage technologies were address by Brendan Andrews, who focused on ultracapacitors (UCs), or supercapacitors. Capacitors store energy within a static-electric field rather than in potential chemical reactions. Substitution of an electrolyte for the conventional dielectric between the electrodes can increase the energy density of UC designs. Although current designs cannot match chemical-based batteries for total energy density, the fast action inherent in a capacitive design can translate into higher power densities required for certain applications.

3.29 University of Cincinnati/Engineering and Scientific Innovations

David McGinnis spoke of his company's efforts to develop an intelligent fire protection technology. Current aviation systems mostly work by flooding the volume of interest with suppression agent in a one-time event. Simply flooding the compartment can require longer times and inefficient use of agent materials. David outlined an "ideal" solution that encompasses rapid fire detection to a measured and dynamic release of agent.

3.30 The Chemours Company

Mark Robin hinted at favorable properties of a proprietary agent under development in the pursuit of low ozone depletion properties and low global warming properties. Mark stated that an ideal candidate would have high mass efficiency, be chemically inert (outside of deployment), provide high volatility to promote efficient performance, be electrically nonconductive to prevent secondary electrical damage, have low toxicity, and be cost effective. His company is developing 3 candidates that attempt to address these ideal properties.

3.31 Robertson Fuel Systems

Nick Twardokus presented a brief on the Thermal Injury Prevention Strategy (TIPS) consortium of industry members with the goal of raising awareness of and spurring action for the prevention of thermal injuries. Over 6% of military deaths are the result of burn injuries, having far-reaching physical and psychological consequences for the wounded Warfighter. The goals of TIPS is to officially update thermal injury data beyond the current baseline. Establishing platform standards and requirements for prevention are being pushed to the highest levels (US Congress) by making TIPS part of the TARDEC survivability initiatives. The consortium is continually recruiting new members and exploring new venues to inform the appropriate communities on TIPS activities.

3.32 Meggitt

Several contractors spoke next concerning their companies' technologies for fuel fire mitigation. Randy Fontinakes from Meggitt summarized his company's products using self-sealing technologies to prevent fuel loss and resulting fire events. Some design considerations included backing boards to try to keep the damage as localized as possible. Container construction suggestions include using particular tank material (no titanium) as well as external (to the tank) treatments that can maximize the performance of self-sealing bladders.

3.33 Amerex

Ken Miar presented on the fire suppression systems that his company supplies to DOD. In-vehicle systems as well as standalone portable extinguishers are among the company's product line. Ken spoke of Amerex's in-house abilities to test solutions that will minimize the risk of immature designs being tested by the military for official qualification.

3.34 Spectrex

Douglas Kulick expounded on the phenomena of slow-growth fire threat exemplified by the pool fire scenario. Typical automatic fire extinguishant systems (AFESs) are geared to the more violent munition-initiated fires. The timeline for that type of fire tends to be orders of magnitude shorter than a long-duration pool fire. The company is advocating for a specification that would include long-duration, slowly evolving fires into future AFES designs.

3.35 TARDEC/Alion Science and Technologies

Steve Hodges from Alion summarized his presentation at the 2014 Fire in Vehicles Conference held in Berlin, Germany. The overarching point made is that because vehicle occupants and flammable materials are necessarily within close proximity, fire prevention and mitigation is the most effective strategy for the protection of life and property. Ten percent of all fire deaths were attributed to vehicular fire events. However, no one solution can be made effective for all scenarios. Outlined in the talk were some well-known consumer vehicle design defects that resulted in increased danger from fire, including the 1978 Ford Pinto rear gas tank and the 1973 GM pickup truck side-saddle vulnerabilities. In addition to combat risks, military vehicles can also suffer from fires resulting from nonhostile action. Lessons learned in the civilian world can inform development of safer military vehicles. In both cases, an overall approach is needed to significantly reduce the risk of fire casualties.

7. References

1. Homan BE, Boyd KJ, McCormick S. Systems fire protection workshop Report. Aberdeen Proving Ground (MD): Army Research Laboratory (US); 2013 Apr. Report No.: ARL-TR-6398.

2. The White House. Fact sheet: Obama administration and private-sector leaders announce ambitious commitments and robust progress to address potent greenhouse gases [accessed 2016 Apr 6]. https://www.whitehouse.gov/the-press-office/2015/10/15/fact-sheet-obama-administration-and-private-sector-leaders-announce.

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Appendix A. Agenda

This appendix appears in its original form, without editorial change.

Day 1

Talk	Title	Speaker	Org.
	Opening Remarks	Kevin Boyd	ARL-WMRD
1	Overview of US Military Vehicle Fire Protection	Steve McCormick	TARDEC
2	Overview of France's Military Vehicle Fire Protection Efforts	Camille Viallon	French MOD
3	Overview of Germany's Military Vehicle Fire Protection Efforts	Felix Kummerlen	German MOD
4	Montreal Protocol	Dan Verdonik	ASA ALT
5	EPA Overview	Margaret Sheppard	EPA
6	Fire Extinguishing Agents for Protection of Occupied Spaces in Military Ground Vehicles	Steve Hodges	TARDEC
7	Use of Alternate Agents in Military Ground Vehicle Fire Suppression Systems	John Porterfield	Kidde
8	Halon Replacements for Commercial Transport	Doug Ingerson	FAA
9	Environmentally Benign, No ODP, No GWP…The Polyhalon!	Casey Chapman	Polyhalon Tech.
10	A Breathable Foam for Thermal and Fire Protection of Passengers in a Military Vehicle	Albert Moussa	Blazetech
11	A comparative study on foam degradation behavior between flourinated and flourine-free foams over different fuels at elevated temperatures.	Katherine Hinnant	NRL
12	Overview of Toxicity and Health Effects Issues for Fire Protection in Army Vehicles	Matt Bazar	MEDCOM PHC
13	TARDEC Funded HD-RAM Studies	Don Grosch	SWRI
14	ARL Mission Program Overview	Barrie Homan	ARL-WMRD
15	Digital Holography for Fuel Spray Characterization	Dan Guildenbecher	Sandia
16	Fire Resistant Energy Attenuating Materials For Use In Army Military Vehicles Commercial Off The Shelf (COTS)	Julie Klima	TARDEC

17	Using Engineering Fire Test Data to Predict the Hazard	Jim Quintiere	U of Maryland
18	Development of Novel Materials for Flame Resistant Uniforms	Tom Tiano	NSRDEC
19	NAVAIR Overview	Ryan Author	NAVAIR
20	Overview of Sandia Fuel Fire Capabilities	Alex Brown	Sandia
21	Research, Development, Testing and Evaluation Capabilities for Fire and Ballistics at Southwest Research Institute	Matt Blais	SWRI

Day 2

Item	Title	Speaker	Organization
	Opening Remarks	Kevin Boyd	ARL-WMRD
22	US Army Aviation Fire Protection	Tim Helton	AMCOM
23	TARDEC Modeling and Simulation	Vamshi Korivi	TARDEC
24	Fire Prediction Model Update	Jamie Edwards	ARL-SLAD
25	Battery Safety in Abnormal Thermal Environments	John Hewson	Sandia
26	USN Lithium Battery Fire Test Summary	Jerry Back	Jensen Hughes
27	Lithium Battery Fire Suppression Experiments	Kevin Boyd	ARL-WMRD
28	Ultracapacitors - Rapid, Reliable, Safe Power	Brendan Andrews	Tecate Group
29	Intelligent Fire Protection System Technologies	Peter Disimile / David McGinnis	U of Cincinnati
30	Development of Zero ODP, Low GWP Clean Agents	Mark L. Robin	Chemours Co.
30	Thermal Injury Prevention Strategy Consortium	Nick Twardokus	Robertson
31	Lessons Learned & Technical Capabilities to Meet Higher Level Threats	Randy Fontinakes	Meggitt
32	Slow Growth Fires: Detection-Testing-Spec Inclusion	Doug Kulick	Spectrex
33	Amerex Overview	Ken Mier	Amerex
34	Vehicle Fires: Research and Effective Mitigation	Steve Hodges	TARDEC

2012 Fire Protection Meeting Review	Homan	ARL-WMRD
2015 Question and Comments	All	
Future Plans	All	

End

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This appendix appears in its original form, without editorial change.

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Appendix C. Presentations

This appendix appears in its original form, without editorial change.

U.S. ARMY TANK AUTOMOTIVE RESEARCH, DEVELOPMENT AND ENGINEERING CENTER

US Army Ground Vehicle Fires

Systems Fire Protection Information Exchange
14-15 Oct 2015

Steve McCormick
US Army TARDEC
steven.j.mccormick.civ@mail.mil

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1

Background

- Fire remains a significant threat to Army vehicles and Soldiers
- Large numbers of vehicles have been lost in theater due to fires caused by ballistic attacks
- Deep-seated external fires can result in total loss of vehicles and potential casualties
- Automatic fire extinguishing systems (AFES) have proven to be effective when vehicle is not overmatched
- Onboard POLs make vehicles particularly susceptible to fires in combat
- Tires/track and external stowage represent secondary fire vulnerabilities

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Ground Vehicle Fire Statistics

- Approximately 1.5% of attacks on US Army vehicles in Iraq and Afghanistan resulted in fires
  - A total of 220 fire casualties occurred from 2007 through 2012
- Dozens of accidental/peacetime vehicle fires occur annually
  - A total of 40 fire casualties occurred from 2002 through 2012

[illegible]	[illegible]	Fires	WIA	[illegible]
OEF*	17,970	240	62	25
OIF/OND*	25,828	401	56	77
Total	43, 798	641	118	102
35 Accidental fires resulting in 33 injuries and 7 fatalities**				

* Operation Enduring Freedom 01 Jan 2007 - 31 Dec 2012

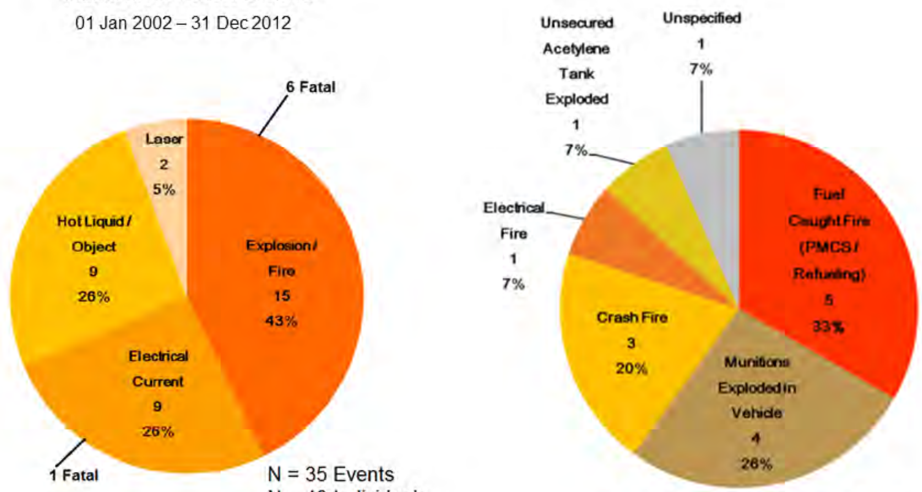
** Operation Iraqi Freedom/Operation New Dawn 01 Jan 2002 - 31 Dec 2012

Ref. Joint Trauma Analysis and Prevention of Injury in Combat (JTAPIC), RFI 2013 N0131, Thermal Injuries, 04 Oct 2013

Accidental Fires (Burn-Causing Fire Events)

Accidental Burn Events

01 Jan 2002 – 31 Dec 2012



N = 35 Events
N = 40 Individuals
Fatal = 7
Non-fatal = 33

N = 15 Burn-Causing Fire Events (10 involving occupied vehicles, 5 during PMCS)

Ref: Joint Trauma Analysis and Prevention of Injury in Combat (JTAPIC), RFI 2013 N0131, Thermal Injuries, 04 Oct 2013

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Combat Fire Incidents

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Combat Fire Incidents

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Combat Fire Incidents

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Combat Fire Incidents

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Combat Fire Incidents

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Combat Fire Incidents

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Peacetime/Accidental Fire Incidents

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Peacetime/Accidental Fire Incidents

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Peacetime/Accidental Fire Incidents

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Peacetime/Accidental Fire Incidents

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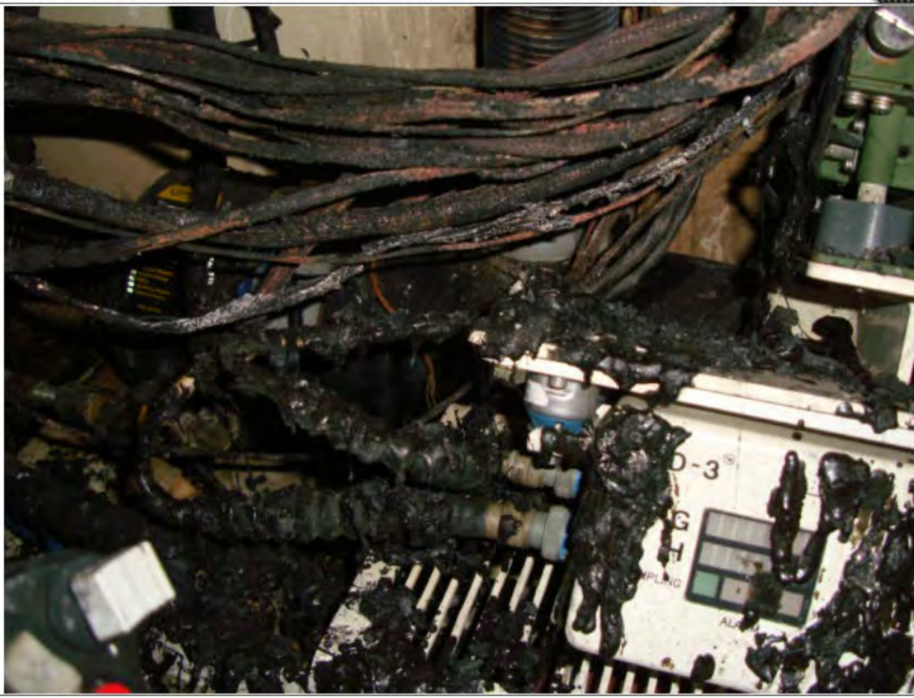
Peacetime/Accidental Fire Incidents



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Peacetime/Accidental Fire Incidents

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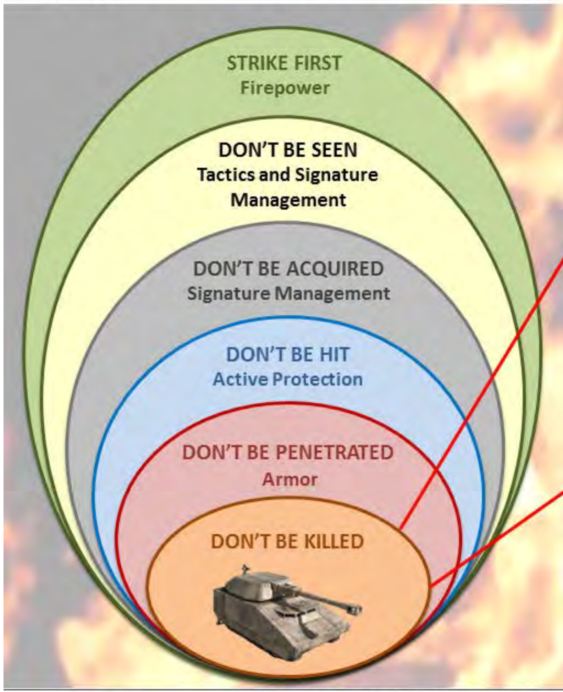
Layers of Combat Vehicle Survivability



Fire Protection

- Compartmentalization
  - Ammunition, fuel, batteries, etc.
- Fire Resistant Materials
- Fire Resistant Uniforms
- Automatic fire extinguishing system
  - crew, engine, cargo
- External fire protection
  - tires, fuel tanks

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Fuel Containment

Federal Motor Vehicle Safety Standard (FMVSS) 301 "Fuel System Integrity"
- Post-crash requirements for motor vehicle fuel systems to reduce damage from fuel spillage and fires.
- Required on all commercial vehicles; applied to most military vehicles via MIL-STD-1180.

External Fuel Tanks
- This approach makes fuel ingress into the crew compartment less likely.

Self-Sealing/Blast-Resistant Fuel Tanks
- Coatings or liners minimize fuel leakage when a tank is compromised.

Integrated Fuel Tanks
- Fires are less likely when armor, self-sealing to minimize fuel loss, and fire protection to suppress fires, are combined.

Fuel Tank Fillers
- These porous materials are intended to slow internal flame propagation.
- These technologies did not show sufficient benefit in ground vehicle tests against overmatching threats to warrant fielding.

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Fire Retardants

FMVSS 302, "Flammability of Interior Materials - Passenger Cars, Multipurpose Passenger Vehicles, Trucks, and Buses"

- Burn resistance requirements for materials used in occupant compartments of motor vehicles to reduce deaths and injuries to occupants caused by vehicle fires.
- Required on all commercial vehicles; applied to most military vehicles via MIL-STD-1180.

Flammability, Smoke, and Toxicity (FST) standard for military ground vehicles

- This standard which is under development will define FST requirements and test procedures for materials used in/on combat and tactical vehicles for improved safety and less vehicle losses due to fire.

FST test equipment (ASTM E 1354)

Materials after FST testing was performed

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Fire Prevention

Vehicle Design

- Compartmentalization of hazardous materials and stowage.
- Fuel system design (fuel line routing, check valves and shutoffs, fuel pumps, etc.).
- Material selection and integration.

Fire Resistant Tires and Track Materials

- Treads made from elastomers that combine fire resistance and mechanical toughness have been demonstrated.
- Candidate materials significantly limited fire propagation without significantly compromising durability.

Fire Resistant Road Wheels and Track Pads | Non Fire Resistant Road Wheels and Track Pads

Fire Resistant Fuel (FRF)

- A number of FRF approaches, including stable emulsions of fire suppression additives in fuel, were investigated to make combat fires less likely and less intense.

JP8 Fuel

Fire Resistant Fuel

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Fire Suppression

Automatic Fire Extinguishing Systems (AFES)
- AFES detect and automatically extinguish fires and explosions in crew, engine, and cargo areas.

External Fire Protection
- External fires are detected thermally and an extinguisher directs fire suppression agent at the protected area.

Fuel Tank Fire Protection
- A blanket or panel filled with extinguishing agent envelopes the fuel tank and when impacted disperses agent to prevent sustained fire.

Handheld Fire Extinguishers
- Mounted so they are available to the crew to fight internal or external fires.

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Personal Protection

Flame and Thermal Protective Items Worn in Combat Vehicles
- **Currently Issued to Combat Vehicle Crew (CVC)**
  - **Improved Combat Vehicle Crewman (iCVC) Coverall** – One piece flame resistant (FR) garment with a front entry, dual slide fastener & extraction capability
  - **Fire Resistant Environmental Ensemble (FREE)** – FR environmental protection for Mounted Soldiers, tailorable to the specific mission profile
- **Also Worn in Combat Vehicles - Primary Wear During Dismounted Operations**
  - **Flame Resistant Army Combat Uniform (FR ACU)** – FR uniform for deployed Soldiers
  - **Army Combat Shirt (ACS)** – FR, lightweight, highly breathable, moisture wicking shirt
  - **Army Combat Pant (ACP) -** FR pant with integrated knee impact protection
  - **FR Gloves**, including **Army Combat Glove (ACG), CVC Glove**
  - **FR Boots**, including **Army Combat Boots (ACB)** for hot and temperate weather
  - **Lightweight Protective Hood (LPH)** – FR balaclava for face & neck protection

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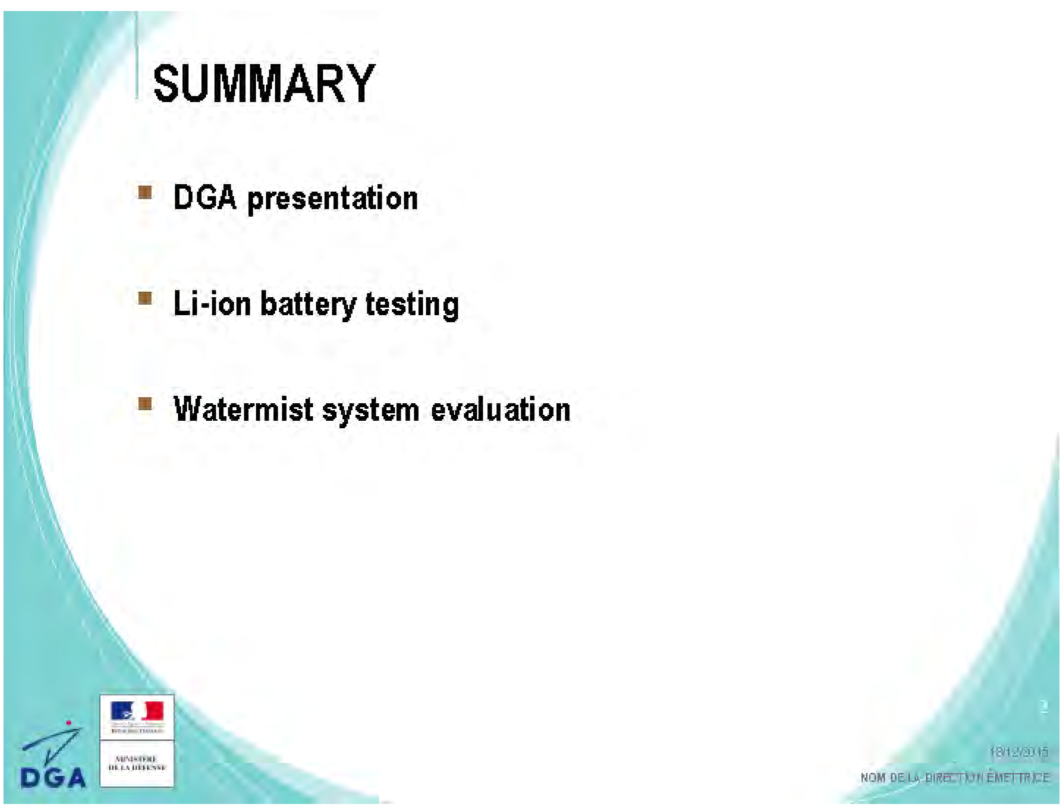
Summary

- Vehicle fires are inevitable when combustible fluids and flammable materials are stored in close proximity to potential ignition sources.
- Combat exacerbates the fire problem.
- Current mitigation techniques have helped to reduce the probability and severity of fire incidents.
- More work needs to be done to protect Soldiers and equipment.



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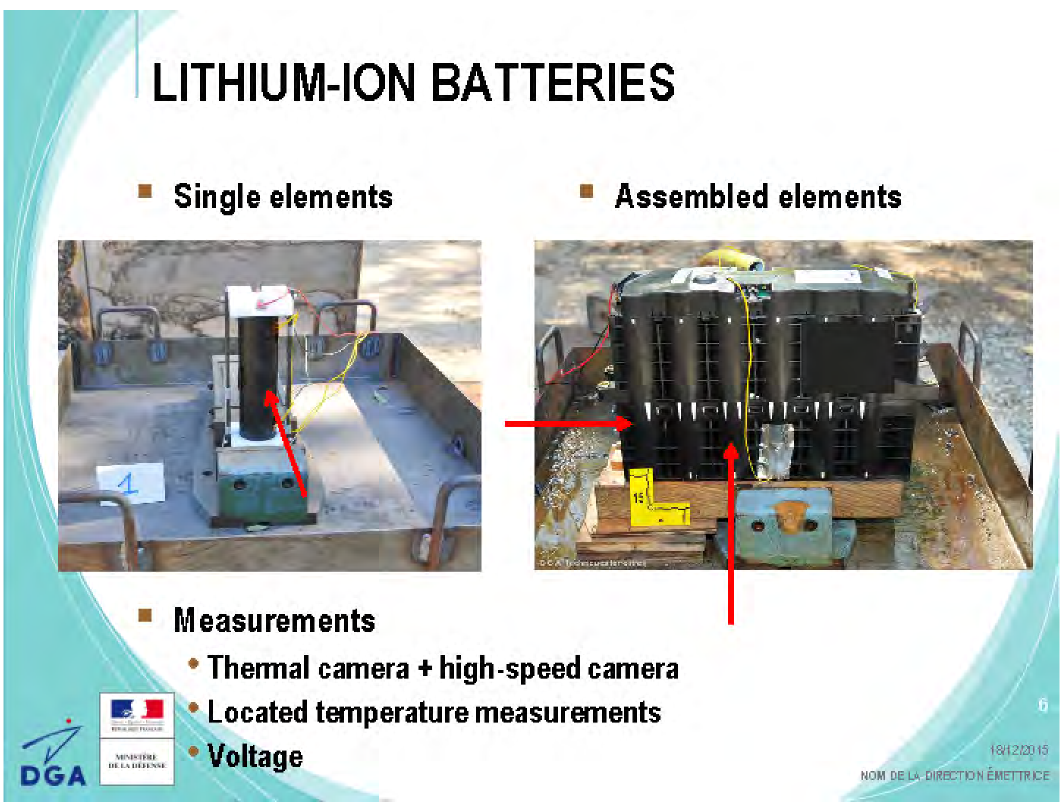
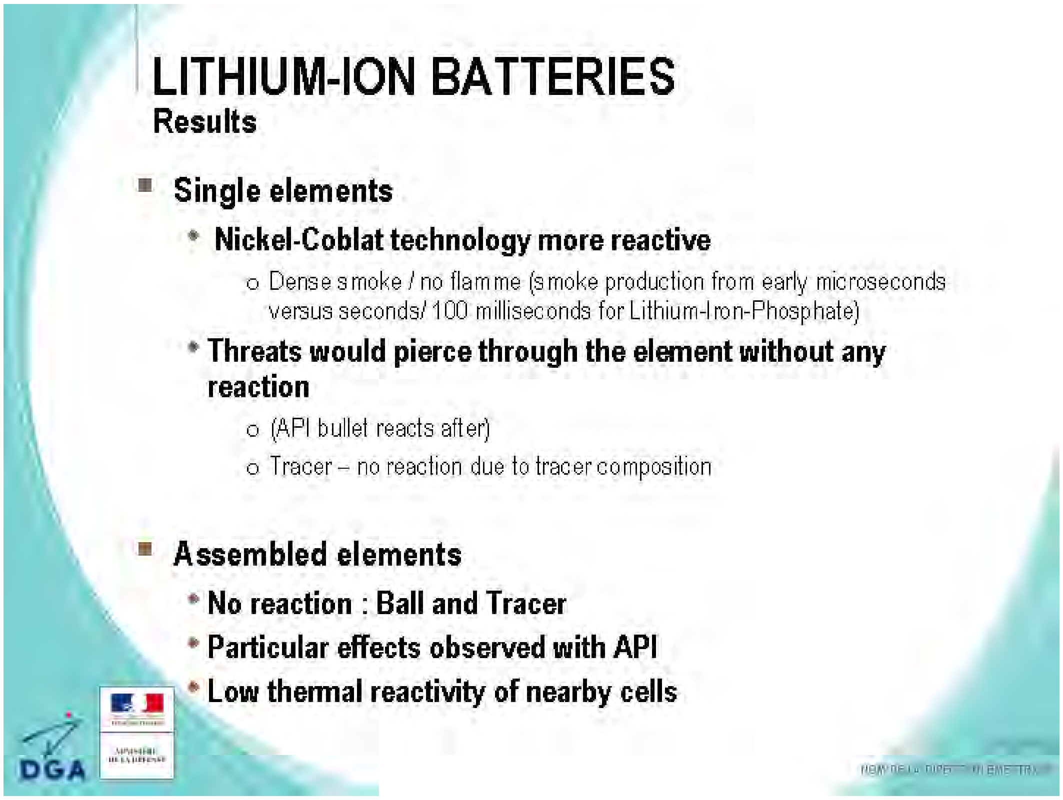
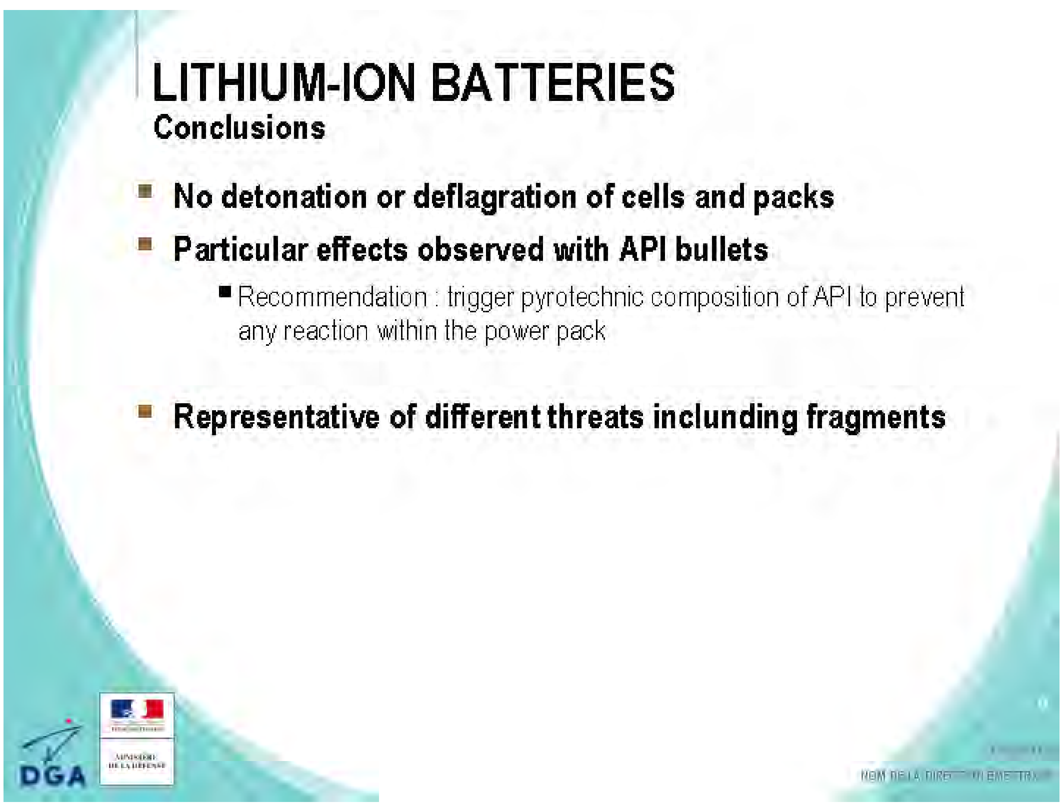
LITHIUM-ION BATTERIES
Study focused on :
Various Li-ion technologies (NCA, LFP)
Various threats (7.62 caliber, Armour Piercing amm, Munition traçante, balle ordinaire)
Various target sizes
Objectives:
Evaluate and compare reactivities of technologies
Compare effects of threats
Evaluate behaviour to adopt for land forces if in contact with Li-ion technology
DGA


LITHIUM-ION BATTERIES
Single elements
Assembled elements
1
Measurements
Thermal camera + high-speed camera
Located temperature measurements
Voltage
DGA
6
18/12/2015
NOM DE LA DIRECTION ÉMETTRICE





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WATERMIST SYSTEM EVALUATION

System

- **Objectives**
  - Engine compartment protection
  - Low speed growth fire (pan fire)
  - No automatic detection
  - Comparison with gaseous agent (no automatic system)
  - 3 tests
- **Pan fire caracteristics**
  - 0.24 m^2 filled with diesel and 1:5 ratio fuel (unleaded)
  - 60 sec pre burn +spray nozzle of diesel for 10 sec
  - Ventilation on/off
- **Measurements**
  - Thermocouples (x4)
  - Video

DGA

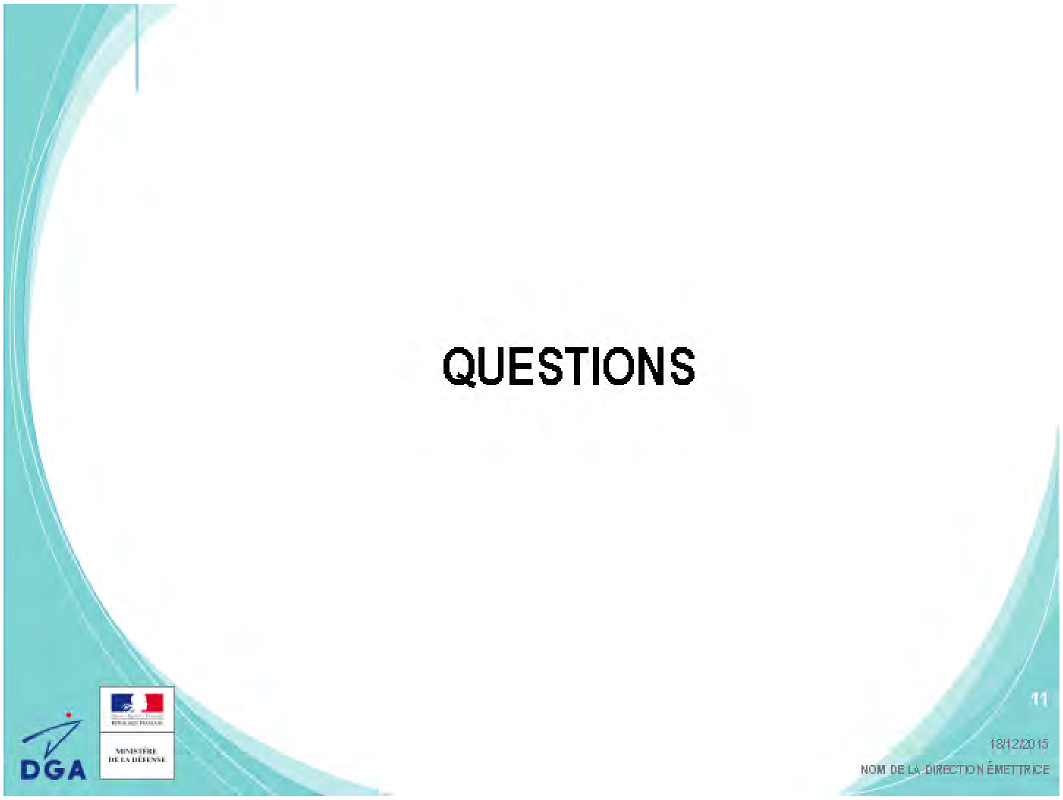
WATERMIST SYSTEM EVALUATION

Results

	Watermist	Gaseous agent
Suppression time	7 – 8 seconds	3-4 seconds
Sensitivity to airflow	Medium	High
Maintenance costs	Low	High
Integration	Medium/bad	Good
Montreal Protocol	Clean agent hence not targeted	Not targeted, but possibility on short/mid term basis

→ **Conclusion :** good potential, but main problem is defining survivability criteria (heat and burns in particular)

DGA


QUESTIONS
11
18/12/2015
NOM DE LA DIRECTION ÉMETTRICE
DGA

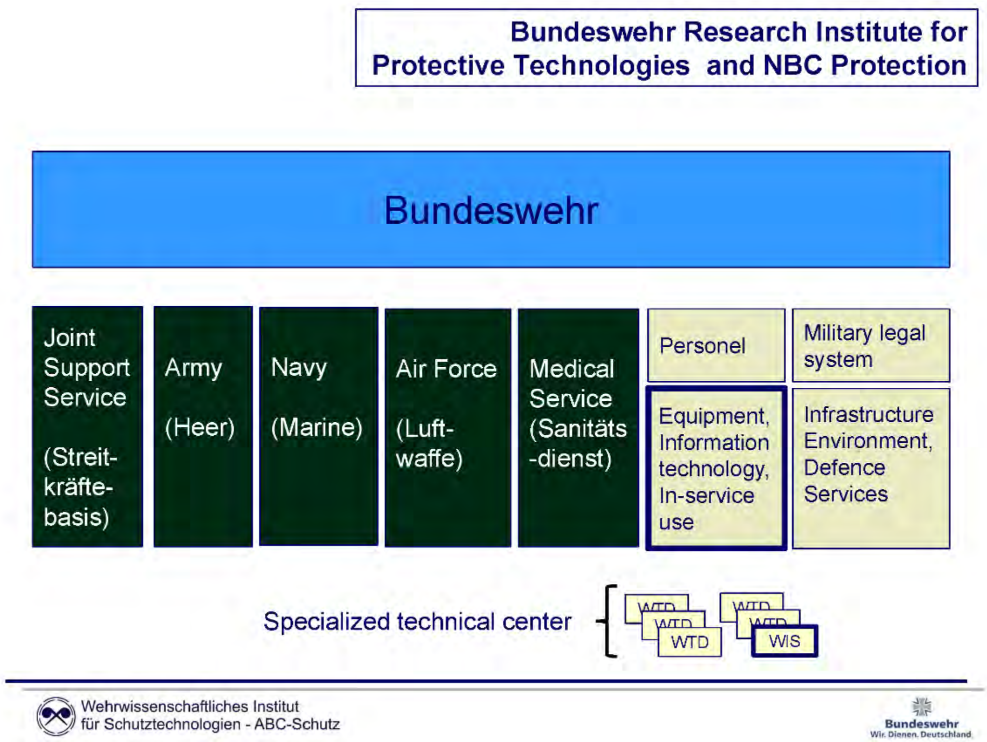
Overview of Germany's Military Vehicle Fire Protection Efforts

TRDir Felix Kümmerlen
WIS 340 – Fire Protection Engineering

Bundeswehr Research Institute for Protective Technologies and NBC Protection

Bundeswehr

- Joint Support Service (Streitkräftebasis)
- Army (Heer)
- Navy (Marine)
- Air Force (Luftwaffe)
- Medical Service (Sanitätsdienst)
- Personel
- Equipment, Information technology, In-service use
- Military legal system
- Infrastructure Environment, Defence Services



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Bundeswehr
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Air Force (Luft-waffe)
Medical Service (Sanitäts -dienst)
Personel
Military legal system
Equipment, Information technology, In-service use
Infrastructure Environment, Defence Services
Specialized technical center
WTD
WIS
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Bundeswehr
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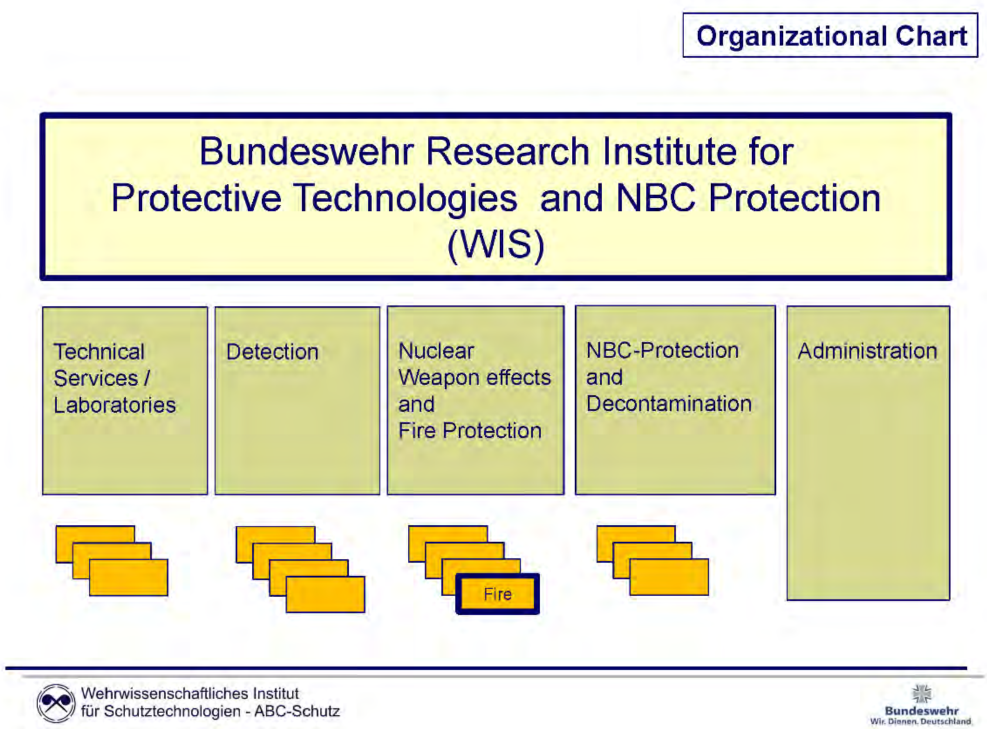

Organizational Chart
Bundeswehr Research Institute for
Protective Technologies and NBC Protection
(WIS)
Technical Services / Laboratories
Detection
Nuclear Weapon effects and Fire Protection
NBC-Protection and Decontamination
Administration
Fire
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Fire Fighting Technology Division

Hand held fire fighting equipment
- Testing
- Spare parts
- Investigation technical incidents

Fire extinguishing systems
- Testing
- Research
- Investigation technical incidents
- Halon

Fire extinguishing agents
- Testing (quality assurance inspection)
- Research (PFT-free AFFF)
- Investigation technical incidents

Flame Proofing
- Thermal manikin ‚Thermomann‘
- Flame impingement testing

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Hand held fire fighting equipment

Management and solution of all technical problems concerning fire fighting equipment

- Procurement of spare parts
- Handling of technical problems forwarded from the troops
- Procurement of new fire fighting equipment
  - ➢ 12 kg und 6 kg ABC powder extinguisher
  - ➢ 2 kg und 5 kg CO_2 extinguisher
- Technical approval of all fire fighting equipment used by Bundeswehr

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Fire extinguishing systems: Kitchen fire fighting system

Kitchen fire fighting system

- Frigate F125
- Certified according to ISO 15371
- In coop with Germanischer Lloyd

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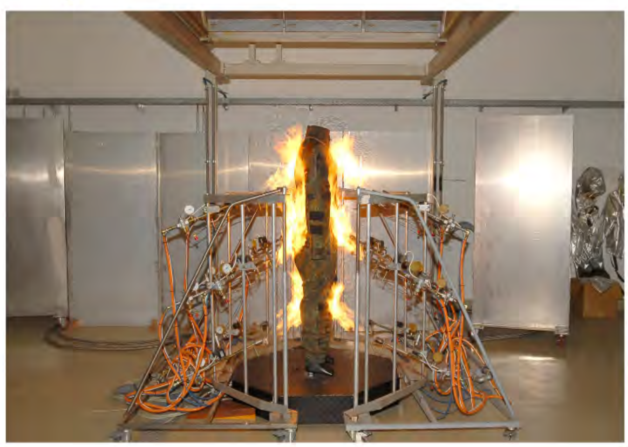
Flame proofing: Thermal resistance of clothing

Soldiers‘ clothing has to provide a lot of protection for e.g. insect bites, NBC-attacs, dirt, sunlight. It should provide camouflage and last, but not least, should give some protection against fire.

Fire resistance is tested among other test with the thermal manikin ‚thermoman‘



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Fire protection of armored vehicles

- Soldiers can face several types of fire threats
  - Fire in engine compartment
    - Without engine running a vehicle cannot move
    - Easy target
    - Scenarios:
      - Fuel line faulty, fuel drops onto hot surface, ignites
      - Shrapnel hits fuel line
  - Fire in crew compartment
    - Crew threatened by heat and toxic gases
    - Scenarios:
      - Ballistic shot hits hydraulic line – flash fire/deflagration
      - Molotow cocktail thrown into crew compartment

Engine compartment fire suppression

Test of suppression performance of engine compartment fire suppression systems

- ➢ Pans with flammable liquid placed at various places within compartment
- ➢ Electrical ignition
- ➢ Discharge of fire extinguishing agent
- ➢ Measurement of time until fire out

Alternatively:
discharge of agent, measurement of concentration of extinguishing agent at various places in the compartment (cold discharge)

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Engine compartment fire suppression

Crew compartment fire suppression system

- Armoured vehicles
- Extremely fast
  (extinguishing time < 150 ms)
  - Fire detection
  - Signal processing / prevention of faulty activation
  - Time for full emission of extinguishing agent
- False activations must not be dangerous to crew
  - toxicity
  - pressure

Examples of fire suppression systems in armored vehicles

Fire suppression system in engine compartment

- TPz Fuchs, SPz Marder, M113, KPz Leopard 2, RakW MARS, FlakPz Gepard, BPz 3 Büffel, PzH 2000, SPz PUMA, GTK BOXER

Fire suppression system in crew compartment

- KPz Leopard 2
- SPz PUMA
- GTK BOXER
- SPz MARDER
- …

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System test with realistic threat

Evaluation of performance of fire suppression systems:

System tests with realistic threat

- Molotov-cocktail
- Deflagration of hydrocarbon mist
- Pan with burning liquid

} Selected according to military evaluation of possible threats

For performance evaluation the following parameters are monitored

- Temperature
- Pressure
- Toxic gases concentricity (vol%)
- Agent concentricity (vol%)
- Time until fire extinguishing
- Tested against STANAG 4317 and occupational safety (in part)

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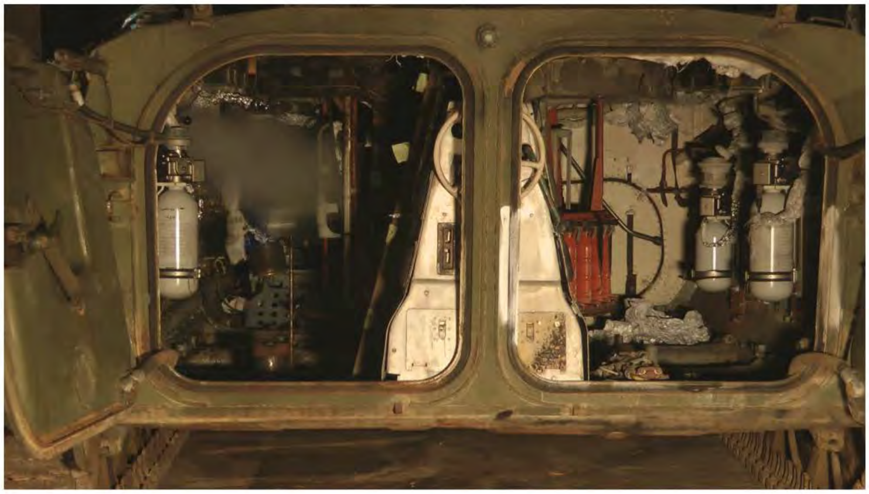
System test with realistic threat - deflagration



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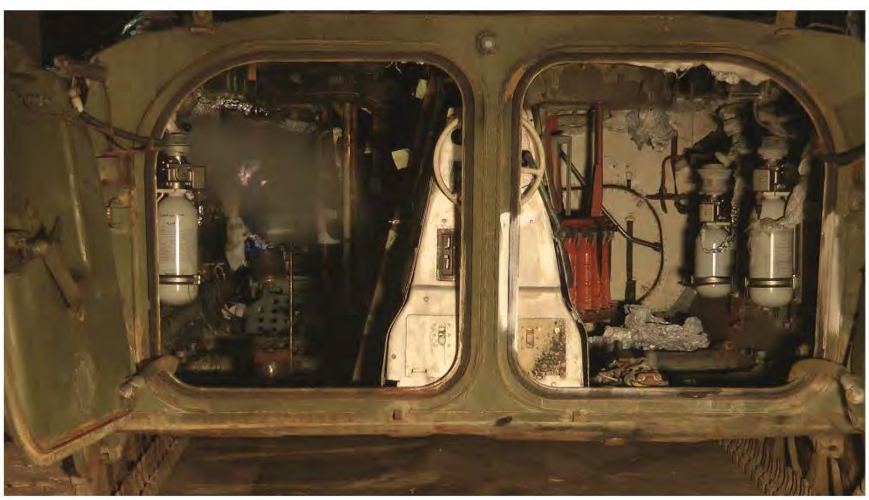
System test with realistic threat - deflagration



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System test with realistic threat - deflagration

System test with realistic threat - deflagration

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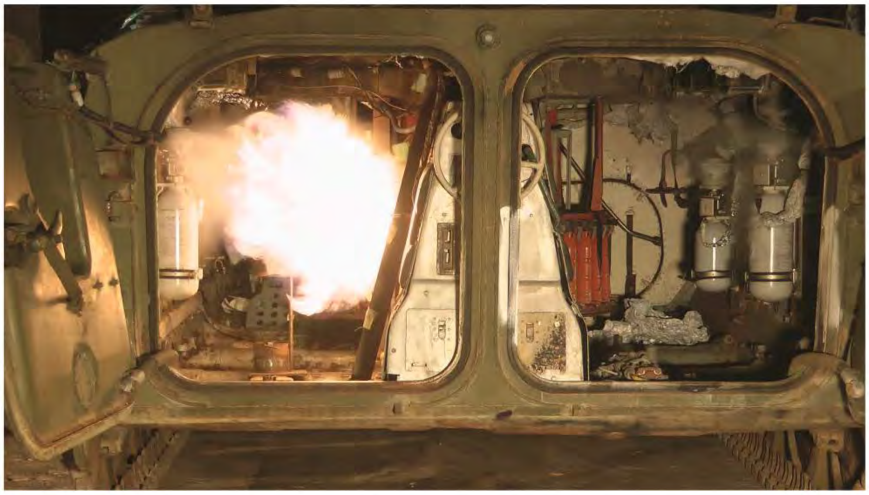
System test with realistic threat - deflagration



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System test with realistic threat - deflagration

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System test with realistic threat - deflagration

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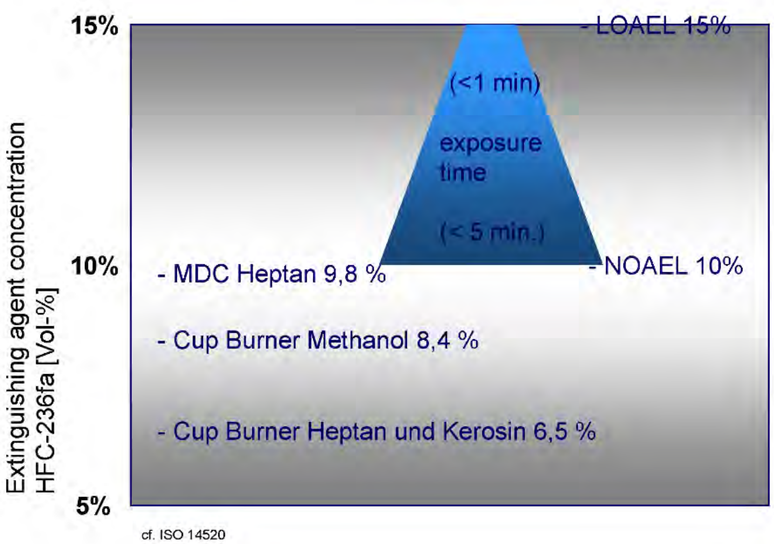
Measurement of extinguishing agent concentration



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System test with agent discharge only

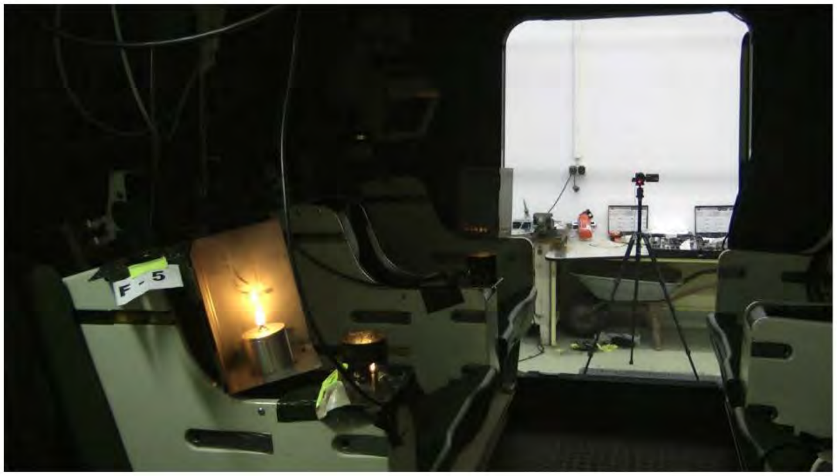
Measurement of extinguishing agent concentration

- Gas sensor
  - Thermal conductivity sensor
  - Calibrated to the extinguishing agent (1,1,1,3,3,3 Hexafluorpropan)
  - +/- 0,1 Vol-% typical
  - Time constant about 1 second

- ‚Flame sentinel'
  - Detect brightness of a petroleum flame
  - Time constant about 1 millisecond
  - Difficult to handle

System test with agent discharge only

System test with agent discharge only



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System test with agent discharge only

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System test with agent discharge only

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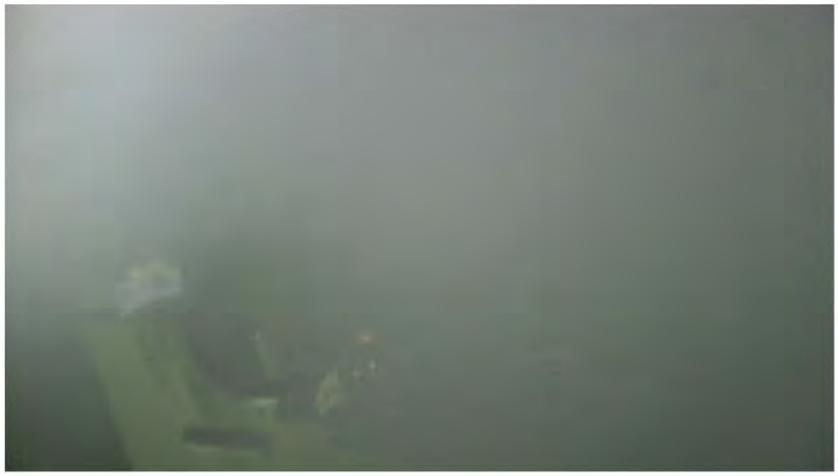

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System test with agent discharge only

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Cold discharge

Accidental activation of a fire suppression system must not cause harm to the crew

- Can be assessed in during cold discharge tests:
  - Agent concentration in crew compartment below LOAEL
  - Noise
  - Pressure raise
  - Mist / fog

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Research

Image processing based deflagration detection:

Improve detection speed and reliability by evaluating

- Brightness
- Size
- Color
- Development over time
- Details published in Fire Safety Journal, April 2014, p 1-10

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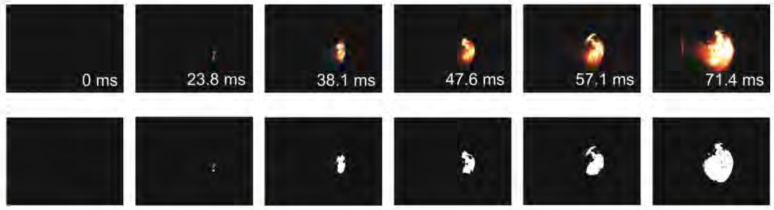
Research



Identified Pixel	**0**	**1047**	**4781**	**6257**	**12919**	**28156**
Spatial expansion parameter	**0,00**	**1,06**	**2,85**	**1,55**	**7,00**	**11,10**
Propability of deflagration using fuzzy logic	**11 %**	**23 %**	**64 %**	**33 %**	**88 %**	**89 %**

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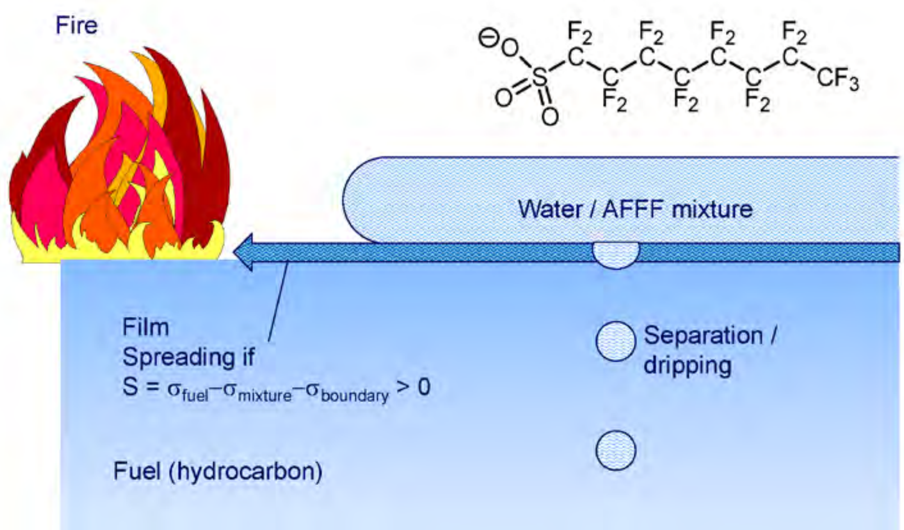
Aqueous Film Forming Foams



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Aqueous Film Forming Foam

The Aqueous Film…

- cools the fuel surface
- acts as vapor barrier
- operates in areas without foam
- autonomously closes perforations of the foam
- works as buffer between fire and foam

AFFF is the most effective agent for pool fires!

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Foam laboratory

The quality of foam is tested with every batch purchased

- Fire extinguishing abilities
  - Foam stability
  - Expansion ratio
  - Spreading coefficient
  - Fire test
  - …
- Storage stability
  - At high temperatures
- Compatibility with other foams
- Compatibility with other extinguishing agents

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Fire testing of AFFF

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Research

Environmental Problems of AFFF:

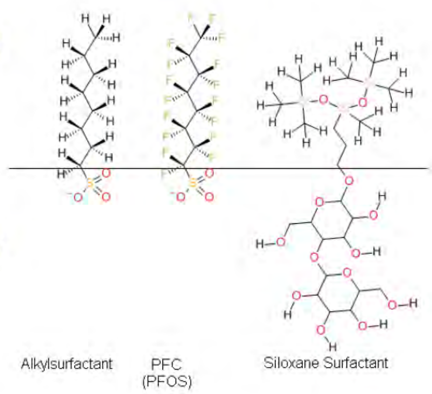
AFFF use PFC (polyfluorinated compounds) to establish the water film.

PFC are persistent.

PFC are strictly regulated in Germany
 proposed regulation in EU

Research:

- Replace PFT-Containing AFFF
- Focus on militarily important fuels
  - Diesel
  - Jet Fuel
  - F-34
  - Cyclohexan (reference)



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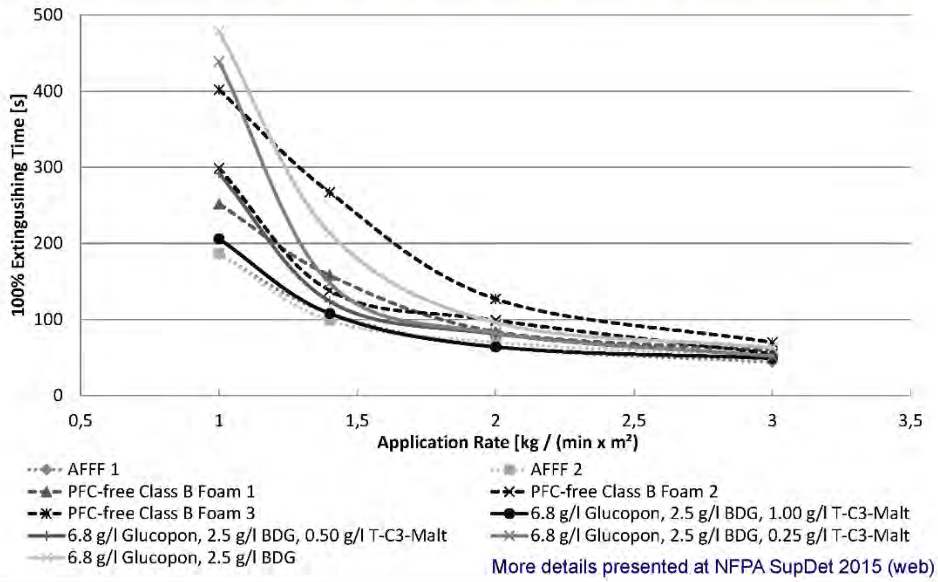
Small Scale Fire Tests – 100% Extinguishing Time



More details presented at NFPA SupDet 2015 (web)

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Conclusion

Within Bundeswehr, performance of fire suppression systems is tested in various ways:

- System tests with realistic threat
- Measurement of detection capabilities
- Measurement of suppression capabilities
- Alternatively: theoretical / numerical analysis

Minimum levels of protection defined by

- Law (occupational safety)
- Military requirements (individually for each system)

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Thank you for your attention

Questions ?

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Fire Fighting Technology Division
Bundeswehr Research Institiute for Protective
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Humboldtstraße 100
D-29633 Munster

Further reading

- Thomas Schröder, Klaus Krüger, Felix Kümmerlen, Image Processing Based Deflagration Detection Within Crew Compartments Of Armoured Vehicles, Proceedings of the 13th International Interflam Conference, 2013
- Thomas Schröder, Klaus Krüger, Felix Kümmerlen, Image processing based deflagration detection using fuzzy logic classification, Fire Safety Journal, Volume 65, April 2014, Pages 1–10, http://dx.doi.org/10.1016/j.firesaf.2014.02.004
- Ralf Helmut Hetzer, Felix Kümmerlen, Dirk Blunk, Fire Testing of Experimental Siloxane-Based AFFF: Results from New Experiments, NFPA Suppression, Detection and Signaling Research and Applications Symposium (SUPDET 2015), http://www.nfpa.org/supdet2015papers

Regulatory Status of Halon and its Alternatives

Daniel P. Verdonik, EngScD
JENSEN HUGHES
Contactor Support to the Office of the Assistant Secretary of the Army for Acquisition, Logistics and Technology

Stratospheric Ozone Protection

- Two Multilateral Environmental Agreements (MEAs)
  - Vienna Convention for the Protection of the Ozone Layer
  - Montreal Protocol on Substances that Deplete the Ozone Layer
- Vienna Convention for the Protection of the Ozone Layer
  - It was agreed upon at the Vienna Conference of 1985
  - Signed on March 22, 1985 by President Reagan
  - Ratified by the Senate August 27, 1986
  - Entered into force in 1988
  - Signed initially by 28 countries
  - Now ratified by 197 states (all 193 UN members and the Holy See, Niue and the Cook Islands) as well as the European Union
  - Set the stage for the possibility of global regulatory action
  - Did not itself call for regulations
  - Led to the Montreal Protocol

Montreal Protocol

on Substances that Deplete the Ozone Layer

- September 16, 1987 - International Ozone Day
- Signed by President Reagan December 21, 1987
- Ratified by Senate April 21, 1988
- Entered into force January 1, 1989
- Signed initially by 46 countries
- One of the most successful treaties of all time
  - Same as Vienna Convention
  - Ratified by 197 states (all 193 UN and the Holy See, Niue and the Cook Islands) as well as the European Union
- Regulates production and sharing of production, called consumption of Ozone Depleting Substances (ODS)
- Does not regulate use

Montreal Protocol

- Originally, the Montreal Protocol required:
  - 50% reduction from 1986 levels in the production and consumption of chlorofluorocarbons (CFC)-11, -12, -113, -114, and -115 by 1998
  - Halons 1211, 1301 and 2402 frozen at their 1986 levels starting in 1992
- Halons – Halogenated Hydrocarbons - are the most destructive of the manmade ODS
  - Production was banned for developed countries on January 1, 1994
  - The first of the ODS to be stopped
  - In developing countries, halons were banned from production on January 1, 2010
- Provides for a mechanism for Essential Use Exemption
  - Request for production and consumption
  - NOT a request to continue to use halons
  - No essential uses for halons 1211 or 1301 have been approved

European Union No 744/2010 – Halon Critical Uses

			Cutoff/End
1. **On military ground vehicles**			
1.1. Engine compartments	Fixed system	1301 1211 2402	2010/2035
1.2. Crew compartments	Fixed system	1301 2402	2011/2040
1.3. Crew compartments	Portable extinguisher	1301 1211	2011/2020
2. On military surface ships			
2.1. normally occupied machinery spaces	Fixed system	1301 2402	2010/2040
2.2. Normally unoccupied engine spaces	Fixed system	1301 1211 2402	2010/2035
2.3. Normally unoccupied electrical compartments	Fixed system	1301 1211	2010/2030
2.4. Command centres	Fixed system	1301	2010/2030
2.5. Fuel pump rooms	Fixed system	1301 2010 2030	
2.6. Flammable liquid storage compartments	Fixed system	1301 1211 2402	2010/2030
2.7. Aircraft in hangars and maintenance areas	Portable extinguisher	1301 1211	2010/2016
3. On military submarines			
3.1. Machinery spaces	Fixed system	1301	2010/2040
3.2. Command centres	Fixed system	1301	2010/2040
3.3. Diesel generator spaces	Fixed system	1301	2010/2040
3.4. Electrical compartments	Fixed system	1301	2010/2040

EU No 744/2010 – Halon Critical Uses

			Cutoff/End
4. **On aircraft**			
4.1. Normally unoccupied cargo compartments	Fixed system	1301 1211 2402	2018/2040
4.2. Cabins and crew compartments	Portable extinguisher	1211 2402	2014/2025
4.3. Engine nacelles and auxiliary power units	Fixed system	1301 1211 2402	2014/2040
4.4. Inerting of fuel tanks	Fixed system	1301 2402	2011/2040
4.5. Lavatory waste receptacles	Fixed system	1301 1211 2402	2011/2020
4.6. Dry bays	Fixed system	1301 1211 2402	2011/2040
5. In oil, gas and petrochemicals facilities			
5.1. Spaces where flammable liquid or gas could be released	Fixed system	1301 2402	2010/2020
6. On commercial cargo ships			
6.1. Inerting of normally occupied spaces where flammable liquid or gas could be released	Fixed system	1301 2402	1994/2016

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EU No 744/2010 – Halon Critical Uses

			Cutoff/End
7. In land-based command and communications facilities essential to national security			
7.1. Normally occupied spaces			
	Fixed system	1301 2402	2010/2025
7.2. Normally occupied spaces			
	Portable extinguisher	1211	2010/2013
7.3. Normally unoccupied spaces			
	Fixed system	1301 2402	2010/2020
8. At airfields and airports			
8.1. Crash rescue vehicles	Portable extinguisher	1211	2010/2016
8.2. Aircraft in hangars and maintenance areas			
	Portable extinguisher	1211	2010/2016
9. In nuclear power and nuclear research facilities			
9.1. Spaces where necessary to minimise risk of dispersion of radioactive matter			
	Fixed system	1301	2010/2020
10. In the Channel Tunnel			
10.1. Technical facilities	Fixed system	1301	2010/2016
10.2. Power cars and shuttle wagons			
	Fixed system	1301	2010/2020
11. **Other**			
11.1. For initial extinguishing by fire brigades where essential to personal safety			
	Portable extinguisher	1211	2010/2013
11.2. For the protection of persons by military and police personnel			
	Portable extinguisher	1211	2010/2013

Global Status of Halons

- **No production (or consumption) for fire protection since 1994 in developed and 2010 in developing Countries**
- **Continue to rely on recycled quantities**
- **Global Banks**
  - **Mass balance: Production – Emissions = Bank**
  - **Estimate emissions**
    - **Atmospheric concentrations and lifetime**
    - **Emissions factors placed on installed quantities**
  - **40,000 – 42,000 t of halon 1301 as of 2014**
  - **22,000 – 33,000 t of halon 1211 as of 2014**
- **Only civil aviation still requires halon in new designs**
  - **Non-civil aviation military new systems do not require halons**
  - **Some non-civil aviation military new systems do (Boeing 737 derivative P-8), others do not (Boeing 767 derivative KC-46)**
  - **Large concern they will run out of halon 1301 before end of lifetime of aircraft being produced currently**

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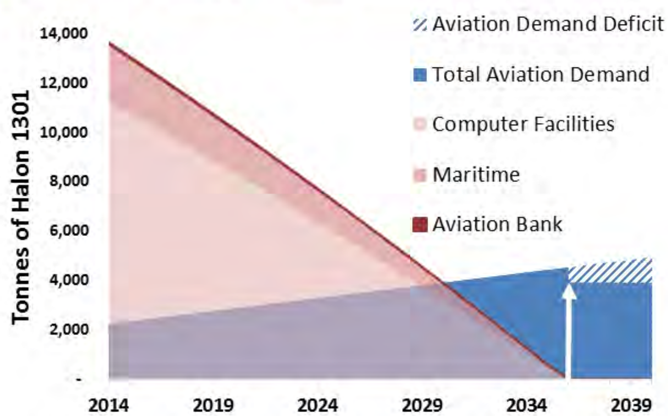
Global Halon 1301 for Civil Aviation Use

- Not all halon 1301 in global bank will be available to civil aviation
  - 41,000 – 43,000 t in global bank
  - Subtract what is not available to civil aviation
    - 17,000 t reserved for future use in ground-based fire protection systems in Japan
    - About 4,600 t reserved by the U.S. military for use in existing critical weapons systems
    - About 1,500 t of halon 1301 in oil facilities on the North Slope of Alaska and other places around the world
    - About 2,200 t already installed on civil aircraft rising to 6,000 t by 2050
- Leaves 14,000 – 17,000 t (33% - 40%) for civil aviation if every other gram of halon 1301 becomes dedicated to civil aviation
- Global and civil aviation emission rates will play an important role in how long civil aviation can be supported
  - HTOC ~3% and SAP data ~4% of bank / year
  - Anecdotal information places civil aviation closer to 5% / year

High Annual Aviation Emission Rate; ~14,000 t



Low Annual Aviation Emission Rate; ~17,000 t runs out in 2045

Not enough halon 1301 in global bank to support civil aviation over 20 - 40 year life of aircraft

What about HFCs?

Climate Protection

- Two MEAs
  - United Nations Framework Convention on Climate Change (UNFCCC)
  - Kyoto Protocol
- UNFCCC
  - Agreed in 1992
  - Signed by President Bush in June 1992
  - Ratified by Senate in October 1992
  - Cooperatively consider
    - Limit average global temperature increases and resulting climate change
    - Cope with inevitable impacts (adaptation)
  - 195 parties to the convention
  - Led to the Kyoto Protocol

Kyoto Protocol

- Adopted in Kyoto on December 11, 1997 – Al Gore big player
- Signed by President Clinton on November 12, 1998
- Not ratified by Senate – did not include developing countries
- Entered into force on February 16, 2005
- Currently 192 parties (Canada withdrew as of December 2012)
- Reduce greenhouse gas (GHG) concentrations in the atmosphere to "a level that would prevent dangerous anthropogenic interference with the climate system" (Art. 2)
- First commitment period started in 2008 and ended in 2012
- Second commitment period began on 1 January 2013 and will end in 2020
  - EU agreed to extend the Kyoto Protocol until 2017
  - Japan, Canada, and Russia did not
- Post 2020 commitment taken up under the UNFCCC

Kyoto Protocol

- The first commitment period covered the basic 6 GHGs:
  1. Carbon dioxide (CO_2);
  2. Methane (CH_4);
  3. Nitrous oxide (N_2O);
  4. Hydrofluorocarbons (HFCs);
  5. Perfluorocarbons (PFCs); and
  6. Sulphur hexafluoride (SF_6)
- The first 3 are typically a result of byproduct emission or decay
- The last 3 are used as replacements for ODS
- Lack of progress on post-Kyoto is linked to the different entities in the climate debate – CO_2 emissions from energy versus CO_2 equivalents (using Global Warming Potentials) from purposefully manmade refrigerants, fire suppressants, solvents, foam blowing agents, etc.

UNFCCC

- Adopted the Durban Platform for Enhanced Action
  - Conference of the Parties (COP) 17 to the UNFCCC in November 2011
- Calls for a new climate change treaty to be signed by 2015 and begin by 2020
- Final treaty to be signed in Paris this December
- "Lima Call for climate action" approved last year
  - Contains elements for a draft negotiating text
  - Key points:
    - Encourages all parties - developed and developing - to consider mitigation measures
    - Invites all countries to submit their intended nationally determined contributions by 1Q 2015
- New accord will include commitments for all countries, both developed and developing

Progress on the Durbin Platform

- Three negotiating sessions so far this year
- Geneva in February
  - Goal to provide negotiating text by May
  - Text grew from 39 to 86 pages
- Bonn in June
  - Main goal was streamline Geneva negotiating text
  - End of meeting text reduced by only 5 pages
- Bonn in August/September
  - Some progress made on negotiating text, but still long way to go to reach agreement in Paris

The Road to Paris is Through Montreal.......

- North America Proposal: US – Canada – Mexico – first submitted an amendment Proposal on HFCs in 2009
  - Originally blocked by developing countries such as Brazil, India, China and South Africa
  - President Obama and Secretary Kerry are personally involved in getting senior leaders of those countries to buy-in.
  - Last few years it has been the Middle Eastern countries that are blocking any possible progress, including having formal discussions in a “Contact Group”
- At the 35th Open-ended Working Group (OEWG) meeting this past April and the 36th OEWG in July, amendments were again discussed that would add HFCs to the Montreal Protocol and slowly phase down production
- HFC amendment proposals in 2015 from North America (US, Canada, and Mexico), Micronesia (Island States), India and European Union

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Montreal Protocol Amendments

- **Island States**
  - 15% reduction in 2017 - 75% in 2029
  - 35% in 2021 - 90% in 2033
  - 55% in 2025
  - Developed country baseline based on 2011-2013 annual consumption of HFCs and 10% of HCFCs
  - Developing country phase down would begin 3 years in 2020 and each step would be one additional year later
  - Developing country baseline based on 2015-2017 annual consumption of HFCs and 65% of HCFCs
- **European Union**
  - 15% reduction in 2019 - 70% in 2028
  - 40% in 2023 - 85% in 2034
  - Developed country baseline based on 2009-2012 annual production/consumption of HFCs and 45% of HCFCs
  - Developing country phase down would include different phase down dates and baselines for production and consumption
  - Begins in 2019 with a freeze, reaches 85% reduction by 2040 with intermediate reduction steps agreed to by 2020

Montreal Protocol Amendments

- **North America**
  - 10% reduction in 2019 - 70% *in 2030*
  - 35% in 2024 - 85% *in 2036*
  - Developed country baseline based on 2011-2013 annual production/consumption of HFCs and 50% of HCFCs
  - Developing country phase down begins in 2021with a freeze, *reaches 85% reduction by 2046, with intermediate reduction steps in 2026 (20%) and 2032 (60%)*
  - Developing country baseline based on 2011-2013 annual production/consumption of HFCs and 75% of HCFCs
- **India**
  - 0% reduction (freeze) in 2016
  - 85% in 2035
  - 15-year grace period for developing countries
  - Nationally determined phase-down steps for HFCs in developing countries
  - Full conversion costs
  - Separates HFCs into 4 different groups in Annex F and puts HFC-23 (FE™-13) in Annex G

Status at July Montreal Protocol OEWG Meeting

- Despite growing support for addressing HFCs under the Montreal Protocol, the parties could not agree on a proposed text for the formation of a contact group
  - Pakistan was the lone obstruction to progress in finalizing the text at July OEWG meeting
  - Instead they agreed to hold a continued OEWG session to address the HFC issue prior to the Meeting of Parties (MOP) in November
- Amendments will be "discussed" at MOP November 1-5 in Dubai
- Key issue will be whether a contact group is formed and actually begins work during the MOP
- With a new climate change treaty under the UNFCCC expected to be approved in December, will be pressure to have some positive outcome on HFCs at this Meeting of the Parties to the Montreal Protocol

National Regulations - HFCs

- European Union F-gas Regulation
  - Became applicable January 1, 2015
  - Gradual phase down beginning with a freeze in 2015, reaching 79% reduction by 2030
  - Bans systems and extinguishers that contain HFC-23 as of January 1, 2016
  - Requires containment and recovery
  - Requires labeling with name (now) and quantity in weight and CO_2 equivalents (2017)
- EU F-gas reporting provisions
  - Companies are required to report any import of fire protection equipment (systems and extinguishers) containing more than 100 tons of CO_2 equivalent HFCs (227ea = 68 pounds)
  - Report for 2014 imports was due March 31, 2015
  - EC published implementing regulation that determines format and method for reports

National Regulations - HFCs

- **Japan HFC Policy**
  - Act on Rational Use and Proper Management of Fluorocarbons and implementing guidelines will be effective from April 2015
  - New measures regarding the promotion of low-GWP/non-HFC alternatives for designated products, the phase-down of HFCs, and the reduction of refrigerant leakage from equipment during use
  - Manufacturers and importers of HFCs subject to a phase-down of 40% reduction of HFC use by 2020 and 52% reduction by 2025
  - Equipment manufacturers have target GWP values set based on the lowest GWP (weighted average by volume) among designated products in the market, also considering issues such as safety, energy efficiency and affordability
  - Room air conditioners - GWP 750 by 2018
  - Cold storage warehouses is 100 GWP and for dust blowers 10 GWP by 2019
  - Commercial air conditioners for offices and stores is 740 GWP and for urethane foam for house-building materials is 100 GWP by 2020
  - Not aware of any fire protection targets

National Regulations - HFCs

- **Canada HFC Regulations**
  - Environment Canada is proposing a hybrid approach for regulatory measures on HFCs
    - Phase down modeled after the North American proposed amendment
    - Product-specific prohibitions with GWP limits and target dates in certain sectors (not fire protection)
  - Consultation meeting in February and sector-specific meetings in March
  - Consultation closed on April 17th
- **Venezuela**
  - New regulations published July 1 in the Official Gazette for the control, use, import and handling of HFC products and mixtures
  - Require companies to have an official license from the Environment Ministry to import, sell and service HFCs
- **Australia**
  - Nationally defined contribution (INDC) as part of the new climate change treaty says Australia will support a phase down under MP and work to reduce domestic emissions by 85% by 2036

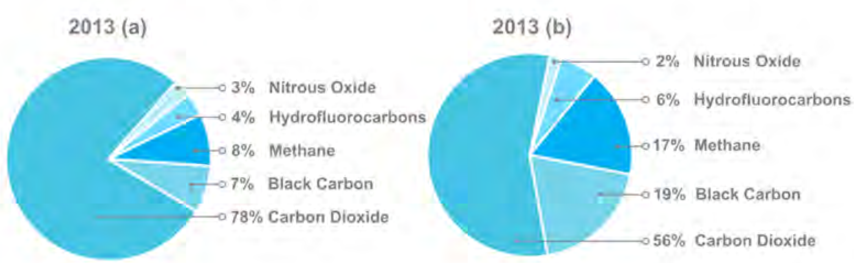
US Activities - HFCs

- **California Air Resources Board (ARB)**
  - California Senate Bill 605 requires ARB to develop a strategy to achieve reductions in Short-lived Climate Pollutants (SLCPs) by end of 2015
  - ARB released concept paper in May that presents ideas for addressing SLCPs, which include methane, black carbon, and HFCs
  - ARB held public workshop on May 27 and a meeting with industry on July 30
  - No mention of fire protection at either meeting

Senate Bill 605

Develop SLCP reduction strategy by Jan 1, 2016

- Concept paper released May 7, 2015
- Draft plan in Aug 2015
- Board consideration in Nov 2015
- Final in Spring 2016



(a) 100-year and (b) 20-Year Global Warming Potential Values

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Mitigation Options

Measure name	Proposed Start Date
Financial Incentive for Low-GWP Refrigeration Early Adoption	2017
HFC Supply Phasedown in CA (aligns w/ North American Proposal to Montreal Protocol)	2018
Upstream High-GWP Fee	2019
Advanced Recycling Fee on F-gases in pre-charged equipment	2019
Sales Ban of Very-High GWP Refrigerant (GWP ≥2500)	2020

US Activities - HFCs

- **Federal Procurement**
  - **Proposed rule published in May would amend the Federal Acquisition Regulation (FAR) to implement executive branch policy in the President's Climate Action Plan to procure, when feasible, alternatives to high-GWP HFCs**
  - **Defense Federal Acquisition Regulation Supplement (DFARS) would follow**
- **White House HFC Meeting**
  - **In September of 2014 the White House held an event with industry leaders focused on reducing global emissions of HFCs**
  - **Commitment by Sevo Systems to enable a reduction of 12 million metric tons of carbon dioxide by 2020 by transitioning to fire suppression systems using FK-5-1-12**
  - **A second White House event in planned for October 15 (tomorrow)**
  - **DoD is making several commitments**

My Personal View........

- Richard Mueller of University of California at Berkley, Berkley Earth Temperature Project
  - Former skeptic of climate change
  - Performed statistical analysis of 1.6 billion temperature reports spanning the last 200 years
  - Study found that earth's surface temperature has increased 1.6 °F since the 1950s and 2.5 °F since 1750
  - Shows natural variation cannot be the cause
  - Rise in CO_2 correlates best with actual warming
  - Concluded that emissions from human activity are the cause
- US Circuit Court of Appeals
  - Upheld US Environmental Protection Agency Endangerment Finding on GHGs
  - Court found that the Endangerment Finding was based upon solid scientific evidence

Whether you believe or not, reality is militaries will need no/low-GWP alternatives looking into the future

My Personal View........

- ODS phase-out viewed globally as a major success
  - Will be the model for man-made GHG regulations
  - Along the lines of Montreal Protocol / EC regulation
- Some applications currently need halon or a high GWP HFC
  - Since caps will be GWP-based, can make many more tons of low GWP agents
  - Location, location, location
  - Direct implications if national security and other specific interests are included within the overall cap
- National security / military needs diverging from industry
  - e.g., uHFC-1234yf is a major player in replacement of HFC-134a in mobile air conditioning
  - Flammability concerns may be larger issue for military
- Need no/low GWP alternatives for all halon uses
  - Industry may not solve this for military / aviation / etc.
  - Scale of market
- Coordinated efforts will be required

EPA Overview

Margaret Sheppard

Stratospheric Protection Division

ARL-TARDEC Fire Protection Information Exchange Meeting

October 14-15, 2015, Aberdeen Proving Ground, MD

Outline

- SNAP submissions for fire suppression
- Sector activities
- SNAP stakeholder meeting on recent and upcoming actions
- Recent petitions related to fire suppressants
- Next steps

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SNAP
SIGNIFICANT · NEW · ALTERNATIVES · POLICY

Evaluates alternatives & lists alternatives as:

- **Acceptable** - those that reduce overall risk to human health & environment
- **Acceptable with use restrictions** - if needed to ensure safe use
- **Unacceptable**

Sectors include:

- Aerosols; Foams; Refrigeration and A/C; Solvents; Fire Suppression; Adhesives, Coatings, Inks, etc.

Considers:

- Ozone Depletion Potential
- Global Warming Potential
- Flammability
- Toxicity
- Local Air Quality
- Ecosystem Effects
- Occupational & Consumer Health/Safety

SNAP Listings for Fire Suppression

End-Use	Acceptable Substitutes	Unacceptable Substitutes	Total Listings
Streaming: HFCs, HCFCs and blends, PFC, dry chemical, fluoroketones (FKs), CO_2, water	24	1	25
Total Flooding: HFCs, HCFCs and blends, PFCs, inert gas/generators, aerosols, FK, CO_2, water	43	4	47
All of Fire Suppression	59	5	64

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SNAP Submissions

- **2-bromo-3,3,3-trifluoropropene (2-BTP)**
  - Streaming and total flooding
  - Parallel review with TSCA New Chemicals Program
  - Ongoing review, considering additional information from submitter
- **Inquiries on potential new submissions**

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Sector Activities

- Aviation
  - FAA Halon Aviation Rulemaking Committee Final Report (Dec. 2014)
  - Ongoing coordination with ICAO, HTOC
- DoD
  - ODS Services Steering Committee
- Standards
  - NFPA, ISO Technical Committees

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President's Climate Action Plan and SNAP

"To reduce emissions of HFCs, the United States can and will lead both through international diplomacy as well as domestic actions"

- International diplomacy
  - Montreal Protocol
  - Other forums both multinational and bilateral
- **Domestic actions:**
  - Federal procurement
  - **EPA's SNAP Program:**
    - **Encourage private sector investment by identifying and approving climate-friendly chemicals**
    - **Prohibit certain uses of the most harmful chemical alternatives**

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Federal Actions Addressing HFCs

- FAR proposed rule (May 11, 2015) addressed HFCs by directing the government to procure alternatives to high-GWP HFCs:
  - Where feasible, substitute acceptable alternatives as identified by SNAP program
  - Vendor reporting on use of HFCs (i.e., refrigerants)
  - Final rule being drafted
- EO 13693 (March 19, 2015) - *Planning for Federal Sustainability in the Next Decade*
  - Direct GHG emissions reduced by at least 40% by 2025
  - Agencies to purchase sustainable products and services identified by EPA programs including alternatives to ODS and high-GWP HFCs, where feasible, as identified by SNAP

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SNAP Stakeholder Meeting

September 11, 2015
Washington, DC

SNAP — Significant · New · Alternatives · Policy

Welcome - Scope of Meeting

- The SNAP Program
  - Recent actions
- Near-term Roadmap and Actions Being Considered
- Discussion Questions
- Next Steps

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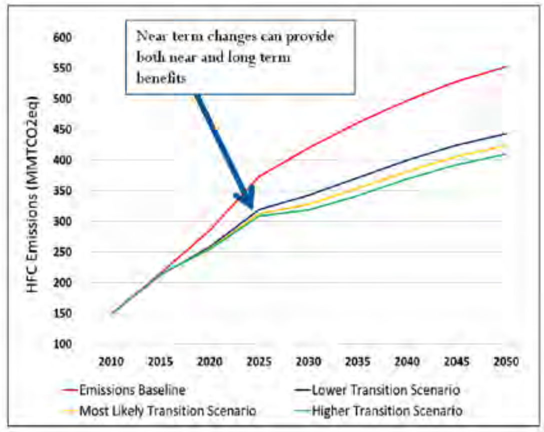
SNAP Action Update

- Issued two acceptability notices adding alternatives
  - Published October 21, 2014
  - Published July 16, 2015
- Issued new rule adding five low-GWP flammable refrigerants with use conditions
  - Published April 10, 2015
- Published Status Change Rule prohibiting certain HFCs in certain end-uses
  - Published July 20, 2015
- HFC Emissions Reductions: 54-64 MMTCO2eq in 2025



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Acceptability Notices

October 2014

R-450A (HFC/HFO blend) RefAC
GWP: ~604 compared to HFC-134a: 1430

1233zd(E) heat transfer & flexible PU foams
GWP <7 compared to alternatives: 1070-4000

CO_2 refrigerated transport
GWP: 1 compared to alternatives: ~1400-4000

Methylal foam blowing end-uses
GWP <3 compared to alternatives: 725-1430

HFO-1336mzz(Z) foam blowing end-uses
GWP: ~9 compared to alternatives: 725-1430

Powdered Aerosol D fire suppression
GWP <25 compared to alternatives: 0-3500

July 2015

R-450A (HFC/HFO blend) RefAC
GWP: ~604 compared to HFC-134a: 1430

R-448A (HFC/HFO blend) RefAC
GWP: 1387 compared to R-404A: 3922

R-513A (HFC/HFO blend) RefAC
GWP: 630 compared to HFC-134a: 1430

R-449A (HFC/HFO blend) RefAC
GWP: 1397 compared to R-404A: 3922

HFO-1336mzz(Z) foam blowing end-uses
GWP: ~9 compared to HFC-245fa: 1030

MPHE RefAC, solvent cleaning aerosols and adhesives/coatings
GWP <3 compared to alternatives: 0-3500

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July 2015: Change of Status Rule

Aerosols	• HFC-125 - January 2016 • HFC-227ea & blends - July 20, 2016 • HFC-134a - July 20, 2016/January 1, 2018
Motor Vehicle Air Conditioning	• HFC-134a in New Light-Duty Systems - MY 2021 • HCFC & HFC Containing Blends in New Light-Duty Systems - MY 2017
Retail Food Refrigeration & Vending Machines	• New Supermarket Systems - January 2017 • New Remote Condensing Units - January 2018 • New Vending Machines - January 2019 • New Stand-Alone Units (small medium-temp, large medium-temp, low-temp)- January 2019/January 2020 • Retrofitted Retail Food Refrig Equipment and Vending Machines - July 20, 2016
Foams	• All End-Uses, Except Rigid PU Spray Foam- Various dates between January 2017-January 2021

Some Key Principles Guiding Our Thinking

- SNAP rules will continue to consider individual end-uses
- No across the board GWP cut offs
- No prohibition on HFCs as a whole, or in any one sector
- New HFCs or HFC blends may be listed if risk not greater than other available substitutes
- Recognition that timing is a critical dimension and that each end use has unique considerations
- Status change actions will be issued through notice and comment rulemaking

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Potential Listings Proposals

- EPA seeking stakeholder input on listings that **could include**:
  - Acceptable alternatives with use conditions
    - Use conditions would mitigate risks, e.g., flammability, exposure limits
    - Fire suppression: e.g., streaming agent for aviation
    - MVAC: HFO-1234yf acceptable for Medium Duty Passenger Vans and Heavy Duty pickup trucks
    - Other refrigeration & air conditioning end-uses for flammable and highly flammable refrigerants
  - Unacceptable alternatives
    - Where risks cannot be mitigated sufficiently, e.g., flammability, toxicity, air quality impacts, climate
    - Certain HC and HC blends for stationary AC retrofits and MVAC systems

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Change of Status EPA is Considering

- Change of listing status from acceptable to unacceptable
  - EPA thinking potentially later transition dates than in July 20th final rule
  - End-uses based on stakeholder comments and EPA analysis
- Sectors and end-uses where safer alternatives may be available
  - Refrigeration and A/C
    - Chillers: e.g., HFC-134a, R-407C, R-410A
    - Refrigerated food processing and dispensing: e.g., HFC-134a, R-404A, R-507A
    - Household refrigerators and freezers: e.g., HFC-134a
    - Cold storage warehouse: e.g., HFC-134a, R-407C, R-404A, R-507A
  - MVAC: HCFC/HFC blends retrofit Light Duty vehicles
  - Foam: e.g., HFC-134a, HFC-245fa, HFC-365mfc, HFC-227ea in rigid PU spray foam; methylene chloride
  - Fire suppression: e.g., PFCs, SF_6, HFC-23

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New Petitions Related to Fire Suppression

- NRDC & IGSD
  - *Remove HFC-23 from the list of acceptable substitutes for all new and retrofit industrial process refrigeration applications effective January 1, 2017. Apply narrow use restrictions to HFC-23 in very low temperature refrigeration and total flooding fire suppression, allowing only for applications in which all other approved alternatives are physically inadequate effective January 1, 2017.*
  - *Remove sulfur hexafluoride (SF_6), perfluorinated compounds (PFCs), HCFC-22 blends, HCFC-124, and trifluoroiodomethane (CF_3I) from the list of acceptable substitutes in all flooding and streaming fire suppression applications effective January 1, 2019.*

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New Petitions Related to Fire Suppression (cont'd)

- EIA
  - *Remove SF_6, HFC-23 and R-508A and R-508B (blends containing HFC-23) from the list of acceptable substitutes in all fire suppression and explosion protection applications, all new and retrofit industrial process refrigeration and very low temperature refrigeration applications, effective January 1, 2017.*
  - *Remove HFC-236fa, HFC-125, HFC-227ea and all remaining PFCs from the list of acceptable substitutes in fire protection and explosion protection for both total flooding and streaming applications effective January 1, 2019. Consider narrowed use restrictions for HFC-134a in these applications, with potential exemption of HFC-227ea for specified applications where HFC-134a or low-GWP alternatives are not feasible for technical or safety reasons.*

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Next Steps

- Continue to expand SNAP acceptable list
  - Additional alternatives under evaluation
  - Additional end-uses are being evaluated
- Continue to work with stakeholders
  - E.g., Cold Food Chain Workshop in Montreal (November)
  - Sector workshops and Stakeholder meetings
- Develop next SNAP Notice for acceptable listings
- Develop next SNAP Rule to include alternatives that are:
  - Acceptable with use conditions
  - Unacceptable
  - Change of status
- Review new petitions

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Thank you!

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U.S. ARMY TANK AUTOMOTIVE RESEARCH, DEVELOPMENT AND ENGINEERING CENTER

Fire Extinguishing Agents for Protection of Occupied Spaces in Military Ground Vehicles

14 October 2015

Steve Hodges
Alion Science & Technology

Steve McCormick
TARDEC GSS

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Background

- This brief is an update of a presentation made at the 2010 NFPA Suppression/Detection Symposium (available at: *www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA517470*) and, in an updated form, published in NFPA's Fire Technology Journal (May 2012).
- The US Army is in the process of modernizing legacy vehicle platforms, including Automatic Fire Extinguishing Systems (AFES).
- Legacy vehicles use Halon 1301 or HFC-227BC to protect the crew. 1301 has high Ozone Depletion Potential (ODP) and Global Warming Potential (GWP). HFC-227 has high GWP.
- The Army is considering replacing legacy agents with more environmentally friendly suppression agents.
- TARDEC was tasked to test alternate agents, including FK-5-1-12.
  - FK-5-1-12 suppression agent has zero ODP and low GWP. The manufacturer has claimed that it is essentially a drop-in replacement for 1301 or HFC-227ea.

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Current Applications

Agents used in US Ground Vehicle Automatic Fire Extinguishing Systems (AFES)

Platform	Crew AFES Agent	Engine AFES Agent
Abrams Main Battle Tank (M1)	Halon 1301	Dry Chemical (NaHCO3)
Bradley Fighting Vehicle (BFV)	Halon 1301	HFC-227ea & HFC-125
Field Artillery Ammunition Support Vehicle (FAASV)	*Halon 1301	HFC-227ea
STRYKER Brigade Combat Team (BCT)	HFC-227BC	HFC-125
Up-Armored HMMWV (UAH)	HFC-227BC	None
Mine Resistant Ambush Protected (MRAP)	HFC-227BC	Various including dry chemical, HFC-125 and HFC-227ea
USMC Light Armored Vehicle (LAV)	HFC-227BC	HFC-125
MRAP All-Terrain Vehicle (M-ATV)	HFC-227BC	Solid propellant
**Joint Light Tactical Vehicle (JLTV)	HFC-227BC	TBD

*Upgrade to HFC-227BC in process

NOTE: this list is not comprehensive.

**In development

Agent Comparisons

	Property	Halon 1301	HFC-227ea[a]	FK-5-1-12[b]	Water+[c]	Dry Chemical[d]
Environmental	Ozone Depletion Potential[e]	16	0	0	0	0
	Global Warming Potential[f]	6900	3500	1	0	0
	Atmospheric Lifetime (yr)	65	33	0.014	0	0
Safety	Design Concentration (%v/v)	5	8.7	6.7[g]	~300 g/m^3	~300 g/m^3
	NOAEL[h] (%)	5	9.0	10	NA	TBD[j]
	LOAEL[i] (%)	7.5	>10.5	10	NA	TBD[j]
Physical	Boiling Point (°C)	-58	-16	49	115	N/A
	Vapor Pressure @ 21°C (bar)	13.7	4.1	0.41	0.03	N/A
	Liquid Density (g/cm^3)	1.56	1.39	1.60	1.27	2.16
	Molecular Weight (g/mol)	149	170	316	31	84
	Heat of Vaporization (J/g)	117	132	88	>2250	N/A

a) HFC-227ea is a form of heptafluoropropane and is sold as a fire extinguishing agent. b) FK-5-1-12 is a perfluorinated six-carbon ketone manufactured and sold as a fire extinguishing agent. c) Water with 50% Potassium Acetate. d) Values given are for sodium bicarbonate-based dry chemical. Potassium bicarbonate crystal density is 2.17 g/cm^3. e) CFC11 baseline, ref. 8. f) CO_2 baseline, ref. 9. g) Concentration advised by the agent manufacturer for this application. h) No Observed Adverse Effects Level. i) Lowest Observed Adverse Effects Level. j) Acceptable concentration levels for this application to be determined by the USA.

Exploratory Tests

Purpose

TARDEC's Exploratory tests are intended to compare various suppression agents, including new, more environmentally friendly ones, with those currently deployed.

Approach

- Three extinguisher suppliers supported the tests (12/08-9/09) – they were asked to provide suppression systems that would yield marginal suppression 'passes' and 'failures' based on current vehicle performance criteria.
- The tests were conducted in a 260 ft^3 (7.36 m^3) box with relatively little clutter, no stowage, and no active air flow.

Tests (continued)

Seven test series conducted between Dec08 and Sep09

- 157 live-fire tests
- 9 suppression agents
  - Halon 1301 - 'halon' *(used in legacy vehicles)*
  - Halon 1301 with Dry Chemicals (DC) – 'halon+' & 'halonK'
  - HFC-227ea with DC – 'HFC227BC' *(used in vehicles since 2001)*
  - FK-5-1-12
  - FK-5-1-12 with DC – 'FK-5-1-12+'
  - Water with Potassium Acetate – 'water+'
  - Two Dry Chemicals – Sodium (+) and Potassium (K) Bicarbonates
- 4 Extinguisher configurations from 3 suppliers
  - N_2 charged with solenoid valve (Abrams, BFV, FAASV, STRYKER, UAH, & some MRAP)
  - N_2 charged with linear actuated valve (NLOS-C Crew & Mission)
  - N_2 charged with SQUIB actuated valve (some MRAP)
  - Hybrid Fire Extinguisher actuated by Gas Generator (experimental)

Test Fires

Unsuppressed

Suppressed

Selected Crew Casualty Criteria

Parameter	Requirement[a]	Test[b]
Fire Suppression	Extinguish all flames without reflash	Y
Skin Burns	Less than second degree burns (<2400°F-sec over 10 seconds or heat flux < 3.9 cal/cm^2)	c
Overpressure[d,e]	Lung damage <11.6 psi; Ear damage ≤ 4 psi	Y
Agent Concentration	Not to exceed Lowest Observed Adverse Effects Level	Y
Acid Gases (HF + HBr + 2·COF_2)	Less than 746 ppm-min (5 min dose)	Y
Oxygen Levels[d]	Not below 16%	Y
Discharge Impulse Noise[f]	No hearing protection limit: <140 dBP Single hearing protection limit: <165 dBP	N
Discharge Forces[a,g]	Not to exceed 8 g and <20 psi at 5 inches	N

(a) Based on "*Medical Evaluation of Non Fragment Injury Effects in Armored Vehicle Live Fire Tests,*" Walter Reed Army Institute of Research, September 1989 except as noted.

(b) Addressed in Exploratory Tests. (c) Temperature recorded with thermocouples.

(d) "Fire Survivability Parameters for Combat Vehicle Crewmen," Memo to the US Army Surgeon General, 20 February 1987.

(e) "Noise Specification for Automatic Fire Extinguishing Systems (AFES)," Dept. of the Army Memorandum, 14 Nov 2013

(f) "Hearing Conservation Program," US Army Pamphlet 40-501, 10 December 1998.

(g) "Evaluation of Potential Physical Injury from Mechanical Forces Due to Automatic Fire Extinguisher System Discharge in the STRYKER Combat Vehicle: An Initial Assessment and Recommendations to Prevent Injury," Walter Reed Army Institute of Research, 21 August 2008

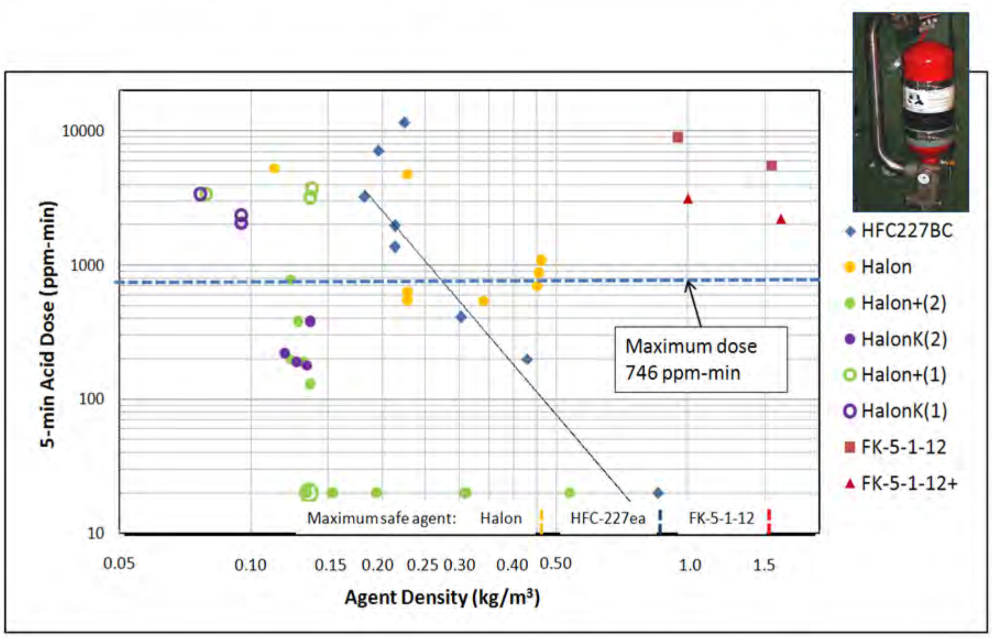
Overview of Results

				**Best Performance			
Agent	Total	*Pass	**Least Agent Weight (lb)	Lowest Acid Dose (ppm-min)	Lowest Pressure Peak (psi)	Fastest Fire Out Time (ms)	Note
Halon	21	12	~5	~500	<1	<200	Legacy fielded product
Halon+	19	16	~2.5	<20	<1	<200	New mix compatible with fielded extinguishers
HalonK	7	4	~2.5	<20	<1	<200	New mix compatible with fielded extinguishers
HFC227BC	36	17	~5	<20	<1	<200	Fielded product
FK-5-1-12	21	0	>25	~2,000	1.2	<200	Available
FK-5-1-12+	15	0	>15	~1,300	1.6	<200	Invention required
Water+	23	12	~4	0	1.5	~400	Development required; operational issues?
NaBC	13	7	~3	0	<1	<200	Available; operational issues?
KBC	2	2	~2	0	<1	<200	Available; safety & operational issues?
Total	157	70					

* The goal was to 'pass' half the tests

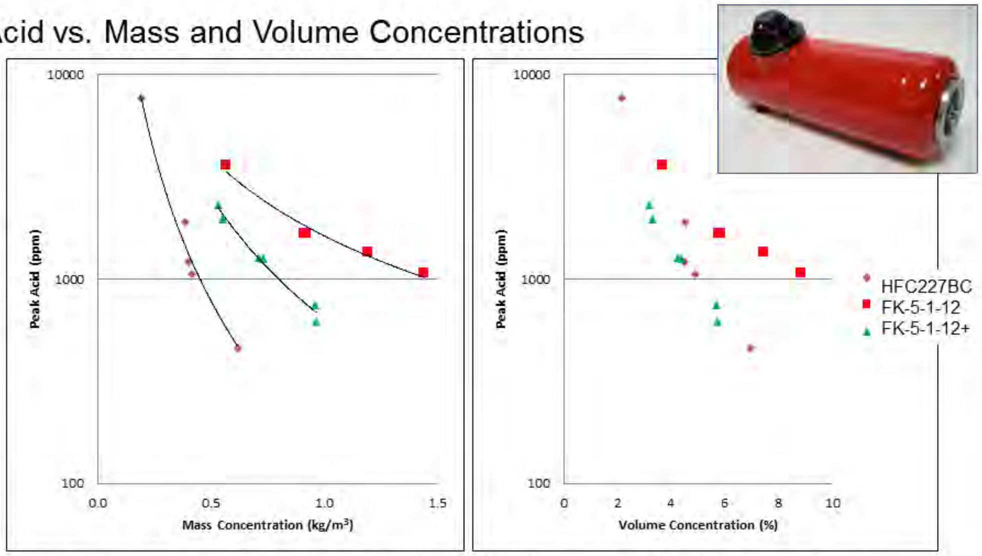
** Best Performance and Least Agent Weight are not obtained simultaneously

Comparison of Fluorinated Agents



Some Insight

- Acid vs. Mass and Volume Concentrations



Note: Although the peak acid levels for ‘HFC227BC’ and ‘FK-5-1-12+’ are similar, the integrated levels used in casualty assessments were very different: none of the FK-5-1-12-based tests ‘passed.’

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Summary

<u>Results from 157 Tests using 9 agents indicate:</u>

•Halon 1301 and HFC-227BC performed similarly, although Halon 1301 yielded relatively higher acid doses, consistent with earlier findings.

•FK-5-1-12 was not effective whether used alone or mixed with dry chemical due to high acid gas levels.

•Dry chemical and water with additives may become viable but further analysis, development and testing are required.

•When used as the sole suppression agent, potassium-bicarbonate-based dry chemical is almost twice as effective by weight as sodium-bicarbonate-based dry chemical, consistent with earlier findings.

•Mixes of Halon with sodium- or potassium-bicarbonate-based dry chemicals performed similarly.

•Halon with sodium- or potassium-bicarbonate-based dry chemicals is twice or more as effective by weight as currently deployed crew agents (Halon and HFC-227BC). This result has been verified in vehicle tests.

•None of the non-Halon agents as evaluated are drop-in replacements for Halon or HFC-227BC.

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Low/No GWP Agents – Project Proposal

- What is the intended end product?
  - The end product of this project is an evaluation of the technical feasibility of emerging low GWP fire extinguishing agents for US Army ground vehicle and aviation weapon system applications.
  - The scope includes ground vehicle crew and engine compartments, aviation engine and auxiliary power unit (APU) compartments, and portable extinguishers.
- What is the technical approach?
  - The technical approach of this joint TARDEC/AMRDEC evaluation effort will look for replacements for the high GWP agents currently used: Halon 1301 and HFC-227ea. Our search for new low or no GWP agents will include:
    - Market survey and determination of chemical properties
    - Toxicity evaluation of candidate agents
    - Long-term storage and material compatibility of agent mixtures and storage containers
    - Agent distribution/hardware/technology development with modeling and simulation
    - Fire-fighting performance testing and optimization
- What specific applications will product transition to?
  - If economically/technically feasible technologies are identified they could, with PM support, be transitioned to:
    - All current and anticipated combat and up-armored tactical ground vehicles
    - Candidates for new aviation systems
    - Legacy systems retrofits

Disclaimer

Reference herein to any specific commercial company, product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the Department of the Army (DoA). The opinions of the authors expressed herein do not necessarily state or reflect those of the United States Government or the DoA, and shall not be used for advertising or product endorsement purposes.

Kidde Dual Spectrum | UTC Aerospace Systems

Alternate Agents for Vehicle Crew Suppression

This Document Contains No Technical Data

1

Agenda

UTC Aerospace Systems

- Overview - Current State of AFES
- Survivability Requirements
- Alternate Agents
- Agent Comparison Matrix
- Benefits
- Risks
- System Considerations
- Conclusion

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Current State of AFES

UTC Aerospace Systems

- Currently fielded crew agents
  - Halon 1301
  - HFC-227BC (5%, 10%, 20% by mass)
- Inerting agents
- Agent mass limited by NFPA requirements (Min, LOAEL)
- Effective concentrations vary by:
  - Temperature
  - Altitude
  - Vehicle Load (Net Free Volume)
- Side effects:
  - High Ozone Depletion Potential (Halon 1301)
  - High Global Warming Impact (Halon 1301, HFC-227ea)
  - Toxic Gas Generation Due To Agent (HF, HBr, HCN, HCl, COF_2)
  - Discharge Temperature

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AFES Survivability Requirements

UTC Aerospace Systems

Parameter	Requirement
Fire Suppression	Extinguish all flames without re-flash
Skin Burns	Less than second degree skin burns: <1316 °C-s over 10 s or heat flux < 160 kJ/m^2 (<2400 °F-s over 10 s or heat flux < 3.9 cal/cm^2)
Overpressure Max	Lung damage: 80 kPa (11.6 psi), Ear damage: 27.5kPa (4 psi)
Agent Concentration	Not to exceed LOAEL
Toxic Gases	CO, CO2, NO, NO2, HF, HCN, HBr, HCl, COF2, Acrolein, Formaldehyde HF + HBr + 2*COF2 less than 746 ppm-min over 5 min
Oxygen Levels	Not below 16%
Discharge Noise	Not to exceed hearing protection level: With hearing protection ------ 162 dB Without hearing protection --- 140 dB
Discharge Forces	Not to exceed 78 m/s^2 (8 g) over 30 ms and 20 psi at 5 inches

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Alternate Agents

UTC Aerospace Systems

- Focus on Zero ODP and Near Zero GWP SNAP-Approved Solutions
- Suitable for Occupied Spaces (No Inert Gas or PXA)
- Minimize Side effects
  - Atmosphere Inerting
  - Weight
  - Obscurity
  - Cleanup/Corrosion

Alternate Crew AFES Agents		
FK-5-1-12	**Sodium Bicarbonate**	**Water + Potassium Acetate**
C6-perfluoroketone FK-5-1-12, (Novec™ 1230) manufactured by 3M	Sodium Bicarbonate + Amorphous Silica	Water + 50% by Volume Potassium Acetate & Corrosion Inhibitors

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Agent Comparison Matrix

UTC Aerospace Systems

Crew AFES Agent Physical Characteristics					
Agent	**HFC-227ea**	**Halon 1301**	**FK-5-1-12**	**Sodium Bicarbonate**	**Water + Potassium Acetate**
Boiling Point (°C)	-16.4 [d]	-58 [a]	49 [d]	N/A	115 [a]
Vapor Pressure @ 21°C (psia) [a]	59	199	5.9	N/A	.44
Molecular Weight	170 [d]	149 [a]	316 [d]	84 [a]	31 [a]
Heat of Vaporization J/g@BP	132	118	88	N/A	Approx. 2260
ODP	0	16 [e]	0	0	0
GWP	3,660 [e]	6,900 [e]	1 [a]	0	0
Atmospheric Lifetime (yrs)	34.2 [e]	65 [e]	.014 [a]	0	0
Min Design Concentration	8.7% by Volume (695 g/m^3) [d]	5% by Volume (327 g/m^3) [b g h]	≥6.4% by Volume (952 g/m^3) [i]	300 g/m^3 [f]	250[a]-900[c] g/m^3
NOAEL %	9 [d]	5 [b]	10 [d]	N/A	N/A
LOAEL %	10.5 [d]	7.5 [b]	>10 [d]	N/A	N/A

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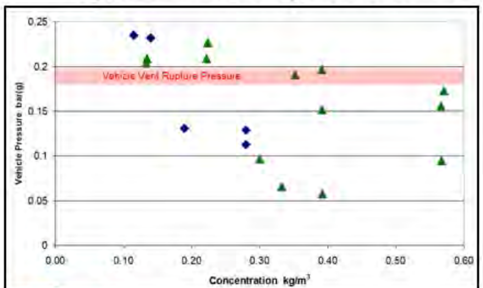
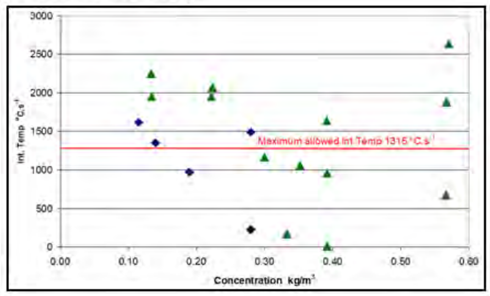
Dry Chemical Risks

UTC Aerospace Systems

- No cooling from agent discharge
  - Higher integrated temperatures
  - Toxic gas vs skin burn
- Lack of post-discharge inerting (Reflash)
- Agent obscurity, inhalation, and cleanup





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Aqueous Solution Benefits

UTC Aerospace Systems

- Offers a Zero ODP and GWP Solution
- Approved for occupied space use by the US Army
- No LOAEL or Toxic Gas Concerns
- Can meet current temperature range
- High Heat of Vaporization
- Widely available from multiple sources without future restrictions anticipated
- Mixture more effective than pure water
- Effective concentrations similar to HFC-227BC
  - Minimal Weight Impact
  - Utilize existing or similar extinguisher technology

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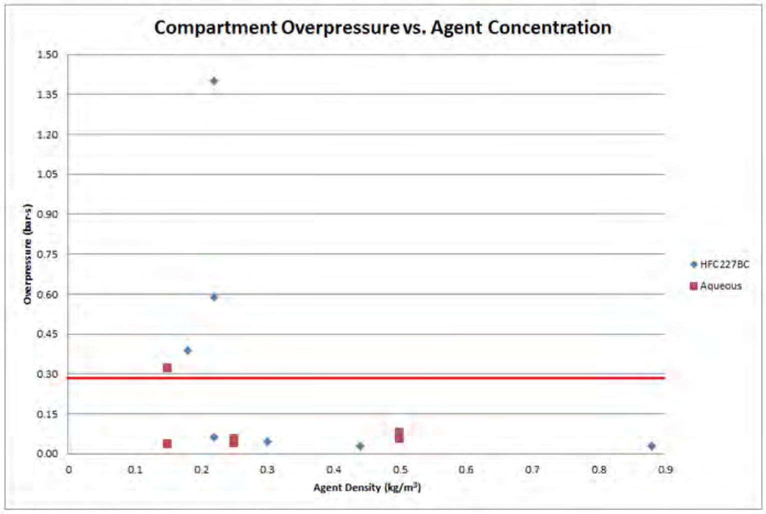
Aqueous Solution Suppression

UTC Aerospace Systems

HFC227BC

Vs.

Aqueous



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Aqueous Risks

UTC Aerospace Systems

- Lack of post-discharge inerting (Reflash)
- Agent cleanup (corrosion, equipment damage)
- Study Required for long term storage compatibility
- Not SNAP listed (Water is listed)
- Low Vapor Pressure
  - Premium on nozzles to provide particle size at required flow rate
  - New distribution techniques may be required
  - Much more sensitive to vehicle clutter

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Conclusion

UTC Aerospace Systems

- Aqueous fire suppression offers an attractive option as a Crew AFES agent with no environmental impacts
- Previous alternate agent comparisons have disregarded Water + Potassium Acetate due to cleanup concerns, lack of an integration design maturity, and lack of in place logistical support.
- Development testing focused on improving the system design of an aqueous crew AFES need to be completed. Distribution methods, nozzles, concentration levels, and post discharge effects should be studied.
- Examination of alternate freeze point depressants may locate an improvement over Potassium Acetate.

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FAA-supported Halon Replacement

Overview and a Focus on the Civil Powerplant

Presented to:

Systems Fire Protection Information Exchange,
US Army Tank Automotive R,E, & D Center and the Weapons & Materials Directorate/US Army Research Laboratory
Aberdeen Proving Ground, MD USA

By:

Doug Ingerson
Federal Aviation Administration
WJ Hughes Technical Center/Fire Safety Branch
Atlantic City Int'l Airport, NJ USA
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Date:

14 Oct 2015

Presentation Content…

An Overview of FAA-supported Activity

- The FAA "Operational" Environment
- International Aircraft Systems Fire Protection Working Group
- Minimum Performance Standards for Halon Replacement

A Focus on Civilian Powerplant Fire Zone Activity

- Its Minimum Performance Standard for Halon Replacement
- The Test Process and its Test Fixture
- A Brief History of the Activity

Overview/FAA-supported Activity

The FAA "Operational" Environment

The FAA is a "large" organization with many interacting parts & purposes

- Involved in activities for air traffic control systems, airports, and civilian aircraft; activities can be R/E&D, T&E, compliance oversight, &/or operations

One part of the picture, regarding airframe development/use…

- The FAA applies "minimum level-of-safety" regulations to civilian aircraft
- The FAA "owns" the airworthiness regulations, not the civilian aircraft fleet
- Applicants, while creating/manufacturing/modifying civilian aircraft, & the FAA interact
- Owners/operators interact with the FAA as they operate civilian aircraft

Halon replacement is considered during airframe development

- Initiated by and occurs at the request of an applicant
- To date, this includes several parties; i.e. applicant, certifying authority (FAA, EASA, etc.), & perhaps the FAA Fire Safety Branch

R/E&D = research, engineering, and development
T&E = test & evaluation
EASA = European Aviation Safety Agency

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Overview/FAA-supported Activity

International Aircraft Systems Fire Protection Working Group

1. On-going interactive forum for the aviation industry & authorities
   A. Started in 1993 as the "International Halon Replacement Working Group"
   B. Administered in "working group" format; currently meeting twice per year
   C. Focus is systemic aircraft fire prevention; i.e. active fire prevention systems
   D. Augmented by subordinate task group support, as topics present
      i.e. halon replacement, fuel tank inerting, lithium batteries, etc.

2. FAA-sponsored; chaired/administered by the Fire Safety Branch
   ==>> link : http://www.fire.tc.faa.gov/ & navigate to the "SYSTEMS" tab…

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Overview/FAA-supported Activity

Minimum Performance Standards for Halon-Replacement

1. Created to coordinate/promote halon replacement
2. Resulted from task groups for each application on a civilian aircraft
   A. Lavatory fire extinguisher
   B. Hand-held fire extinguisher
   C. Extinguishment systems for the powerplant/auxiliary power unit fire zones
   D. Cargo compartment extinguishment systems
3. Information included :
   A. A requirement to address considerations external to the test process
      i.e. effectiveness across operational envelopes, maintained safety-of-flight during use, sufficient product longevity, acceptable toxicity, etc.
   B. Descriptions of test environment & process; includes a halon "benchmark"

Successfully satisfying MPSHR assessment does not assure certification…

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Overview/FAA-supported Activity

Minimum Performance Standards for Halon-Replacement

lavatory :

"Development of a Minimum Performance Standard for Lavatory Trash Receptacle Automatic Fire Extinguishers"
link : http://www.fire.tc.faa.gov/pdf/ar96-122.pdf

hand-held :

"Development of a Minimum Performance Standard for Hand-Held Fire Extinguishers as a Replacement for Halon 1211 on Civilian Transport Category Aircraft"
link : http://www.fire.tc.faa.gov/pdf/01-37.pdf

powerplant (not formally published) :

"Minimum Performance Standards for Halon 1301 Replacement in the Fire Extinguishing Agents/Systems of Civil Aircraft Engine and Auxiliary Power Unit Compartments (MPSHRe rev04)"
link : http://www.fire.tc.faa.gov/pdf/systems/MPSErev04_MPSeRev04doc-02submtd.pdf

cargo compartment :

"Minimum Performance Standard for Aircraft Cargo Compartment Halon Replacement Fire Suppression Systems (2012 Update)"
link : http://www.fire.tc.faa.gov/pdf/TC-TN12-11.pdf

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Focus/Powerplant Activity

Minimum Performance Standard for Halon Replacement

1. Currently exists in its 4^{TH} revision (a working draft)
2. Candidate is reasonably "mature"; i.e. capable of real-world use
3. Halon 1301 parity is attained in a "realistic" nacelle-fire simulator

Generic Testing

A. Comparing flame suppression behaviors (reignition time delay)
   i. Suppression relates to extinguishant distribution in the forced flow
   ii. Extinguishant distributions are described by measured delivery criteria
B. Candidate is challenged by 4 test configurations (2 flows x 2 fire threats)
C. Halon 1301 benchmarks are known for each test configuration

"Real-world" Testing

D. Optional requirement : "real-world" demonstration for atypical candidates
E. A *recommendation for certification* is the "largest" candidate quantity acceptably comparing to the halon benchmark

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Focus/Powerplant Activity

The Test Process and its Test Fixture

1. Not done in a "real" powerplant fire zone, but something close
   A. Simply too many different installations & operating schedules…
   B. Task group elected to :
      i. Include salient features : geometry, ventilation, agent distribution, fire threats
      ii. Test at some enveloping conditions
      iii. Create a "repeatable" test method that included replicate series of tests
2. Resulted with :
   A. Two forced air flow rates: 1.2 kg @ 38°C & 0.45 kg @ 127°C
   B. Two fire threats: 0.95 L/min concurrent spray & 274x521 mm pool (66°C)
      i. Persistent fuels; turbine fuel in spray/pool; lubricant, hydraulic fluid in spray
      ii. Persistent ignition sources; hot-surface/electrical in spray, electrical in pool
   C. Analogous agent condition, storage, & injection into the ventilation stream

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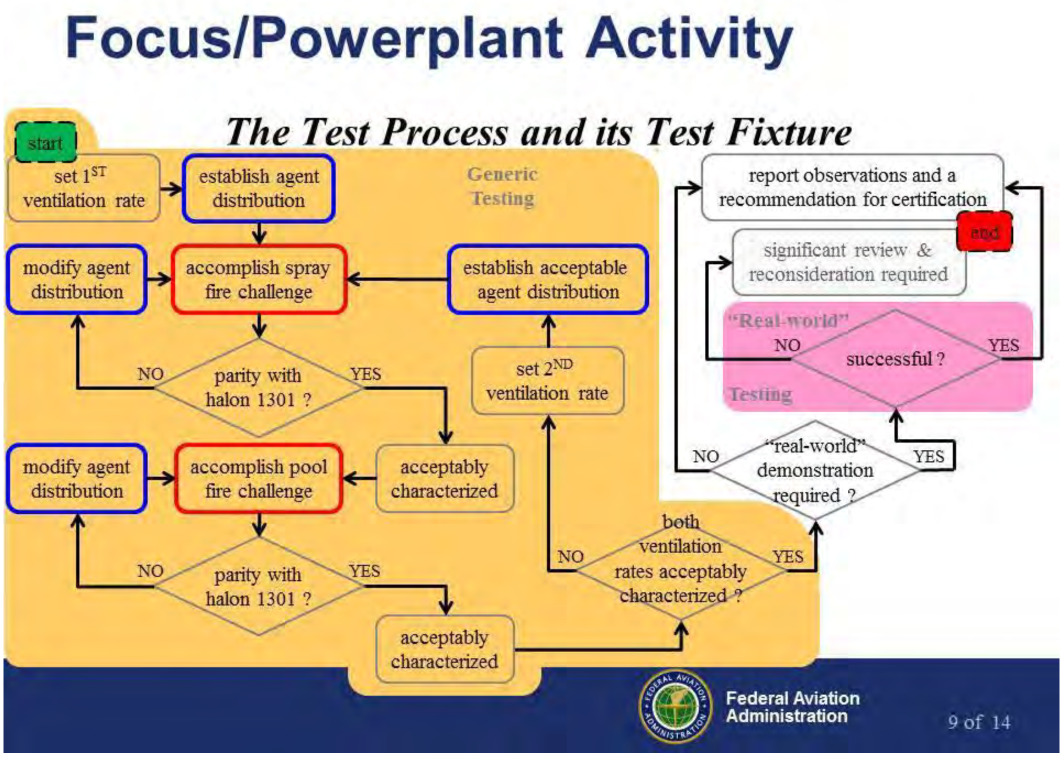
Focus/Powerplant Activity
The Test Process and its Test Fixture
start
set 1ST ventilation rate
establish agent distribution
Generic Testing
modify agent distribution
accomplish spray fire challenge
establish acceptable agent distribution
NO
parity with halon 1301 ?
YES
set 2ND ventilation rate
modify agent distribution
accomplish pool fire challenge
acceptably characterized
NO
parity with halon 1301 ?
YES
acceptably characterized
NO
both ventilation rates acceptably characterized ?
YES
report observations and a recommendation for certification
end
significant review & reconsideration required
"Real-world" Testing
NO
successful ?
YES
NO
"real-world" demonstration required ?
YES
Federal Aviation Administration
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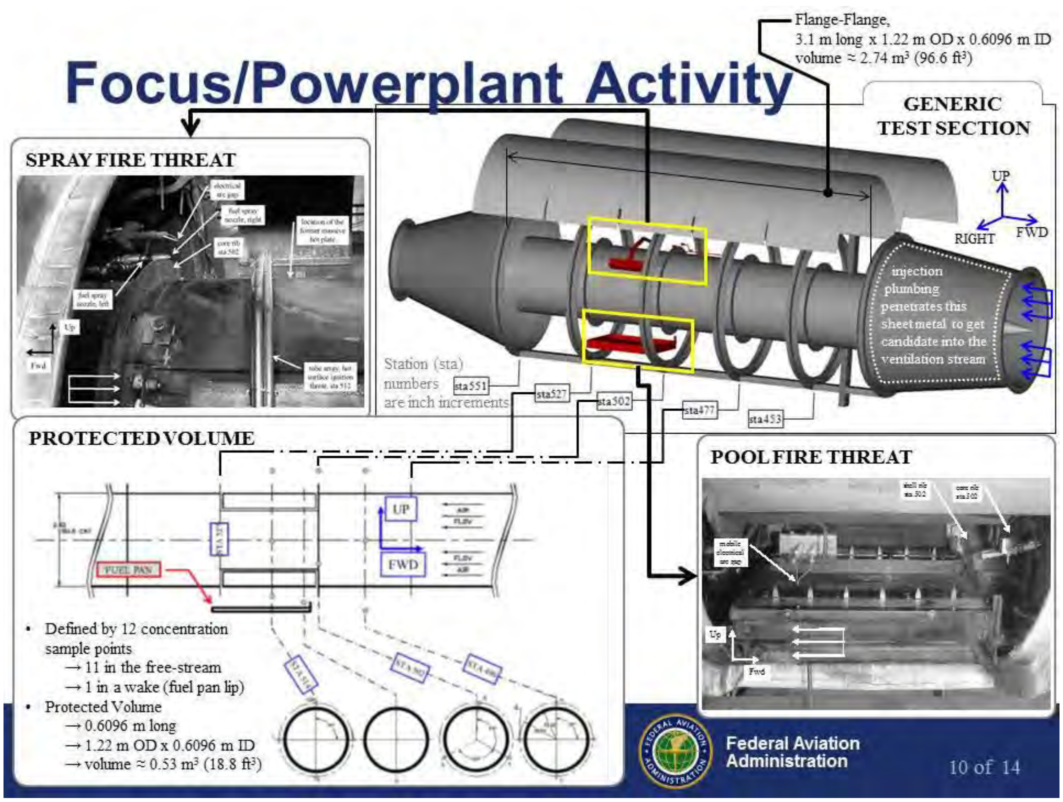
Flange-Flange,
3.1 m long x 1.22 m OD x 0.6096 m ID
volume ≈ 2.74 m³ (96.6 ft³)
Focus/Powerplant Activity
GENERIC TEST SECTION
SPRAY FIRE THREAT
UP
RIGHT
FWD
injection plumbing penetrates this sheet metal to get candidate into the ventilation stream
Station (sta) numbers are inch increments
sta551
sta527
sta502
sta477
sta453
PROTECTED VOLUME
FUEL PAN
UP
FWD
POOL FIRE THREAT
• Defined by 12 concentration sample points
→ 11 in the free-stream
→ 1 in a wake (fuel pan lip)
• Protected Volume
→ 0.6096 m long
→ 1.22 m OD x 0.6096 m ID
→ volume ≈ 0.53 m³ (18.8 ft³)
Federal Aviation Administration
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Focus/Powerplant Activity

A Brief History of the Activity

1. MPSHRe outcomes per revision 03
   A. 2003-2006, HFC-125 & CF_3I
      i. Candidates recommended by IASFPWG (IHRWG)
      ii. Recommendation for certification (residence for ½ sec throughout fire zone)
         a. 17.6%v/v HFC-125 (DuPont FE-25, pentafluoroethane)
         b. 7.1%v/v CF_3I (iodotrifluoromethane)
      iii. No significant action from civilian sector at this time with either candidate
      iv. CF_3I challenged by (a) toxicological concerns & (b) use when all is "cold"
      v. HFC-125 (a) approximately doubles in mass & storage volume compared to halon 1301 & (b) can over-pressurize a fire-containing volume
   B. 2004, American Pacific Corporation, 2-BTP, Boeing/Kidde Aerospace
      i. Can notably over-pressurize a fire-containing volume
      ii. Applicant withdrew candidate from further consideration for this application

2-BTP = 2-bromotrifluoropropene

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Focus/Powerplant Activity

A Brief History of the Activity

1. MPSHRe outcomes per revision 03
   C. 2006-2011, FK-5-1-12 (3M Corporation Novec 1230), Airbus
      i. Recommendation for certification : 6.1%v/v FK-5-1-12 for ½ sec
      ii. Aircraft integration modified following 2006 MPSHRe assessment
      iii. Applicant discontinued further work; too challenging to use when all is "cold"
   D. 2006-2008, Kidde KSA, $NaHCO_3$ solid aerosol, Boeing/Kidde Aerospace
      i. Initial MPSHRe assessment results suggested atypical design criteria
         a. Initial results indicate sub-cup-burner extinguishment concentration
         b. FAA fire prevention rationale & initial concentration value conflicted
         c. Results from 2006 with FK-5-1-12 alluded to this problem
      ii. FAA Fire Safety Branch discontinued support for its MPSHRe assessment
2. 2009-2010, MPSHRe modified via task group action; revision #4

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Focus/Powerplant Activity

A Brief History of the Activity

3. MPSHRe outcomes per revision 04
   A. 2010-2012, Kidde KSA, $NaHCO_3$ solid aerosol, Boeing/Kidde Aerospace
      i. Completed MPSHRe generic testing
      ii. Atypical candidate; FAA required "real-world" demonstration
         a. Solid aerosol ≠ halon 1301; notably dissimilar substances
         b. Different concentration measurement methods
         c. Tested in FAA-owned Boeing 747SP, #2 Pratt & Whitney JT9D
         d. Spray/pool fires in fire zone not extinguished; pool suppressed (reignited)
      iii. FAA support concluded; further candidate development desired by industry
   B. 2014-2015, Meggitt Blend A, CO_2/FK-5-1-12 blend, Airbus/Meggitt
      i. Completed MPSHRe generic testing
      ii. Investigated/addressed possible concentration measurement challenge
      iii. Project on-going; conclusions not attained…

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Thank you.

Federal Aviation Administration

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Polyhalon Technologies

Polyhalon Technologies

ARL/TARDEC Fire Protection Information Exchange Meeting

October 14, 2015

Embedded Firefighting Agents Providing Protection 24/7

Polyhalon Technologies

What are Polyhalons?

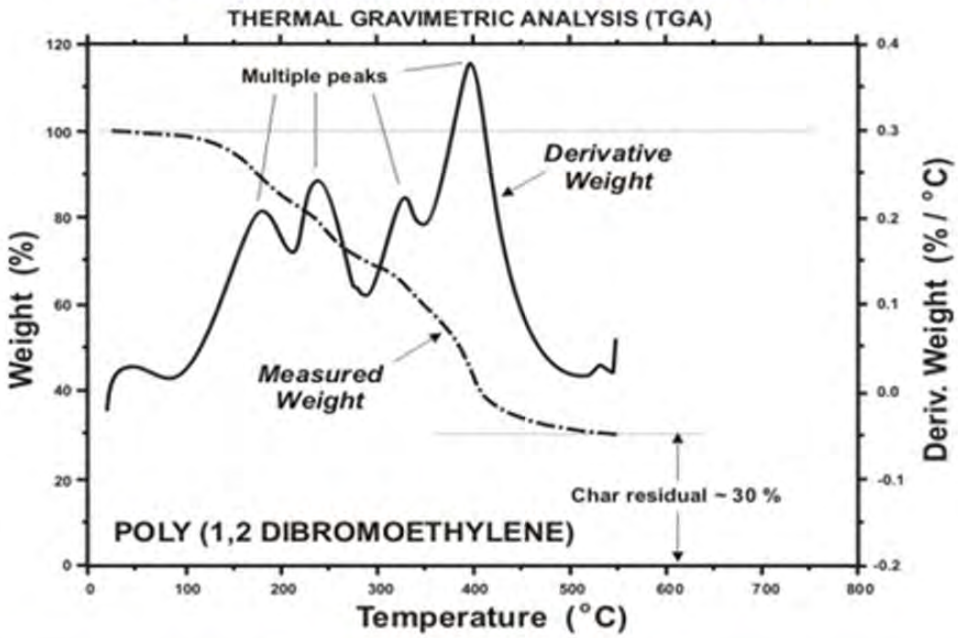
Polyhalons are a novel approach to fire protection:

- A solid polymer made up of Halon or Halon-like repeat units
  - The stable polymer is in the solid state until a fire event at which point a Halon-like, gaseous degradation product is released, essentially providing a "smart Halon"
  - In the solid polymer or neat form, the Polyhalon agent has no ozone depletion potential (ODP), no greenhouse warming potential (GWP), and no toxicity concerns associated with agent
- In the event of a fire, the polymer de-polymerizes at a specific temperature releasing the Halon or Halon-like product into the fire, extinguishing the fire
- Can be utilized in neat form, e.g., a powder, or applied via a coating, embedded into materials, etc.

Embedded Firefighting Agents Providing Protection 24/7

Polyhalon Technologies

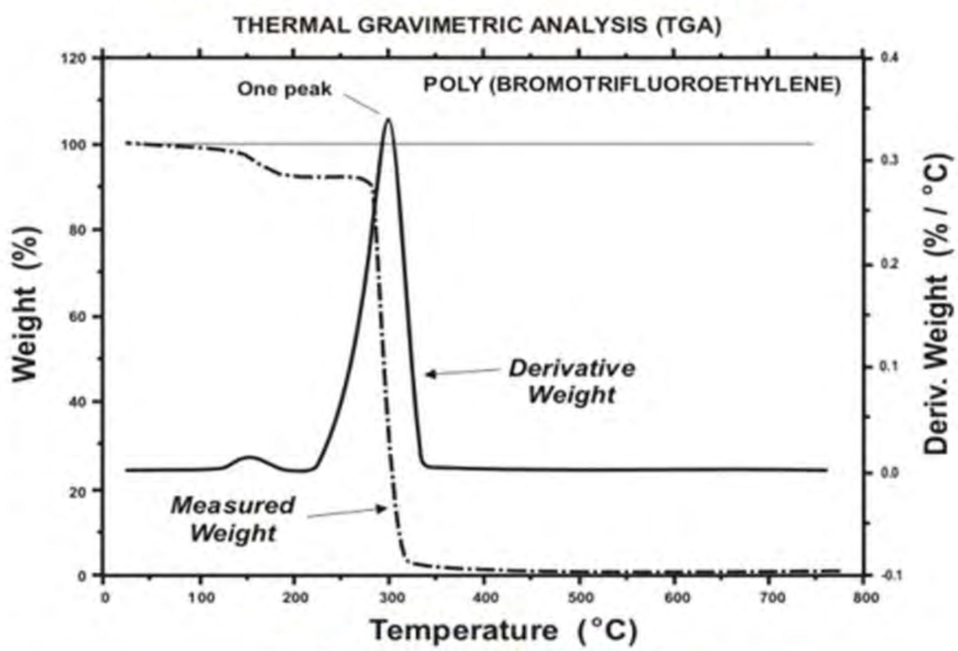
TGA PLOT OF INEFFECTIVE POLYMER COMPOUND



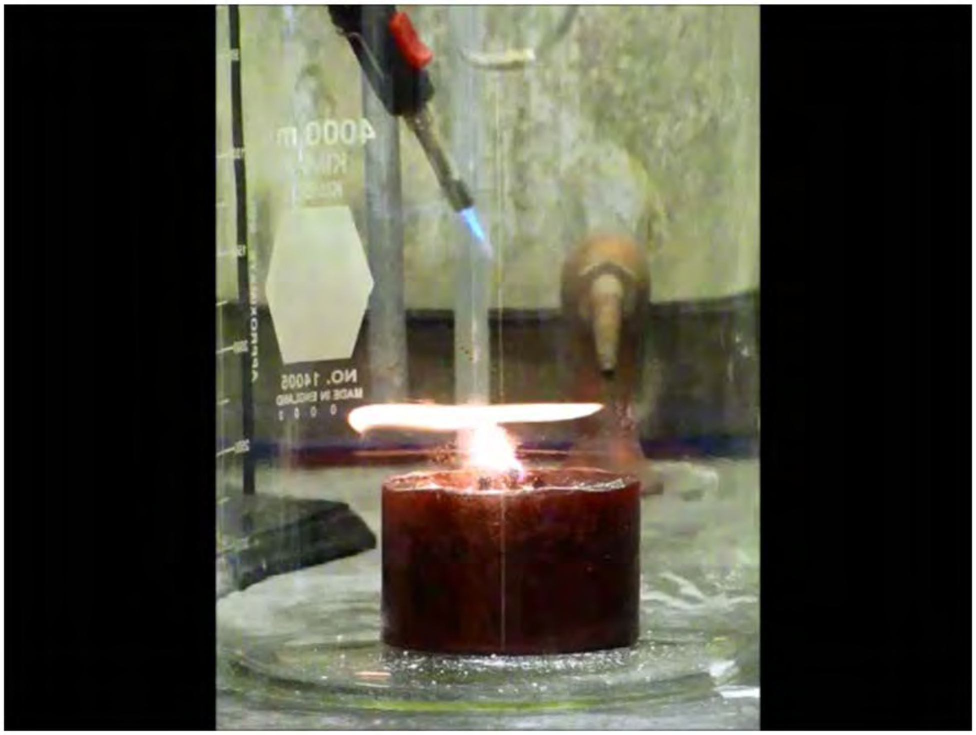
Embedded Firefighting Agents Providing Protection 24/7

Polyhalon Technologies

TGA PLOT OF EFFECTIVE POLYMER COMPOUND



Embedded Firefighting Agents Providing Protection 24/7



Performance and Benefits

- Will act on a fire to chemically inhibit a fire event and does so rapidly - on a millisecond time scale with chemistry similar to Halon 1301
- Will not release fire suppressing gases until a fire event occurs - smart release
- Remains active once released - will act to extinguish both primary (initial) and secondary fire events
- Estimated: 0.02-0.03 lb./cubic foot to protect a given area (multiple times more effective on a pound for pound basis than current technologies)
- Capable of being embedded into preexisiting materials to potentially provide weight neutral protection
- Can be mixed with other technologies to provide custom, tailored solutions for platform-based protection - adding to flexibility with performance and cost
- Clean agent with little or no char remains after the fire event and no chilling effects
- Effective on all types of fires

Environmental Considerations

In its neat state:

- No ozone depletion potential (ODP)
- No greenhouse warming potential (GWP)
- Very little to no toxicity
- Resistant to molds and mildews; impervious to biological actions and humidity
- Not caustic or corrosive

Polyhalon Technologies

Polyhalon Compounds

Polymers That 'Break' Properly, Have Low Residual Char, and May Serve as Polyhalon Fire Fighting Agents

Synthesized Compound Chemical Name	Acronym	Breaking Temperature
Polybromotrifluoroethylene	PBTFE	300° C (572° F)
Polyvinyl Tribromoacetate	PVTBA	210° C (410° F)
Poly[1,4-(2,2,3,3 tetrabromobutane) oxalate]	PTBBO	265° C (509° F)

Embedded Firefighting Agents Providing Protection 24/7

Technical Information

- Particle size
  - Emulsion form - can be controlled, current particle size is micrometer size – less than 10 micrometers in emulsion form that can coalesce during evaporation to forming larger particle sizes or films
  - Dry form – spherical in shape, diameter size ranges between ~ 200 – 450 nm; average 350 nm. Can be formulated to readily coalesce into films
- Density
  - ~ 2g/ml
- Heat Capacity and Thermal Conductivity
  - Expected to be similar to CTFE (Kel-F) heat capacity ~0.859 $JK^{-1}g^{-1}$ and thermal conductivity ~0.200 - 0.220 W/m-K)
- Hydrophobic: moisture should not affect product or cause caking
- Active agent molecular weight of 161
- Acidic byproducts are similar to those of a Halon reagent that has acted on a fire

Polyhalon Technologies

Steps Needed to Use

- Further refinement of polymerization process
- End-use testing and registration
  - EPA SNAP – not necessary as the technology is a polymer, not a gas
  - EPA TSCA
  - REACH (EU)
  - Specific end-use (e.g. ASTM E 84 Steiner Tunnel Test)
  - Others? Modality seems to differ with “standard” design tests…
- Continued R&D to identify Polyhalons with various depolymerization points, polymer properties and deployment formulations

Embedded Firefighting Agents Providing Protection 24/7

Contact Information

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Evaluating the Difference in Foam Degradation between Fluorinated and Fluorine-free Foams for Improved Pool Fire Suppression

Katherine Hinnant[1,2], Ramagopal Ananth[1], Michael Conroy[1], and Bradley Williams[1]

[1] Naval Research Laboratory, Chemistry Division, Washington DC, USA
[2] NOVA Research, Inc., Alexandria VA, USA

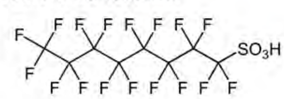
Update Systems Fire Protection Information Exchange Meeting
Aberdeen Proving Ground, MD

Problem

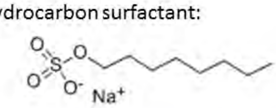
Fluorinated Firefighting Foams (AFFF)

- Developed to combat pool fires for military and civilian applications - extremely effective
- Long fluorocarbon surfactants are environmentally persistent and can bio-accumulate to potential harmful concentrations
- Current EPA restrictions have limited the length of fluorocarbon surfactants, but this is only a short term solution
- Alternative commercial firefighting foams have been developed with hydrocarbon surfactants, but fail to meet military standards
- **What are the key differences between fluorinated and fluorine-free foams?**

Fluorocarbon surfactant:



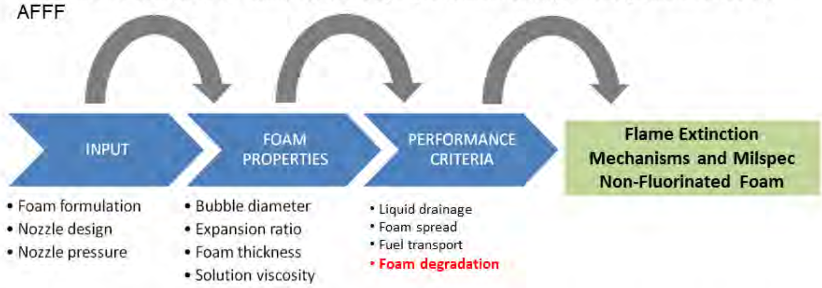
Hydrocarbon surfactant:



NRL. Navy Technology Center for Safety and Survivability. Code 6180 Oct 2015

Approach

OBJECTIVE: Quantify the effects of low expansion foam properties on fire suppression mechanisms of aqueous foams for developing environmentally friendly alternatives for AFFF

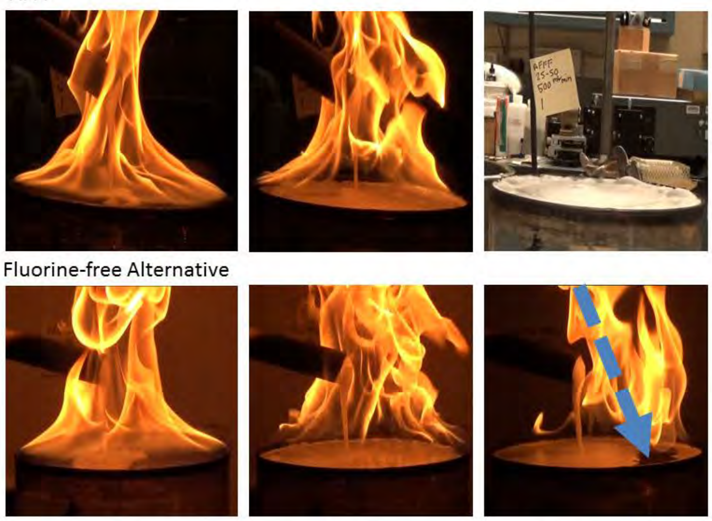


- The key mechanisms are **low fuel transport and low foam degradation** that cut off fuel supply to fire and cause fast flame extinction
- Foam degradation affects a foams ability to cover the liquid pool surface to successfully stop the transfer of fuel vapors to the flame above

Pool Fire Extinction Experiment

AFFF

Extinction



18 seconds

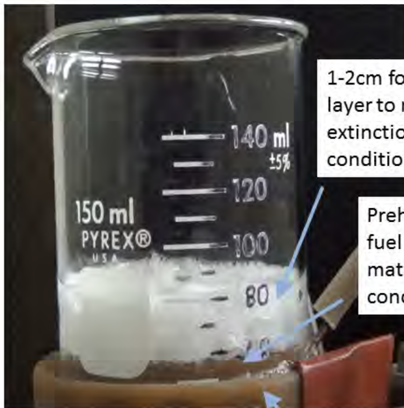
Fluorine-free Alternative

40 seconds

t = 0 seconds t = 10 seconds t = 25 seconds

Approved for public release; distribution is unlimited.

High Temperature Degradation Experiment



1-2cm foam layer to match extinction conditions

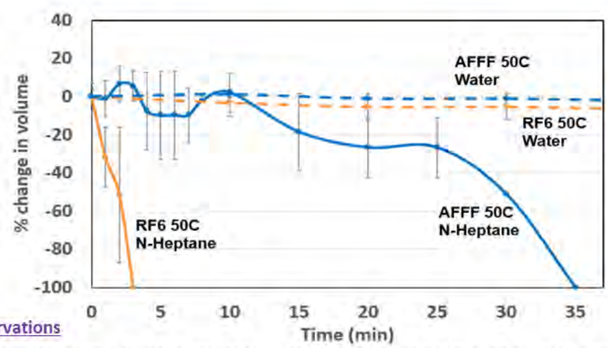
Preheated fuel to match fire conditions

Heating tape to maintain constant fuel temperature

The foam volume was measured versus time

Parameter	Value
Foam	AFFF (Buckeye Inc.)
	Fluorine-free, RF6 (Solberg Inc.)
Fuel Type	Water
	N-Heptane
	Iso-Octane
	Methylcyclohexane
Temperature	50°C

Fuel Effect on Foam Degradation

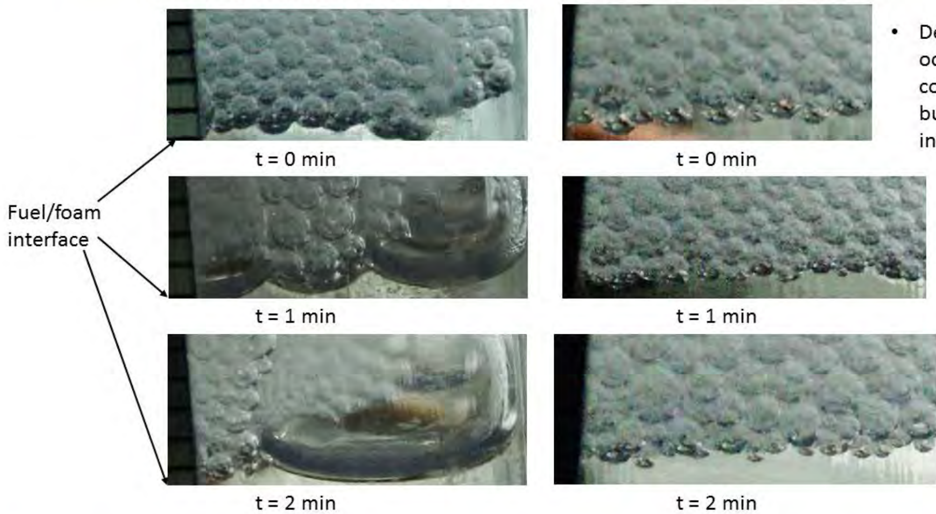


Observations

- AFFF had a much longer foam lifetime than fluorine-free, RF6, when exposed to n-heptane, fluorination appears to reduce degradation
- The presence of fuel influences foam degradation with RF6 foam lifetime changing from **over an hour on water to 3 minutes** on n-heptane, degradation seen during extinction may be caused by fuel and not pool temperature
- RF6 degradation time scale relevant to extinction time scales (1-2 minutes), could be effecting extinction performance

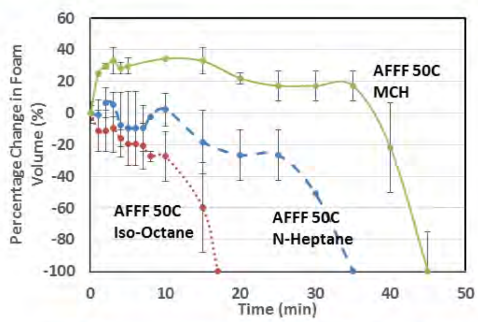
Effect of Fuel on Bubbles at Foam/Fuel Interface

Fluorine-free Foam on N-Heptane 50°C | Fluorine-free Foam on Water 50°C



- Degradation occurs by rapid coalescence of bubbles near the interface
- Lamella (bubble walls) are destabilized by the fuel

Fuel Effect on Foam Degradation



Observations

- Different fuels led to different degradation rates
- Differences in fuel properties such as fuel/water solubility or surface tension could be affecting the lamella and leading to differences in degradation

Fuel	Chemical Formula	Molar Mass (g/mol)	Vapor pressure 25°C (mm Hg)	Solubility (mg/100 g) 20 – 25°C	Surface Tension (dynes/cm³)	AFFF Foam Lifetime (min)
Iso-octane	C_8H_{18}	114.14	41.25	25	19	17
n-Heptane	C_7H_{16}	100.13	39.97	20	19.7	35
Methylcyclohexane	C_7H_{14}	98.11	46	15	23.4	46

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Conclusions for Foam Degradation

- AFFF has a foam lifetime an order of magnitude longer than fluorine-free foams which may be contributing to its superior firefighting performance
- Foam lifetime changes due to fuel through its destabilization of the foam bubbles leading to increased bubble coalescence and foam degradation
- The changes in foam lifetime may be explained by fuel properties such as fuel surface tension and fuel solubility

Moving Forward

- Define mechanism by which fuel interacts with foam bubbles to increase foam degradation and how it is affected by a surfactant
- Use information of foam degradation to guide the development of environmentally friendly surfactants for firefighting foams

Overview of Toxicity and Health Effects Issues for Fire Protection in Army Vehicles

APHC

ARMY PUBLIC HEALTH CENTER (Provisional)

Matthew Bazar

14-15 Oct 2015
Systems Fire Protection Information Exchange, APG, MD

UNCLASSIFIED

Briefing Outline

PURPOSE: To provide an overview of the Toxicity Clearance process and issues encountered during evaluation of fire extinguishing agents and systems.

1. Public Health Command – Toxicology's role
2. Exposure scenarios and health effects criteria
3. Toxic gases
4. Powder inhalation
5. Low level oxygen
6. Thermal criteria issues for aqueous agents

"The views expressed in this presentation are those of the author(s) and do not necessarily reflect the official policy of the Department of Defense, Department of the Army, U.S. Army Medical Department or the U.S."

APHC Toxicology's Role

- AR 40-5 Toxicity Clearance
  - DA Pamphlet 70-3 requires a Toxicity Clearance (approval) prior to use of a new material or chemical.
  - Approval is based on the specific product application or use condition.
- Develop health effects criteria for military unique exposure scenarios
- Provide consult and support for evaluation of test data
- Related ARs:
  - AR 70-1 Army Acquisition Policy
  - AR 40–10 Health Hazard Assessment Program in Support of the Army Acquisition Process

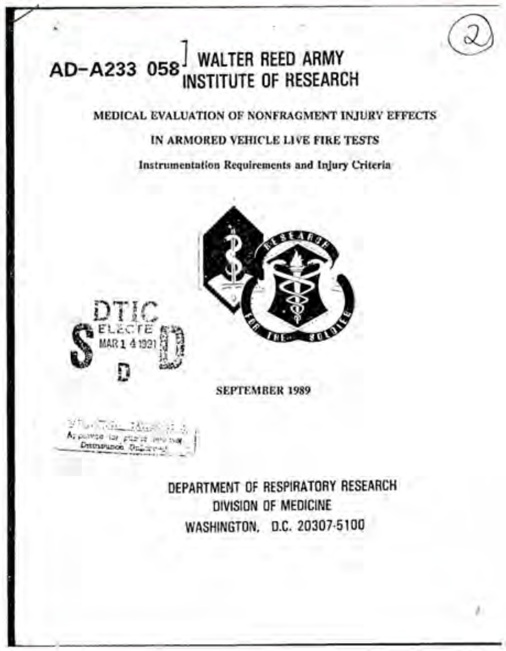
Exposure and Health Effects Criteria Considerations

- Agents: gas, powder, liquid
- Occupied vs Unoccupied space
- Occupational vs military unique (i.e., live-fire event, brief, high conc.)
- Accidental/incidental discharge vs live-fire response
  - Agent toxicity
  - Toxicity of pyrolysis products
- Exposure: inhalation, oral, dermal, ocular
  - Nose vs open-mouth breathing
- Effects: immediate vs delayed
  - i.e., cardiac sensitization, irritation, pulmonary edema, lung particulate loading, oxygen displacement, cognition

Live Fire Test Criteria

<u>WRAIR 1989</u>;
AFES evaluation criteria originally developed for Bradley Fighting Vehicles.

Supplemented as necessary with provisional criteria and Army OTSG memorandum.


AD-A233 058 WALTER REED ARMY INSTITUTE OF RESEARCH

MEDICAL EVALUATION OF NONFRAGMENT INJURY EFFECTS IN ARMORED VEHICLE LIVE FIRE TESTS

Instrumentation Requirements and Injury Criteria

DTIC ELECTE MAR 1 4 1991 S D D

SEPTEMBER 1989

DEPARTMENT OF RESPIRATORY RESEARCH
DIVISION OF MEDICINE
WASHINGTON, D.C. 20307-5100

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Toxic Gas Injury Criteria (WRAIR 1989)

- Primary mission is avoiding incapacitation.
- Evaluating combat survivability, levels of hazard and injury; <u>lies between civilian occupational health standards and lethality information</u>.
- Prediction of toxicological hazard is made for unmasked exposures lasting up to 5 minutes after penetration.
- It is expected that protective masks will be donned if the vehicle is not evacuated.

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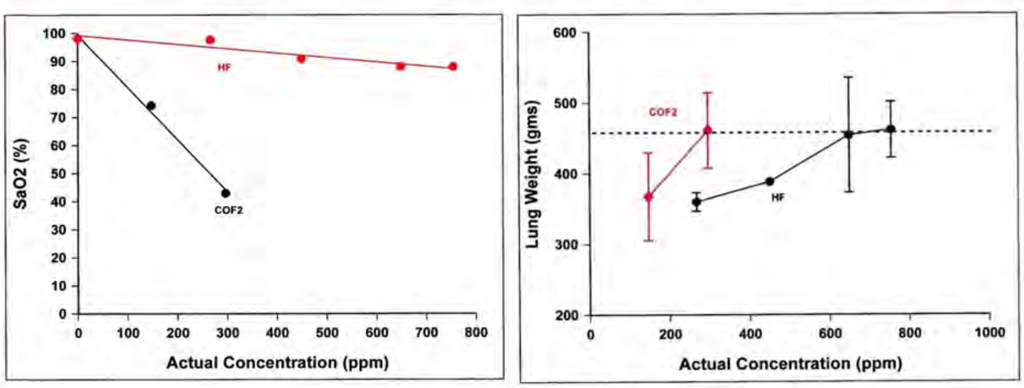
Selected Toxic Gas Criteria

Selected Toxic Gas Criteria	Incapacitation Threshold (ppm-min)	Est. 100% Incapacitation (ppm-min)
CO_2	30,000 (3%)	N/A
CO + NO	37,250	62,750
HF+HBr +HCl+2*COF_2	746	2237
Formaldehyde	150	N/A
HCN	75	225

- Additivity assumed for acid halides
- Provisional criteria assumes COF_2 is more toxic than HF by 2x
- Provisional Methyl Isocyanate (MIC) criteria developed for plastic urethane/polyurethane combustion

Sheep HF and COF_2 inhalation exposures



- Saturated blood oxygen (SaO_2) from 5-minute exposures reveal that COF_2 is more noxious than HF on a ppm basis
- Lung gravimetrics reveal a concentration dependent response
- Dashed line shows similar mean lung weights in the highest exposures

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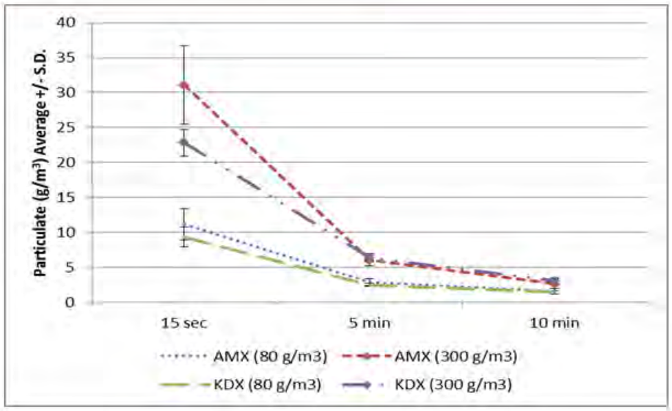
Sheep Dry Powder Exposures



- Design concentrations ≠ breathing zone concentrations
- Discharge efficiencies 89-98% within UL 1254 requirement of 85%
- Design concentrations up to 300 g/m^3 are not expected to adversely affect crew survivability

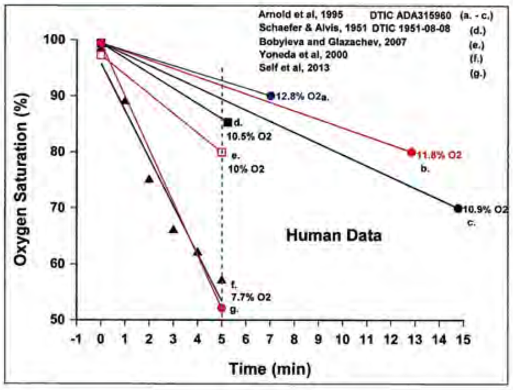
Minimum Oxygen Criteria Issues

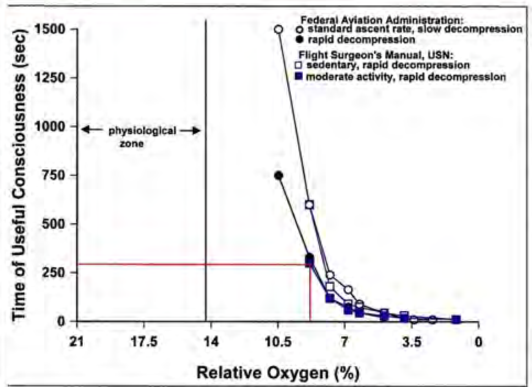
- Minimum level of 16% appears overly restrictive
  - Emphasis on brief hypoxic exposure as the result of a catastrophic event rather than intermittent or continuous low level exposure

- For catastrophic events: Criteria based on concentration and exposure duration appears warranted based on FAA and Navy Time of Use Consciousness (TUC) levels and peer reviewed literature appear warranted

- Uncertainties include predisposition of individuals to hypoxia, effect of prior or existing lung injuries, and potential for increased toxicity of chemicals present.

SaO_2 vs Time of Useful Consciousness (TUC)

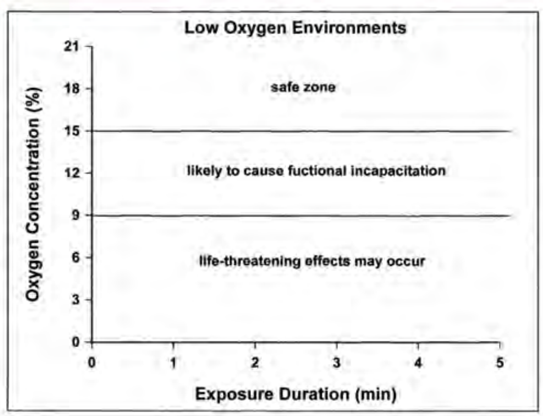




- Human data compared at the 5-minute time point reveal a dose-response effect between the relative O_2 and SaO_2
- Comparison of TUC's among different scenarios define the relative O_2 concentration of 9% where a 5-minute TUC is reported

Proposed Draft Oxygen Criterion

- O_2 levels ≥ 15%
  no deterioration in function
  is expected
- Duration ≤ 5-min from 9-15% O_2,
  fractional incapacitation
  is expected and can be estimated
- O_2 levels ≤ 9% may be
  survivable for short duration but
  should be considered on a
  case-by-case basis by medical experts



- Long term objective is to merge the toxic gas acute exposure criteria with O_2 criterion based on the end point of saturated blood oxygen (SaO_2)

Thermal Criteria Issues for Aqueous Agents

- WRAIR (1989) specifies heat dose of 3.9 cal/cm2 (163 kJ/m2) for a 10-second exposure to prevent second degree burns.
  - Criterion and model based on air temp not liquids
- Aqueous agent AFES exposure considerations:
  - Agent toxicity, droplet size, combustion by-products
  - Discharge w/o a fire present and high ambient temp
  - Discharge in response to a fire event
- Aqueous agent issues:
  - Applicability of current heat flux criteria for aqueous agents
  - Two-stage AFES (i.e., primary + mist systems)
  - Potential for heat stress and adverse core temp change from extended exposure scenarios

Summary

- New agents require Toxicity Clearances and assessment of pyrolysis products
  - May require development of provisional exposure criteria
- Recent APHC/TOX small/large animal studies address:
  - HF / COF_2 toxicity
  - powder inhalation
  - aqueous agent inhalation toxicity
- Current HX criteria remains protective due to overestimation of HF
- Revised minimum O_2 criterion for live-fire events being investigated
- Thermal criteria for aqueous agents is an open issue

HYDRODYNAMIC RAM STUDIES AT SWRI

Donald J. Grosch
Southwest Research Institute®
San Antonio, Texas 78238

Presented at the
Systems Fire Protection Information Exchange
October 14, 2015

1

Program Description

- TARDEC-funded project (began Oct. 2011)
- Goal was to study the interaction of various threats with liquid-filled tanks to better understand the vulnerability of ground vehicle fuel tanks to attack.
- Experiments were conducted with water as a surrogate for fuel.

2

Initial Testing

- A re-usable test fixture for the large threats

Replaceable Entry and Exit Panels

Large Lexan Windows on Both Sides (for HSV) and Top (for light for the HSV)

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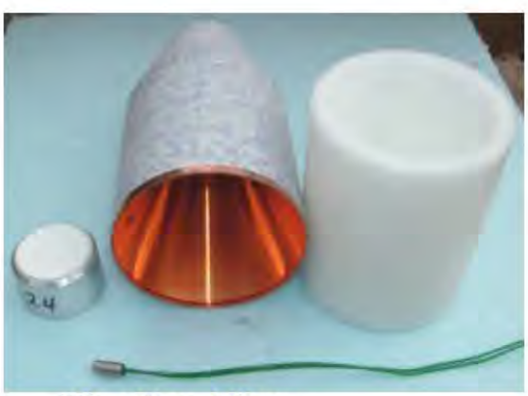
3

IED Threat: Shaped Charge

- The main threat of interest is the RPG
- We use the Viper shaped charge as a surrogate for the RPG



Viper Shaped Charge

2.60” Cone Diameter

~1-pound of LX-14

4

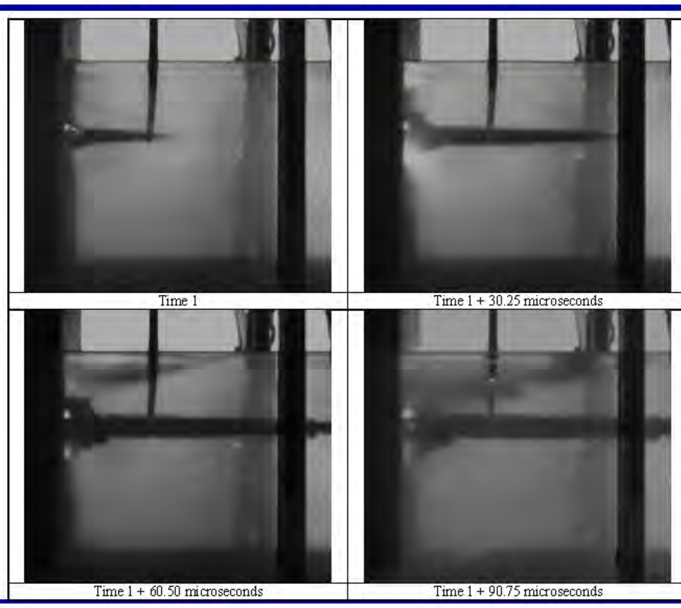
3 High-Speed Video Cameras per Test

Phantom HSV Cams
#1: Tight Side View
#2: Wide Side View
#3: Overall View

5

Tight Side View

Used to observe Viper travel through water



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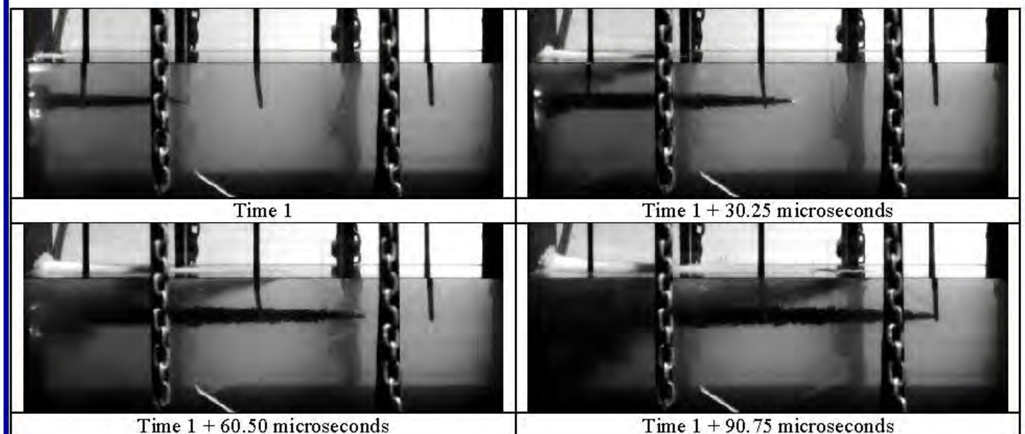
Wide Side View

Used to observe Viper travel through water



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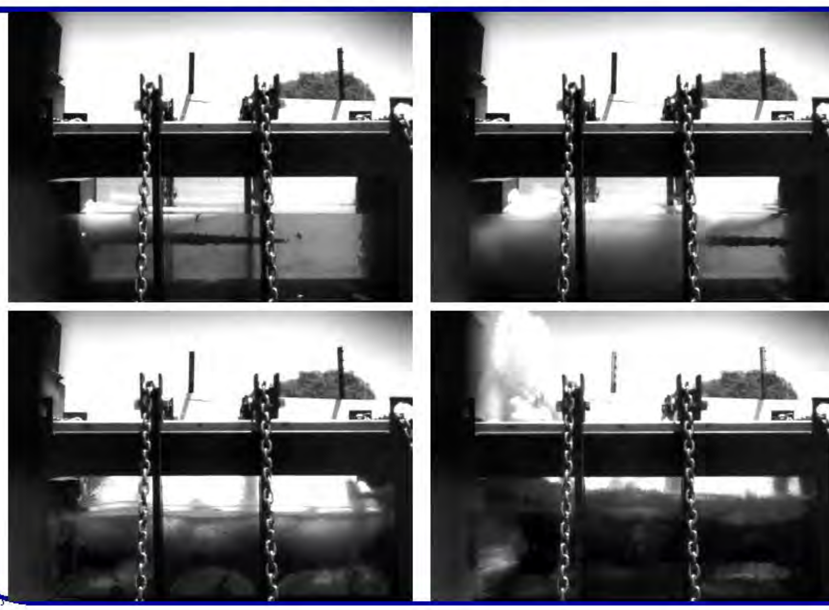
7

Overall View

Used to observe Threat/Water Interaction,
Jetting of Water Out Top, or Threat Exit



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Overall View

Used to observe Threat/Water Interaction

Slow
Early

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9

Overall View

Top Window Removed for Some Tests

Fast
Late

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10

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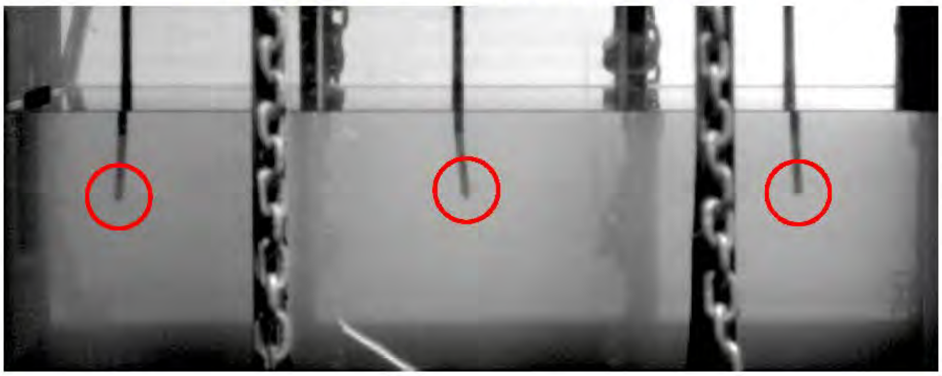
PCB 138A06 Tourmaline Pressure Gauges

- All gauges 6" to the side of the shotline



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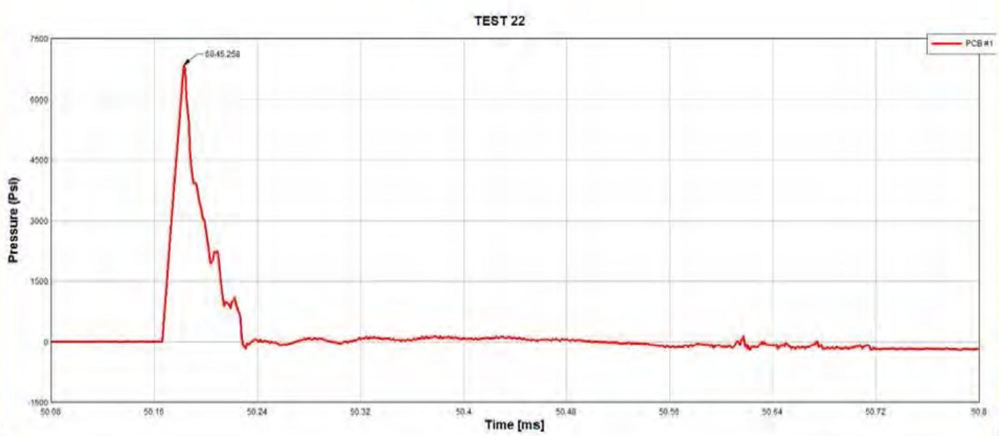
PCB #1

Sample Trace



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12

Exit Panel Hole

- So far, the main thing that has sparked our interest is the large exit hole
- With a single layer of 0.090" 6061-T6 aluminum, a large, petalled hole is generated
- If the rest of the tank holds together, this is where all the "fuel" exits the tank
- What can we do to prevent this large hole?

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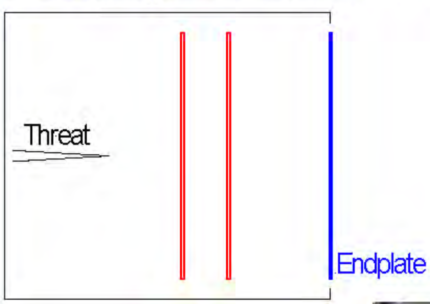
Exit Panel Hole

- Attempts to reduce size of exit hole: Inside Stripper Plates



Two 0.090" Alum Stripper Plates
4.5" Apart and 10" from End Plate

Result: Small holes in the inside stripper plates; same large hole in exit panel

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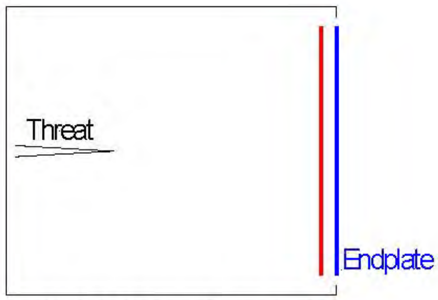
Exit Panel Hole

- OK, so the rush of water out the hole creates the petalling.
- Put the stripper plate closer to the exit panel.

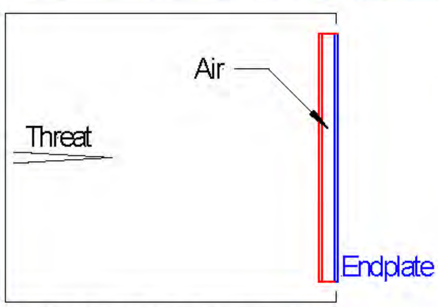


Single 0.090" Alum Stripper Plate
1.25" from End Plate

Result: Small hole in the inside stripper plate; same large hole in exit panel

Exit Panel Hole

- OK, the water between the plates still rushes out and creates the petalling.
- Put air between the stripper plate and the close **exit panel.**



Single 0.090" Alum Stripper Plate
1.25" of Air in Between

Result: Small hole in the inside stripper plate; same large hole in exit panel

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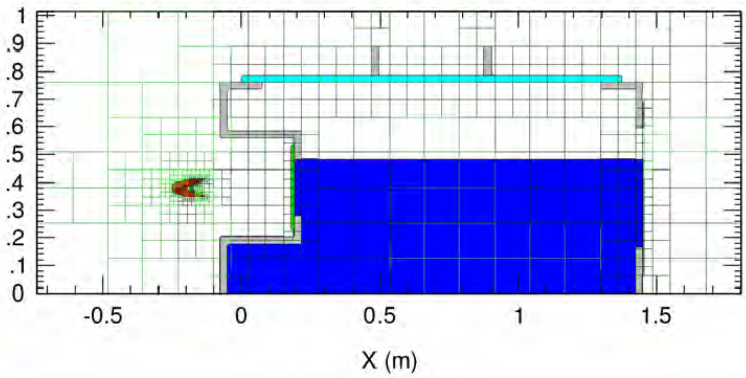
Computational Study using CTH

- Modeled the Viper threat.
- Simulation includes the formation of the shaped charge jet.
- The automatic mesh refinement is such that maximum resolution is about 1 cell across the thickness of the liner (actual thickness ~ 0.1").



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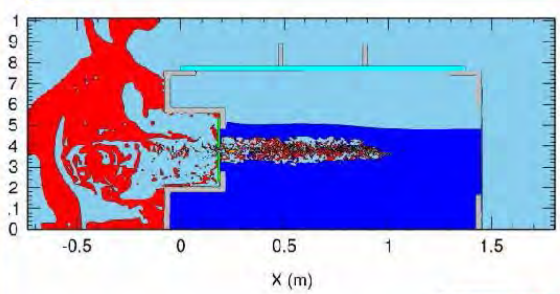
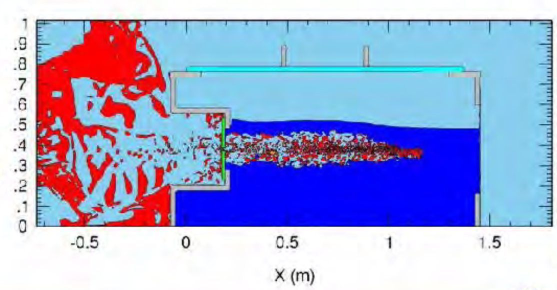
Computational Study



at T = 0.78 msec



at T = 1.17 msec

18

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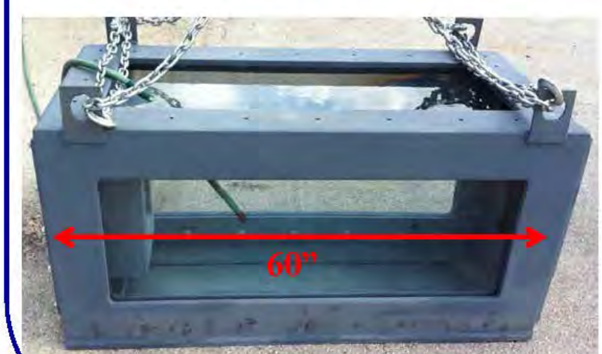
Ballistic Threat Testing

- The Viper shaped-charge generated a large hydraulic ram and resulted in a very disruptive fluid response
- Program re-focused to look at less-disruptive ballistic threats
- Put more emphasis on the characterization of the liquid spray exiting the tank

19

Smaller Test Tank

- For the Ballistic Threats, we fabricated a smaller tank that was closer in size to what an actual vehicle fuel tank might be (18” long instead of 60”).



Shaped Charge Test Tank

Ballistic Test Tank

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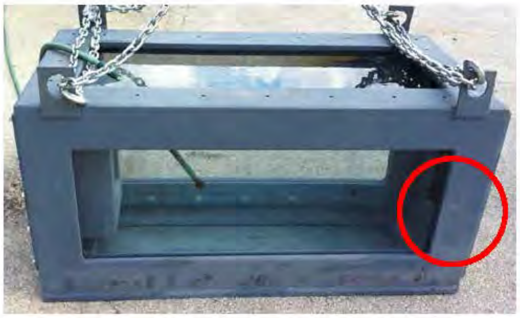
Ballistic Test Tank

- The 5-inch blind spot at the exit panel was eliminated.



- Allows for the viewing of the threat as it impacts the exit panel

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Ballistic Threats

- 20mm FSP
- .50-cal FSP
- .50-cal APM2
- 25mm APDS

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APM2 Similarity to Shaped Charge

- The APM2 threat interacted with the fluid in a manner quite similar to that seen with the Viper shaped charge

So, most of the testing and analysis done with this threat

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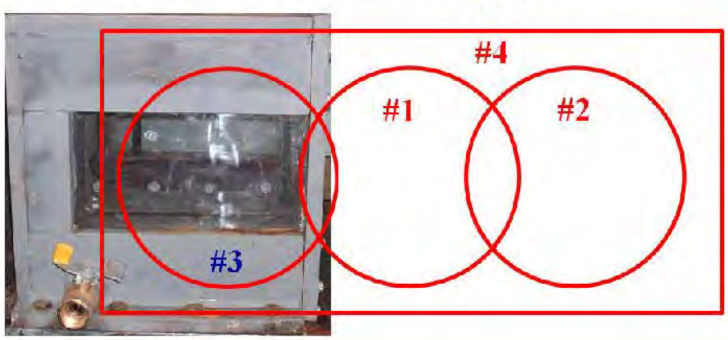
HSV Placement

- The HSV cameras were positioned to obtain the following
  - #1: Spray pattern characteristics as it exited the tank
  - #2: Spray pattern characteristics a little downrange of the exit panel
  - #3: Interaction pattern of the threat and the exit panel
  - #4: An overall view of the tank and the spray



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HSV Placement

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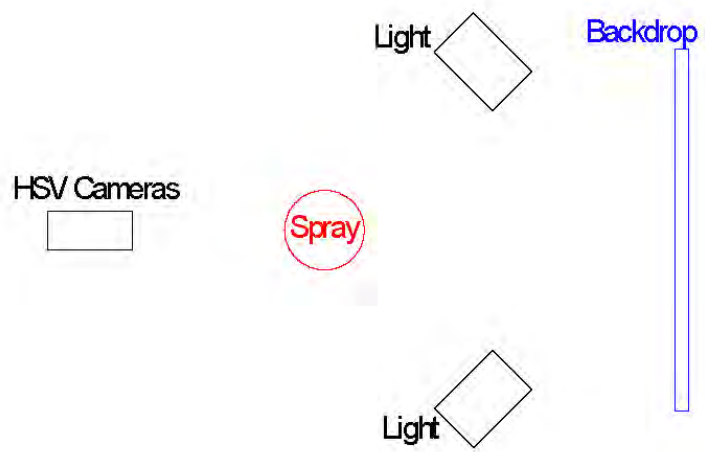
Used an Illuminated Backdrop

- DOW blue styrofoam as backdrop
- High-intensity lights on the backdrop

26

Illuminated Backdrop



27

Illuminated Backdrop

This method worked well for imaging the spray particles to be characterized

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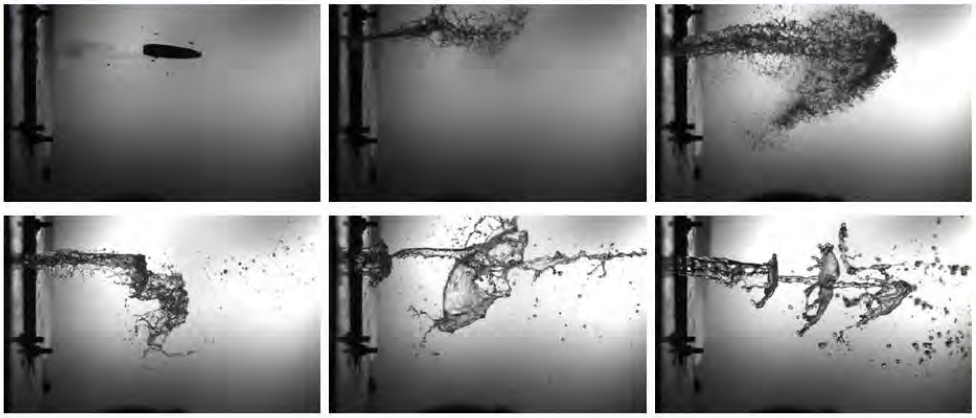
Study of Fluid Type

- 2 tests into water
- 2 tests into Viscor L4264V-96, a diesel reference fluid

- Results showed spray droplets generated by water and diesel were essentially the same

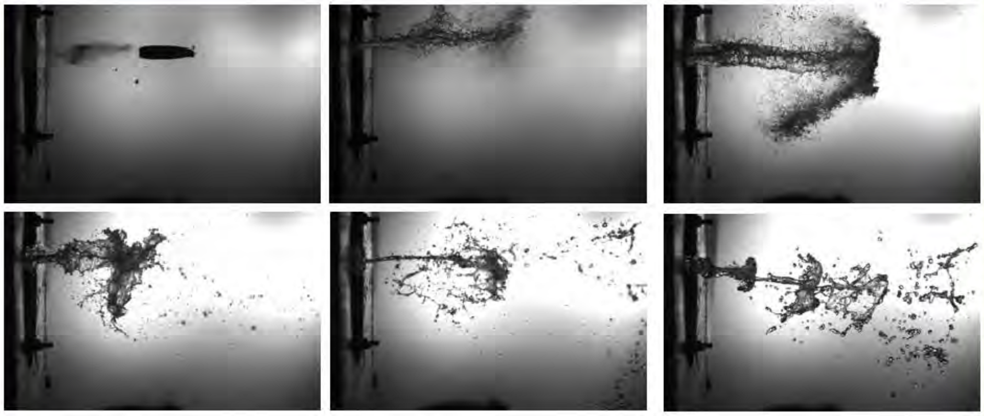
29

Study of Fluid Type – Water Test #1



30

Study of Fluid Type – Water Test #2



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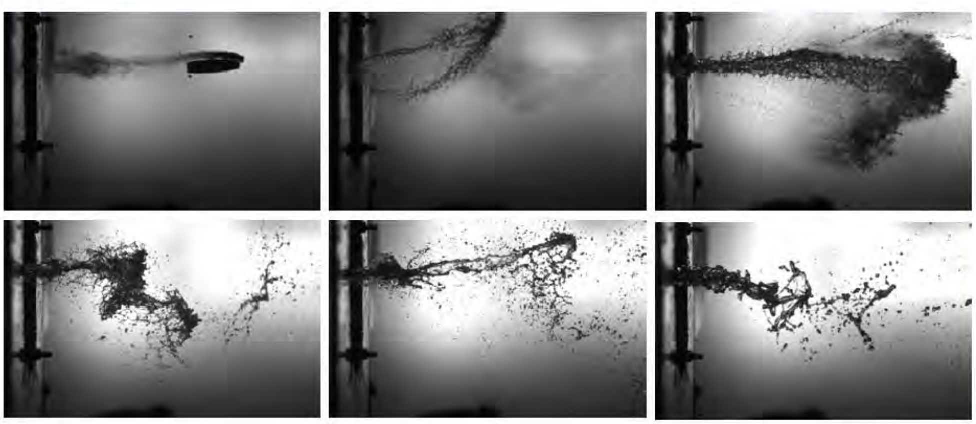
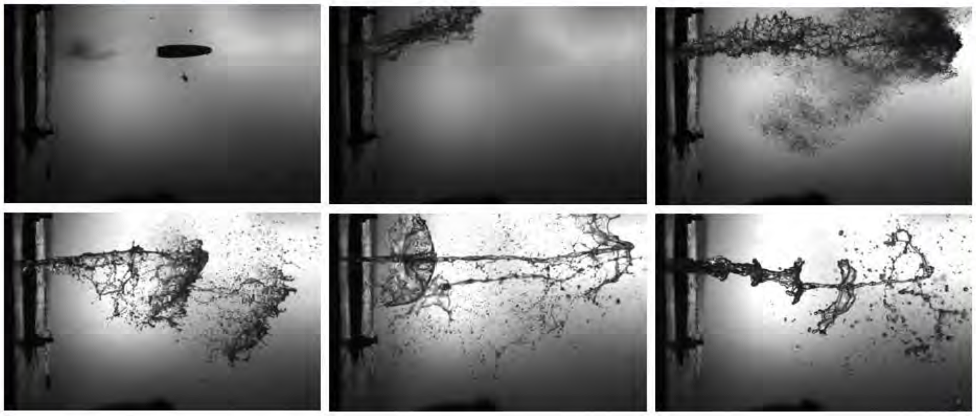
Study of Fluid Type – Diesel Test #1



32

Study of Fluid Type – Diesel Test #2



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Spray Characterization

- Quantitative data related to spray characteristics include:
  - Droplet size
  - Droplet size distribution
  - Droplet velocity
  - Velocity distribution, as a function of droplet size

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Spray Characteristics

- The spray event is broken into four phases:

Penetration entrained droplets | Initial liquid surge | Subsequent series of surges

Terminates with liquid draining from exit hole

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Measurement Techniques

- There are a number of techniques commonly used at SwRI for droplet size, distribution, and velocity measurements:
  - Laser diffraction and Mie scattering
  - Phase Doppler Analysis (PDA)
  - Particle/Droplet Image Analysis (PDIA)
- Commercial measurement products are available:
  - Malvern
  - Oxford Lasers
  - Dantec
  - LaVision
  - Many others…

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Laser Diffraction

- Measures droplet size, distribution, and Sauter mean diameter
- Generally assumes spherical particles
- Limited range of droplet sizes that can be measured at one time, optics must be changed for large, medium, or small categories
- Limited analysis volume, limited by beam diameter (< 6 mm)
- Not capable of measuring velocities

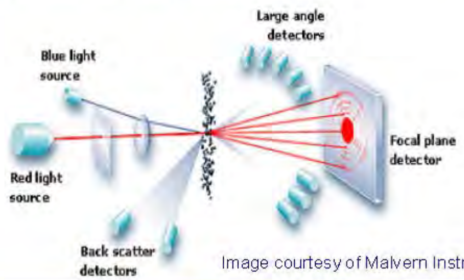

Image courtesy of Malvern Instruments, Ltd.

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Phase Doppler Analysis

- Has the capability to measure droplet size and distribution
- Also provides velocity measurements and velocities correlated with droplet size
- Limited droplet size range that can be measured at one time
- Very limited sample volume

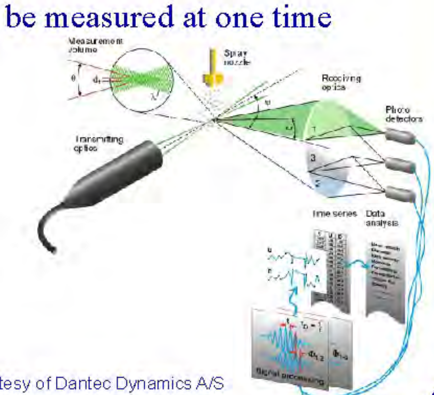

Image courtesy of Dantec Dynamics A/S

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Particle/Droplet Image Analysis - PDIA

- Is capable of measuring droplet size, distribution, and velocities
- Capability to sample over relatively large area
- Minimum droplet size is dependent on the resolution of image
- Velocity measurements are determined by interframe cross-correlated particle tracking

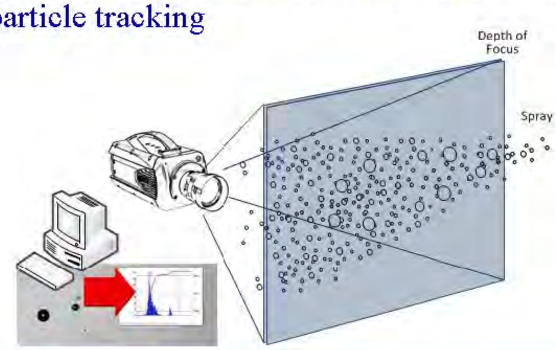
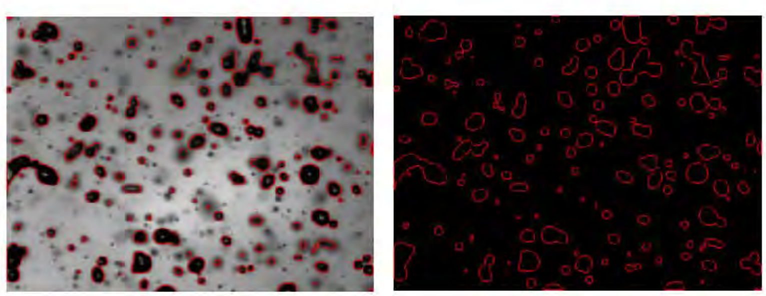


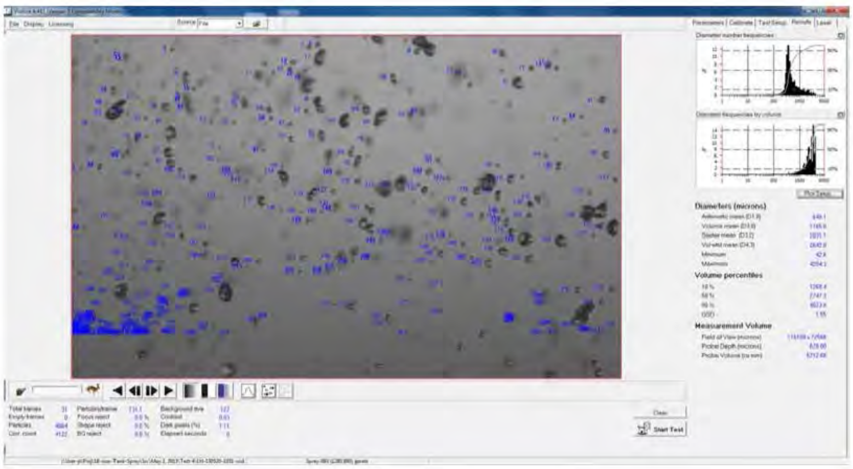
Image Analysis

- Subtract background from droplet shadowgraph
- Analyze gradient in image to eliminate out of focus droplets
- Utilize edge detection image processing techniques to determine droplet boundary
- Compute droplet size, sphericity, and distribution



Droplet Size Distribution

- Utilized Oxford Laser's VisiSize software



Obtaining Velocity

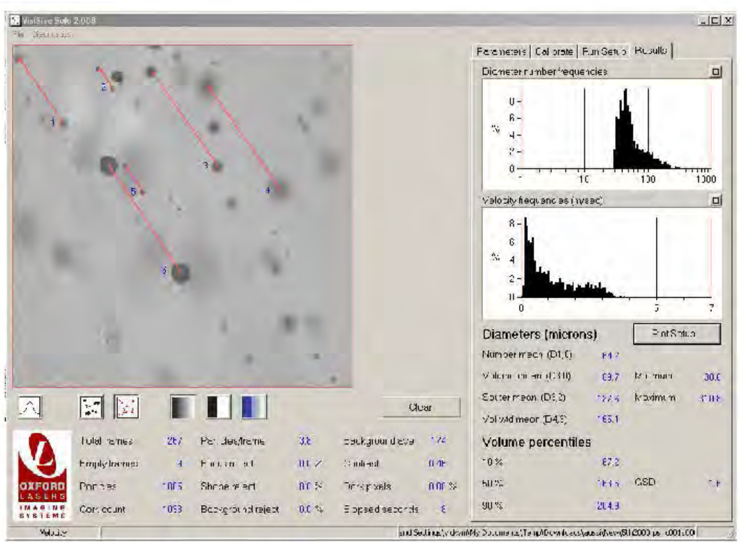
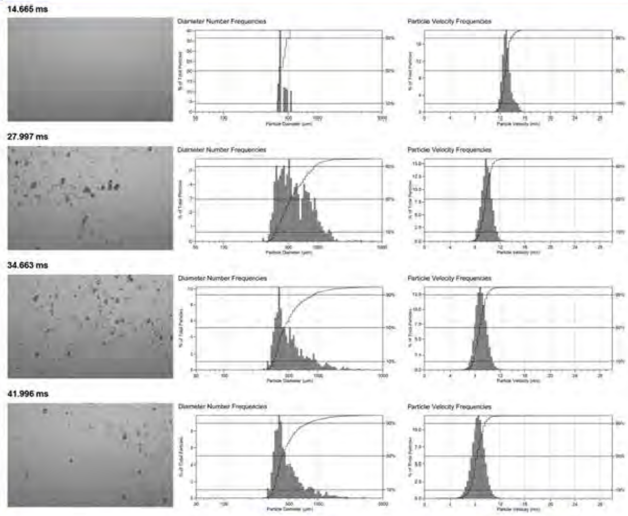


Image courtesy of Oxford Lasers, Inc.

Results

Data provided to Vamshi Korivi (TARDEC)



y-axis: % of total droplets

Droplet Diameter (μm)

Droplet Velocity (m/s)

10/13/2015

43

End of Slides

10/13/2015

44

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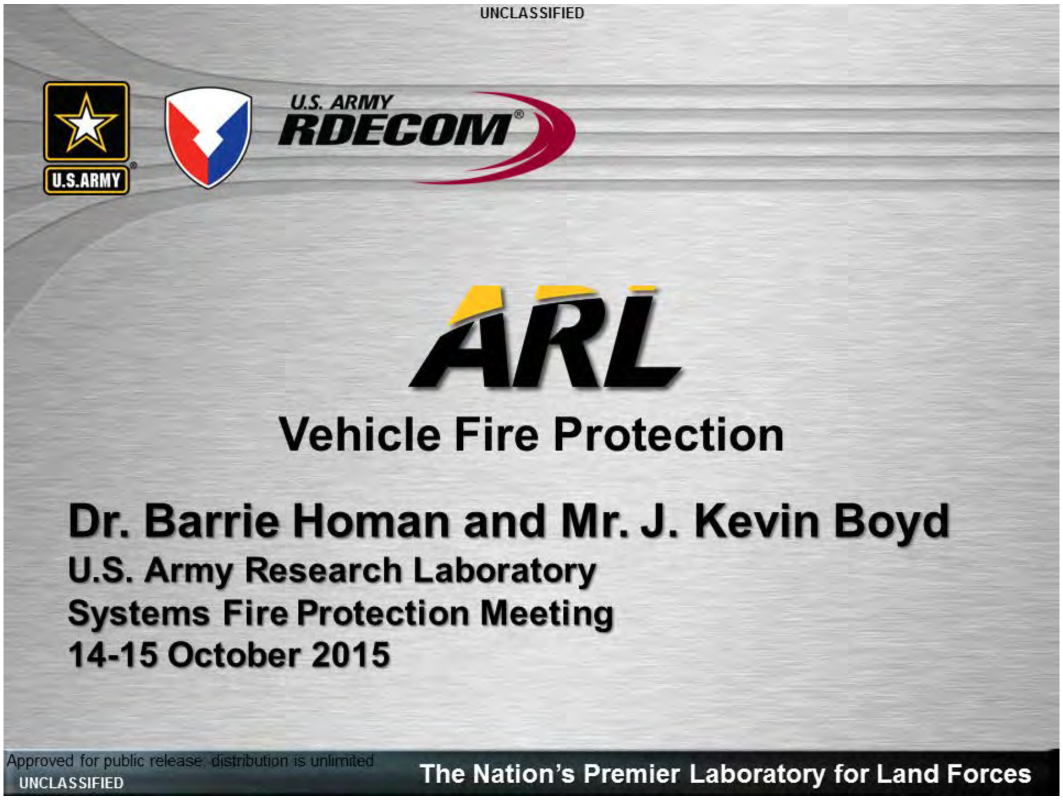
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Vehicle Fire Protection
Dr. Barrie Homan and Mr. J. Kevin Boyd
U.S. Army Research Laboratory
Systems Fire Protection Meeting
14-15 October 2015
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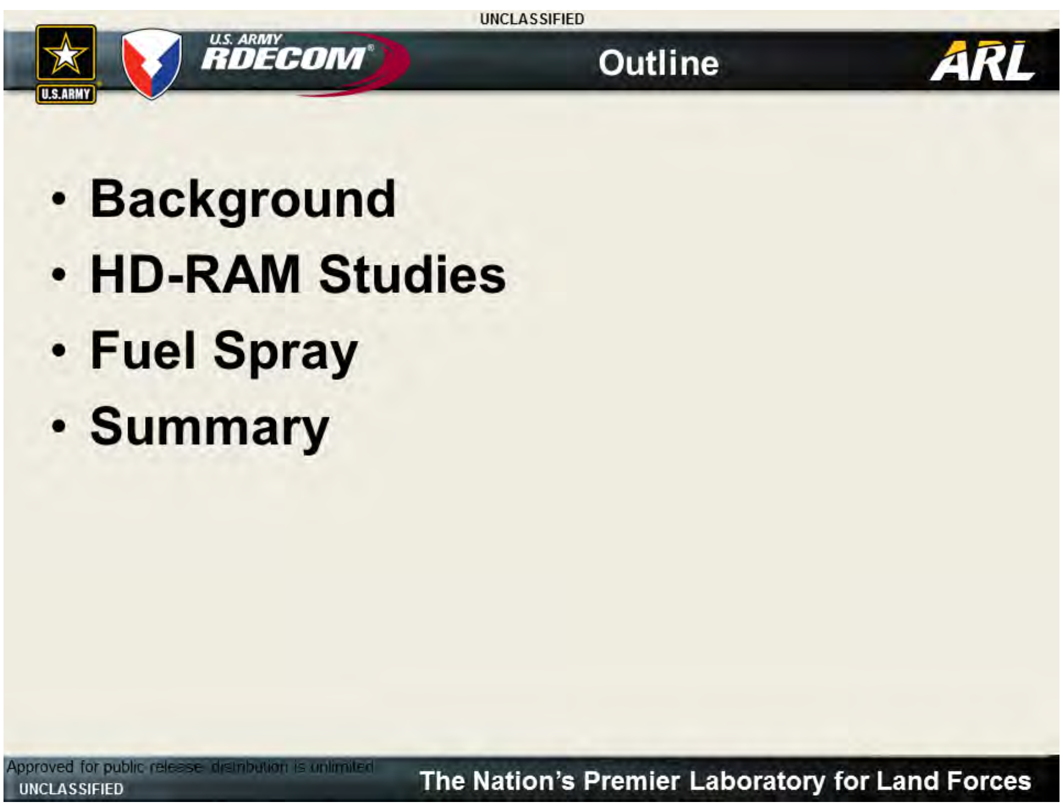
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Outline
ARL
• Background
• HD-RAM Studies
• Fuel Spray
• Summary
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Background

Fire were a leading cause of ground vehicle losses and a major source of Soldier casualties in OIF and OEF (Fuel fire problem mentioned in the 2014 Quadrennial Defense Review).

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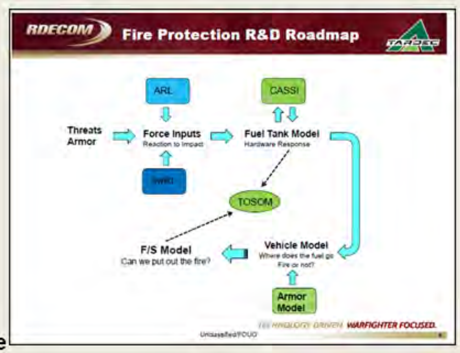
Background

- TARDEC developed a Fire Protection R&D Roadmap with ARL.
- Characterization of HD RAM
  - High energy threats (SCJ)
    - Proved violent
  - Lower energy threats (bullet, FSP)
    - Useful for model and experiment development
- Fuel Spray characterization
  - Development of facilities for ARL to conduct more fundamental investigation of fuel fires.
    - Large and small tanks along with optical mass flow meter. (SWRI)
- Future



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Background

TARDEC ARL

The energy and HD-RAM associated with SC, EFP, and Fragmenting IEDs is orders of magnitude greater than small arms/bullet impact.

7.62-mm bullet impact of a surrogate fuel tank containing JP8 fuel heated to 20°F above the fuels flash point.

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Background

TARDEC ARL

Current state of the art for ground vehicle fuel tanks is add-on appliqués, in-tank inerting materials, or self sealing bladders. There is no integrated approach to fuel tank design.

Failure to take HD-RAM into consideration.

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Fluid Spallation

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Fluid spallation is a major damage mechanism to the fuel tank.

Shot Line

EFP Threat

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Problem

TARDEC ARL

Force Inputs: Overall reaction from threat.

- Does fuel spray from tank?
  - Does the threat fireball interact with spray?
  - Is the spray distribution threat dependant?
  - What are droplet sizes and velocities?
- How does fuel tank fail?
  - Tank failure greatly increases the severity of and the ability to extinguish a fuel fire.
  - What are fuel tank failure modes?
    - HD RAM
    - Shock
    - Blast
  - Are failure modes different for different threats?

Severity of fuel fires are dependant on these parameters.

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HD RAM Studies

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- HD ram is main damage mechanism to the fuel tank.
- HD ram is the main cause of finely dispersed external fuel spray that is highly flammable and the source of damaging fires.
- Investigation of the SC jet/EFP penetration of a generic fuel tank
  - SC and EFP experiments proved too violent.
  - Blast, fireball, liquid spray etc. make if difficult to study the events experimentally and in the models.
  - Refocused on 20mm FSP and .50 cal studies.
- HD-RAM has more than one component
  - Cavitation bubble causing spray from the tank
  - Fluid spallation from liquid/ullage interface that can cause damage and failure of the fuel tank.

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Digital Image Correlation

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Conducted experiments with 33 gallon drums.
- Flash from threat impact and fluid spray interfered with the DIC technique.

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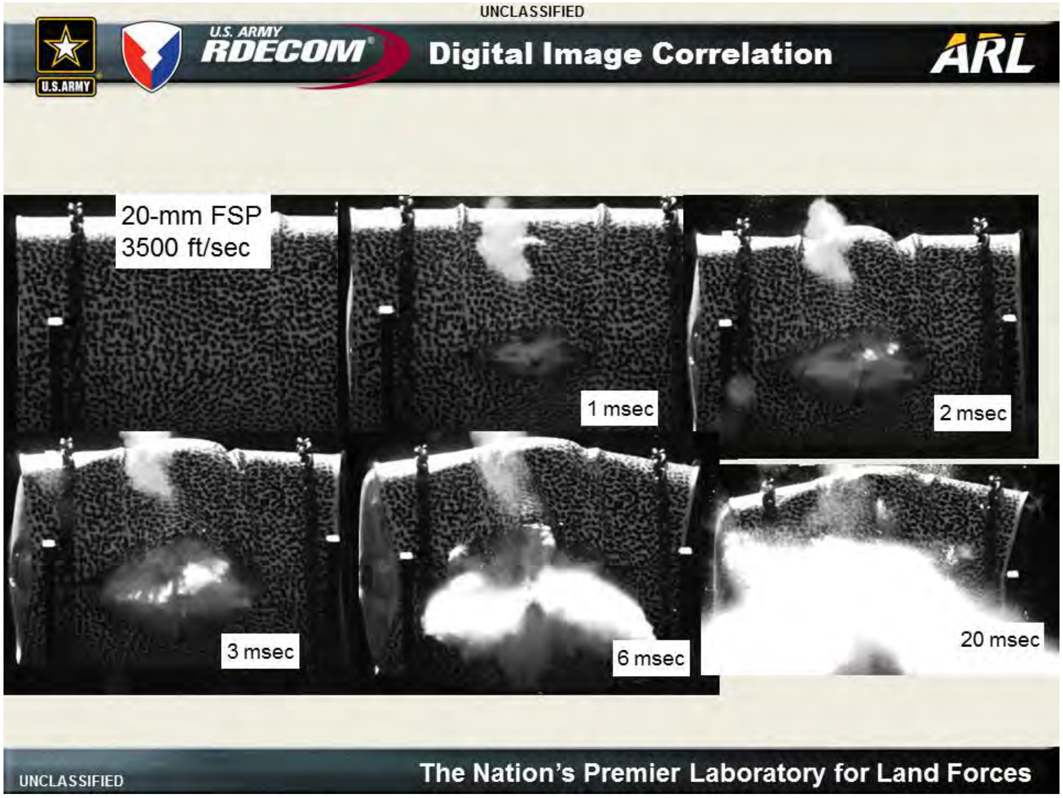

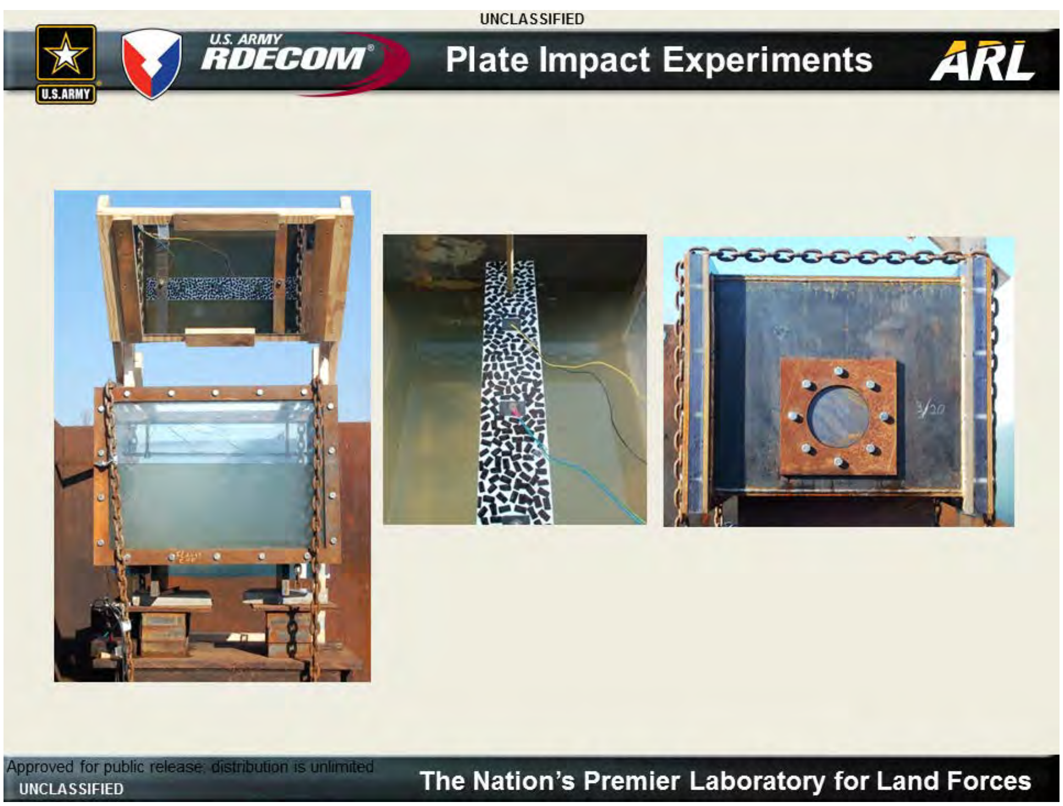

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Plate impact Experiments

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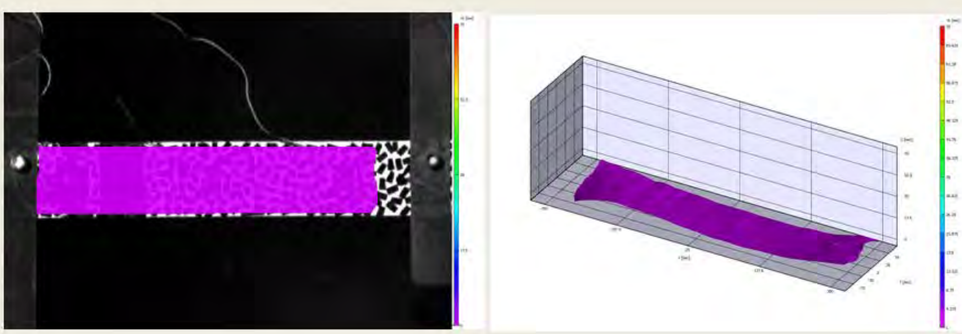
1/4 inch sensor plate

ARL



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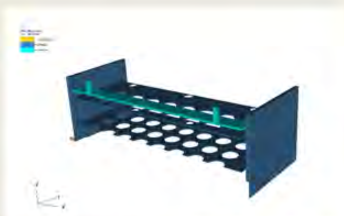
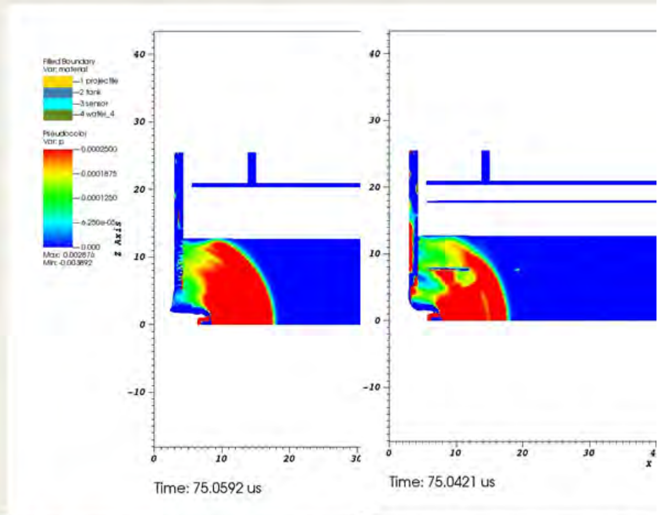
Baffle Plate

- Reduce damage from shock/spallation
  - Preliminary models show reduction of pressure
  - Indication of reduced pressure measurements

- Threat-target match required
  - Small SCJ
    - overmatch for thin tank
    - Undermatch for thick tank
  - Large SCJ – overmatch for everything





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Fuel spray

- Concentrate efforts on characterization of fuel spay
  - New facility using SWRI developed mini fish tank
  - Adaption/development of fuel characterization
    - High Brightness Imaging
      - – Shadowgraphy
      - – Planar illumination imaging
    - Absorption fuel flow measurements
    - Holograpy
  - Facility in place with diagnostics check out underway

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Summary

ARL

- HD-RAM is major driver
  - Tank damage/failure
  - Production of external fuel spray -> cause of most vehicle fires
  - Developed facility to measure forces from HD-RAM
    - Force from spallation of water surface (momentum transfer)
- Baffle mitigation
  - Preliminary results (model and experiment) show possibilities

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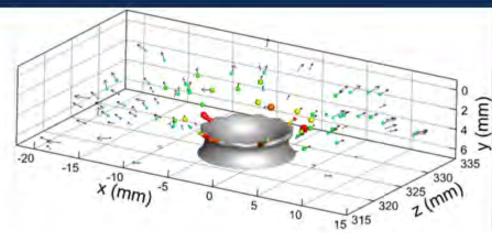

Digital In-line Holography (DIH) for 3D Quantification of Liquid Sprays

Daniel R. Guildenbecher

October 14, 2015

U.S. DEPARTMENT OF ENERGY NNSA

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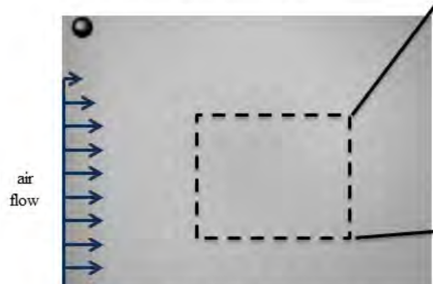
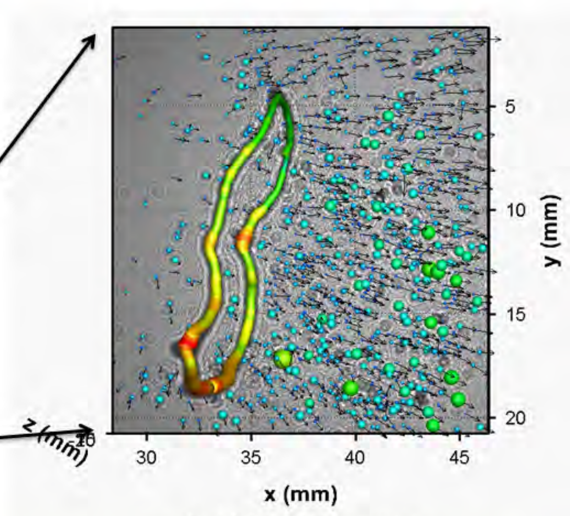
Motivation: 3D imaging for a 3D world

Widely available 2D imaging or point-wise measurement techniques are often insufficient to resolve 3D flow phenomena

- Repetition needed to capture spatial statistics



high-speed video of a ethanol drop in an air-stream



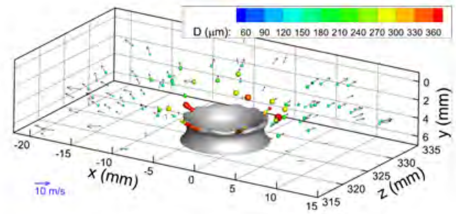
digital holographic measurement (Gao, Guildenbecher et al, 2013, *Opt. Lett.*)

Holography is an optical technique to record and reconstruct a 3D light field

Outline for talk

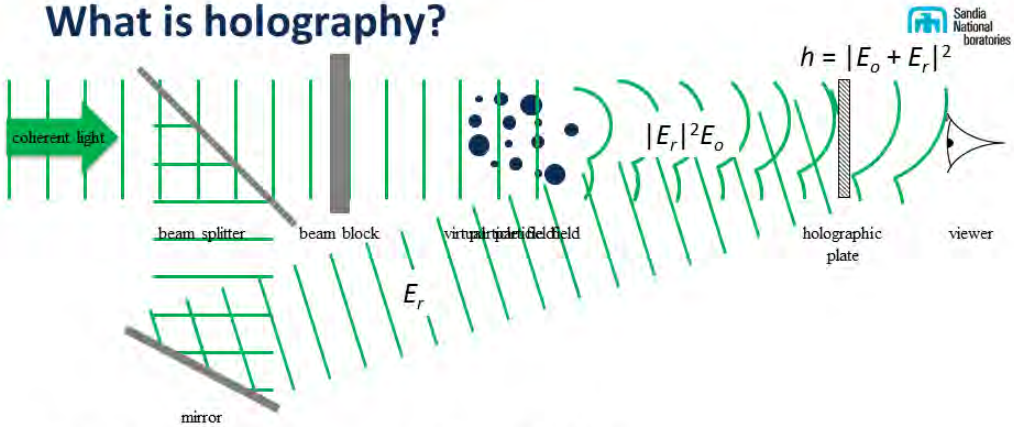
Introduction to holography and the "digital revolution"

Application to liquid sprays



Propellant fire measurements

What is holography?



Optical method first proposed by Gabor in 1948

1. Coherent light diffracted by particle field forms the object wave, E_o
2. Interference with a reference wave, E_r, forms the hologram: $h = |E_o + E_r|^2$
3. Reconstruction with E_r forms virtual images at original particle locations

$$h \cdot E_r = \underbrace{(|E_o|^2 + |E_r|^2)E_r}_{\text{DC term}} + \underbrace{|E_r|^2 E_o}_{\text{virtual image}} + \underbrace{E_r^2 E_o^*}_{\text{real image}}$$

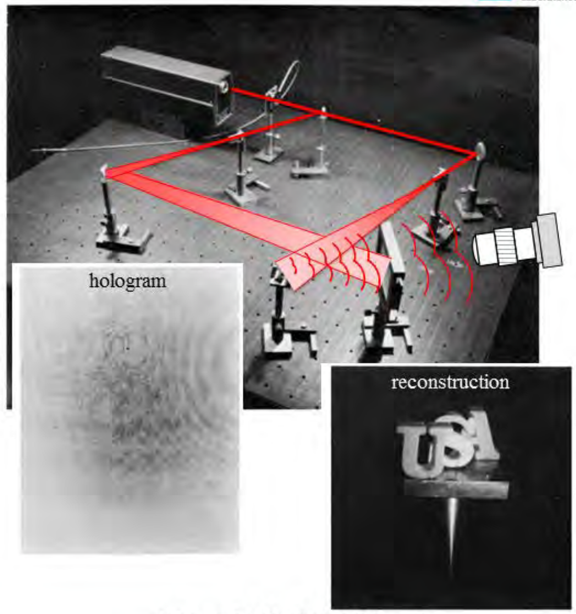
Analog holography

Applications of holography took off with invention of the laser in 1960

<u>Challenges:</u>

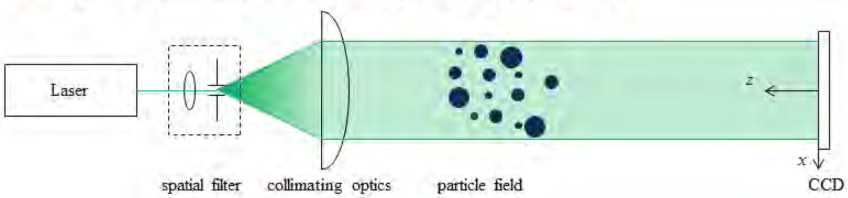
- Darkroom needed to process the hologram
- Limited temporal resolution
- Manual post processing

Thompson et al, 1967, *Appl. Opt.*



Collier et al, 1971, *Optical Holography*

Digital in-line holography (DIH)



Holographic plate and wet-chemical processing replaced with digital sensor

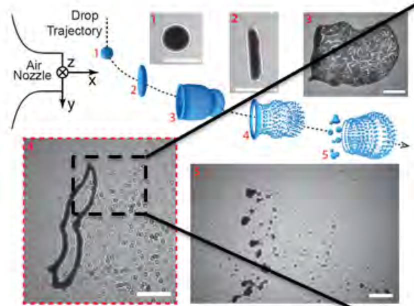
- First proposed by Schnars and Jüptner in '90s
- <u>Advantages:</u> (1) no darkroom, (2) temporal resolution is straight forward, (3) results can be numerically refocused and post-processed
- <u>Challenge:</u> Resolution of digital sensors (order 100 line pairs/mm) is much less than resolution of photographic emulsions (order 5,000 line pairs/mm)
  - For suitable off axis angles, θ, the fringe frequency, f, is typically too large to resolve with digital sensors ($f = 2\sin(\theta/2)/\lambda$)
  - Rather, the in-line configuration ($\theta = 0$) is typically utilized

Numerical refocusing

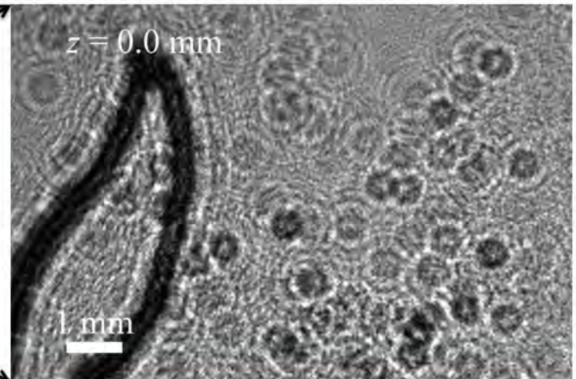
Light propagation in a non-absorbing, constant index of refraction medium is described by the diffraction integral equation:

$$E(x,y,z) = \frac{1}{\lambda} \iint E(\xi,\eta,z=0) \frac{e^{-jkr}}{r} d\xi d\eta \quad \text{where: } r = \sqrt{(\xi - x)^2 + (\eta - y)^2 + z^2}$$

- $E(\xi,\eta,0)$ ≡ complex amplitude at hologram plane = $h(\xi,\eta)\cdot E_r^*$
- $E(x,y,z)$ ≡ refocused complex amplitude at optical depth z



digital holograms of the breakup of an ethanol drop in an air-stream (Gao, Guildenbecher et al 2013, *Opt. Lett.*)



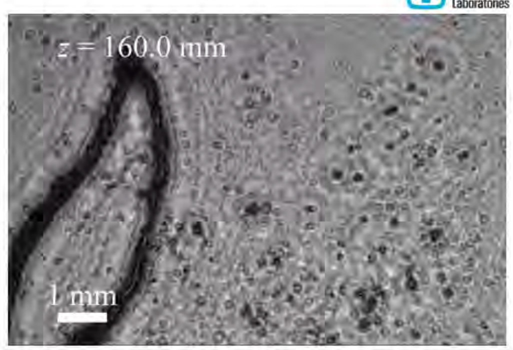
recorded hologram, $h(\xi,\eta)$ / reconstructed amplitude through depth, z

Data processing

Acquisition and refocusing of a digital hologram is relatively straightforward.

However…

For quantitative measurements, methods are required to locate and measure particles.



Challenge: *depth-of-focus problem*

The spatial extent of the diffraction pattern limits the angular aperture, Ω, from which a particle is effectively reconstructed (Meng et al, 2004, *Meas. Sci. Technol.*)

- From the central diffraction lobe → $\Omega \approx 2\lambda/d$
- Using the traditional definition of depth-of-focus, δ, based on change of intensity within the particle center → $\delta \approx 4\lambda/\Omega^2$
- Therefore: for in-line holography, $\delta \approx d^2/\lambda$
  - Example: d = 300 μm, λ = 532 nm → $\delta \approx$ 170 mm!

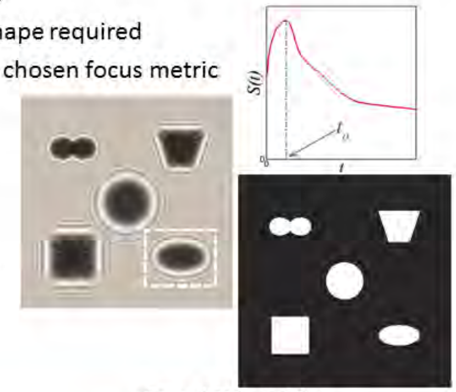
Data processing

Literature contains two basic methods to find the focal plane:

1. Fit a model to the observed diffraction patterns (inverse method)
   - Generally accurate with small depth uncertainty
   - Limited to objects with known diffraction patterns (spheres)
2. Reconstruct the amplitude (or intensity) throughout depth and apply a focus metric to find "in-focus" objects
   - No *a-priori* knowledge of particle shape required
   - Accuracy is a strong function of the chosen focus metric

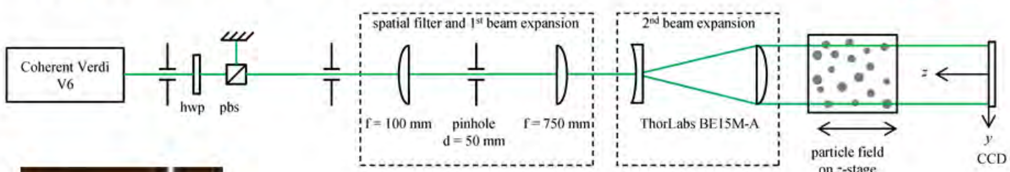
Hybrid method:

- Focus metric is a combination of amplitude minimization and edge sharpness maximization
  - Details in Guildenbecher et al 2013, *Appl. Opt.;* Gao et al 2013, *Opt. Express;* Gao et al 2014, *Appl. Opt.*



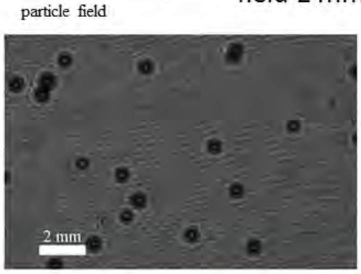
Gao et al 2014, *Appl Opt.*

Experimental validation

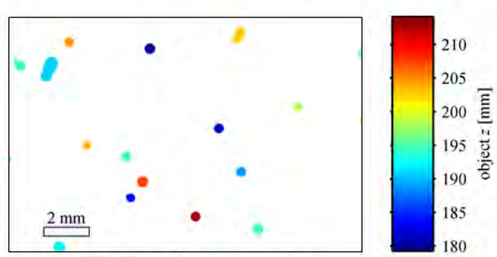


particle field

- Quasi-stationary particle field
  - Polystyrene beads ($\bar{d} \approx 465\ \mu m$) in 10,000 cSt silicone oil
  - Settling velocity ≈ 0.8 μm/s
- Multiple holograms recorded, displacing the particle field 2 mm in the *z*-direction between each acquisition

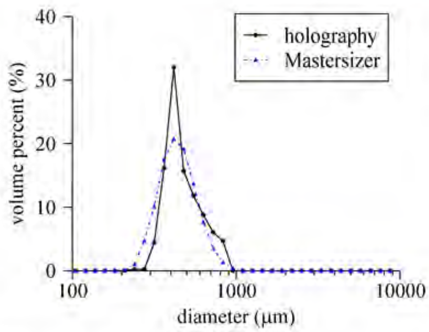


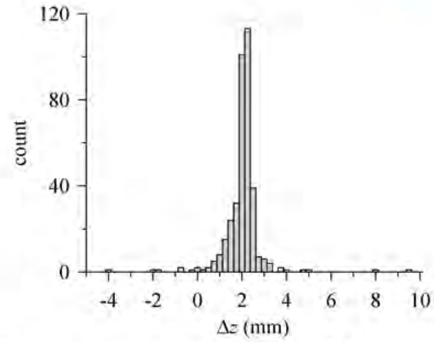
hologram



Detected objects colored by *z*-position

Experimental validation





Diameter measured from area of the detected 2D morphology

- Actual mass median diameter = 465 μm
- Measured mass median diameter = 474 μm
  - Error of 2.0% with respect to actual value

Displacement found by particle matching between successive holograms

- Actual displacement = 2.0 mm
- Mean detected displacement = 1.91 mm +/- 0.81 mm
  - Standard deviation of 1.74 times mean diameter

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Application to Liquid Sprays

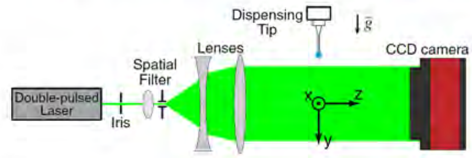
Aerodynamic drop fragmentation

Experimental configuration: Double-pulsed laser and imaging hardware as typically used in PIV

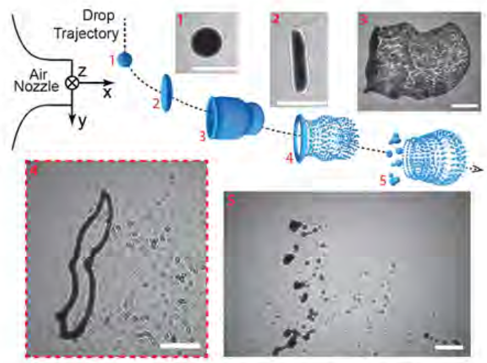
- λ = 532 nm, 5 ns pulsewidth
- Interline transfer CCD (4008 × 2672, 9 μm pixel pitch)
- Temporal separation, Δt = 62 μs, determined by laser timing

Note: without a separate reference wave, coherence length requirements in DIH are greatly relaxed.

- Expensive injection seeders are not always needed
- Faster lasers (ps or fs) can be used with some advantages (e.g. Nicolas et al 2007, *Opt. Express*)



Optical configuration (Gao, Guildenbecher et al 2013, *Opt. Lett.*)

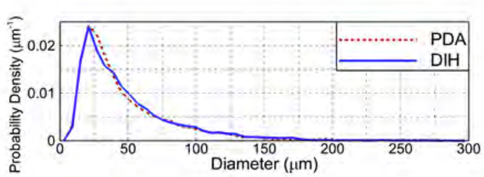


digital holograms of the breakup of an ethanol drop in an air-stream (Gao, Guildenbecher et al 2013, *Opt. Lett.*)

Aerodynamic drop fragmentation

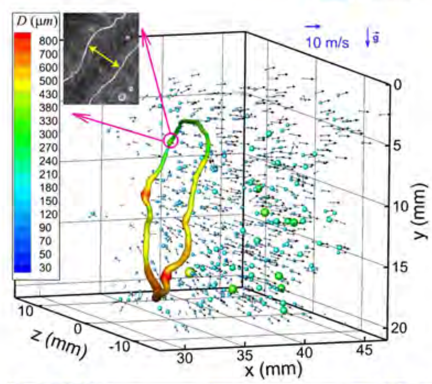
Secondary drop sizes/positions extracted by the hybrid method

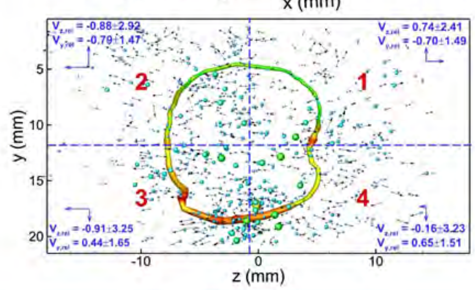
- Comparison with phase Doppler anemometer (PDA) data confirms accuracy of measured sizes



Ring measured from *z*-location of maximum image gradient

- Total volume of ring + secondary drops is within 2.2% of the initial volume

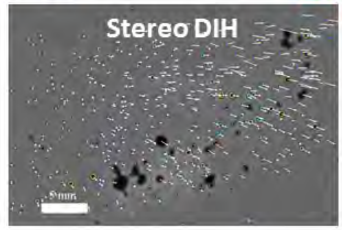


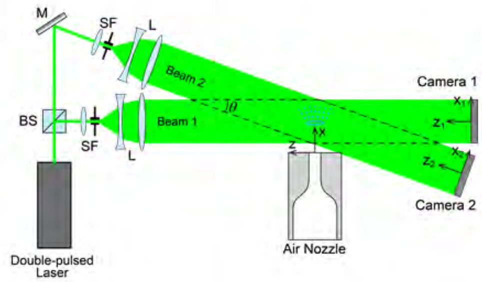


Aerodynamic drop fragmentation

Velocimetry suffers from uncertainty in the out-of-plane (z) position

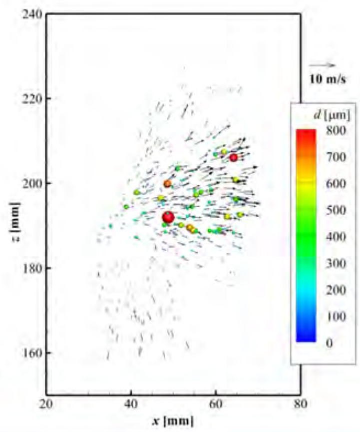
- A stereo-view configuration is one solution





Advantages:
- Improved z-uncertainty
- Eliminates false particle size and position measurements

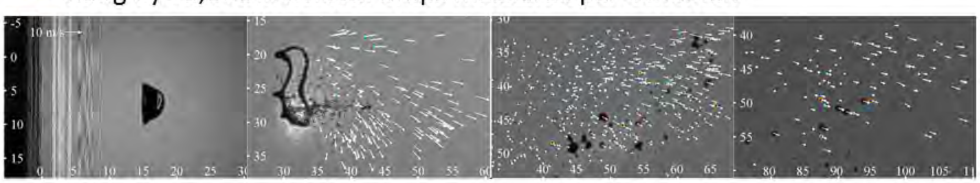
Challenges:
- Increased experimental complexity
- Careful calibration required



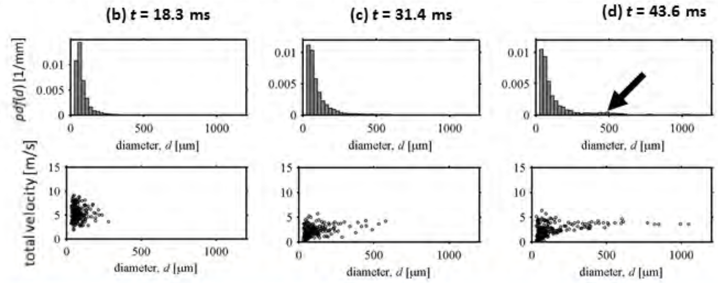
Aerodynamic drop fragmentation

Ensemble averaging of 44 realizations at each condition

- Roughly 10,000 individual drops measured per condition



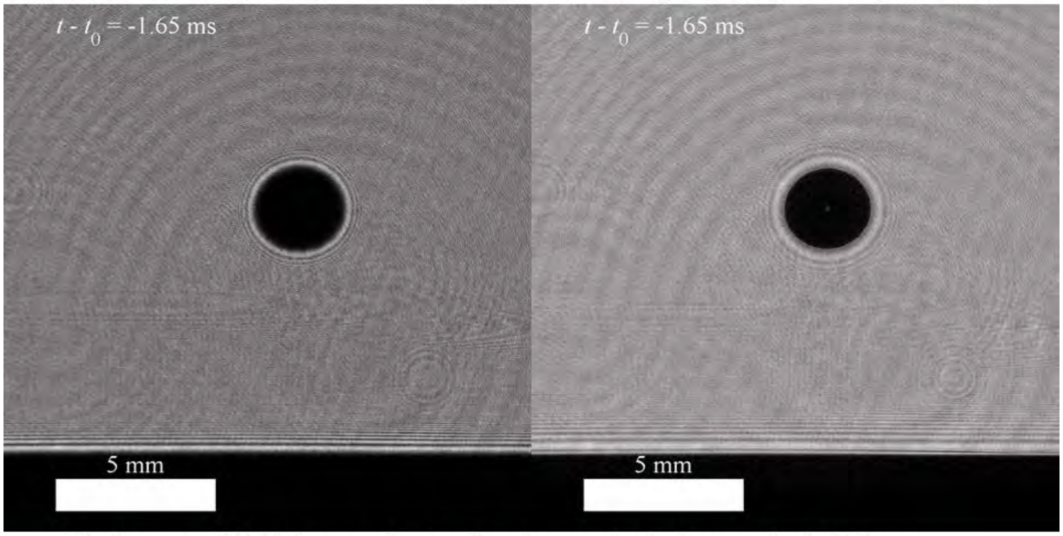
(a) t = 0 ms (b) t = 18.3 ms (c) t = 31.4 ms (d) t = 43.6 ms



DIH is particularly advantageous for rapid quantification of particle statistics

High-speed (kHz) DIH

Increased temporal resolution is possible using high-speed (kHz rate) cameras



Challenges: (1) higher readout noise, fewer pixels, larger pixel pitches
(2) very large data sets (10s of Gb)

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High-speed (kHz) DIH

Processing of a single hologram can take roughly 30 min on a typical CPU

- Much of that time spent on numerical refocusing:

$$E(x,y,z) = FFT^{-1}\left[FFT\left[h(\xi,\eta)\right] \cdot G\left(f_x, f_y, z\right)\right]$$

  - Refocusing to a single depth, z, requires:
    - (1) calculation of $G(f_x, f_y, z) = \exp\left[-jkz\sqrt{1-\lambda^2 f_x^2 - \lambda^2 f_y^2}\right]$
    - (2) multiplication of two large arrays, $FFT[h(\xi,\eta)] \cdot G(f_x,f_y,z)$
    - (3) a two-dimensional inverse FFT

Graphical processing units (GPUs) are well suited to these tasks

- E.g. NVIDIA Tesla K40 GPU, Dual Xeon CPU, Matlab v2014a with parallel computing toolbox → *per-frame processing time of ~7 seconds*

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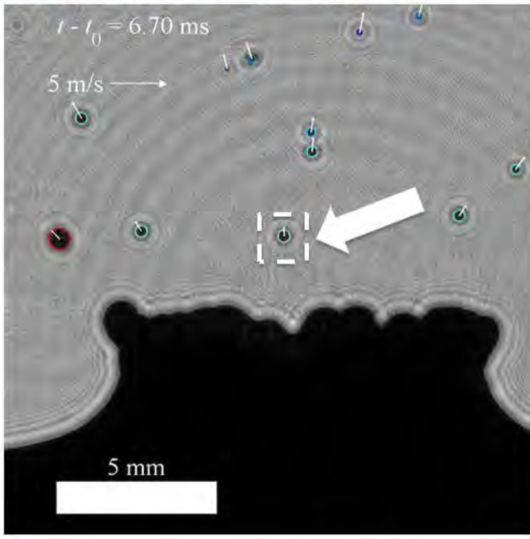
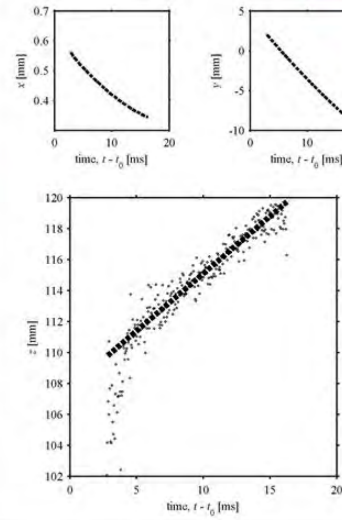
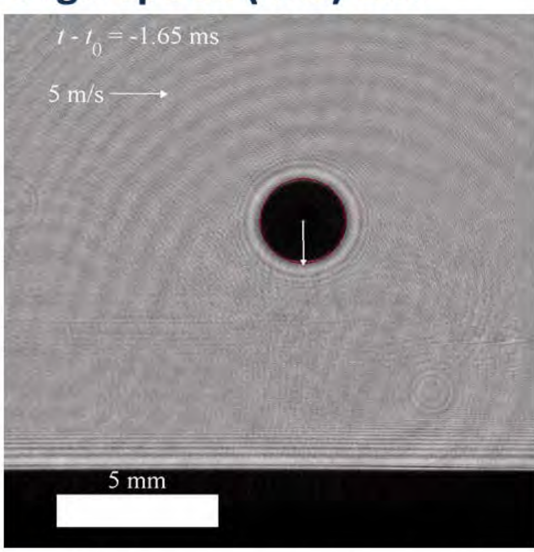
High-speed (kHz) DIH

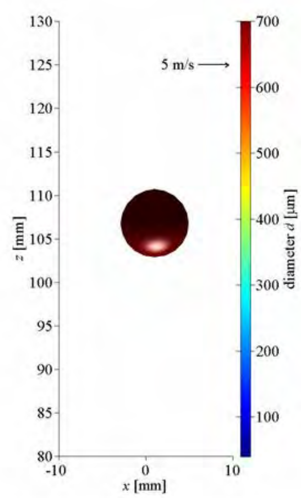




- Frame-to-frame particle matching illustrates the depth-of-focus problem
- With sufficient temporal resolution, particles trajectories can be fit to temporal models

High-speed (kHz) DIH





- Multi-frame trajectory fitting leads to a 36X reduction in *z*-uncertainty

Breakup of a water jet in a shock-tube

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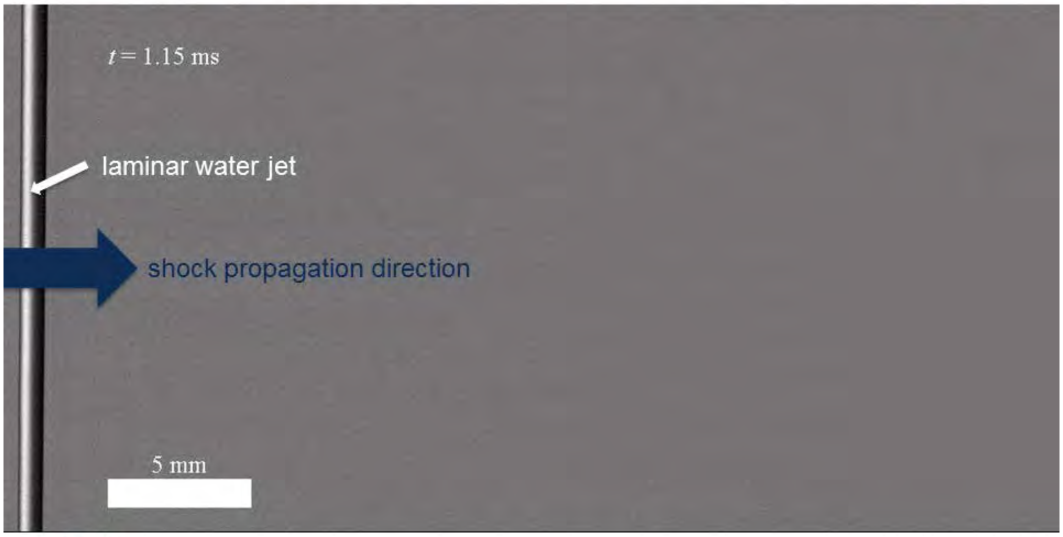
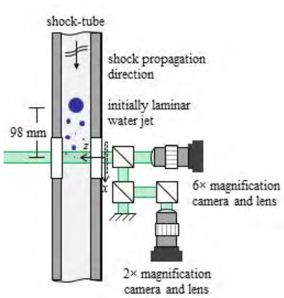


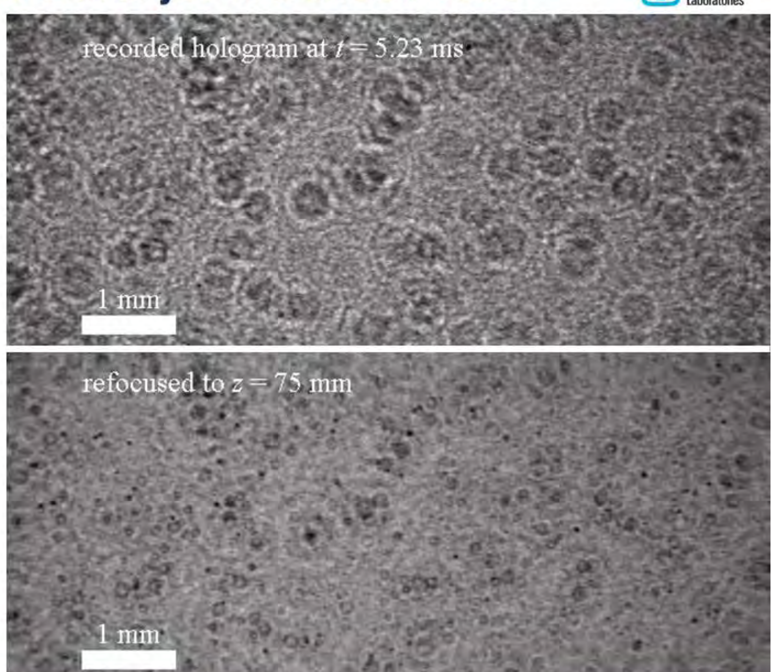
Goals:

1. Quantify the fragment sizes and velocities as a function of shock strength
2. Investigate the relation between surface instabilities and fragment properties

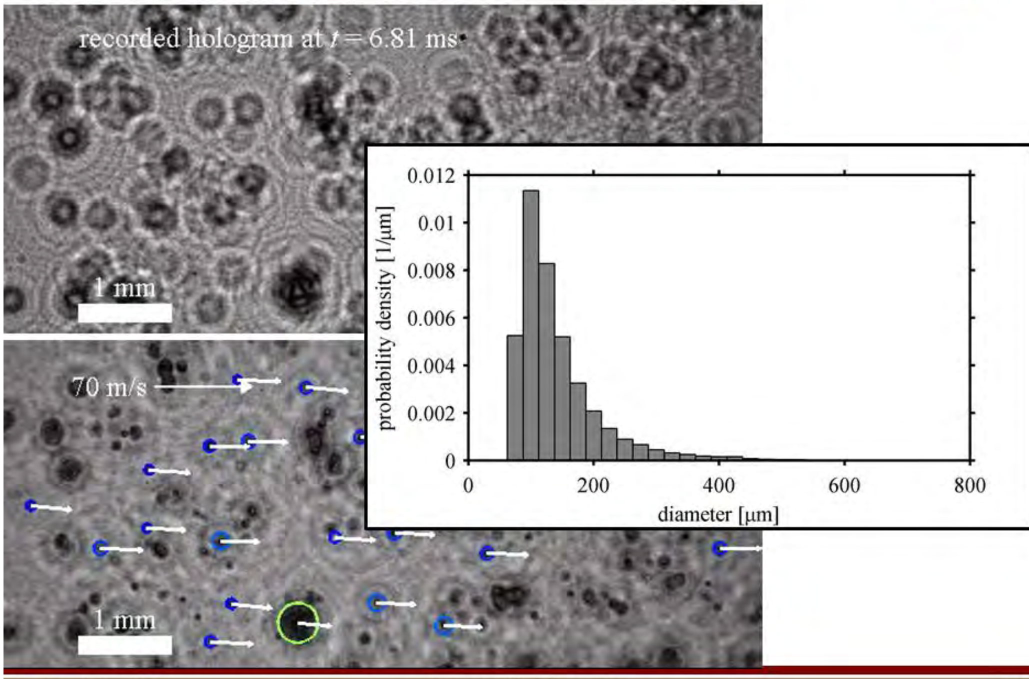
Breakup of a water jet in a shock-tube

Sandia National Laboratories





Breakup of a water jet in a shock-tube



Alternative 3D measurements

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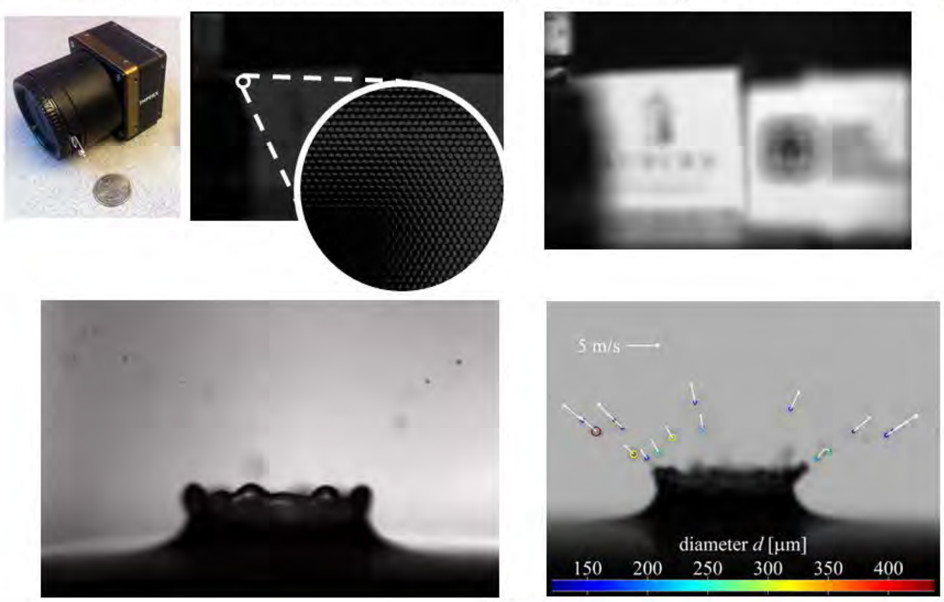
Plenoptic cameras use micro-lens arrays and white light to create a 3D image



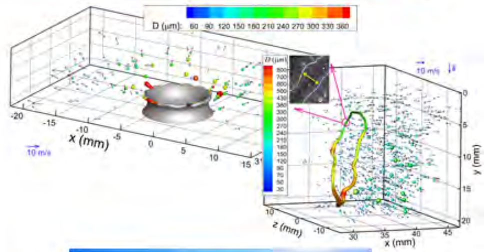
Thoughts on applications to fuel sprays

Sandia National Laboratories

DIH has many advantages:	**… and challenges:**
• Simple optical configuration	• Depth-of-focus problem
• 3D-3C measurement	• Data processing
• Rapid quantification of statistics	• Small field of view
• Captures details of transient events	• Limited to dilute sprays

For modeling of liquid fuel sprays DIH/plenoptic imaging could provide:

- Detailed particle statistics of laboratory scale problems which form the basis of fuel spray models (e.g. drop impact, aerodynamic breakup)
- Qualitative, 3D imaging of larger, more realistic phenomena
  - Quantitative imaging may be possible in sub-regions of the flow and/or downstream positions where particle density is reduced



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Propellant fire measurements

26

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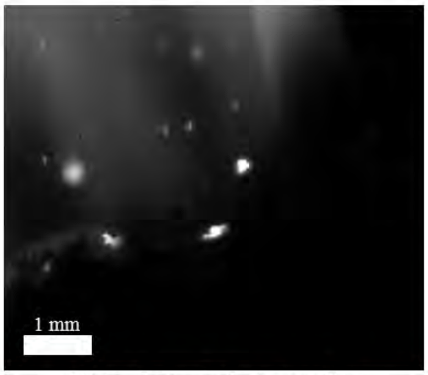
Aluminum drop combustion in propellants

Motivation: rocket failures can lead to propellant fires

- Sandia Laboratories is interested in predicting the response of objects in this environment

http://www.cbsnews.com/news/rocket-crash-no-immediate-threat-to-station-but-cause-is-unknown/

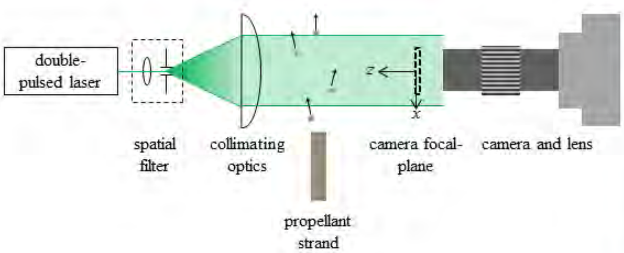


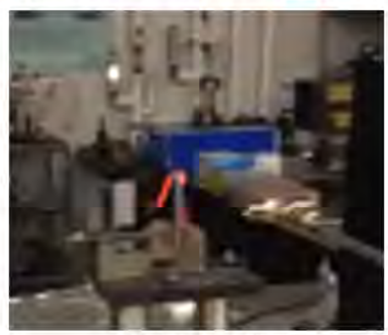
high-speed video of a burning propellant

Aluminum agglomeration at the surface yields large reacting drops with high damage potential

- Prediction requires knowledge of particle *size*, *velocity*, and *temperature*

Aluminum drop combustion in propellants





propellant in the text fixture

Propellant: solid-rocket propellant pressed into a pencil size strand

- Combusts from the top surface down, ejecting molten aluminum particles traveling a few m/s

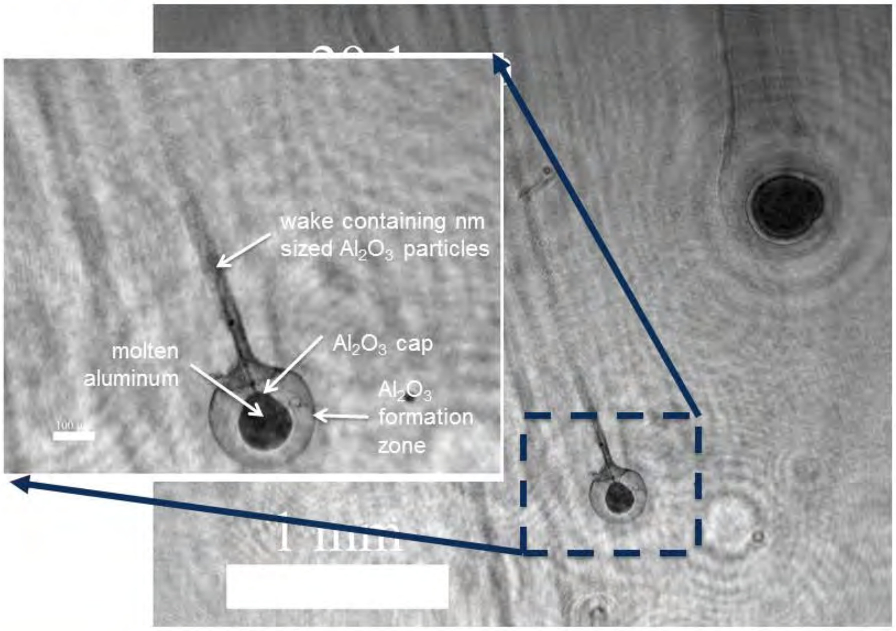
Laser: Continuum Minilite Nd:YAG, 532 nm wavelength, 5 ns pulse duration

Camera: sCMOS from LaVision at 15Hz

Lens: Infinity K2 long distance microscope with CF-4 objective

- ~ 6X magnification

Aluminum drop combustion in propellants



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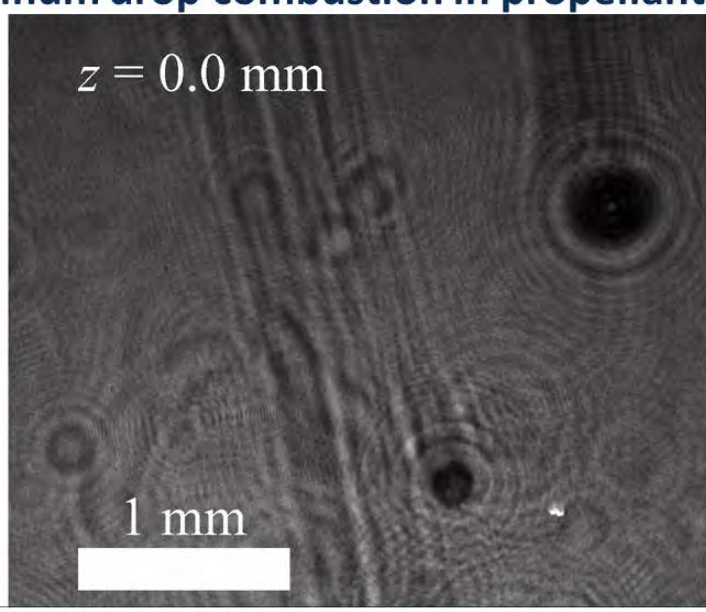
Aluminum drop combustion in propellants



Algorithms automatically measure unique features of burning aluminum

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Aluminum drop combustion in propellants

Three strand burns → 5594 images and 17496 measured drops

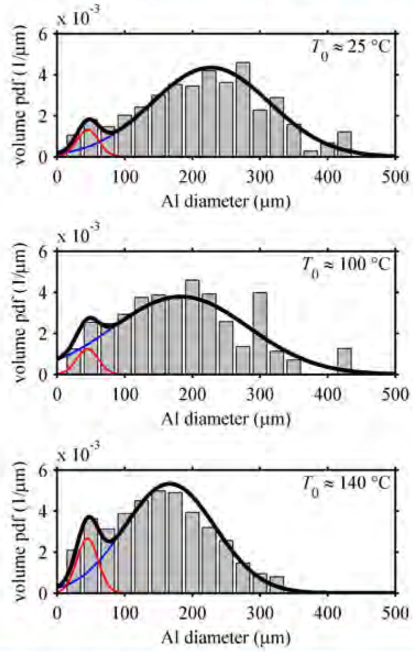
- Main peak due to agglomerated particulates
- Peak at 50 μm due to non-agglomerated particulate

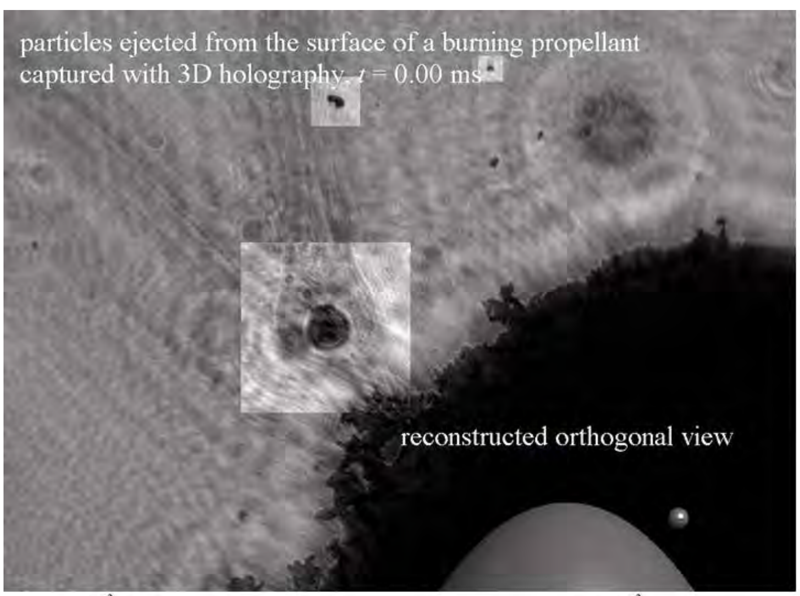
Experiments repeated at higher initial temperature (faster burn rate)

- Main peak is reduced due to decreased residence time for agglomeration
- Peak at 50 μm remains

Trend is consistent at still higher initial temperatures

- Main peak reduced further
- Peak at 50 μm remains



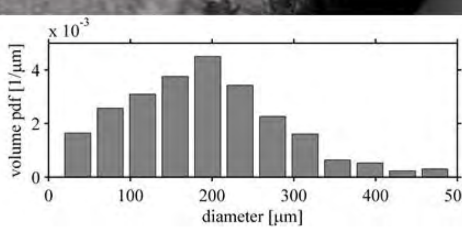


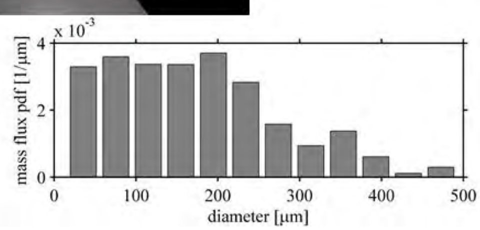
Recorded at 20,000 fps

Camera: Photron SA-Z

Laser: Coherent Verdi V6

43,684 frames → 15,991 measured drops





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Acknowledgements:

This work was supported by the Laboratory Directed Research and Development and the Weapons Systems Engineering Assessment Technology program at Sandia National Laboratories (SNL)

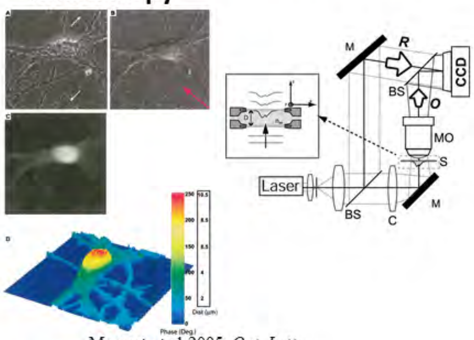
Many thanks to all of my excellent collaborators: *Jian Gao* (Johns Hopkins University), *Phillip L. Reu* (SNL), *Jun Chen* (Purdue University), *Sean P. Kearney* (SNL), *Kathryn G. Hoffmeister* (SNL), *Paul E. Sojka* (Purdue University), *Thomas W. Grasser* (SNL), *H. Lee Stauffacher* (SNL), *Marcia A. Cooper* (SNL), *Luke Engvall* (University of Colorado), *Justin L. Wager* (SNL), *Thomas A. Reichardt* (SNL), *Paul A. Farias* (SNL), and many others….

Questions

Backup slides

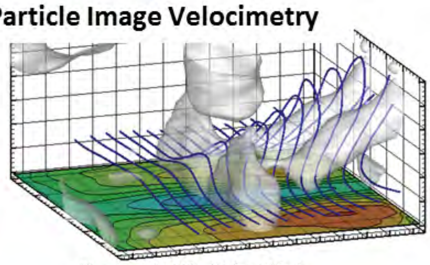
DIH in the literature

Microscopy



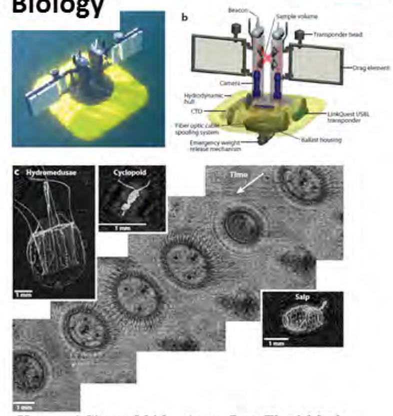
Marquet et al 2005, *Opt. Lett.*

Particle Image Velocimetry



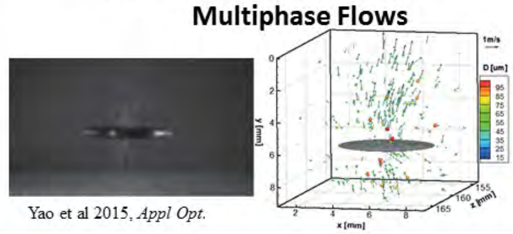
Sheng et al 2009, *J. Fluid Mech.*

Biology



Katz and Sheng 2010, *Annu. Rev. Fluid Mech.*

Multiphase Flows



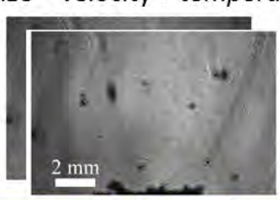
Yao et al 2015, *Appl Opt.*

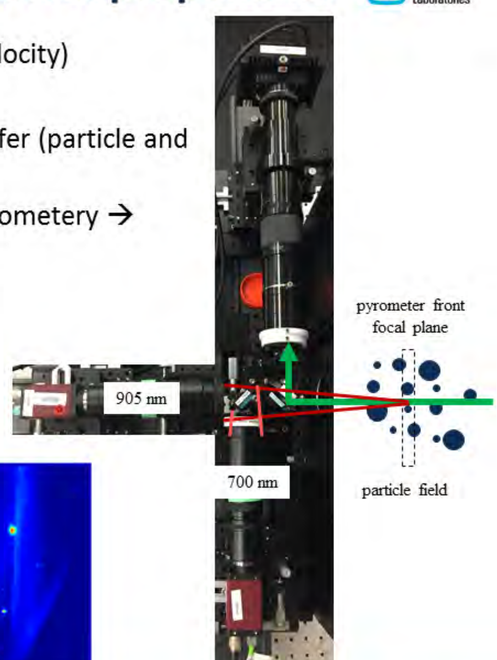
Aluminum drop combustion in propellants

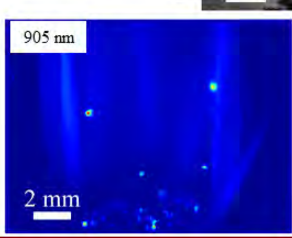
DIH gives mass transfer (particle size + velocity)

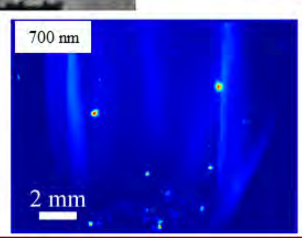
We really need to quantify the heat transfer (particle and gas phase)

- Combination of DIH and two-color pyrometery → particle size + velocity + *temperature*









Aluminum drop combustion in propellants

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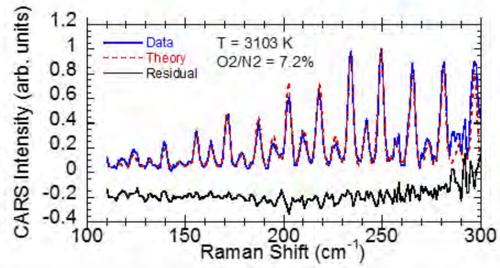
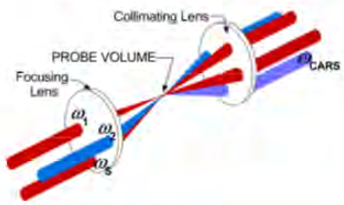
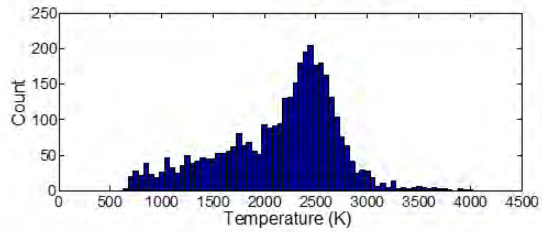
Gas phase temperature can be measured using fs/ps CARS

- Advantages compared to ns CARS:
  - Low (mJ) pulse energies → reduces dielectric breakdown
  - Time-delayed probe → eliminates background signal
  - Enhanced precision ~ 1%



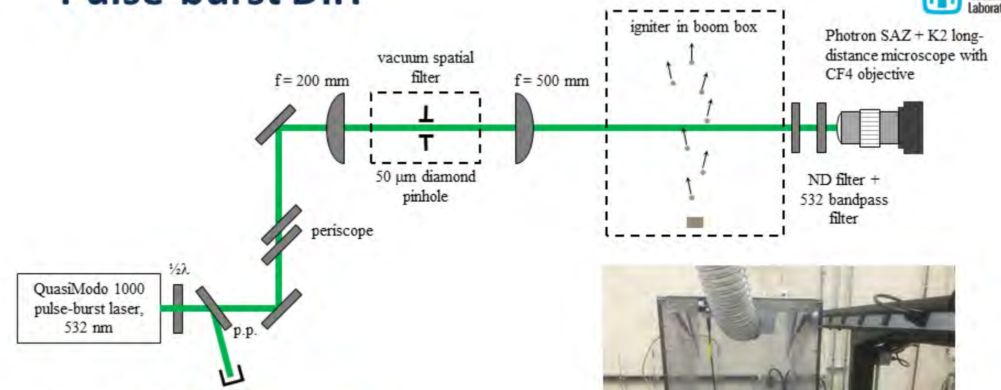


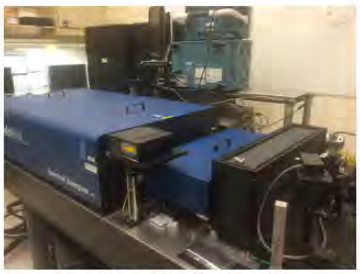


See poster: *Hybrid fs/ps CARS for sooting and metalized flames* by Kathryn Hoffmeister, Sean Kearney, Daniel Guildenbecher, and Caroline Winters

New concepts and opportunities

Pulse-burst DIH

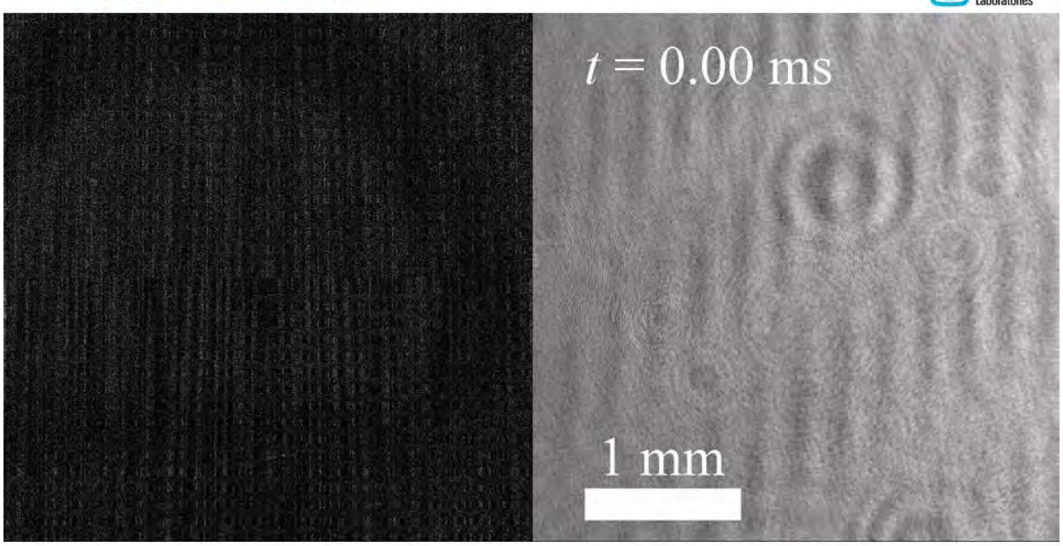




Spectral Energies pulse-burst laser

boom-box and high-speed DIH imager

Pulse-burst DIH

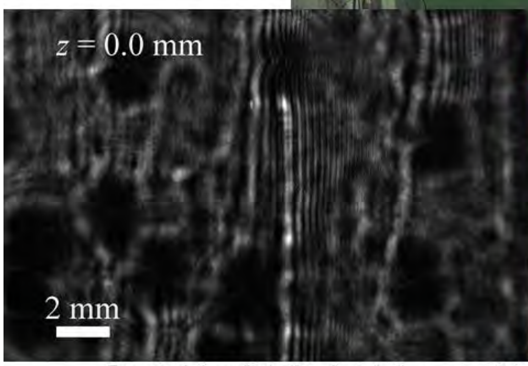


- Beam quality is sufficient for DIH
- Freezes high-speed particles and penetrates through flash and smoke
- Noise due to soot and index-of-refraction gradients

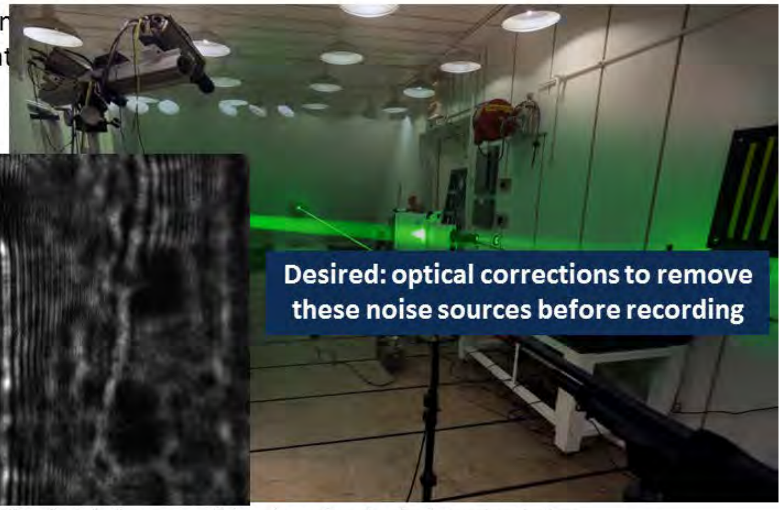
Optical challenges in DIH

Coherent imaging is susceptible to:

- Image distortion through index of refraction gradients
- Loss of phase ir to multiple-scat

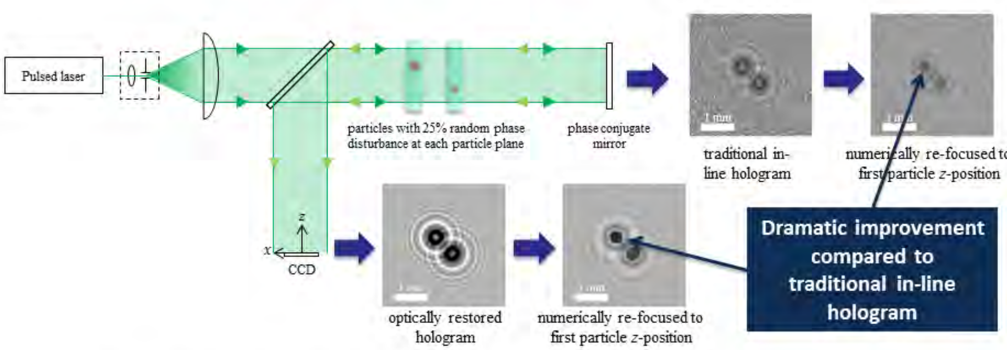


Reconstructed amplitude throughout depth, z



Holography configuration for shotgun investigations

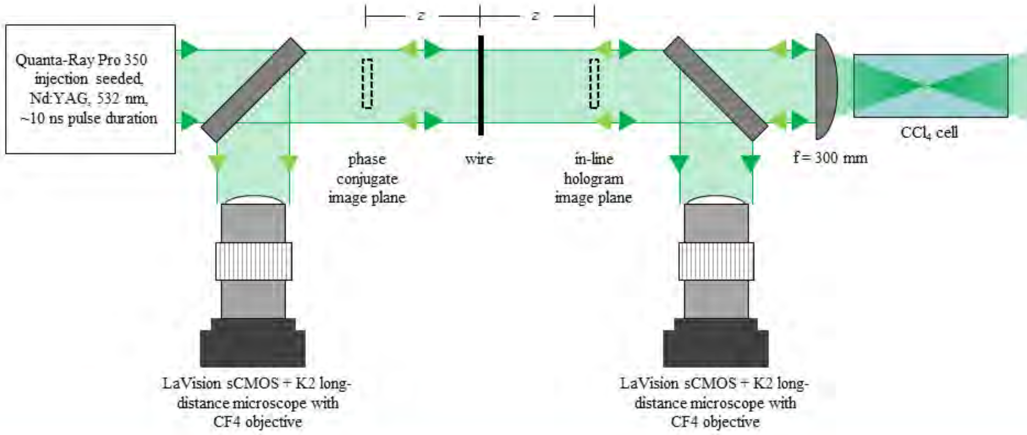
Phase-conjugate DIH theory



- Phase-conjugate mirror reflects the incoming wave with opposite phase
  - Non-linear optical effect achieved through passive means (stimulated Brillouin scattering) or active means (degenerate four-wave mixing)
- After double passing, the phase disturbance is canceled

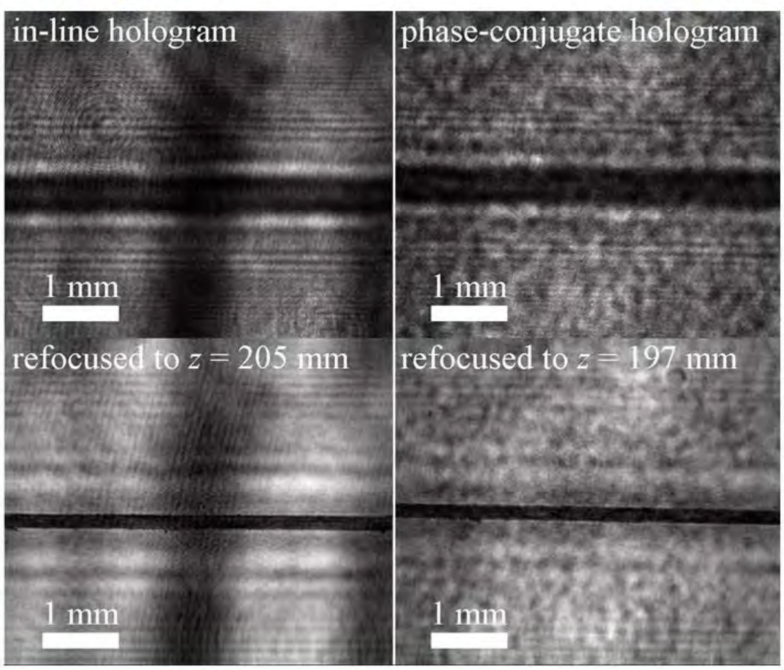
SBS phase-conjugate DIH

A focused beam in a non-linear medium induces phase conjugation via stimulated Brillouin scattering (SBS)



SBS phase-conjugate DIH

Without a disturbance both views give similar results



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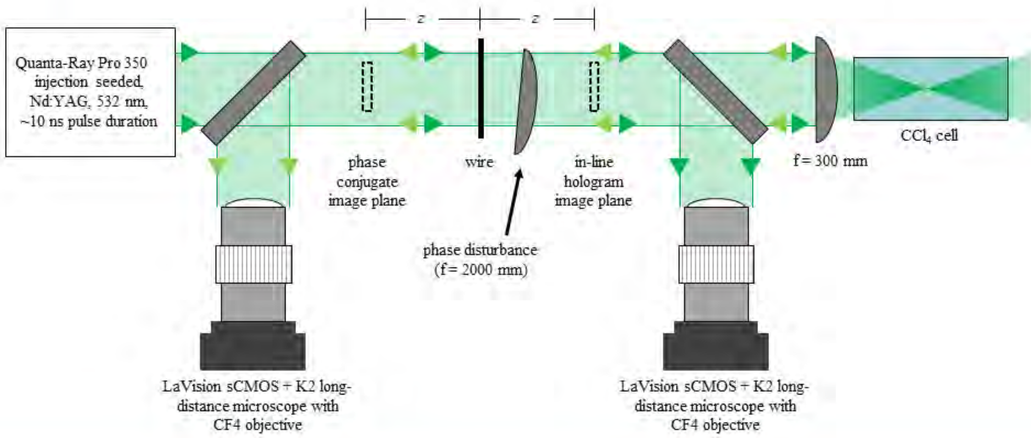
SBS phase-conjugate DIH

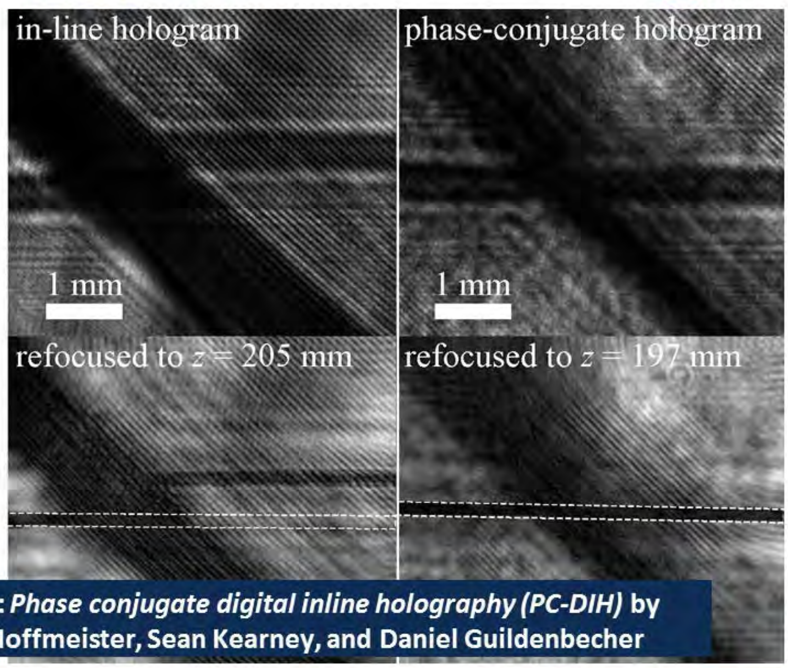
A focused beam in a non-linear medium induces phase conjugation via stimulated Brillouin scattering (SBS)

- A misaligned lens in the beam path causes a phase disturbance



SBS phase-conjugate DIH

Phase conjugation corrects image distortion



See poster: *Phase conjugate digital inline holography (PC-DIH)* by Kathryn Hoffmeister, Sean Kearney, and Daniel Guildenbecher

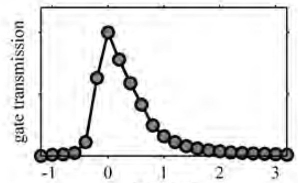
Ballistic DIH

Sandia National Laboratories

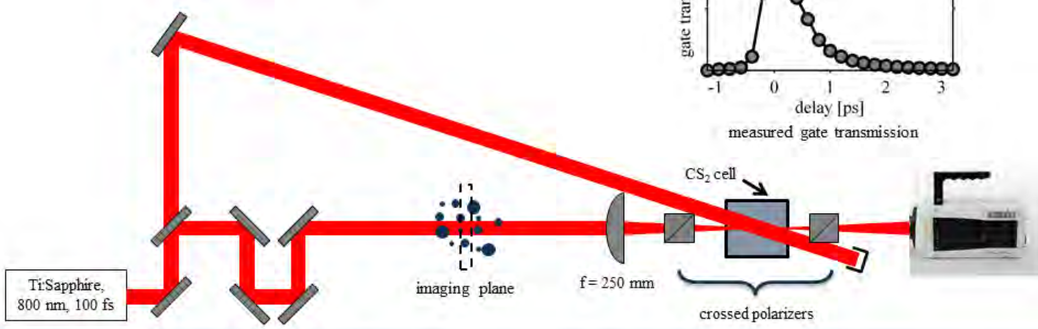
Multiple scattering can be reduced through ps time gating

- Combination with DIH might enable scatter free 3D imaging through optically dense media
  - First proposed by: Trolinger et al 2011, *International Journal of Spray and Combustion Dynamics*

ballistic image of a diesel spray (Linne et al 2006, *Exp. Fluids*)



measured gate transmission



Ballistic DIH

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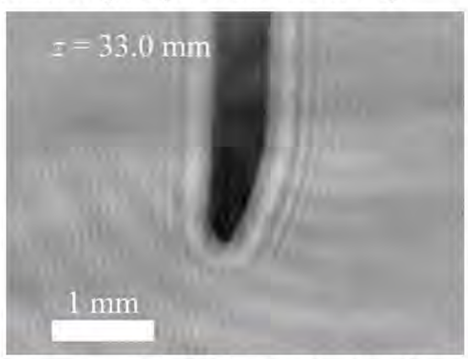
DIH imaging through a Kerr gate (no scatter sources)



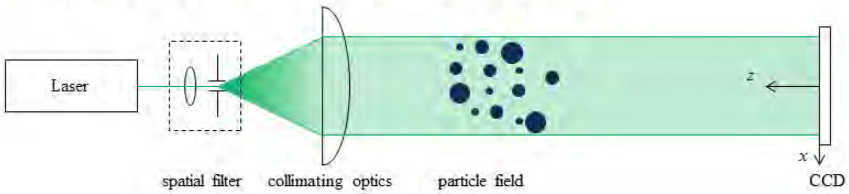
DIH image of a needle recorded with the ballistic configuration (1.6 ps switch delay)

See poster: *Ballistic imaging holography* by Derek Dunn-Rankin, Ali Ziaee, Jim Trolinger

Next step: Explore ballistic DIH through dense scattering sources

- Challenge: *Can we retain sufficient image fidelity and coherence to resolve 3D phenomena?*

Where is the reference wave?



Hologram is the combination of object and reference waves: $h = |E_o+E_r|^2$

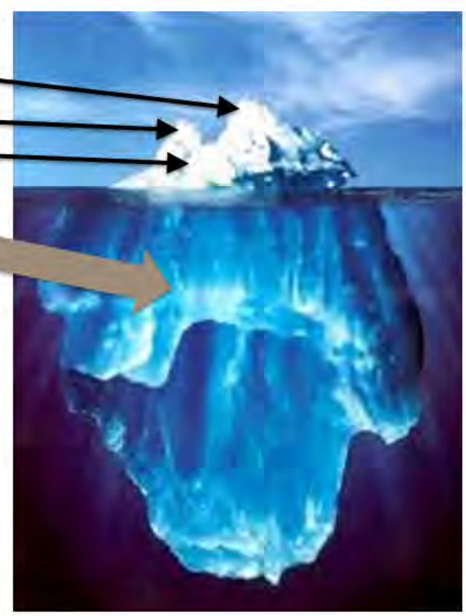
- Reconstruction with E_r gives: $h \cdot E_r = \underbrace{(|E_o|^2 + |E_r|^2)E_r}_{\text{DC term}} + \underbrace{|E_r|^2 E_o}_{\text{virtual image}} + \underbrace{E_r^2 E_o^*}_{\text{real image}}$
  - In off-axis holography, these terms are spatially separated are we attempt to reconstruct the original object wave, E_o
- In in-line holography, we actually want to reconstruct the combination of the reference wave and object wave, E_o+E_r
  - Rearranging: $h \cdot E_r = \underbrace{|E_o|^2 E_r}_{\text{DC term}} + \underbrace{|E_r|^2(E_o+E_r)}_{\text{virtual image}} + \underbrace{E_r^2 E_o^*}_{\text{real image}}$

Data processing

The basic DIH system includes:

- Coherent light source (laser)
- Particle field
- Image recorder (digital camera)

- **DATA ANALYSIS SOFTWARE**



Currently each group has their own code:

- Hybrid : Guildenbecher, Gao, et al
- Laplacian: Choi and Lee
- Correlation coefficient: Yang et al
- Minimum edge intensity: Tian et al
- Variance: Palero et al.
- Etc…

SBS phase-conjugate DIH

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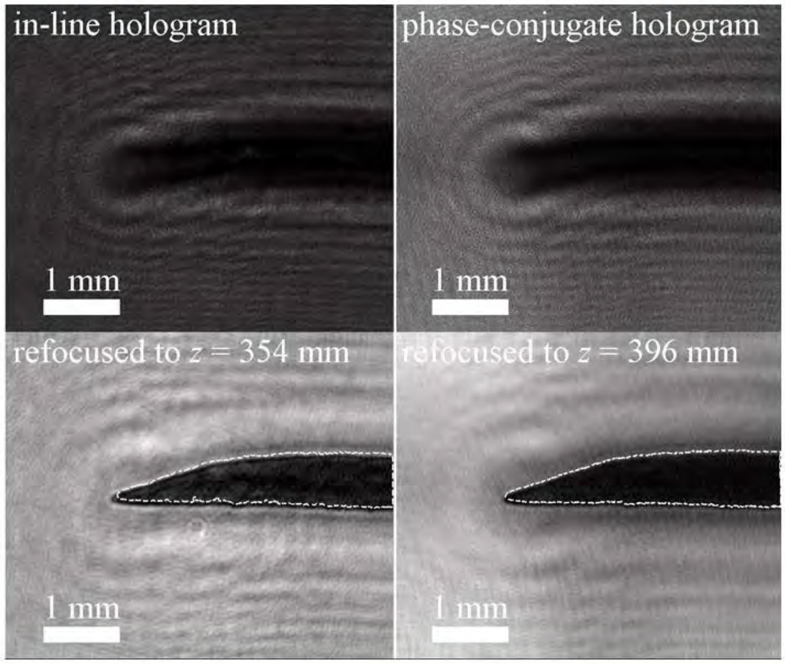
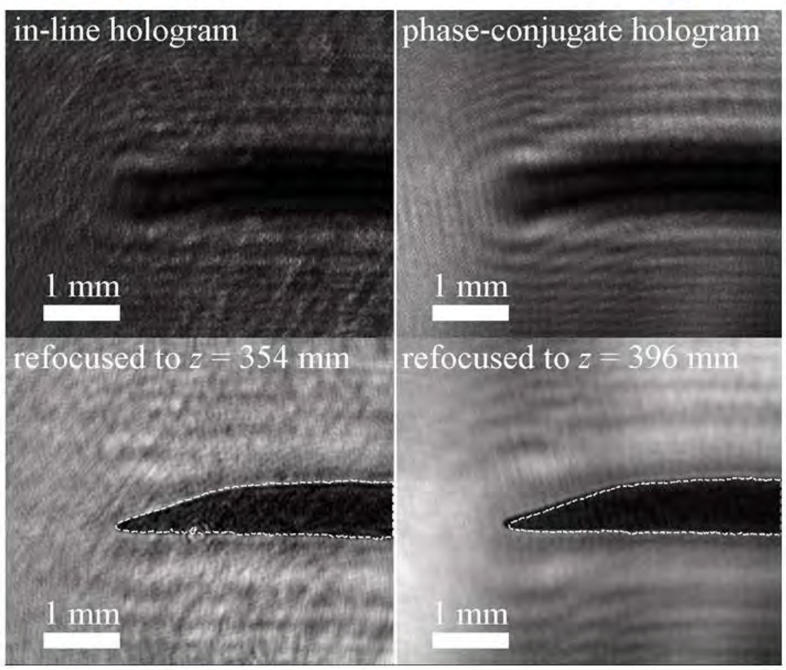
A hot plate creates a phase disturbance in the air



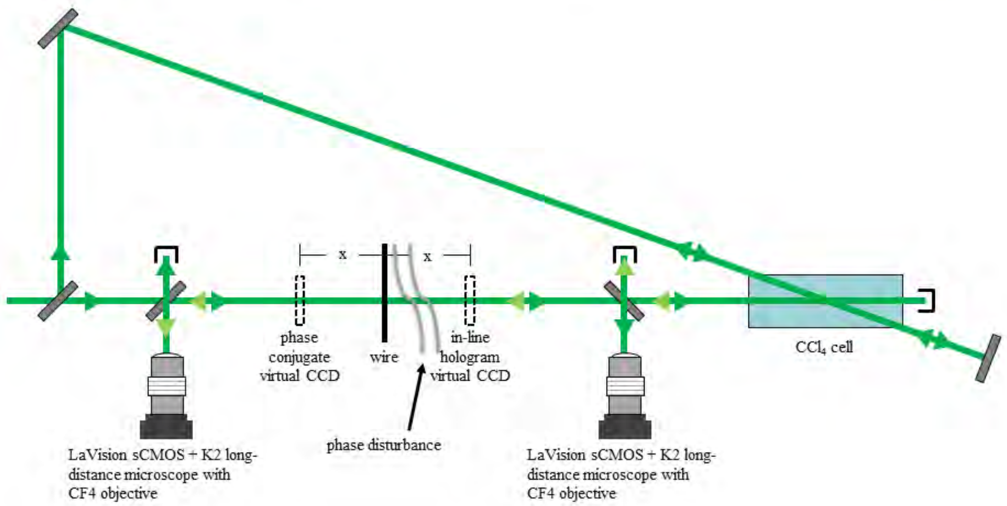
SBS phase-conjugate DIH

Sandia National Laboratories

A butane igniter creates a more severe phase disturbance

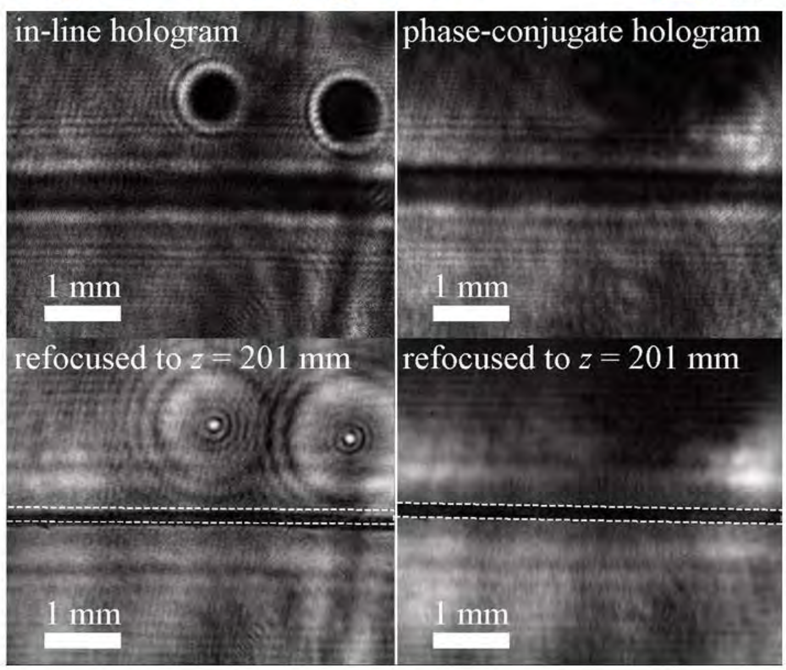


4-wave mixing phase-conjugate DIH



4-wave mixing phase-conjugate DIH

Glass with a uneven layer of optical glue creates a severe distortion



Drop impact on a thin film

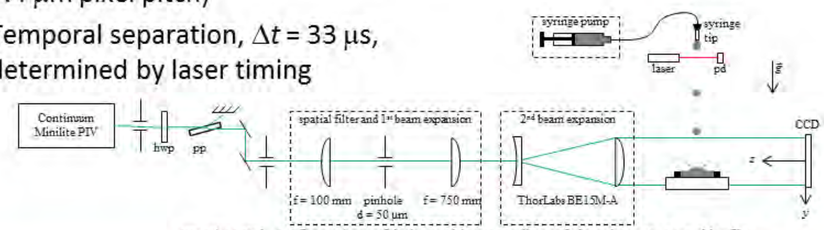
Motivation: measurement of secondary droplets by other methods requires significant experimental repetition

- Process symmetry provides opportunities to validate accuracy

Experimental configuration:

- Double pulsed laser (λ = 532 nm, 5 ns pulsewidth)
- Interline transfer CCD (4872 × 3248, 7.4 μm pixel pitch)
- Temporal separation, Δt = 33 μs, determined by laser timing

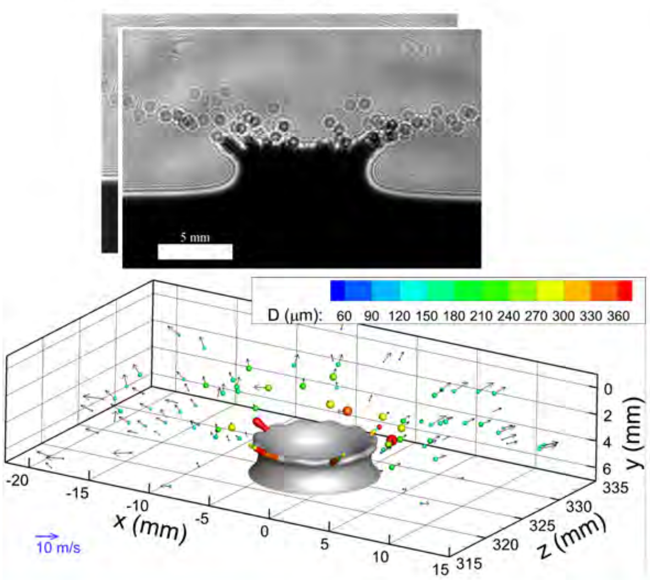
impact of a 3 mm water drop on a 2 mm water film (Guildenbecher et al, 2013, *Exp. Fluids.*)

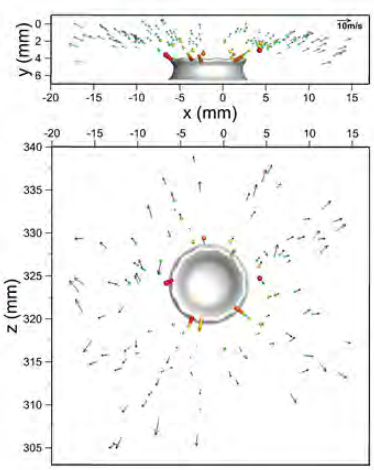


experimental configuration of holographic recording of drop impact on a thin film (Guildenbecher et al, 2014, *Exp. Fluids.*)

Drop impact on a thin film

Processed with the hybrid method





holographic reconstruction of drop impact on a thin film (Guildenbecher et al, 2014, *Exp. Fluids.*)

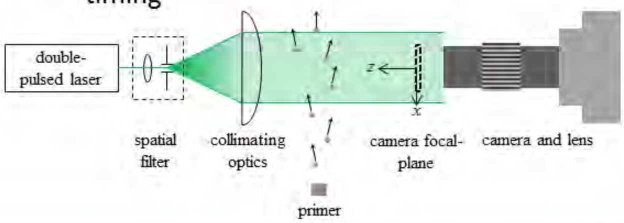
Approved for public release; distribution is unlimited.

Percussion primers

Motivation: No viable technique currently exists to quantify the size and velocity distribution from the hot particles in percussion primers

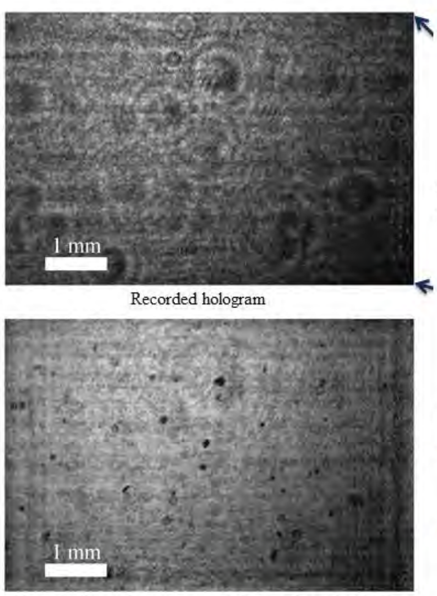
Experimental configuration:

- Double pulsed laser (λ = 532 nm, 5 ns pulsewidth)
- Interline transfer CCD (4872 × 3248, 7.4 μm pixel pitch)
- ~6X magnification achieved using Infinity K2 long distance microscope with CF-4 objective
- Temporal separation, Δt = 2 μs, determined by laser timing



High-speed video of event

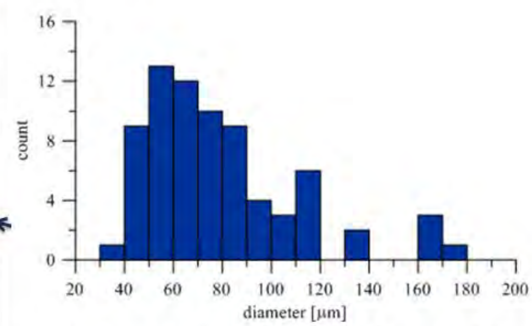
Percussion primers



Recorded hologram

Numerically re-focused to z = 200 mm from the CCD

Five holograms recorded at these conditions



First known quantification of particle size

- Particle size distribution shows the expected behavior
- Probability goes to zero at large and small particle diameters

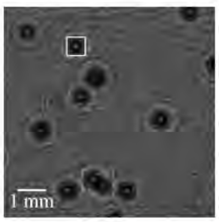
Cross-correlation method

Theory: in-focus particle images from two sequential holograms contain correlated information

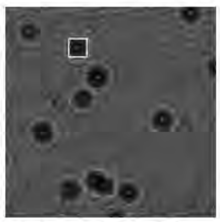
- The maximum cross-correlation, c, gives the displacement (Δx, Δy)

$$c = \max_{\Delta x, \Delta y} \left[\sum_m \sum_n \mathrm{Img}_1(m,n) \mathrm{Img}_2^*(m,n)(m-\Delta x, n-\Delta y) \right]$$

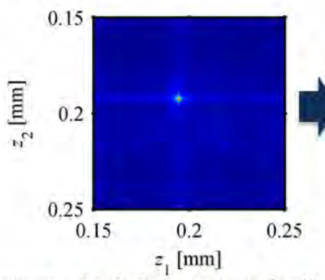
- Img_1 and Img_2 chosen as the edge sharpness images from the two frames
- z positions in each frame (z_1 and z_2) are found from the maximum value of c over all possible combinations of z_1 and z_2



hologram (Guildenbecher et al, 2013, *Opt. Lett.*)



hologram after displacing the particle field by 2 mm (Guildenbecher et al, 2013, *Opt. Lett.*)

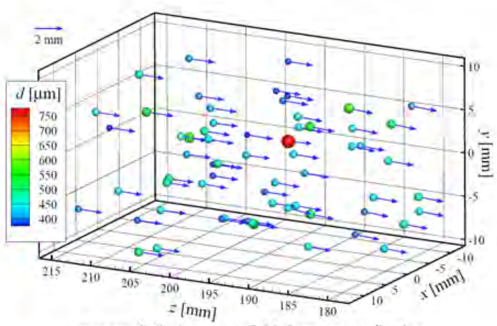


maximum value of c for the particle in the white boxes (Guildenbecher et al, 2013, *Opt. Lett.*)

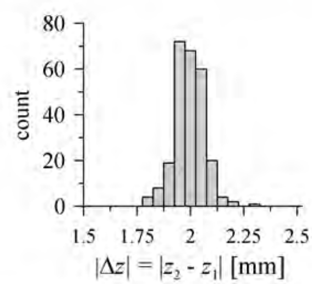
z_1 = 194.72 mm,
z_2 = 192.72 mm,
Δz = 2.00 mm

Cross-correlation method

Again, experimentally validated with quasi-stationary particles in silicone oil



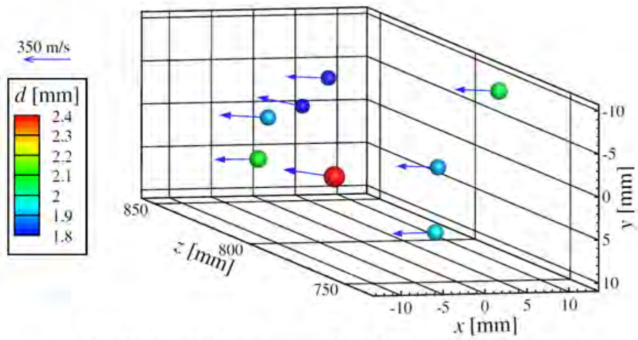
measured displacement field from one realization (Guildenbecher et al, 2013, *Opt. Lett.*)



measured z-displacements from all realizations (Guildenbecher et al, 2013, *Opt. Lett.*)

- Actual displacement = 2.0 mm
- Mean detected displacement = 1.996 mm +/- 0.072 mm
  - Standard deviation of 0.15 times mean diameter
  - Order of magnitude improvement compared to uncertainties in the literature

Sonic pellets from a shotgun

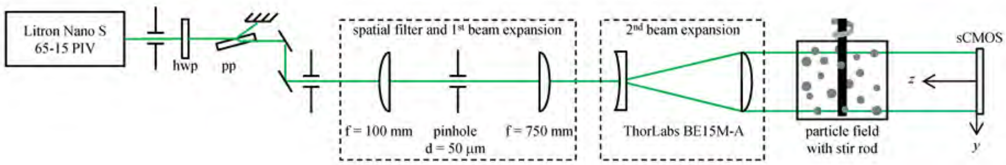


particle field from the shotgun measured with the cross-correlation method (Guildenbecher et al, 2013, *Opt. Lett.*)

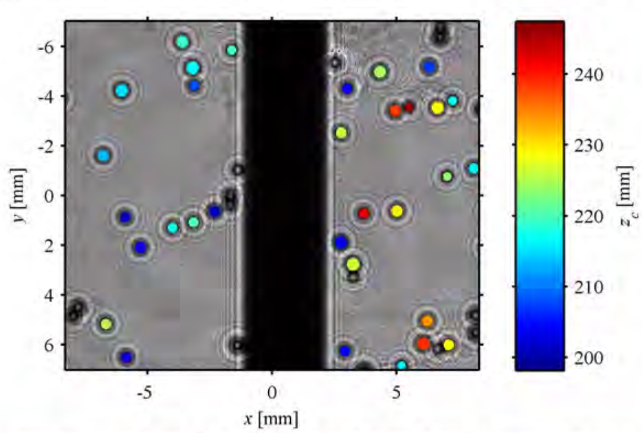
Results closely match the expected mean velocity (350 m/s) and diameter (2.0 mm)

- Uncertainty in Δz is on the order of 0.2 particle diameters

3D, 3C fluid velocity measurements?



- Particles stirred by a rotating rod (r_0 = 1.58 mm, ω_0=100 rpm)
- Recorded at 15Hz with a LaVision sCMOS camera (2560 × 2160, 6.5 μm pixel pitch)



particles measured with the hybrid method, background shows the recorded holograms

3D, 3C fluid velocity measurements?

Sandia National Laboratories

For all trajectories

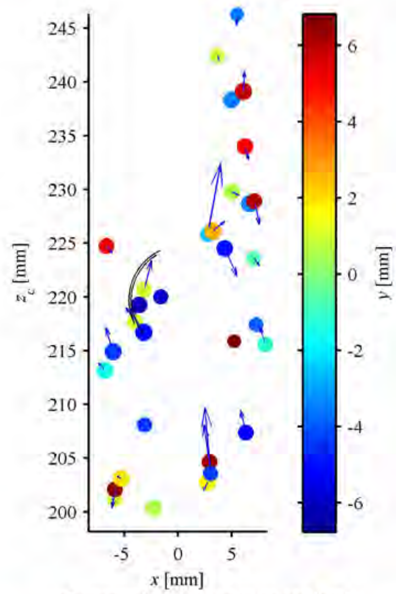
- Error in measured z = -0.04 ± 1.51 mm
- Error in measured Δz = -0.03 ± 1.05 mm
  - Standard deviation of $2.3 \cdot \bar{d}$

Experiments repeated with smaller particles ($\bar{d} = 118 \mu m$, see paper for details)

- Error in measured z = -0.003 ± 0.379 mm
- Error in measured Δz = -0.001 ± 0.302 mm
  - Standard deviation of $2.6 \cdot \bar{d}$

Next steps:

- Compare results with alternative particle detection methods
- Use results to quantify effects of particle overlap and other experimental noise sources



all measured x-z trajectories vs. predicted

3D, 3C fluid velocity measurements?

Sandia National Laboratories

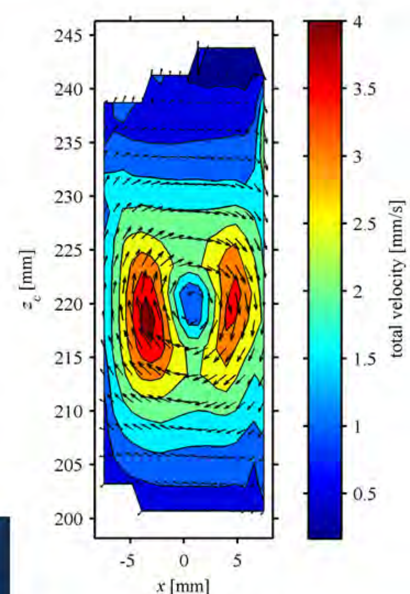
Advantages:

- Simple optical setup requiring only one line-of-sight view
- Large depth of field (hundreds of mm possible)
- Particle sizes can be measured (if desired)

Challenges:

- High uncertainty in the z-direction
- Particle field must be relatively sparse providing only limited vectors
- Vectors at random positions
- Methods not as mature as PIV or even tomographic-PIV

Note: the literature contains many works on holographic-PIV. My own work has not been focused on these applications



mean measured x-z velocities

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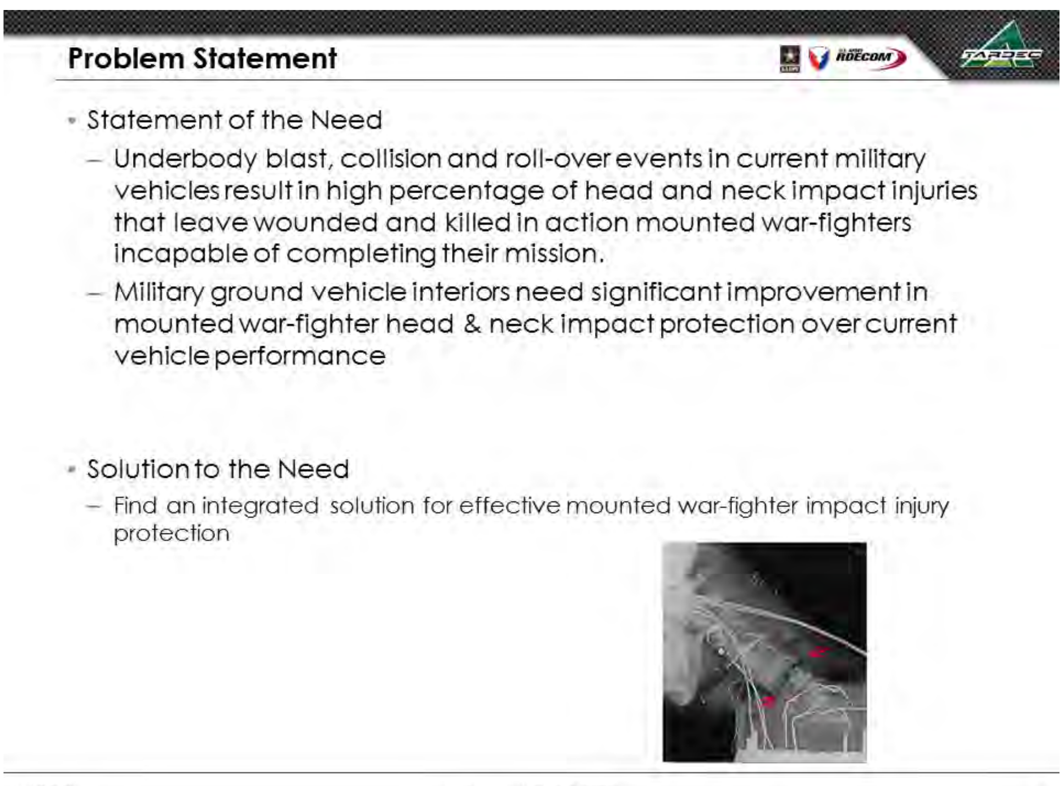
U.S. ARMY
RDECOM
TARDEC
U.S. ARMY TANK AUTOMOTIVE RESEARCH, DEVELOPMENT AND ENGINEERING CENTER
Fire Resistant Energy Attenuating
Materials for use in Military Vehicles
Julie Klima
TARDEC Ground System Survivability
Interior Blast Mitigation Team
14 October 2015
UNCLASSIFIED: Distribution Statement A. Approved for public release.

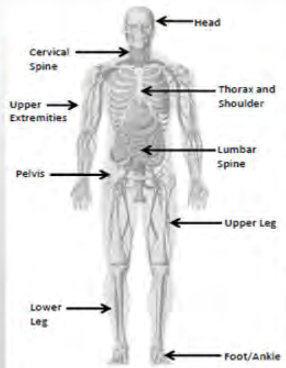

Problem Statement
RDECOM
TARDEC
• Statement of the Need
– Underbody blast, collision and roll-over events in current military vehicles result in high percentage of head and neck impact injuries that leave wounded and killed in action mounted war-fighters incapable of completing their mission.
– Military ground vehicle interiors need significant improvement in mounted war-fighter head & neck impact protection over current vehicle performance
• Solution to the Need
– Find an integrated solution for effective mounted war-fighter impact injury protection

Injury Data

Medical Research and Materiel Command
U.S. Army Aeromedical Research Laboratory
Fort Rucker, Alabama

Whole-Body Summary

KIA	Injuries (n=2180)	Indiv (m=116)
Head and Face	24%	84%
Cervical Spine and Neck	7%	52%
Upper Extremity	7%	49%
Torso (shoulder and abdomen)	35%	78%
Lumbar Spine	5%	30%
Pelvis (perineal and hip)	8%	51%
Lower Extremity	1%	9%
Upper Leg	4%	44%
Lower Leg (knee)	4%	43%
Foot/Ankle	7%	36%



WIA	Injuries (n=1664)	Indiv (m=439)
Head and Face	9%	16%
Cervical Spine and Neck	6%	19%
Upper Extremity	7%	16%
Torso (shoulder and abdomen)	20%	32%
Lumbar Spine	17%	35%
Pelvis (perineal and hip)	4%	8%
Lower Extremity	1%	2%
Upper Leg	2%	8%
Lower Leg (knee)	11%	28%
Foot/Ankle	23%	33%

n = total number of injuries for KIAs and WIAs, respectively
m = total number of individuals for KIAs and WIAs, respectively

February 1, 2012 40

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Background - Vehicle Baseline Testing

- Testing the original structure of the vehicle without the addition of interior impact protective solutions, IIPS.
  - head impact injury performance of the vehicle's current design state
  - determines whether adding energy attenuating materials would be beneficial in reducing potential head impact injuries.
- Impact locations were selected based upon the proximity to the occupant's head in the upward and lateral motion typical of an underbody blast.
- Testing conducted at Soldier System Interface Impactor (SSII) Laboratory
  - Selfridge Air National Guard Base
- Free Motion Headform (FMH) injury assessment values compared to Occupant Centric Protection (OCP)
  - Threshold: HIC(d) ≤ 1000
  - Objective: HIC(d) ≤ 700
- FMH Impact Speed Measurement
  - 24 kph ± 1.0 kph
- Advanced Combat Helmet (ACH)
  - FMVSS 201U test equipment had too much variation for repeatability
  - Testing as conducted without an ACH where applicable

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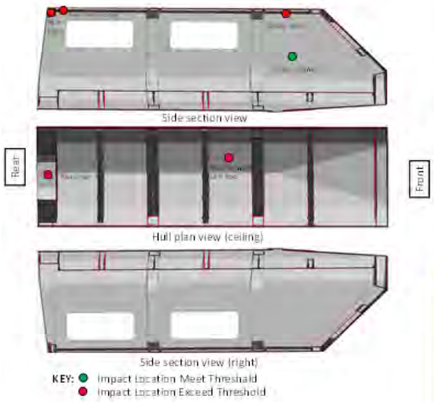
Vehicle A Baseline Testing

- 87 head impact tests performed from June 2013 to July 2013
- Baseline testing without ACH was conducted on 6 locations



*Testing conducted without ACH

Data Takeaway:

- Very rigid interior design, significantly higher than the injury criteria requirements (HIC(d) < 1000)
- Threshold requirement met for 1 location
  - Driver Sidewall
- Driver sidewall location consists of an electrical door panel which may act as an energy attenuator providing enough energy dissipation to prevent impact related head injuries without needed additional protection.
- Next Steps:
  - Addition of EA materials to each baseline location.

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Background – Material Testing

- Soldier System Interface Impactor (SSII) Laboratory located at Selfridge Air National Guard Base to conduct head impact testing

- FMH injury assessment values compared to Occupant Centric Protection (OCP)
  - Threshold: HIC(d) ≤ 1000
  - Objective: HIC(d) ≤ 700
- Current FMH analysis includes:
  - HIC(d) = 0.75446 (Free Motion Headform HIC) + 166.4
  - $\text{HIC} = \left[\frac{1}{t_2-t_1}\int_{t_1}^{t_2} a(t)dt\right]^{2.5}(t_2-t_1)$
- FMH Impact Speed Measurement
  - 24 kph ± 1.0 kph
- Advanced Combat Helmet (ACH)
  - FMVSS 201U test equipment had too much variation for repeatability
  - Testing as conducted without an ACH where applicable

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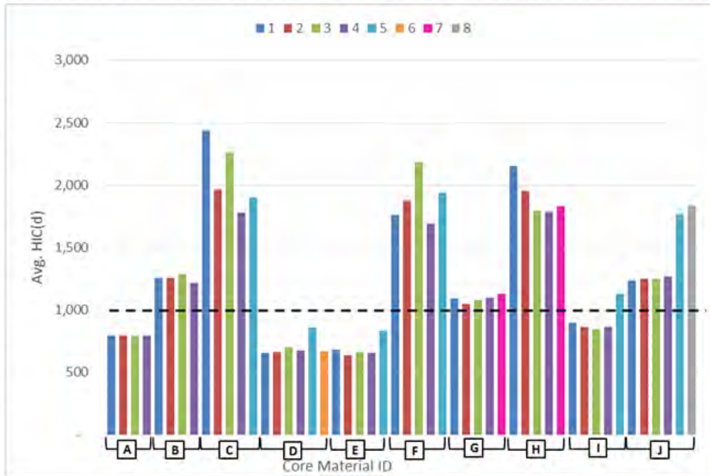
Material Analysis of Alternatives (AoA)

Core Material ID	Facesheet Material ID	Facesheet Material	Material	Thickness
A	1	Fabric	Plastic	1.4 inch (35.5 mm)
A	2	Fabric		
A	3	Fabric		
A	4	Fabric		
B	1	Fabric	Plastic	0.8 inch (20.3 mm)
B	2	Fabric		
B	3	Fabric		
B	4	Fabric		
C	1	Fabric	Plastic	0.5 inch (12.7 mm)
C	2	Fabric		
C	3	Fabric		
C	4	Fabric		
C	5	Rigid		
D	1	Fabric	Plastic	1.5 inch (38.1 mm)
D	2	Fabric		
D	3	Fabric		
D	4	Fabric		
D	5	Rigid		
D	6	Fabric		
E	1	Fabric	Plastic	1.5 inch (38.1 mm)
E	2	Fabric		
E	3	Fabric		
E	4	Fabric		
E	5	Rigid		
F	1	Fabric	Plastic	0.5 inch (12.7 mm)
F	2	Fabric		
F	3	Fabric		
F	4	Fabric		
F	5	Rigid		
G	1	Fabric	Foam	1.0 inch (25.4 mm)
G	2	Fabric		
G	3	Fabric		
G	4	Fabric		
G	7	Fabric		
H	1	Fabric	Foam	0.5 inch (12.7 mm)
H	2	Fabric		
H	3	Fabric		
H	4	Fabric		
H	7	Fabric		
I	1	Fabric	Non-resilent	1.6 inch (40.6 mm)
I	2	Fabric		
I	3	Fabric		
I	4	Fabric		
I	5	Rigid		
J	1	Fabric	Non-resilent	0.78 inch (19.8 mm)
J	2	Fabric		
J	3	Fabric		
J	4	Fabric		
J	5	Rigid		
J	8	Rigid		

- 150 head impact tests performed from January 2013 to May 2014
- Each core material was tested with a different durable exposed surface sheet to understand the effects the exposed surface sheet had on the energy attenuation characterizes of the core materials.
- Core material target thickness range: 25.4 mm (1.0 inch) to 38.1 mm(1.5 inch)
- Core material tested thickness range: 12.7 mm (0.5 inch) to 41 mm (1.6 inch)



Flame, Smoke, & Toxicity (FST) Methodology

- Current FST Standard: FMVSS 302
- TARDEC had very little data characterizing the thermal characteristics of the ignition sources typical to U.S. Army vehicles.
  - ignition time
  - heat generation
  - flame spread of the fire initiator
- Characterizing the fire initiator provides important information used to select appropriate fire assessment test methods.
- TARDEC developed fire resistance requirements based upon subject matter experts from NAVSEA and TARDEC's Fire Protection Team.
- NAVSEA conducted ASTM testing on selected material samples

Requirment	Objective	Test Method
Avg. Peak Heat Release Rate 50 kW/m2	< 85 kW/m^2	ASTM E1354
Peak Heat Release Rate after Ignition 50 kW/m2 @ 20 s, 180 s, & 300 s	< 60 kW/m^3	
Flame Spread Index	< 30	ASTM E162
Smoke Desity Flamming @ 240 s	Dm < 200	ASTM E662
Smoke Desity Non-Flamming @ 240 s		

IAV Fire

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ASTM E1354 – Cone Calorimeter

- Heat Release Rate determined by measurement of oxygen consumption
  - determined by the oxygen concentration and the flow rate in the exhaust product stream
  - heat evolved from the specimen per unit of time
- $\dot{Q}(t) = \left(\frac{\Delta h_c}{r_o}\right)(1.10)C\sqrt{\frac{\Delta P}{T_e}}\frac{(X_{O_2}{}^{O} - X_{O_2}(t))}{1.105 - 1.5X_{O_2}(t)}$.

Requirements	
Avg. Peak Release Rate	< 85 kW/m²
Avg. Heat Release Rate @ 60 sec, 180 sec, & 300 sec	< 60 kW/m²

ASTM E1354 @ 300 seconds - Core Material G

		ASTM E1354 @ 50 kW/m²			
		Avg. Peak Release Rate (kW/m²)	Avg. Heat Release Rate @ 60 s	Avg. Heat Release Rate @ 180 s	Avg. Heat Release Rate @ 300 s
Core Material ID	B	1,019	117	394	NC
	G	415	260	342	277
	J	442	83	260	191
	L	675	142	413	317
	M	558	137	324	308
	N	376	168	221	215
	O	296	173	208	194
	P	82	49	36	NC
Facesheet Material ID	1	430	215	137	NC
	2	542	239	114	79
	3	693	311	180	NC
	4	771	371	210	NC
	5	462	146	208	NC

* NC = Not calculated; all flaming extinguished prior to this time point.

ASTM E162 – Surface Flammability of Materials

- Flame Spread Index (Radiant Panel Index)
  - Product of the flame spread factor, F, and the heat evolution factor, Q
  - If flame spreads from the pilot burner position to the first 3 inch park or from any 3 inch mark to the next in three seconds or less, is denotes with flashing

Requirements	
Flame Spread Index	< 30

Core Material B Flaming ,Dripping, and Flashing at 60 sec

		ASTM E162 @ 50 kW/m²	
		Flame Spread Index	Flaming, Dripping, or Flame Running (Y/N)
Core Material ID	B	20	Yes
	G	1800	No
	J	123	No
	L	90	Yes
	M	116	Yes
	N	492	Yes
	O	309	Yes
	P	22	No
Facesheet Material ID	1	412	No
	2	582	Yes
	3	957	No
	4	1318	Yes
	5	158	No

- TPE engineering polyurethane and polyethylene core materials
  - quickly ignited
  - exhibited rapid flame progression
  - flamed, dripped, and/or flame running

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ASTM E662 – Specific Optical Density of Smoke

Requirements	
Smoke Density Flaming @ 240 sec	D_m < 200
Smoke Density Non-Flaming @ 240 sec	D_m < 200

ASTM E662 @ 50 kW/m²

		Flaming Mode: Specific Optical Density (D_m)	Flaming Mode: Flaming, Dripping, or Flame Running (Y/N)	Non-Flaming Mode: Specific Optical Density (D_m)	Non-Flaming Mode: Flaming, Dripping, or Flame Running (Y/N)
Core Material ID	B	155	Y	6	N
	G	323	N	144	N
	J	16	N	1	N
	L	296	N	7	N
	M	300	Y	13	N
	N	582	N	320	N
	O	465	N	176	N
	P	23	N	6	N
Facesheet Material ID	1	106	N	154	N
	2	174	N	177	N
	3	187	N	185	N
	4	175	N	124	N
	5	196	N	28	N

- Optical Density: measurement characteristic of the concentration of smoke
- Specific optical density calculated at any given time:

$$D_s = G\left[\log_{10}\left(\frac{100}{T}\right) + F\right]$$

- Flaming mode
  - 6 tube burner is used to apply a row of flame across the lower edge of exposed specimen
  - Application of 6-tube burner and specified irradiance level from heating element
- Non-flaming mode
  - Specified irradiance level from heating element

ASTM E662 @ 178 seconds - Core Material O

Summary – Material FST Testing

		ASTM E1354 @ 50 kW/m²: Avg. Peak Release Rate (kW/m²)	ASTM E1354: Avg. Heat Release Rate @ 60 s	ASTM E1354: Avg. Heat Release Rate @ 180 s	ASTM E1354: Avg. Heat Release Rate @ 300 s	ASTM E162 @ 50 kW/m²: Flame Spread Index	ASTM E162: Flaming, Dripping, or Flame Running (Y/N)	ASTM E662 @ 50 kW/m² Flaming Mode: Specific Optical Density (D_m)	ASTM E662 Flaming Mode: Flaming, Dripping, or Flame Running (Y/N)	ASTM E662 Non-Flaming Mode: Specific Optical Density (D_m)	ASTM E662 Non-Flaming Mode: Flaming, Dripping, or Flame Running (Y/N)
Core Material ID	B	1,019	117	394	NC	20	Yes	155	Y	6	N
	G	415	260	342	277	1800	No	323	N	144	N
	J	442	83	260	191	123	No	16	N	1	N
	L	675	142	413	317	90	Yes	296	N	7	N
	M	558	137	324	308	116	Yes	300	Y	13	N
	N	376	168	221	215	492	Yes	582	N	320	N
	O	296	173	208	194	309	Yes	465	N	176	N
	P	82	49	36	NC	22	No	23	N	6	N
Facesheet Material ID	1	430	215	137	NC	412	No	106	N	154	N
	2	542	239	114	79	582	Yes	174	N	177	N
	3	693	311	180	NC	957	No	187	N	185	N
	4	771	371	210	NC	1318	Yes	175	N	124	N
	5	462	146	208	NC	158	No	196	N	28	N

* NC = Not calculated; all flaming extinguished prior to this time point.

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Conclusion

- TARDEC identified a limited number of core and facesheet materials which are capable of complying with the fire resistance requirements
- TARDEC acknowledges these test methods and criteria may be more severe than needed, however some materials were determined to be capable of complying with these requirements, making it a viable option. On-going research and development efforts continue.
- TARDEC is further characterizing fire ignition sources and fire resistance standards with the intent to refine these requirements as more knowledge is gained.
- MIL-PRF-32518 Performance Specification Interior Head Impact Protection for us in U.S. Army Military Vehicle Interiors

Future Work

- TARDEC wishes to expand the number of materials known to provide sufficient energy attenuation, are capable of complying with the HIC(d) < 700 requirement and also provide adequate fire resistance
  - Phase II SIBR Flame, Smoke, and Toxicity Resistant Recoverable Interior Trim Energy Absorption Material
- Collaboration with FAA in FY16 for further development of fire resistance requirements for version 2 of MIL-PRF-32518

USING ENGINEERING TEST DATA TO PREDICT FIRE HAZARD, DATA WITH MEANING

J. G. QUINTIERE, U OF MD
IN AFFILIATION WITH FAA TECH CTR

MANY TESTS FOR FLAMMABILITY

- A fire test is a means of determining whether products meet minimum performance criteria as set out in a building code or other applicable legislation. Successful tests results in the issuance of a certification listing with a numerical ranking FOR THE TEST.
- Every local jurisdiction, every US agency, and every country has its own tests.
- Even tests for the same purpose, e.g. the flammability of lining materials, give differing results.
- Results are in numerical ranking, not engineering data.

EXAMPLE OF TESTS THAT DO NOT AGREE

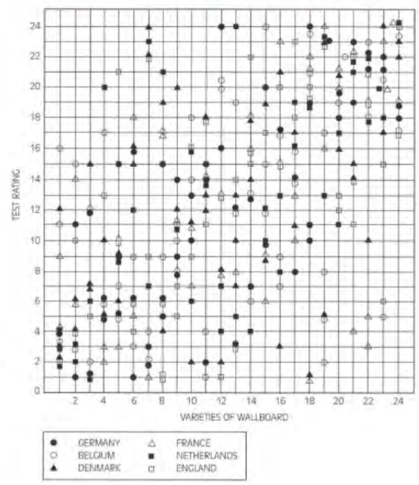


Figure 1-4
Disparities among fire tests—rankings of twenty-four materials by six national flammability test methods. From Emmons, Ref. 7.

6 national tests of 24 materials; perfect agreement would be 45° line

KEY PROPERTIES FOR FIRE GROWTH ON MATERIAL

Table 1. Canonical Set of Flammability Parameters

Parameter	Physical Meaning	Measurement Means
HRP Heat Release Parameter	$\Delta h_c / L$	Slope of Peak HRR and Flux
TRP Thermal Response Parameter	$\sqrt{\frac{\pi}{4} k\rho c}\left(T_{ig} - T_o\right)$	Slope of (Time to ignition)$^{-1/2}$ and Flux
CHF Critical Heat Flux	$h_t(T_{ig} - T_\infty),\ h_t = h_r + h_c$	Lowest Flux for Piloted Ignition
AEP Available Energy Parameter	Total energy per unit surface area	Area under HRR and Flux curve

- All are measurable in Cone Calorimeter or FM FPA apparatus
- Also micro-tests can produce many of these.

KEY PROPERTIES ALLOW COMPUTATION OF HRR, IGNITION, AND SPREAD

- Burning rate or energy release rate per unit area

$$\dot{m}_F'' L = \dot{q}_{net}'' \quad [1]$$

$$\dot{Q}'' = \dot{m}_F'' \Delta h_c = \dot{q}_{net}'' \Delta h_c / L, \ \mathrm{HRP} \equiv \Delta h_c / L$$

- Time to ignition (for thermally thick materials)

$$t_{ig} = \frac{\frac{\pi}{4} k \rho c \left(T_{ig} - T_o\right)^2}{\dot{q}''^2} = \left(\frac{TRP}{\dot{q}''}\right)^2 \ \text{for } \dot{q}'' > \mathrm{CHF}. \quad [2]$$

- Flame speed is $v \equiv \dfrac{dz_p}{dt} \approx \dfrac{z_f - z_p}{t_{ig}} = \dfrac{\delta}{t_{ig}}$ [3]

  where the heated length, δ, depends on whether the flame spread is opposed or wind-aided.

LINK TO APPLICATION IS HEAT FLUX

- Heat flux characteristic of particular test can allow correlation to test result.
- Prediction of heat flux in CFD code (dubious) can allow prediction of fire growth.
- Heat flux characteristic of particular fire scenario can give quantitative information on the performance of material tested.

IN GENERAL

HRR depends on key properties and fire scenario

$$\dot{Q} = \int_{t_{ig}}^{t} \dot{Q}'' v_x v_y \, dt$$

$$= \text{Function}(t, \text{Material:HRP, TRP, CHF, AEP \& Scenario: Flame heat flux, Ignition area})$$

ISO Room Corner

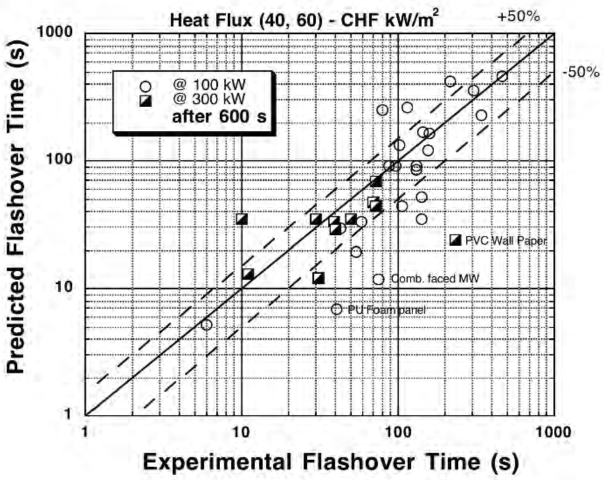
UL 94

ISO ROOM CORNER

, "INHERENT FLAMMABILITY PARAMETERS – ROOM CORNER TEST APPLICATION", *FIRE AND MATERIALS*, VOLUME 33, ISSUE 8, PAGES 377-393, DECEMBER 2009, QUINTIERE, J. G. AND LIAN, DANJUN

$$t_{FO} = 0.06533 \cdot AEP^{0.1297} HRP^{-0.2208} TRP^{1.3293}$$

Figure 7. Flashover Time Predicted



UL-94 J. G. QUINTIERE, BRIAN P. DOWNEY AND RICHARD E. LYON, AN INVESTIGATION OF THE UL-94V PLASTICS FLAMMABILITY TEST *SIXTH FIRE AND EXPLOSION HAZARDS SEMINAR* (FEH6) 2010, UNIVERSITY OF LEEDS 11-17 APRIL 2010.

$$\dot{Q}'' = \left(\dot{q}''_{flame\ zone} - \epsilon\sigma\left(T_{ig}^{\ 4} - T_{\infty}^{\ 4}\right)\right) \times HRP$$

$$\dot{q}''_{net,incident} = \dot{q}''_{flame\ zone} - CHF$$

$$\dot{q}''_{flame\ zone} = 65\ kW/m^2$$

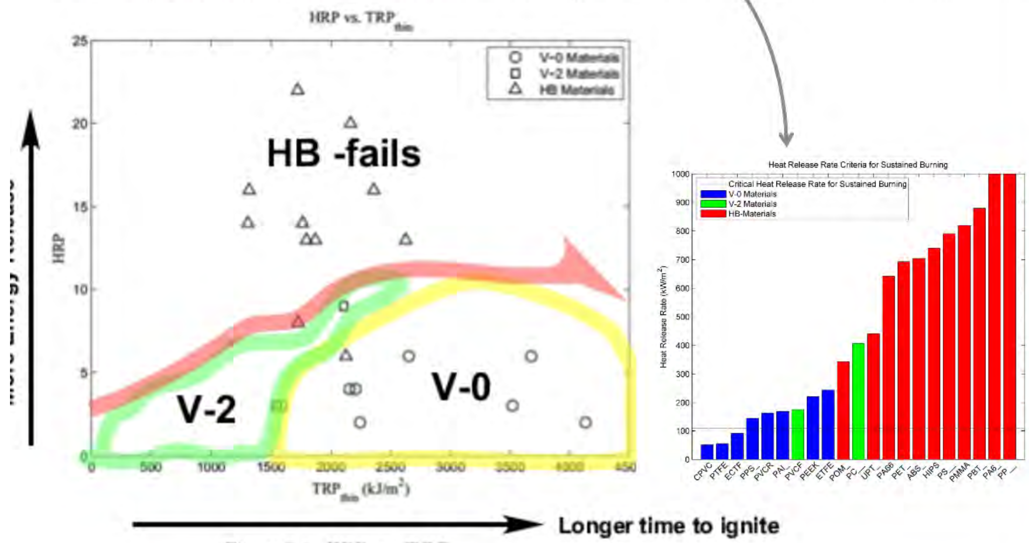


Figure 7.6: HRP vs. TRP_{thin}

PICK A TEST BECAUSE

- ❑ Adopted by regulators
- ❑ International
- ❑ Supported by Industry
- ❑ Has a clear numerical scale
- ❑ Invented especially for an application
- ❑ Has the support of national labs
- ❑ Gives real engineering data

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Flame and Thermal Resistant Fibers and Fabrics Development Program

U.S. Army Natick Soldier Research, Development & Engineering Center, Natick, MA 01760
Thomas Tiano / WFD
FY16 Overview - October, 2015

UNCLASSIFIED

FR Materials Program

Outline

- Goals and Background
- Program Model and Description
- Technical Process
- Specific Technical Efforts

2

FR Program Goals

Goal:

Develop next-generation flame and thermal resistant materials with the following characteristics

- Improve the performance-to-cost ratio over presently-used FR military materials in Army Combat Uniforms such as the FRACU
- Increase durability and abrasion resistance
- Utilize U.S. made materials - Berry Amendment compliant
- Reduce cost to enable distribution to a wider array of soldiers
- Reduce/eliminate hazardous/toxic fabrication processes

Background

- FRACU was introduced in 2007
- Fabric composition: 65% FR rayon, 25% para-aramid, and 10% nylon fiber
- FR rayon is not produced in the United States:
  - the production process is not environmentally friendly and does not meet EPA standards
  - requires a waiver for procurement
- FRACU fabric is 3x more costly than the NyCo blends used in the ACU

In Comparison

- ACU is made from a 50:50 Nylon/Cotton blend made in the U.S.

4

FRACU Performance Criteria

- Performance criteria were defined by the existing fabrics per MIL-DTL-44436A for ACU and GL-PD-07-12 Rev 8 For FR ACU
  - Vertical Flame 2 sec afterflame, 4-inch char length
  - Fabric areal weight with coating must be less than or equal to 7.0 +/- 0.5 oz/sq yd
  - Air permeability must be > 25 CFM

5

FR Materials Program Methodology

- Pilot program initiated in FY16
- Utilizes unified phase-gate approach for development of FR textiles, fibers, fabrics and coatings
- Effort involves both 6.2 and 6.3 funding
- Success of this program will be judged on two overarching criteria:
  - Ability to transition promising technologies through advancing TRLs with the goal of ultimately transitioning to 6.4 and beyond.
  - Ability to enhance the overall knowledge base for FR materials (FR R&D database)

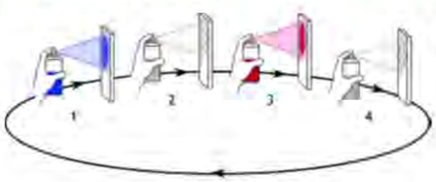
Current Efforts in FR Materials

- Current efforts include a mix of ongoing contracts and internal and external new starts
- Majority of efforts center around FR coatings for Nylon/Cotton (NyCo) fabric currently used in the ACU as NyCo is:
  - Lower cost then FRACU fabric
  - More durable than FRACU fabric
  - Currently used and understood by the Army
- Many efforts focus on Phosphorus-containing compounds shown to:
  - Evolve phosphorus containing gases that limit exposure to oxygen
  - Decompose to phosphoric acid forming a glassy layer promoting char yield
- Past efforts have had mixed success:
  - Coatings have shown to impart acceptable FR protection to fabric – passing vertical flame test
  - Most coatings have not shown high launderability, being damaged after 1 wash cycle
- Durability of FR coatings will be of major emphasis

7

LbL Application of FR Coatings to NyCo

GOAL: Create a durable, launderable, flame retardant (FR) coating for NyCo fabric using layer-by-layer (LbL) application of polymer electrolytes.



Izquierdo, A., Ono, S., Voegel, J., Schaaf, P., Decher, G. *Dipping versus Spraying: Exploring the Conditions for Speeding up Layer-by-Layer Assembly*. Langmuir, 2005, 21 (16), 7558.

Thin films will be created by alternately spraying aqueous mixtures of positively and negatively charged polymer electrolytes. Ammonium polyphosphate (APP) will be used as a phosphorus-containing FR polyelectrolyte.

PROS of LbL:

- Versatile - Can use various polymer systems
- Doesn't change the intrinsic properties of underlying material
- Applies a thin, even coating instead of risking a poorly blended composite

CONS of LbL:

- Durability – coatings do not maintain FR performance after laundering

APPROACH: Various methods will be explored to increase the durability of the LbL FR coatings.

- **Encapsulation of APP:** Encapsulation will help prevent the phosphorus-containing additive from leaching out of the coating during washing.
- **Cross-linkers:** Cross-linking the polyelectrolyte may help bind the coating to NyCo
- **UV-Curing:** The addition of covalent bonds by exposing the coatings to UV radiation may increase durability
- **Hydrophobic Coatings:** A final hydrophobic polyelectrolyte layer could prevent water from causing the coating to swell, which leads to phosphorus leaching from the polymer matrix and decreased FR performance
- **Swelling Resistant Polymer Systems:** Choosing a non-swelling polymer electrolyte system consisting of high molecular weight polymers will also prevent the phosphorus from leaching out of the polymer matrix.

Principal Investigator: Melissa Roth/WFD

Advanced Printing Paste For Thermally Protective Garments

SciGenesis Contract

Objective:

Combine IR reflective pigments and char promoters into a screen-printable paste.

- IR reflective pigments are used to color match the camouflage FR-print pastes

Technical Approach:

- ➢ Addition of commercially available char promoters - Pyrovatex (monomeric) PNW (oligomeric)
- ➢ A complete study into the properties of binders is being conducted

Present results:

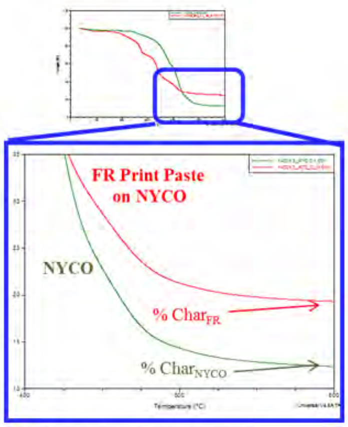


Table 3. Testing Various FR Chemicals on Cotton, Nylon and NYCO (50/50).

Experimental	Weave	Pyrovatex CP New: Aerotex M3	PNW: Sancure	VFT	Afterflame (s)	Char (in.)
100% Cotton	Quilting Plain	24.4:5.5	0	Pass	0	4
100% Cotton	Burlap Plain	24.4:5.5	0	Pass	0	4
100% Cotton	Burlap Plain	0	24.4:5.5	Pass	0	4
100% Nylon	Plain	24.4:5.5	0	Fail	18.5	12
100% Nylon	Ripstop	24.4:5.5	0	Fail	20.5	12
100% Nylon	Ripstop	0	24.4:5.5	Pass	0	1
NYCO (50/50)	Ripstop	24.4:5.5	0	Pass	0	1
NYCO (50/50)	Ripstop	0	24.4:5.5	Pass	0	1

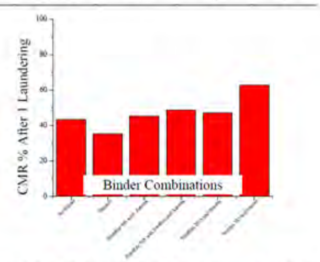


Figure 3. Coating Mass Retention (CMR) of print pastes containing various binders.

Principal Investigator: Anabela Dugas/WFD

9

Durable Coatings on NYCO Blends for FR Uniforms

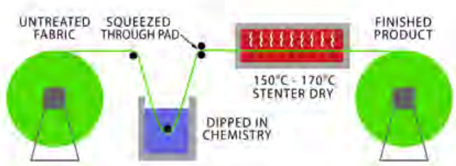
Alexium Contract

Objective:

Investigate and mature through a series of demonstrations alternative coating formulations and fiber and/or fabric constructions

Characteristics and Benefits:

- No melt, no drip, self extinguishing
- Applied using conventional textile processing
- Cost effective
- Halogen and Formaldehyde free
- Compatible with other fabric treatments
- Designed to meet FR standards after 50+ launderings



Technical Approach:

- ➢ Modifications of Alexium's commercially available FR treatments: NYCOLON and NUVALON
  - ➢ Proprietary organophosphorous and binder package
  - ➢ Typical Formulation:
    - ▪ 70% Alexiflam RD
    - ▪ 20% 3121 (urethane)
    - ▪ 5% Web (cross-linker)
    - ▪ 5% H2O
  - ▪ Modifications will be design to decrease required loading to minimize impact on fabric weight and breathability
- ➢ Investigation of alternative fiber and/or fabric constructions in conjunction with modified coating formulation

Principal Investigator: Thomas Tiano/WFD

10

Multifunctional Textile Coatings of Military Fabrics

Materials Modification, Inc (MMI) STTR Phase II Contract # W911QY-15-0024

Objective:

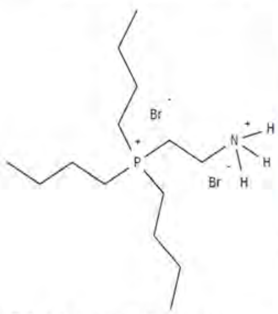
Develop a FR coating for NyCo utilizing ionic liquids (liquid salts) containing imidazolium and phosphonium cations.

- High temperature stable (>250°C)
- Colorless (do not interfere with camouflage)
- Utilize bromine counter ion

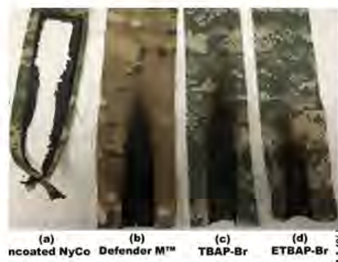
Technical Approach:

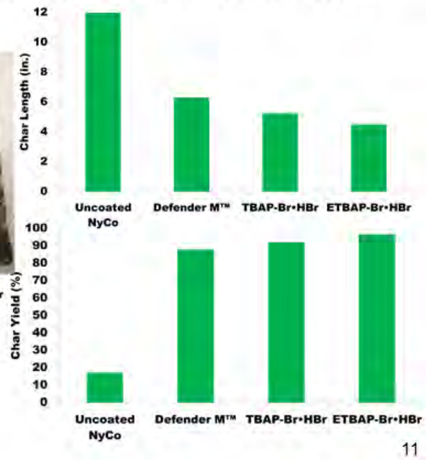
- Scaling process for preparing ionic liquids.
- Utilize commercially available Melamine resin for binder
- Durability testing and human skin compatibility of the coating will be addressed in Phase II of this research.

Present results:



Tributyl aminoethyl phosphonium bromide hydrobromide (ETBAP-Br•HBr)





Principal Investigator: Kris Senecal/WFD

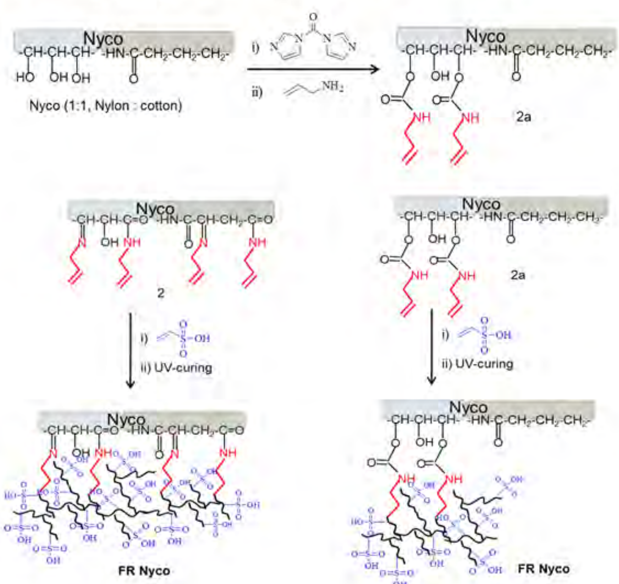
11

Development of durable flame retardant coatings through surface treatment, chemical functionalization and UV-curing

GOAL: Develop a strategy for durable conformal coatings through surface treatment methods followed by covalent functionalization

Technical Approach:

- Corona or plasma treatment of fabric to activate surface for enhanced binding of the coating
- Covalently functionalize of FR additives followed by crosslinking



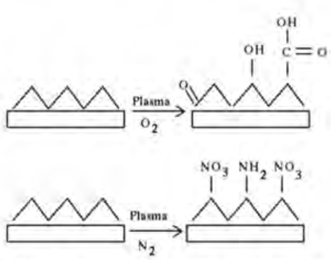


Fig. 2: An example of surface activation by substituting hydrogen in a polymeric chain with other groups such as O, OH, COOH, NO_3, NH_2. etc.

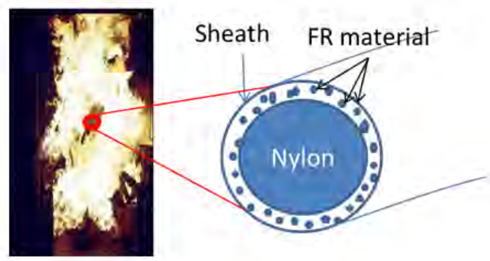
Principal Investigator: Ravi Mosurkal/WFD

Low Cost FR Bi-Component Fiber

GOAL: Impart flame resistance to nylon fiber via bi-component fiber extrusion versus adding a coating to the fabric.

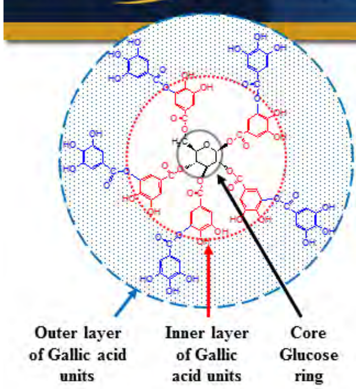
- Allows permanent incorporation of flame retardants
- Overcomes high processing temperature barrier of Nylon

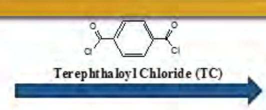
- ***Technical Approach:***
  - Utilize in-house expertise at the High Performance Fiber Facility (HPFF) at NSRDEC
  - Develop a bi-component fiber, based on sheath/core processing, in which the nylon core fiber is encapsulated by a sheath of a secondary polymer, which is compounded with, and acts as the carrier for, commercially available flame retardants.
  - Perform sheath-polymer/FR-material compounding studies
  - Prepare bi-component fibers consisting of nylon core and polymer/FR sheath
  - Test fibers via PCFC
  - Prepare swatches containing novel fiber
  - Flame test swatches

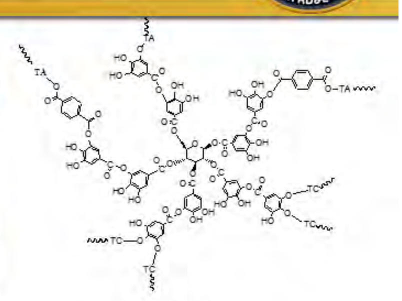


Principal Investigator: Betty Anne Welsh/WFD

Bio-inspired Polyphenols as Flame Retardants







Modified Tannin as an additive for nylon

Lignin and Tannins are natural polyphenols present in the tree bark

Sequoia Trees – Alive after forest fires: Mother Nature's Wonder

Materials	Heat Release Capacity, J/g-K	Total Heat Release, KJ/g
TA	152	5.6
TA TC	76	6.2

Thermal properties from Microcalorimetry

Materials	Heat Release Capacity, J/g-K	Total Heat Release, KJ/g
Nylon 6	687	31
Nylon 6+ 15% TA	508 (-26%)	28.6 (-7.7%)
Nylon 6 + 15% TA TC	463 (-33%)	27.2 (-12.3)

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Rejuvenating FR Coating for NyCo

LynnTech Contract

Objective:

Develop a temporary coating that can be washed and rejuvenated repeatedly maintaining the physical appearance and flexibility of the fabric.

- Coating will be applied during uniform laundering
- Prior coatings will be completely removed during laundering
- Coatings will maintain efficacy during rain/water exposure

Technical Approach:

- Utilize water soluble phosphates
- GearAid Revivex Air Dry waterproofing spray

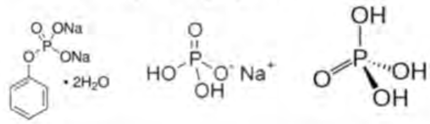

Table 13. ASTM VFT results and wt% change due to laundering for cold water rejuvenation of fabrics coated with PA/Na1P and SPP/PA.

Rejuvenation cycle	ASTM D6423 VFT results			Laundering	Control fabric
	After flame	After glow	Char Length	Overall wt% change	Overall wt% change
1	2.9 sec	0 sec	2.75"	-0.6	-1.4
2	1.5 sec	0 sec	1.0"	-0.6	-3.0
3	3.0 sec	0 sec	3.75"	-1.2	-3.9
4	3.8 sec	0 sec	4.25"	-1.9	-4.1
5	2.7 sec	0 sec	4.0"	-1.9	-4.4
6	3.0 sec	0 sec	5.0"	-4.0	-4.7
7	1.6 sec	0 sec	2.25"	-5.6	-4.8
8	3.1 sec	0 sec	3.88"	-6.5	-5.0
9	3.5 sec	0 sec	4.0"	-6.7	-5.2
10	4.0 sec	0 sec	4.25"	-7.0	-5.6

Rain testing weight loss and ASTM VFT results for coated fabrics

Soaking	ASTM D6423 VFT results			
Time (Hours)	Weight Loss %	After flame	After glow	Char Length
0	0	1.9 sec	0 sec	1.75"
1	1	3.6 sec	0 sec	3.88"
2	1	2.9 sec	0 sec	3.88"
4	2	3.5 sec	0 sec	5.0"

Principal Investigator: Thomas Tiano/WFD

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Back-up slides

16

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Decision Criteria

- Technologies are evaluated by the Technical Panel as they progress through a series of Technology Maturation Gates
- Decision criteria includes:
  - Technical performance (tested or anticipated based on literature data)
  - Anticipated scale-ability to manufacturing
  - Anticipated cost
- Specific criteria are defined for each gate

Technical Evaluation Criteria - Gate 1

Candidate Material	1 → Vertical Flame ASTM D6413: 12" x 3" size afterflame (seconds)		2 → Fabric Areal Weight (oz/sq yd)		3 → Air Permeability ASTM D737: 12" x 12" and fabric assessment (cfm)	4 → Camouflage Performance (Visual and NIR) per ACU: 12" x 12" Multispectral*		Evaluation Result
	Before wash	After 1 AATCC-135 wash	Before wash	After 1 AATCC-135 wash	Before wash	Before wash	After 1 AATCC-135 wash	
XXX								
FR ACU Type I (Class 1 – UCP)	Pass 2 sec	Pass	Pass Required 5.5-8.5 Ave 6.7	Pass	Pass Required >10	Pass	Pass	
ACU (Class 6 –UCP)	Fail >30 sec	Fail	Pass Required 6-7 Ave 6.51	Pass	Pass Required <10	Pass	Pass	

Vertical Flame - must be equivalent to the FRACU at 2 sec afterflame to Pass
Fabric areal weight with coating must be less than or equal to 7.5 oz/sq yd to Pass
Coatings must decrease initial ACU air permeability by no more than 20% to Pass
**per MIL-DTL-44436A for ACU and GL-PD-07-12 Rev 8 For FR ACU*

Collaboration partnering with PM-SCIE - Gate 2

- Technical Criteria
  - 5 launderings then criteria 1
  - Hand-feel – TBD
  - Mid scale test
  - Skin irritation – Modified Draize Test
  - Toxicity of combustion products
- Manufacturability
  - Larger specimens – min 20"x20"
  - Reproducibility x 3 mid-scale
  - Industry partner
- Cost criteria – Cost estimate to demonstrate <= FRACU fabric

NAVAIR Aircraft Fire Protection Overview

October 14, 2015

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NAVAL AVIATION TECHNOLOGIES

Responsibility

To Promote the Highest Levels of Aircrew Safety and Aircraft Survivability, through:

- Acceptable Fire Protection System Designs
- Proper Development and Implementation of Halon Alternatives
- Appropriate Fleet Implementation and System Maintainability

NAVAL AVIATION TECHNOLOGIES

NAVAIR Fire Protection Team

Tom Rudowsky
AIR-4.3 Air Vehicle Department Head

Steve Thoman
AIR-4.3.5 Subsystems Division Head

John Krohn
AIR-4.3.5.1 Thermal Systems Branch Head

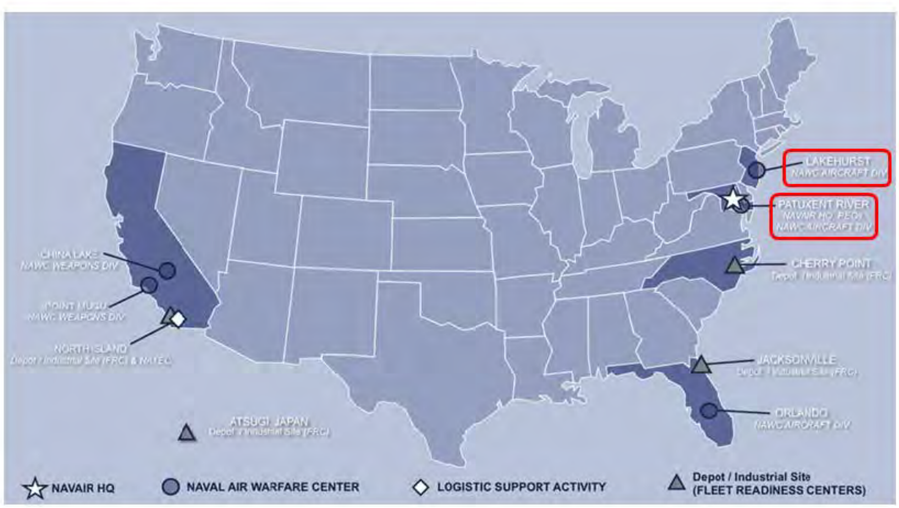
Mike Cosgrove
Aircraft Fire Protection Team Lead

Marco Tedeschi
Aircraft Fire Protection Technical Specialist

Mike Kubina
Aircraft Fire Protection Engineer

Ryan Arthur
Aircraft Fire Protection Engineer

NAVAIR Locations



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Current Challenges

- **Single Engine Aircraft Fire Suppression System Utilization**
  - Engine fire suppression has historically required fuel shutoff to the engine
  - Can suppression systems be effective without engine shutdown?

- **Fire Protection Systems on Unmanned Air Vehicles**
  - Cost and weight savings have kept fire protection systems to a minimum on Navy UAVs
  - As UAV cost and complexity grow, so does the need for full fire protection systems

- **Life Limits and Calibration of Fire Detectors**
  - Ongoing Engineering Investigations regarding pneumatic fire detector operations
  - Efforts to design and validate on-aircraft fire detector calibration tests

- **Service Life Assessment Program (SLAP) Efforts**
  - Efforts underway to extend the service life of fire protection-related hardware
    - In support of overall air system SLAP
  - Fire protection is CAT 1 priority (safety of flight)
  - Focus on components not normally inspected or maintained

Single Engine Aircraft Fire Suppression System Utilization

- **Engine fire suppression systems historically requires the following:**
  - Confirmation of fire
  - Shutdown of effected engine (i.e. fuel shutoff)
  - Discharge of fire suppression agent
  - *Lengthy timeline considering the rapid speed of fire growth/spread*

- **Re-ignition Prevention Challenges**
  - Reduction of fuel vapor concentrations
  - Removal of ignition sources
  is short-lived

- **Alternative Fire Suppression System Methods (Automatic Fire Suppression)**
  - Continued engine operation during fire suppression attempt
  - Provide immediate suppressant agent discharge before fire intensity grows
  - Effective against ballistically induced fires where ignition source is short-lived

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Fire Protection Systems on Unmanned Air Vehicles

- **Historically UAVs Have Minimal Fire Protection**
  - Only 1 Navy UAV to date has implemented a fire detection system
  - No suppression systems have been installed to date on Navy UAVs
  - Rely on visual confirmation of fire (i.e. during take-off and approach)
  - Evolution of UAVs (higher cost/more complex) makes argument for full fire protection systems

- **UAV Fire Protection Incorporation Challenges**
  - Weight and cost impact of system development and incorporation
  - Only protecting an asset (consumable)

- **Argument for Full Fire Protection Systems**
  - Increased cost and complexity makes UAV return more desirable
  - Detection capability could provide time to change path from undesired ditching position
    - Enemy territory or high-populated area

NAVAL AVIATION TECHNOLOGIES

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Life Limits and Calibration of Fire Detectors

- **Most Common Detector Types Used on Navy Aircraft**
  - Pneumatic Fire Wire
  - Optical Fire Detectors (OFDs)

- **Historically Viewed as Aircraft Life Components**
  - Only require replacement if damaged or failing BIT
  - Fire exposure does not necessarily affect future performance
  - Initial calibration (by OEM) is sufficient

- **Ongoing Challenges**
  - Current on-aircraft functional test of OFDs (red-lens flashlight) is insufficient
  - Pneumatic fire detectors not alarming at advertised temperature set-points
    - Potential life limit for calibraition
  - Need for on-aircraft functional testing capabilities to ensure detectors are within calibration

NAVAL AVIATION TECHNOLOGIES

Service Life Assessment Program (SLAP) Efforts

- **Comprehensive evaluation of the fire protection system (FPS) for age-related safety risks:**
  - F/A-18 initiated program to allow continued flight operation beyond original service life limits
    - SLAP program is tailored from the Naval Aviation Subsystems Safety Integrity Program (NASSIP)
  - Analyze and assess current and predicted future condition of fire protection-related hardware as required
  - Determine if current life management practices are acceptable for an extended life aircraft
    - Maintenance
    - Inspections
  - Correlate original qualification efforts to updated aircraft life requirements
  - Provide disposition options for each FPS component to the program office to ensure the continued safe operation of fire protection systems
    - Ex./ F/A-18
      - Fire and overheat detectors, fire extinguishers, CADs – follow current inspection / maintenance practice
      - Fire extinguisher discharge tubing – stress test analysis
    - Subject to revision based on any additional data received

Aircraft Fire Protection Lab Mission Statement

The NAVAIR Aircraft Fire Protection Laboratory provides complete test support for all Navy air vehicle fire protection systems. It is equipped with unique state-of-the-art aircraft nacelle simulators utilized for developmental and qualification testing of fire suppression systems. In addition, the facility capabilities include firewall material testing, fuel tank inerting simulation and potential for future growth within the thermal test field. While the primary customers are U.S. Naval Aviation and the Department of Defense, service is also provided to other government agencies and industry.

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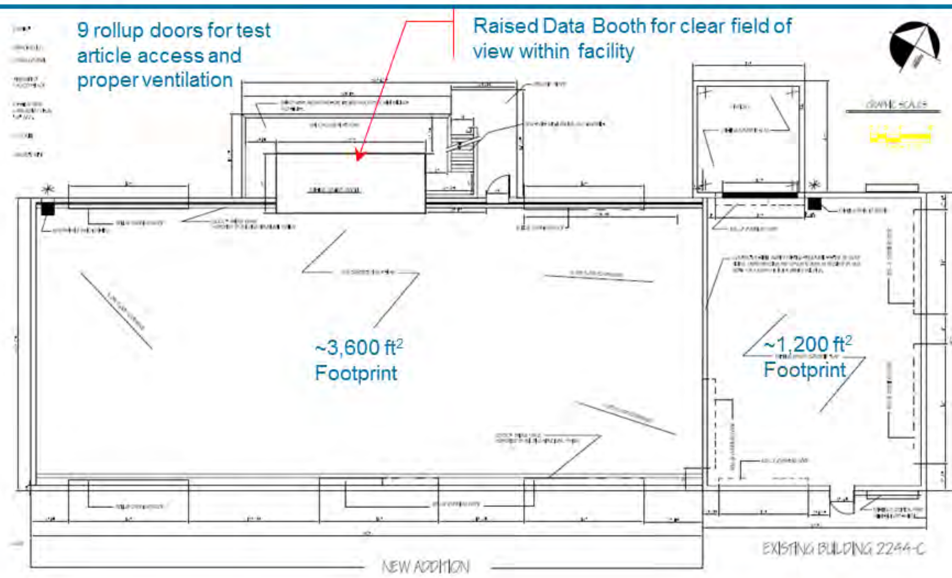
Facility Layout



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Aircraft Fire Protection Lab Capabilities

- **Aircraft Engine Nacelle Simulation**
  - ¼" steel hardened simulators to support all ranges of fire testing
  - High fidelity nacelle clutter to emulate production nacelle airflow
    - High airflow (5000 SCFM electric blowers) on site
  - Simulators on site support wide range of aircraft
- **Data Acquisition Suite**
  - Recording and real-time viewing of pressure, temperature and flow measurements
  - Multi-device video recording
  - Fire Gas Chromatograph for fire suppression concentration testing
- **Aircraft Fuel System Simulation**
  - Large outdoor footprint to support aircraft fuel system
    - Indoor facility also available
  - High capacity tanks to support aircraft fuel systems
  - Shop air supply on site to simulate OBIGGS/OBOGGS
- **Fabrication**
  - Unlimited on-base fabrication
  - Limited on-site fabrication
    - Mig welder
    - Lathe/milling machine
    - Band saw
    - Drill press

NAVAIR

Platforms/Programs Supported

- **Since Original Construction In 1998**
  - F/A-18 E/F
  - MH-60R/S
  - P-8A
  - V-22
  - NGP (Next Generation Program – Fire Suppression)
  - Joint Live Fire
  - JASPO (Joint Aircraft Survivability Program Office)
  - AERMIP (Aircraft Equipment Reliability and Maintainability Improvement Program)

NAVAL AVIATION TECHNOLOGIES

NAVAIR

Projects Accomplished

- **1998-2000, F/A–18 E/F Halon 1301 Replacement**
  - Halon 1301/HFC-125 performance equivalency tested via fire testing of redesigned agent distribution system
- **2001, F/A-18 E/F Firewall Testing**
  - Fire tested firewall/thermal shield panels for improved fire safety & enhanced aircraft survivability
- **2002, MH-60R Aux Fuel Tank Flame Testing**
  - Testing to determine thermal capabilities of auxiliary fuel tanks' cavity walls
- **2002, F/A-18 E/F Nacelle Simulator Input/Output Boundary Condition Flows**
  - Airflow testing to provide boundary conditions for CFD models of the simulator
- **2002, V-22 MATS Flame Test**
  - Testing to determine thermal capabilities of intumescent paint (primer) on MATS fuel tanks
- **2004-2005, AERMIP: Improved Firewall Materials**
  - Design/fabrication of burner rig to test/qualify firewall materials
- **2004, Joint Live Fire: H-60 Nacelle FIREX Effectiveness Evaluation of Ballistically Induced Fires**
  - Established baseline system performance on an undamaged engine nacelle and determined effectiveness threshold of Halon 1301 and HFC-125 systems against simulated ballistic fires

NAVAL AVIATION TECHNOLOGIES

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Projects Accomplished (Cont'd)

- **2004, F-18 E/F Nacelle Simulator Pool Fire Testing**
  - -Fire testing to validate customer model
- **2005, JASPO: Automatic Engine Fire Suppression Evaluation**
  - -Testing of automatic fire detection/suppression systems in engine nacelle
- **2006-2007, MH-60R/S Halon Replacement Risk Reduction Testing**
  - \- Halon 1301/HFC-125 performance equivalency tested via fire testing and concentration testing using redesigned agent distribution system

\- **2007, P-8A OBIGGS Fuel Trap Test**
  - \- Tested model of wing tank distribution portion of OBIGGS system to mitigate fuel traps

- **2008-2009, P-8A Halon Replacement Risk Reduction Testing**
  - \- Halon 1301/HFC-125 performance equivalency tested via fire testing and concentration testing using redesigned agent distribution system

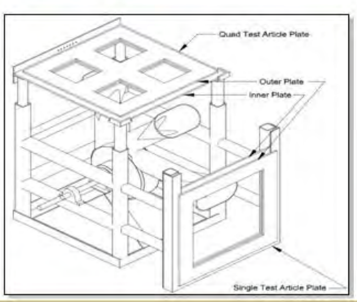
\- **2008-2009, P-8A OBIGGS Fuel Flow Test**
  - -Fuel transfer tests performed to characterize two phase flow pressure drop and determine required orifice sizes for fuel transfer and wash flow lines

- **2010, P-8A Nacelle FIREX Effectiveness Evaluation of Ballistically Induced Fires**
  - \- Established baseline system performance on an undamaged engine nacelle and determined effectiveness threshold of Halon 1301 and HFC-125 systems against simulated ballistic fires

NAVAL AVIATION TECHNOLOGIES

NAVAIR

Questions?



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Sandia National Laboratories

Fire Science & Technology

ARL/TARDEC Fire Protection Information Exchange Meeting

October 14-15, 2015, ARL Conference Center 4503, Aberdeen, MD, USA

Overview of Sandia Fuel Fire Capabilities

Alexander L. Brown; albrown@sandia.gov; (505)844-1008

John C. Hewson; jchewso@sandia.gov; (505)284-9210

Fire Science and Technology Department

SAND2015-8834 C

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000

Outline

- Introduce Sandia National Labs Fire Programs (3 min)
  - Programmatic Focus
  - Thermal Test Complex (TTC)
  - Burnsite
- Experimental Work (8 min)
  - Diagnostics
  - V&V Role
  - Some specific project results
- Modeling Efforts (8 min)
  - Unique modeling tools
  - Suppression, solid materials in fires,

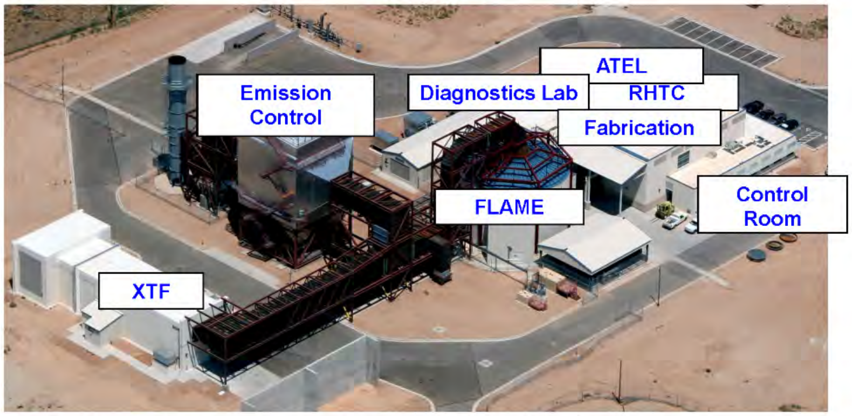
2

Sandia Fire Science Department

- Sandia is a FFRDC laboratory managed by LMC for the US DOE
  - Around 10,000 employees, a wide range of program areas
  - Major locations in Albuquerque, NM and Livermore, CA
- The NM Fire Science and Technology Department is in the Engineering Sciences Center, and supports a range of missions with cutting-edge technologies and capabilities
  - Located on Kirtland AFB
  - Around 30 full-time employees varying from research staff to technologists
  - Fire research includes staff in other complimentary departments at Sandia, mostly in part-time roles
- Primary role is in support of the US weapon stockpile
  - Nuclear weapon components safety, normal and abnormal thermal environments
  - Sandia has large energy programs, also leading to significant project work
  - We support DOD and other government agencies, some commercial work
- We normally do work that can't be done elsewhere

3

Thermal Test Complex



- XTF – Horizontal Wind Tunnel for Fires in Cross Wind
- FLAME – Vertical Wind Tunnel for Fires in Calm Conditions
- RHTC – Full Scale Radiant Heat (Fire Loading Simulator) Lab
- ATEL – Abnormal Thermal Environment Lab
- Supporting infrastructure
  - Diagnostics development and instrumentation labs
  - Control room
  - Fabrication areas
  - Emission Control

XTF Capabilities

- **Test Cell Dimensions**
  - 25 ft x 25 ft by 83 ft long
  - (7.6 m x 7.6 m by 25 m long)
- **Fuel Sources**
  - Liquid
    - JP-8 – 10 ft dia. (20 MW)
  - Gas source easily added
- **Heat Sources**
  - Radiant Heat Panels
    - 2.88 MW
- **Air Sources**
  - Full Cross Section
    - 8 ft/sec (2.4 m/s)
  - Limited Cross Section (~1/4)
    - 34 ft/sec (10 m/s)
- **Explosives**
  - <106 lbs (damage/no-injury)

New FLAME Facility

- **Test Cell Dimensions**
  - 60 ft dia. x 40 ft high
  - (18.3 m dia. x 12.2 m high)
- **Fuel Sources**
  - Liquid
    - JP-8/Ethanol
    - 10 ft (3.05 m) dia. (20 MW)
  - Gas
    - $CH_4/H_2/N_2$
    - 10 ft (3.05 m) dia. (20 MW)
- **Heat Sources**
  - Radiant Heat Panels
    - 5.2 MW
- **Air Sources**
  - Push/Pull Fan Arrangement
    - 150,000 cfm
    - Annular/Central flow
- **Walls**
  - Water Cooled

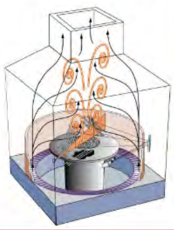
Burnsite and Other Areas

- **Burnsite: Open Pool**
  - 10 meter diameter fires
  - Large jet fuel reservoir

[redacted]

- **Burnsite: Igloo**
  - 54’ x 26’ x 14’ bunker for fire testing
  - Ceiling vents and one sided entry

- **Burnsite: Old FLAME facility**
  - 6 m internal square test section
  - Water cooled walls, remote site



- **South End of Sled Track**
  - Open space for a variety of burn conditions
  - Detonation and large pool environments

Historical Experimental Work

- V&V programmatic driver
- Laser diagnostics applied to fire tests
- Battery Fires (in John Hewson’s presentation)
- Propellants
- Composite Materials
- Particle transport (in Dan Guildenbecher’s presentation)

8

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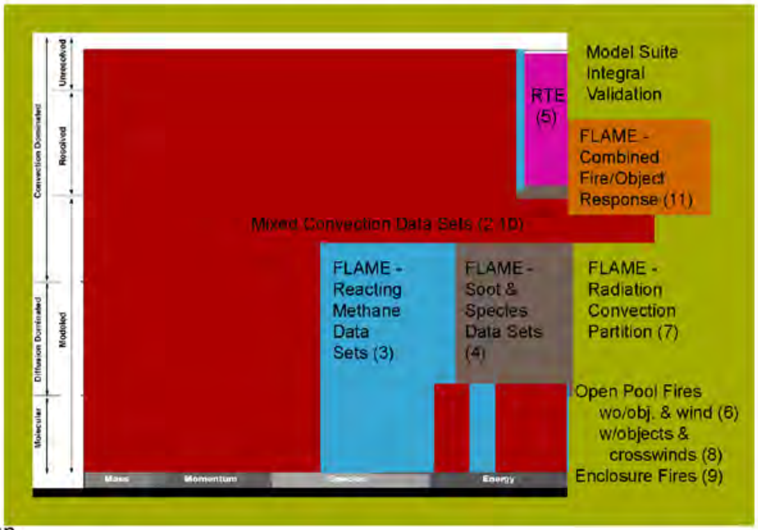
Fuego Validation Test Plan



Validation plan
- Verification completed before validation
- Builds from simple to full physics coupling
- Tailored to application space

Some Fundamental Validation Data

- Helium Plume –
  - O'Hern, T. J., Weckman, E. J., Gerhart, A. L., Tieszen, S. R., Schefer, R. W., 2005, "Experimental Study of a Turbulent Buoyant Helium Plume," Journal of Fluid Mechanics, 544:143-171.
- Hydrogen and Methane Fires –
  - Tieszen, S. R., O'Hern, T. J., Weckman, E. J. and Schefer, R. W., 2004, "Experimental Study of the Effect of Fuel Mass Flux on a One Meter Diameter Methane Fire and Comparison with a Hydrogen Fire," *Combustion and Flame* 139:126-141
  - Tieszen, S. R., O'Hern, T. J., Schefer, R. O., Weckman, E. J., and Blanchat, T. K., 2002, "Experimental Study of the Flow Field In and Around A One Meter Diameter Methane Fire," *Combustion and Flame*, 129:378-391
- Soot –
  - Murphy, J.J., and Shaddix, C.R., 2006, "Soot Property Measurements in a Two Meter Diameter JP-8 Pool Fire," *Combustion Science and Technology* 178:865-894.
  - Murphy, J. J. and Shaddix, C. R., 2004, "Soot Properties and Species Measurements in a Two-Meter Diameter JP-8 Pool Fire: 2003 Test Series," Sandia National Laboratories, Albuquerque, NM, SAND2004-8085
  - Murphy, J.J., and Shaddix, C.R., "Soot Property Measurements in a Two-Meter Diameter JP-8 Pool Fire," in press, Combustion Science and Technology.
- Mixed Convection –
  - Siebers, D. L., Schwind, R. G. and Moffat, R. F. 1982. Experimental Mixed Convection From a Large, Vertical Plate in a Horizontal Flow. paper MC13, 3, Proc. 7th Int. Heat Transfer Conf., Munich, 1982
  - Siebers, D. L. 1983, Experimental Mixed Convection Heat Transfer From a Large, Vertical Surface in a Horizontal Flow PhD thesis, Stanford University
  - Siebers, D. L., Moffat, R. F. and Schwind, R. G. 1985. Experimental, Variable Properties Natural Convection From a Large, Vertical, Flat Surface. *J. Heat Transfer*, 107, February, 124-132
- Turbulent Mixed Convection –
  - Kearney, S. P., Grasser, T. W., Liter, S. G., Evans, G. H., Greif, R., "Experimental Investigation of a Cylinder in Turbulent Thermal Convection with an Imposed Shear Flow, AIAA-2005-1124, 43rd AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, 10-13 Jan., 2005.

10

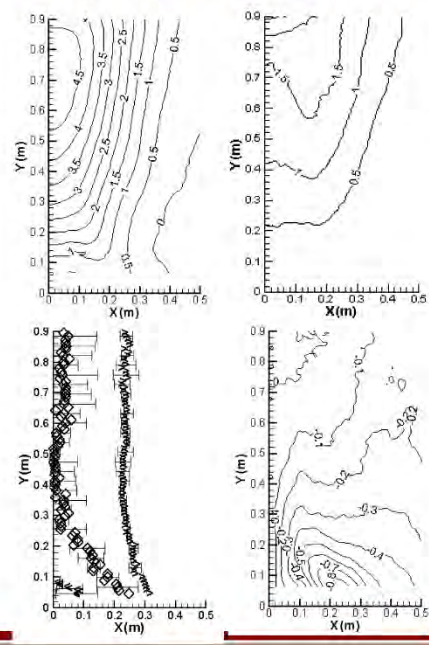
PIV Diagnostics in FLAME

- Illumination sources
  - Two Nd:YAG lasers
    - 300 mJ per sheet at 532 nm
    - Variable laser pulse separation 1 μs to > 1ms
  - Two UV excimer lasers
    - 200 mJ per pulse at 308, 240 nm
    - Laser pulse repetition rate 200 Hz
- Use frame-straddling CCD cameras
  - Photometrics CoolSnap Diff HQ:
    - 1024 × 1024 pixels, 8 bit
  - Redlake Megaplus 4.0/E:
    2048 × 2048 pixels, 8 bit
  - Extensive analog film cameras
- Data processing
  - IDT ProVision 2.02
  - ImagePro
  - PIV Sleuth (UIUC)
- Particle seeding
  - Plume/fire particles 4-60 μm diameter
  - Wind tunnel/jet particles 0.2-0.3 μm diameter

1 meter CH_4 Fire at 0.040 kg/m^2s

Vertical Velocity (m/s)

Turbulent Kinetic Energy (m^2/s^2)



Radial Position of Maximum Reaction Rate (m)

Horizontal Velocity (m/s)

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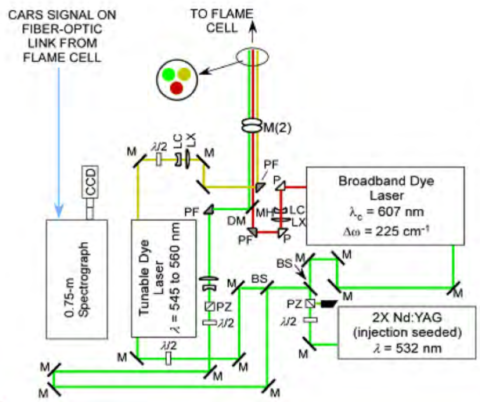
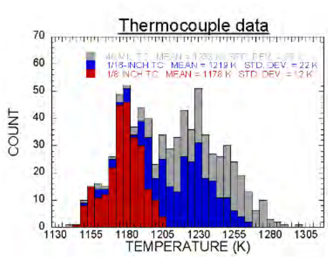
Dual-Pump CARS Instrument at FLAME

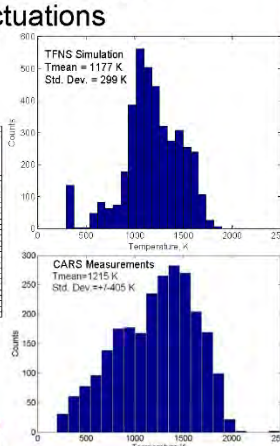
- First-ever implementation of CARS for large-scale fire testing
- Methanol and sooting methanol/toluene blends have been tested to date
- Simultaneous mole-fraction measurements have been added to thermometry capabilities

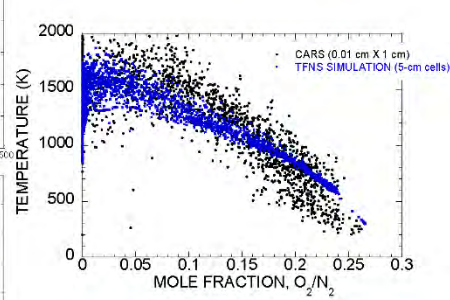


Results – Temperature and O_2 Data from a Methanol Pool Fire

- First experiments conducted in methanol fire
- Nonsooting fuel is simpler starting point for diagnostic development
- Temperature and simultaneous O_2 data extracted
- Nearby thermocouples cannot follow turbulent fluctuations







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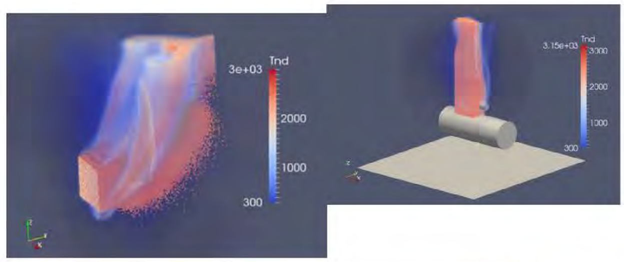
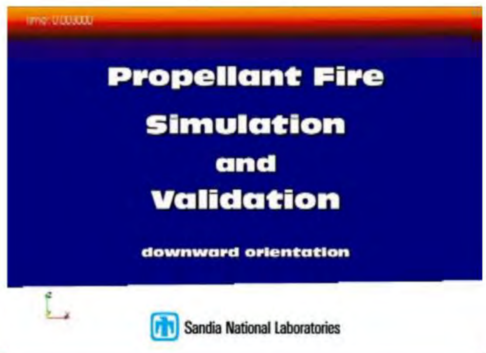
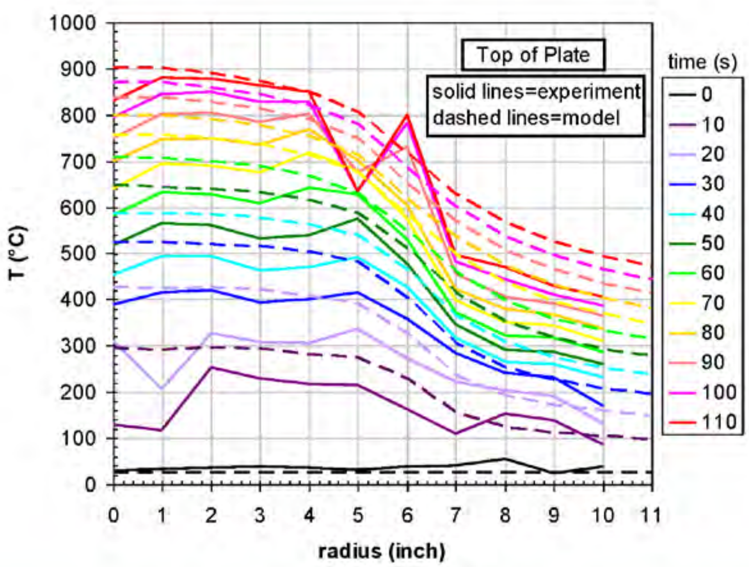
Propellant Tests and Models





Temperatures Beneath a Propellant



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Composite Material Fires

- Increasingly used in aviation applications, carbon fiber epoxy materials exhibit complex behavior in fires
- Experimental program focused on the thermal environment with tests ranging from micrograms to hundreds of kilograms

Back-side of a heated panel

Rubble fire involving 900 lbs. of composite material and 320 gal. of jet fuel

End of burn for a test involving 40 kg of crib-arranged composite material in an insulated enclosure (with AFRL-Tyndall)

Modeling at Sandia

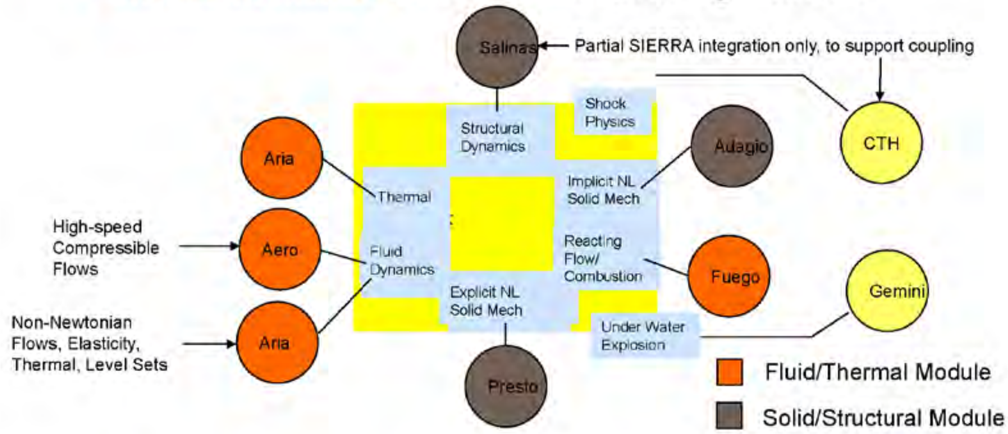
Enabled by world class computing resources, dedicated programs to support tools designed to take advantage of resource.

Outline:

- Introduction to SIERRA
- Vulcan/SIERRA-Fuego history
- Code coupling
- Propellants/Particle Combustion Models
- Solid reacting materials
- Spray and chemical suppression

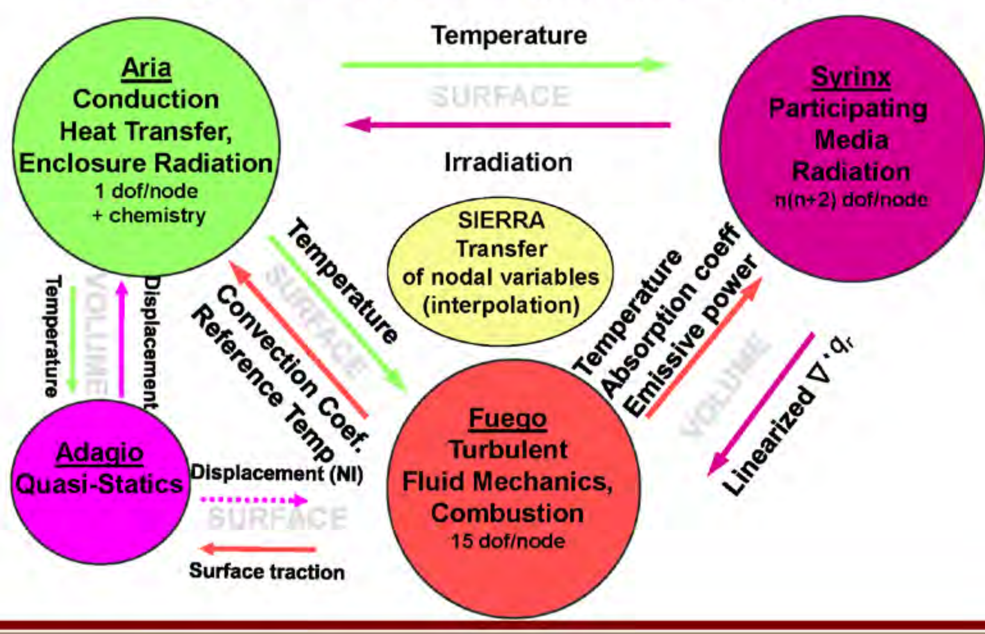
SIERRA Mechanics: The Big Picture

- *SIERRA Mechanics* consists of the following modules:



•Modules can readily be coupled for multi-physics applications
•Strategic activities underway to combine modules
•SIERRA open source capabilities enable non-open source codes

Coupled-Mechanics Example
Object-in-Fire with Structural Response



Vulcan/Fuego History

- In the early 1990s, Sandia began fire simulation work with a reacting CFD code, Vulcan, based on ComputIT Kameleon
  - Structured elements, limited solver capabilities
  - Currently a 'legacy' code, not heavily used
  - Was a platform for some suppression work, initial particle model development
- A few years later, the DOE ASC program began funding SIERRA/Fuego, which is currently our standard tool
  - Unstructured mesh support, rich solver capabilities
  - Massively parallel, designed to run on high performance computers
  - Currently the active model development platform
  - Enables more complex analyses

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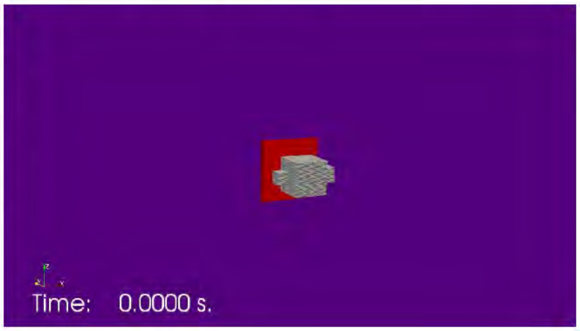
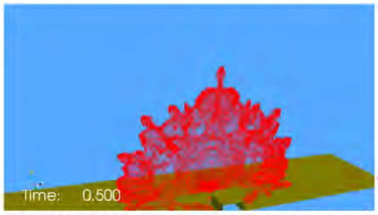
SIERRA-Presto/Fuego Coupling

- Methods are being developed to couple structural mechanics and fluid mechanics calculations in SIERRA
  - Data are limited in this regime
  - Limited validation of model methods –
  - Brown, A.L., G.J. Wagner, and K.E. Metzinger, "Impact, Fire and Fluid Spread Code Coupling for Complex Transportation Accident Environment Simulation," *Journal of Thermal Science and Engineering Applications*, Vol. 4, No. 2, pp. 021004-1 to 021004-10, June 2012.
- Capability represents a unique modeling and simulation capability
- Detonation and impulse initiated dispersal events have been simulated





Model liquid dispersion from a liquid tank impact

Corresponding experimental dispersion

22

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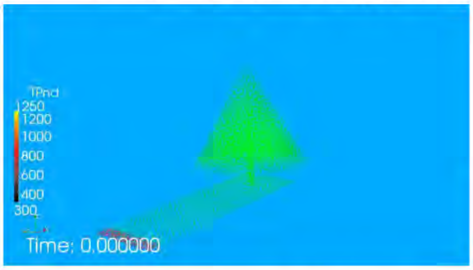
Particle Combustion Model

- Primarily used in the past for two projects:
  - Wildland fire predictions for idealized trees
  - Aluminized propellant reactions
  - Has more general applicability

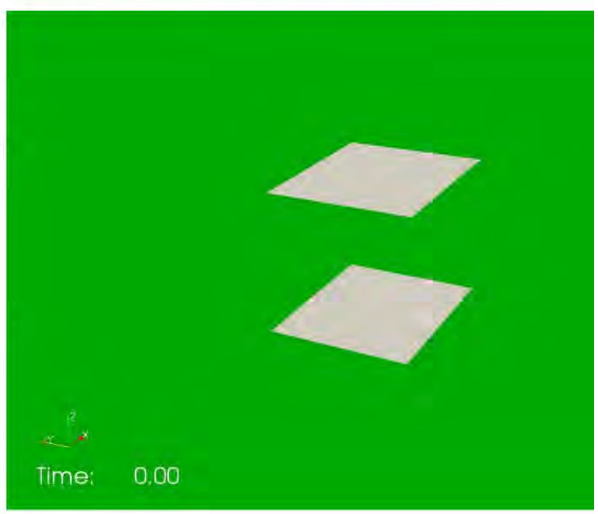


Particles arranged to represent wildland plants

Particles emerging from aluminized propellants

1-D Solid Reacting Boundary Condition

- Recent work demonstrates the verification of the methods and compares to data in the context of a sensitivity analysis.
  - Brown, A.L., D. Glaze, F. Pierce, "Sensitivity Analysis and Verification of a 1-D Surface Solid Combustion Model for a Fire CFD Boundary Condition," The 2014 ASME/AIAA Summer Conference, Atlanta, Georgia, June 16-20, 2014.
- Data source:
  - Ndubizu, C.C., R. Ananth, P.A. Tatem, "Transient burning rate of a noncharring plate under a forced flow boundary layer flame," Combustion and Flame, 141, 131-148, 2005.



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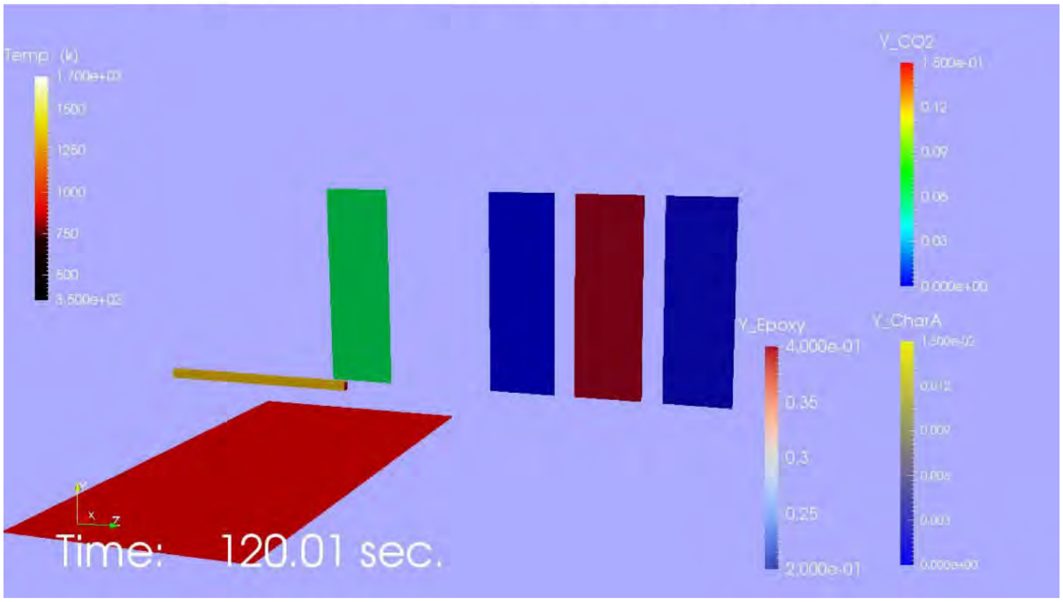
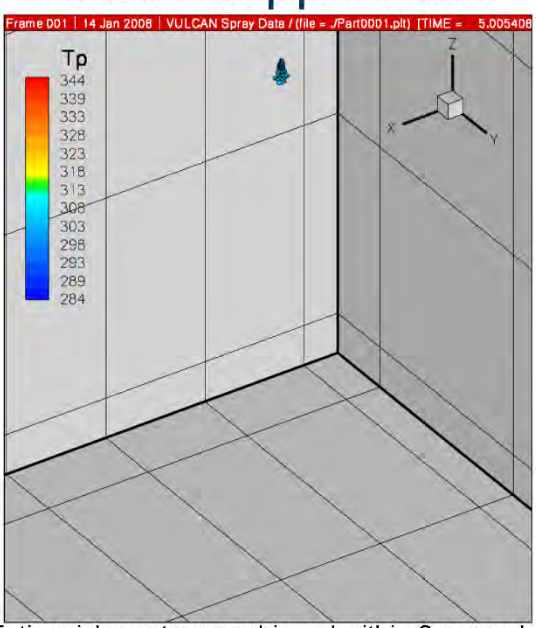
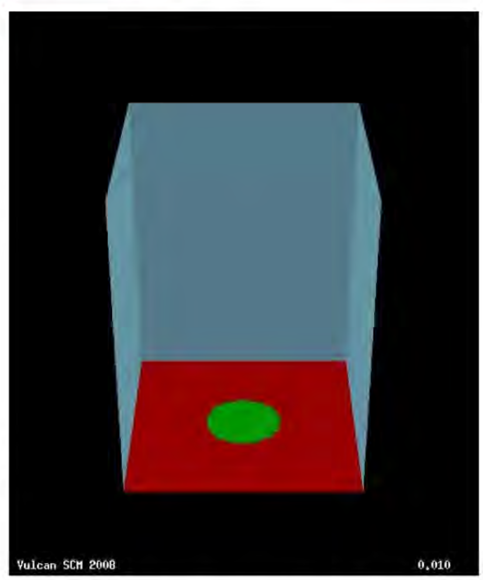
3-D Solid Reacting Material Model

- New model includes porous transport, charring reactions, oxidative reactions.
  - Hubbard, J.A., A.L. Brown, A.B. Dodd, S. Gomez-Vasquez, and C.J. Ramirez, “Aircraft carbon fiber composite characterization in adverse thermal environments: radiant heat and piloted ignition flame spread,” Sandia Report SAND2011-2833.



Vulcan Suppression Modeling

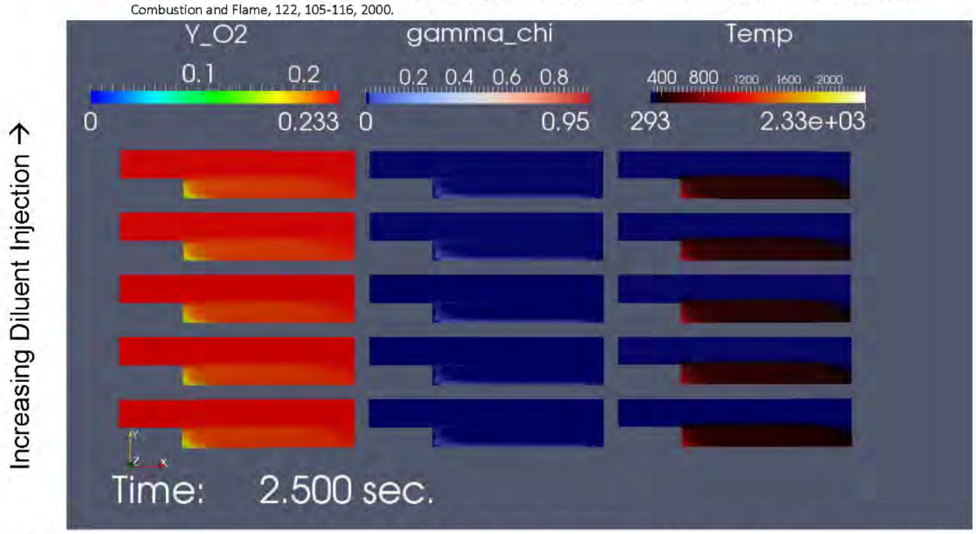




Extinguishment was achieved within 2 seconds, from the point of water spray injection (5 sec) to about 7.0 sec.

Fuego EDC Suppression Modeling

- A fire stabilized behind a backward facing step
  - Takahashi, F., W.J. Schmoll, E.A. Strader, V.M. Belovich, "Suppression of a Nonpremixed Flame Stabilized by a Backward-Facing Step," Combustion and Flame, 122, 105-116, 2000.



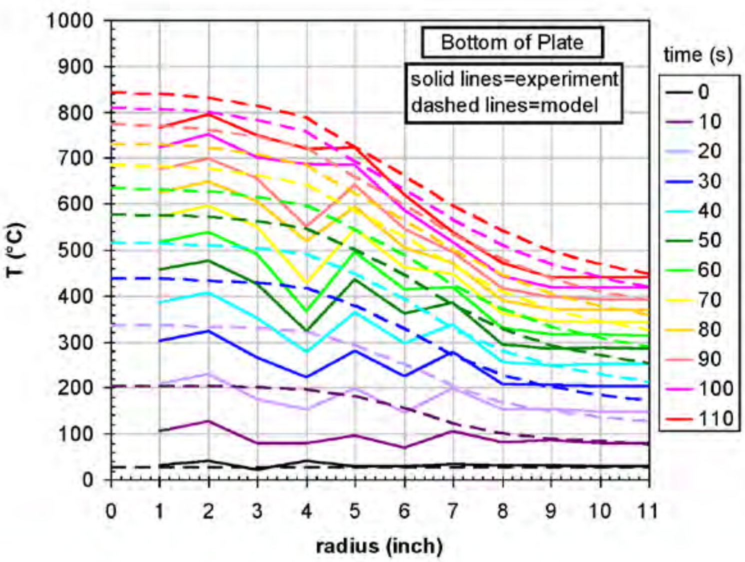
Extinguishment was approximate in time to the experiments, and close in terms of diluent concentrations

Summary

- The Sandia Fire Science and Technology department is a DOE facility that solves high consequence fire problems
  - Unique experimental facilities
  - World class diagnostics
  - High-performance scientific computing capabilities
  - Unique engineering modeling capabilities to solve multi-physics problems
  - People with quality characteristics to match the hardware and software
- Many of our capabilities align well with the objectives of the this exchange meeting
  - Presentation material selected to align with the statement of interest
- We collaborate with the DOD on problems of mutual interest

Acknowledgements

- A large number of Sandia staff colleagues contributed to the material in this presentation, including major R&D contributions from Sheldon Tieszen, Sean Kearney, Joe Jung, Stefan Domino, Tom Blanchat, Walt Gill, Jim Nakos, John Hewson, Greg Wagner, Flint Pierce, David Glaze, Vern Nicolette.



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Southwest Research Institute
FIRE TECHNOLOGY DEPARTMENT

Oct 14, 2015

FIRE TECHNOLOGY DEPARTMENT
Current Facts

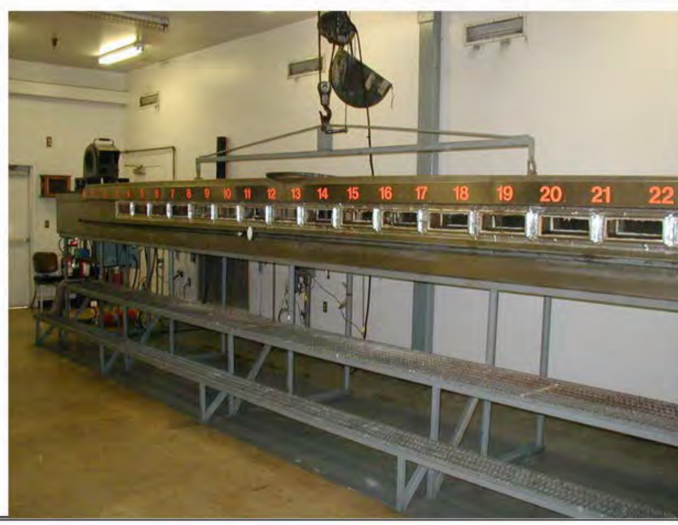
- Includes 48,500 ft^2 (4,500 m^2) of laboratory space,1500 acres (6 km^2) in Sabinal
- Divided into 3 operating sections
  - Material Flammability
  - Fire Resistance
  - Engineering and Research
- 42 employees total – includes 11 degreed staff
  - 1 Ph.D. in Fire Protection
  - 1 Ph.D. in Chemistry
  - 3 M.S. in Fire Protection
  - 1 B.S. in Fire Protection
  - 4 B.S. in Mechanical Engineering
  - 1 B.A. in Business

Material Flammability
Cone Calorimeter

Material Flammability
Smoke Chamber with FTIR

Material Flammability
IMO Surface Flammability Test

Material Flammability
Steiner Tunnel



Material Flammability
Roofing and Radiant Panel Ignition Tests

Fire Resistance
Bellcore NEBS and SBI Tests

Fire Resistance
Furniture and Industrial Calorimeters

Fire Resistance
Large Vertical Furnace

Fire Resistance
Small Horizontal Furnace

Fire Resistance
Plastic Fuel Tank Testing

Fire Resistance
Jet-Fire Testing

Engineering and Research
Sprinkler Testing

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Specialty Large Energy Burns

- Rocket Fuel MW burns
  - Design
  - Fabricate
  - Test
- RFAS – HEAF test
  - 240 MW test for 3 seconds

[redacted]

Explosive energy

- Hydrogen Safety
- Alternative Fuels
- Structural impacts of gas explosions
- Flammability ranges
- Reactor design safety limits

[redacted]

Engineering and Research
Pool Fire Tests

Engineering and Research
PRV Valves

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Engineering and Research
Explosive Environment Test

Engineering and Research
Radiant Exposure to LPG Tank

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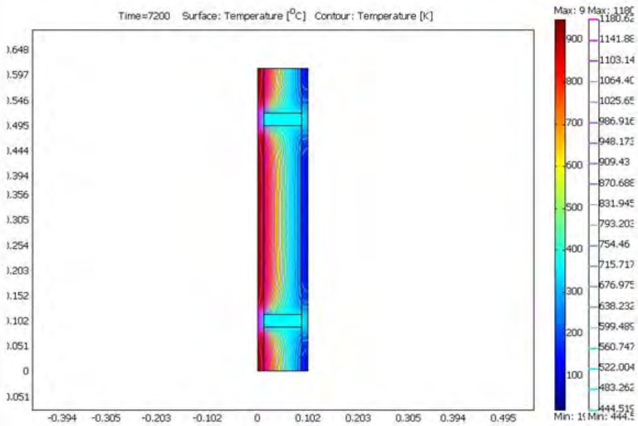
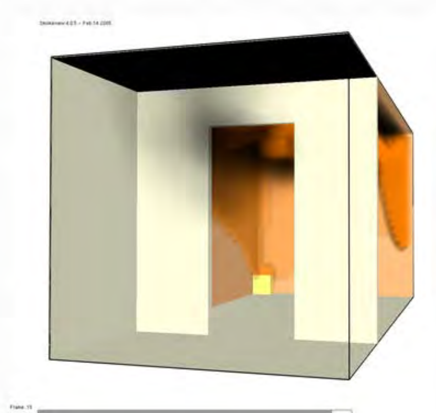
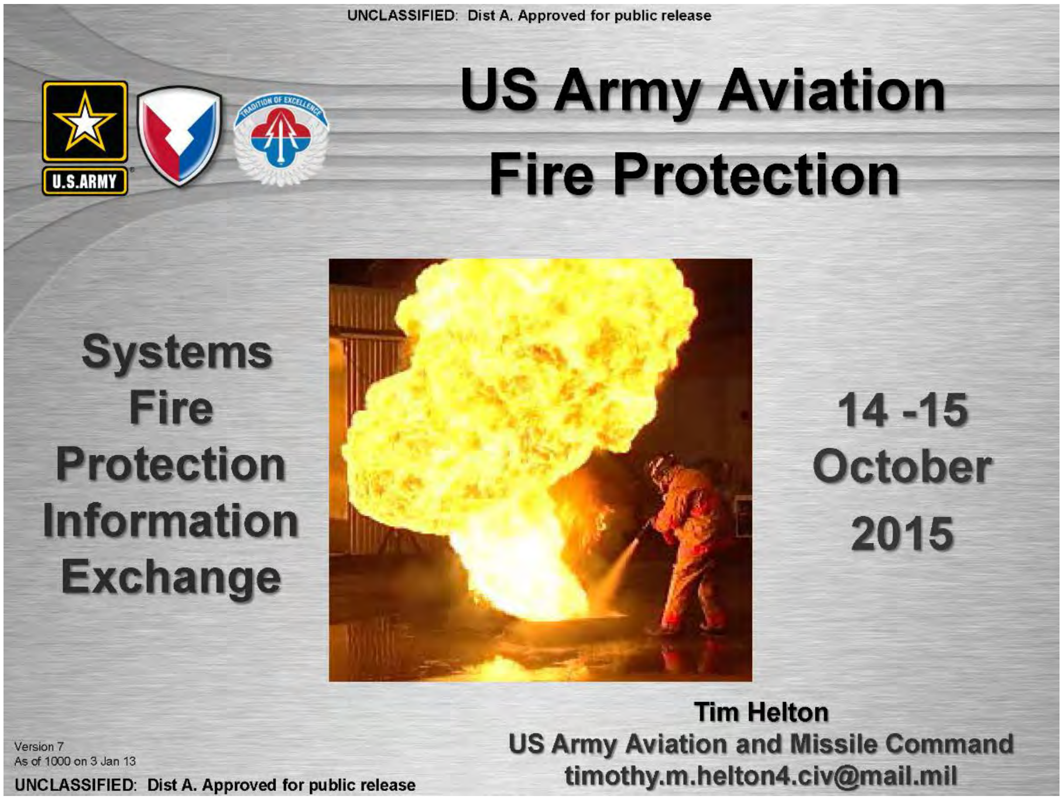
Engineering and Research
Finite Element Method Modeling



Engineering and Research
Computational Fluid Dynamics Modeling

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U.S.ARMY
US Army Aviation
Fire Protection
Systems
Fire
Protection
Information
Exchange
14 -15
October
2015
Tim Helton
US Army Aviation and Missile Command
timothy.m.helton4.civ@mail.mil
Version 7
As of 1000 on 3 Jan 13
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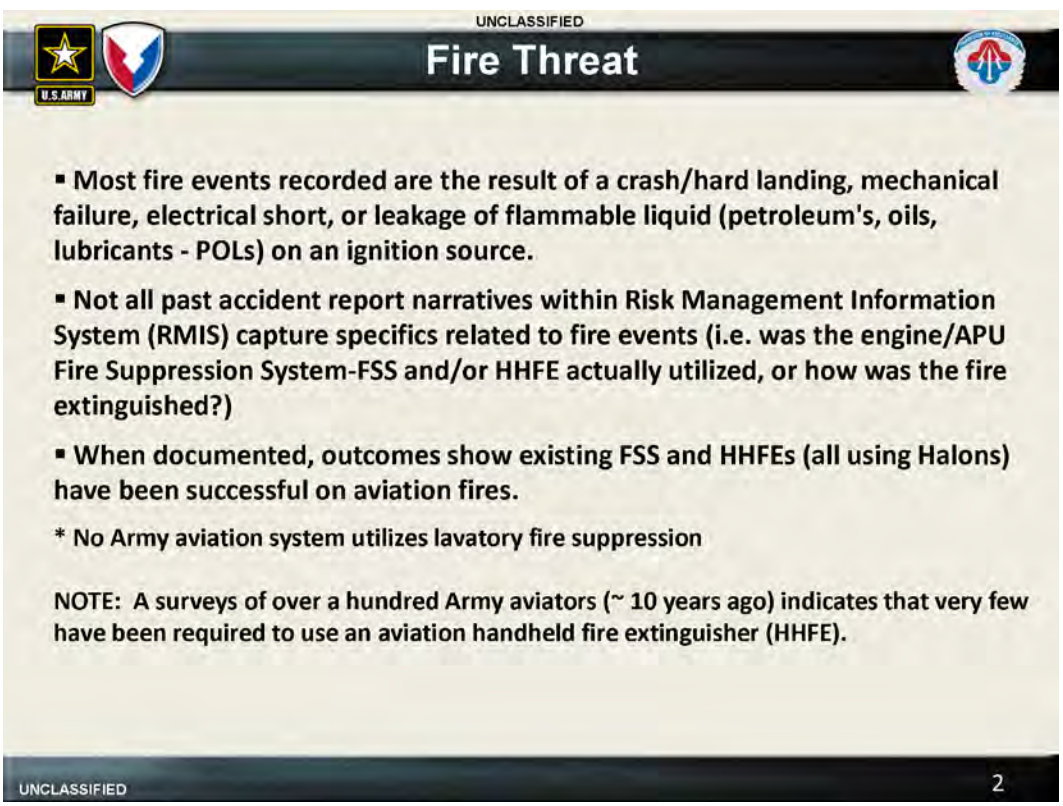
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Fire Threat
▪ Most fire events recorded are the result of a crash/hard landing, mechanical failure, electrical short, or leakage of flammable liquid (petroleum's, oils, lubricants - POLs) on an ignition source.
▪ Not all past accident report narratives within Risk Management Information System (RMIS) capture specifics related to fire events (i.e. was the engine/APU Fire Suppression System-FSS and/or HHFE actually utilized, or how was the fire extinguished?)
▪ When documented, outcomes show existing FSS and HHFEs (all using Halons) have been successful on aviation fires.
* No Army aviation system utilizes lavatory fire suppression
NOTE: A surveys of over a hundred Army aviators (~ 10 years ago) indicates that very few have been required to use an aviation handheld fire extinguisher (HHFE).
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Fire Threat - Example

Generator Fire on an AH-64

UNCLASSIFIED 3

UNCLASSIFIED

Halon FSS Replacement Efforts

Cargo Helicopter (CH)

- **The CH Project Management Office (PMO) initiated its phase of the PEO Aviation Halon Replacement Program (HRP) July 2005. In-flight concentration testing of HFC-125 (Pentafluoroethane) began March 2006 on board a CH aircraft at the Aviation Technical Test Center (ATTC).**
- **Test results were less than the 26% volumetric concentration required and was therefore unacceptable with the current extinguishing system plumbing configuration.**
- **After evaluation of test data, the CH PMO decided to continue the test program to assess the impact of infrared suppression system (IRSS) equipment mounted on the nacelle**
- **HFC-125 concentration testing was performed with the IRSS installed on the test CH-47 aircraft. Results did not indicate any significant change in concentration levels. Again, testing did not meet required concentration level of 26% for .5 seconds.**

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Halon FSS Replacement Efforts

Attack Helicopter (AH)

- An AH PMO HRP was initiated in December 2003.
- Program personnel, PEO Aviation and others evaluated HFC-125 test results from a final report provided by the Wright Patterson Air Force Base (WPAFB) fire test facility in June 2007.
- Review of the test data contained in the report was very inconclusive due to problems with test equipment.
- AH PMO investigated obtaining test hardware and equipment that was constructed and purchased for this testing from WPAFB.
- The AH PMO monitored the flight testing performed for the Cargo Helicopter and was unable to leverage anything from this work.
- No additional testing was performed.

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Halon FSS Replacement Efforts

Utility Helicopter (UH)

- Testing in an MH-60 Iron-Bird Test Module at Patuxent (PAX) River Naval Air Station was completed in 2007.
- From these test results, PMA-299 investigated using the on-board H-60 Halon cylinders (charged with HFC-125) fired simultaneously (Single Shot Extinguishing System Capability).
- PMA-299 tested with dual H-53 cylinders (charged with HFC-125), simulating a redundant shot system, and never achieved the target design concentration in the same 0.5 second interval for fire suppression
- While NAVAIR safety approved a single shot configuration, concurrent efforts to document the plumbing changes for the new system and development of a qualification test plan were completed
- The MH-60 configuration will not allow for cylinders larger than the H-53's.
- PMA-299 performed flight testing and ultimately decided to remain with Halon in 2012
- The Army's UH-60 FSS cylinder configuration is different and would allow for larger cylinders, however a dual shot (redundant) system would be **required.** HFC-125 was not deemed a feasible option for the Army UH-60s.

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Halon Replacement for Engine/APU Fire Suppression

- Army Aviation SMEs participated in the FAA's Halon Aviation Rulemaking Committee (ARC) IPT
- Will continue to participate in the Halon Alternatives for Aircraft Propulsion Systems (HAAPs) Consortium (formerly the Aviation Halon Engine/APU Replacement Industrial Consortium (IC))
- Continue to participate in the International Aviation System Fire Protection Working Group (IASFPWG)
- Continue to team with TARDEC requesting Army Environmental Requirements Technical Assessment (AERTA) RDT&E funding for work in the area of No/Low Global Warming Potential Fire Suppression Alternatives in Army Applications (Not approved at this time)
  - Currently awaiting final decision regarding funding for FY 16
  - If and when funded the amount could be significantly lower that what was requested
- Periodically meet with PMOs, ASA(ALT) support, other DoD Services and government agencies along with industry SMEs to discuss status of replacements/along with current & future programs/meetings

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Brief History Army Aviation Wpn Sys Handheld Fire Extinguisher (HHFE)

- The Aviation Project Offices and other stakeholders had <u>No Historical Data</u> regarding Army Aviation HHFEs
- Halon 104 (Carbon Tetrachloride–CTC) is thought to be an initial HHFE agent on Military Aircraft through the end of WWII
- CTC is thought to have been replaced with Halons 1001, 1011, 1211, 1301 and CO2 throughout the years.
- Halon 1211 and 1301 were developed in the late 40's. Halon 1301 HHFEs was introduced as a replacement for CO2 HHFEs used on rotary wing aircraft in the late 70's/early '80s.
- In the early '90s, ATCOM and NAVAIR initiated an effort to replace Halon 1301 HHFEs (NSN: 6830-00-555-8837) - CO2 was the replacement agent selected
- The CO2 HHFE replacement was abandoned by the Army in 1999 at AMCOM
- TACOM/Abram's Potassium Acetate HHFE deemed too conductive for aviation applications in 2006
- Commercial Industry had not developed a non-Halon HHFE that would not present a dramatic increase in size and weight over the current configuration
- PEO Aviation initiated an effort to develop a non-Halon HHFE in 2007
- Army aviation developed a new Aviation Weapon System HHFE using HFC-227ea mixed with a special sodium bicarbonate powder (SBCs) (Contract awarded by DLA Troop Support in April 2015).
- HFC-227ea/SBCs HHFEs should be delivered in September 2016. Fielding will take place via attrition.

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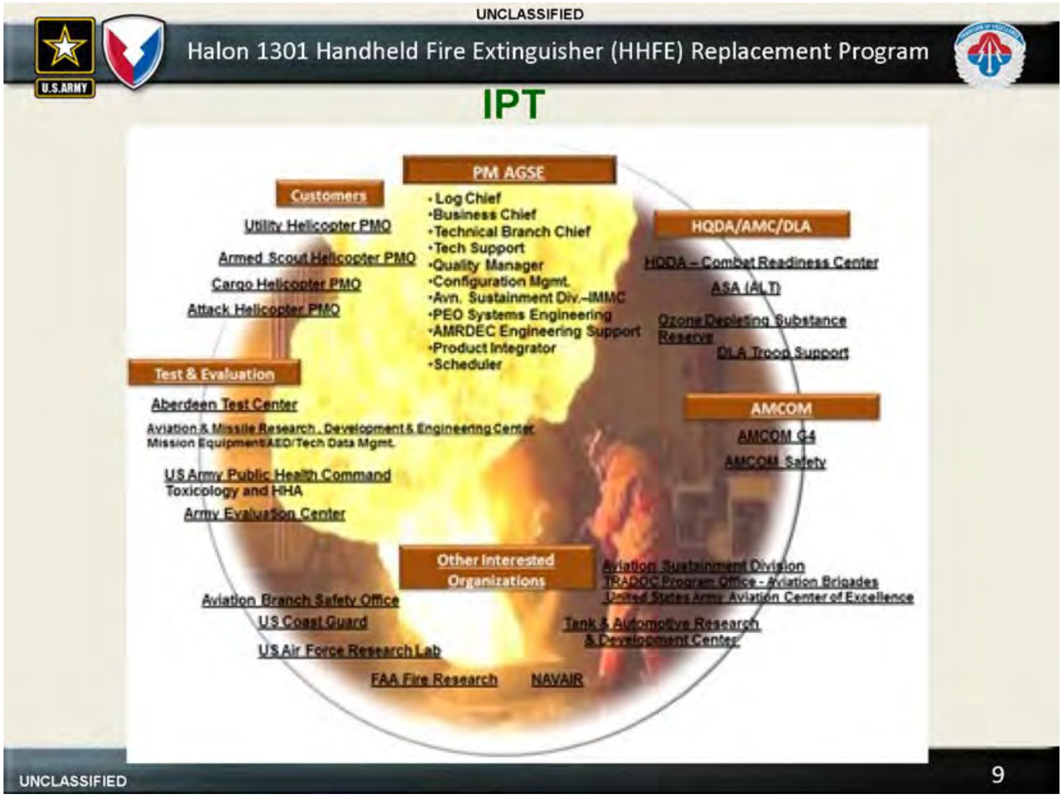
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U.S. ARMY
Halon 1301 Handheld Fire Extinguisher (HHFE) Replacement Program
IPT
PM AGSE
•Log Chief
•Business Chief
•Technical Branch Chief
•Tech Support
•Quality Manager
•Configuration Mgmt.
•Avn. Sustainment Div.–IMMC
•PEO Systems Engineering
•AMRDEC Engineering Support
•Product Integrator
•Scheduler
Customers
Utility Helicopter PMO
Armed Scout Helicopter PMO
Cargo Helicopter PMO
Attack Helicopter PMO
HQDA/AMC/DLA
HQDA – Combat Readiness Center
ASA (ALT)
Ozone Depleting Substance Reserve
DLA Troop Support
Test & Evaluation
Aberdeen Test Center
Aviation & Missile Research, Development & Engineering Center
Mission Equipment/AED/Tech Data Mgmt.
US Army Public Health Command
Toxicology and HHA
Army Evaluation Center
AMCOM
AMCOM G4
AMCOM Safety
Other Interested Organizations
Aviation Sustainment Division
TRADOC Program Office - Aviation Brigades
United States Army Aviation Center of Excellence
Aviation Branch Safety Office
US Coast Guard
US Air Force Research Lab
Tank & Automotive Research & Development Center
FAA Fire Research
NAVAIR
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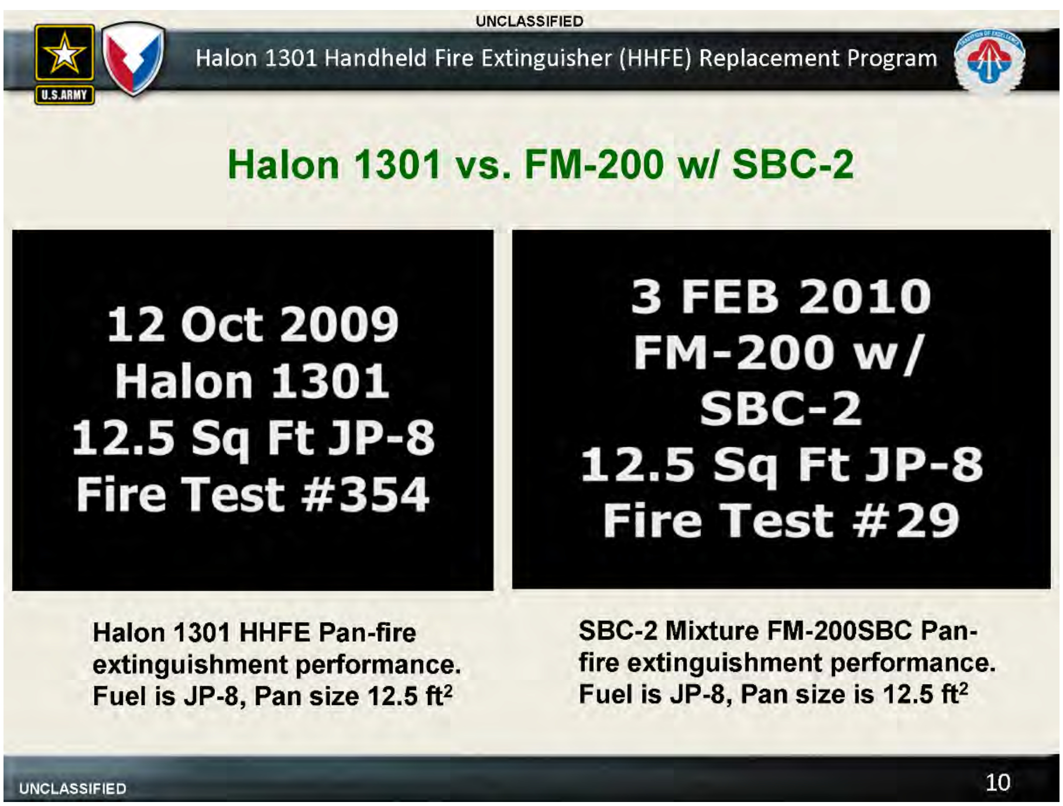
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U.S. ARMY
Halon 1301 Handheld Fire Extinguisher (HHFE) Replacement Program
Halon 1301 vs. FM-200 w/ SBC-2
12 Oct 2009
Halon 1301
12.5 Sq Ft JP-8
Fire Test #354
3 FEB 2010
FM-200 w/
SBC-2
12.5 Sq Ft JP-8
Fire Test #29
Halon 1301 HHFE Pan-fire extinguishment performance. Fuel is JP-8, Pan size 12.5 ft²
SBC-2 Mixture FM-200SBC Pan-fire extinguishment performance. Fuel is JP-8, Pan size is 12.5 ft²
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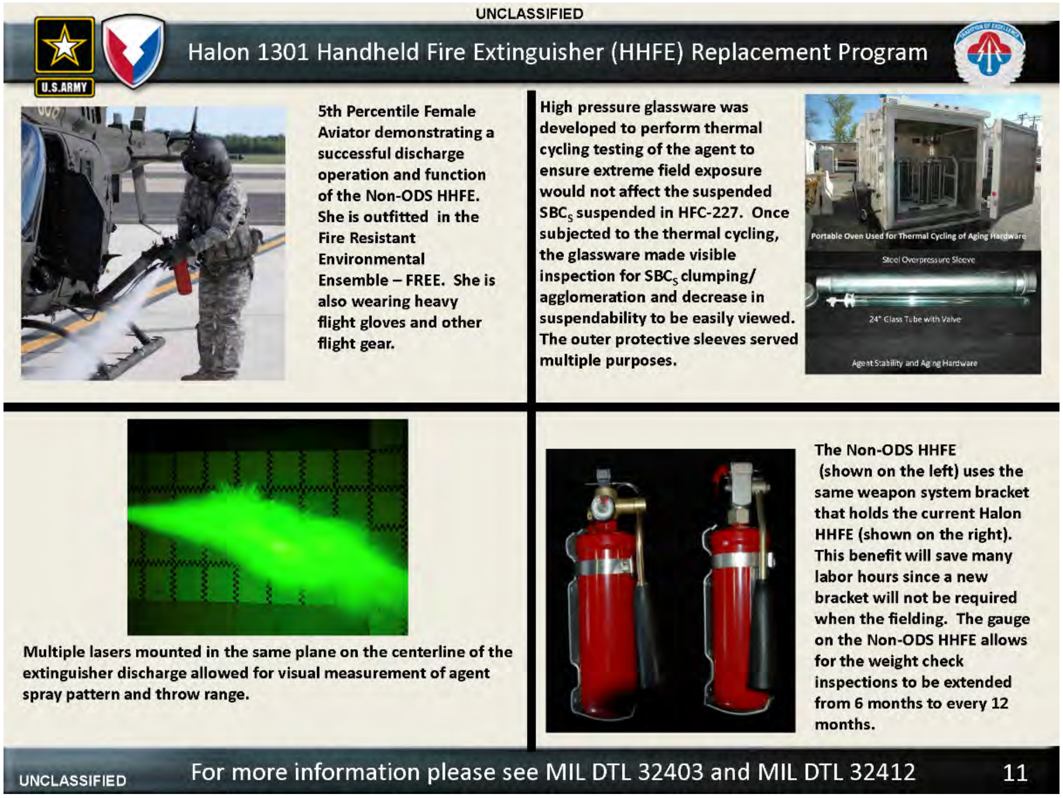
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U.S.ARMY
Halon 1301 Handheld Fire Extinguisher (HHFE) Replacement Program
5th Percentile Female Aviator demonstrating a successful discharge operation and function of the Non-ODS HHFE. She is outfitted in the Fire Resistant Environmental Ensemble – FREE. She is also wearing heavy flight gloves and other flight gear.
High pressure glassware was developed to perform thermal cycling testing of the agent to ensure extreme field exposure would not affect the suspended SBC_S suspended in HFC-227. Once subjected to the thermal cycling, the glassware made visible inspection for SBC_S clumping/ agglomeration and decrease in suspendability to be easily viewed. The outer protective sleeves served multiple purposes.
Portable Oven Used for Thermal Cycling of Aging Hardware
Steel Overpressure Sleeve
24" Glass Tube with Valve
Agent Stability and Aging Hardware
Multiple lasers mounted in the same plane on the centerline of the extinguisher discharge allowed for visual measurement of agent spray pattern and throw range.
The Non-ODS HHFE (shown on the left) uses the same weapon system bracket that holds the current Halon HHFE (shown on the right). This benefit will save many labor hours since a new bracket will not be required when the fielding. The gauge on the Non-ODS HHFE allows for the weight check inspections to be extended from 6 months to every 12 months.
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For more information please see MIL DTL 32403 and MIL DTL 32412
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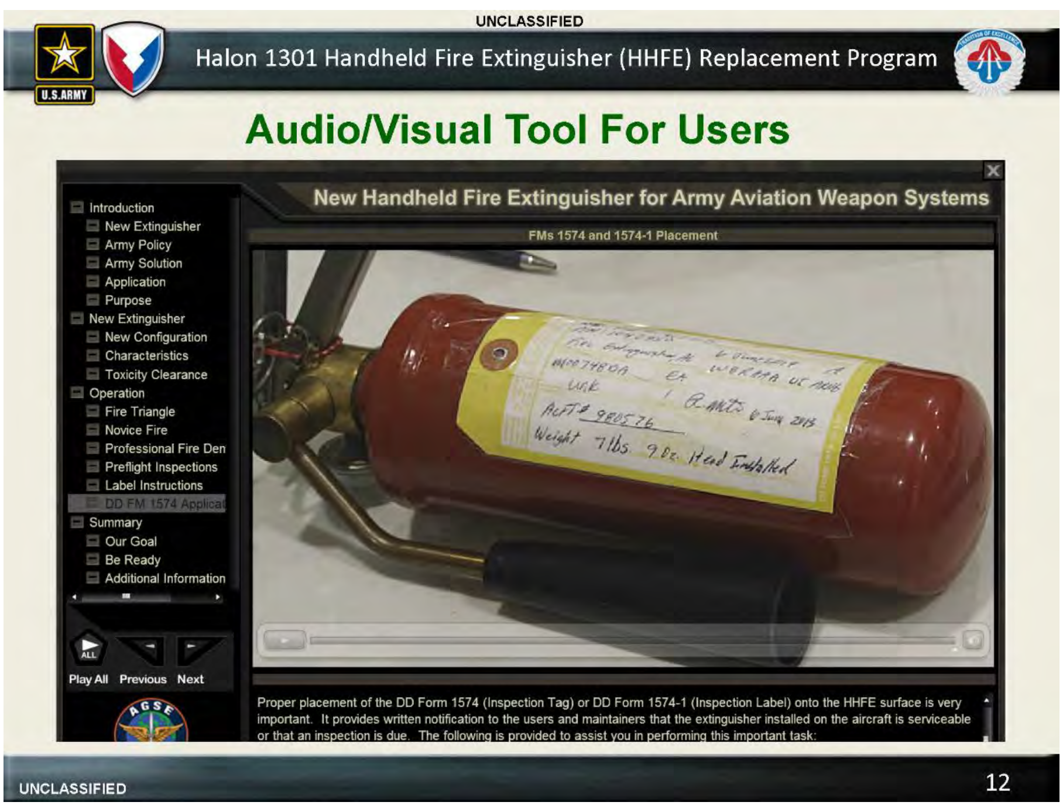
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U.S.ARMY
Halon 1301 Handheld Fire Extinguisher (HHFE) Replacement Program
Audio/Visual Tool For Users
New Handheld Fire Extinguisher for Army Aviation Weapon Systems
FMs 1574 and 1574-1 Placement
Introduction
New Extinguisher
Army Policy
Army Solution
Application
Purpose
New Extinguisher
New Configuration
Characteristics
Toxicity Clearance
Operation
Fire Triangle
Novice Fire
Professional Fire Den
Preflight Inspections
Label Instructions
DD FM 1574 Applicat
Summary
Our Goal
Be Ready
Additional Information
ALL
Play All Previous Next
Proper placement of the DD Form 1574 (Inspection Tag) or DD Form 1574-1 (Inspection Label) onto the HHFE surface is very important. It provides written notification to the users and maintainers that the extinguisher installed on the aircraft is serviceable or that an inspection is due. The following is provided to assist you in performing this important task:
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Halon 1301 Handheld Fire Extinguisher (HHFE) Replacement Program

- Future Tasks (preparation for fielding – FY 15/16)
  - Continue to update the Technical Data Package (TDP)
  - Finalize Manual Review and Develop Initial MIM
  - Develop articles for PMO Newsletters , Flight Fax Magazine, other Army publications
  - Launch Video via AGSE Joint Technical Date Integration (JTDI)
  - Provide 2028 Changes to ALC
  - FAT should begin in FY 16 (Delayed as of today – we are working)
  - Support to be provided as required
  - Trial requisitions
- Post fielding tasks (FY 17 – ?)
  - Value Engineering (VE) Program for a lighter cylinder configuration
  - VE Program for extending service life
  - Updates to Specifications, TDP, etc., Misc. technical information

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Army Aviation Fire Protection

Questions?

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U.S. ARMY TANK AUTOMOTIVE RESEARCH, DEVELOPMENT AND ENGINEERING CENTER

Fire Suppression M&S Validation (Status & Challenges)

Systems Fire Protection Information Exchange
14-15 Oct 2015

Dr. Vamshi M. Korivi
US Army TARDEC
Vamshi.m.korivi.civ@mail.mil

Contributors: Fire Protection Team (TARDEC), Navy Research Labs, CERDEC & ADAPCO

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Outline

- Introduction
- Physics being solved
- Reduced Chemical Kinetics:
  - Complete description of suppression is complex
  - HFP (+SBC); Halon (+SBC), potassium acetate solution.
- Fire Suppression Evaluation Criteria
- Simulation Results & Comparison with Test Data:
  - Cup Burner
  - Exploratory Test Box
  - Crew Compartment
    - » Concentration
    - » Live Fire Simulation
  - Engine Compartment (In-Progress)
- Summary & Future Work

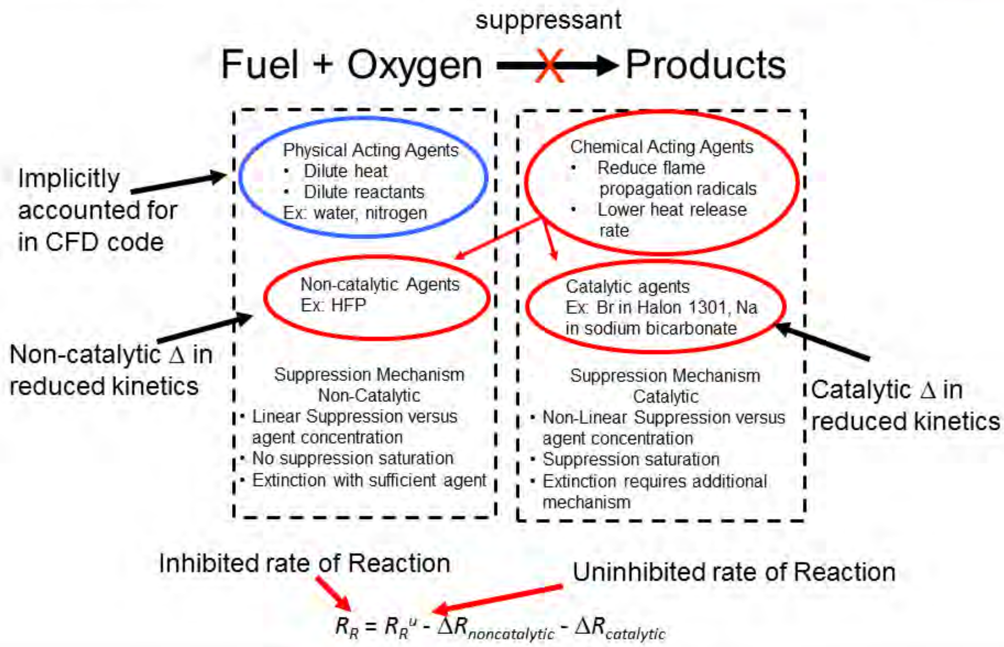
Introduction

- Develop a Computational Fluid Dynamics (CFD) capability for modeling suppression events in ground combat vehicles.
- Using known component parameters, M&S allows:
  - To conduct trade studies between various layouts.
  - Reduces time and cost to compare multiple configurations.
  - Provides insight by complementing testing

Physics Being Solved

Transient Analysis	• Model fuel spray and fire ball development • Suppressant Discharge + Acid Mitigation
Turbulence Model	• K-Epsilon with Realizable Wall functions • Segregated Solver
Lagrangian Physics	• Two-Way Coupling • Evaporation & Devolatization
Suppressant Discharge	• Discharge from Pressurized bottle • Liquid & Vapor Phase
Combustion Model	• Hybrid EBU with finite rate Kinetics • 14 Species & 12 reactions
Radiation Model	• Participating Media Discrete Ordinate Method • WSG model for CO2, H2O and Soot
Suppression	• Catalytic & Non-Catalytic effects • Acid Levels

Inhibition of JP-8 Combustion

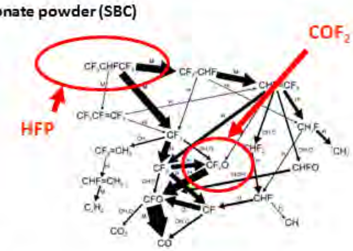


$$R_R = R_R{}^u - \Delta R_{noncatalytic} - \Delta R_{catalytic}$$

Overview of Reduced Kinetics Scheme for FM200

Inhibition of JP-8 combustion by HFP (FM200) and/or sodium bicarbonate powder (SBC)

Mechanism: ≈800 chemical reactions
(200 for hydrocarbon fuel—more for JP-8; 600 for fluorine chemistry)
Predicts flame inhibition, acid gas formation
Useful for modeling laboratory experiments
Not useful for modeling large-scale fire suppression



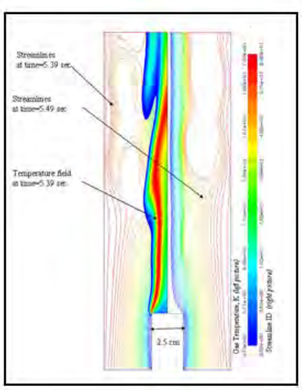
- **R1**: JP-8 + O_2 => CO + CO2 + H_2O
- **R2**: CO + O_2 <=> CO_2
- **R3**: HFP + JP-8 + O_2 => HF + COF_2 + CO + H_2O
- **R4**: COF_2 + H_2O => CO_2 + HF
- **R5**: $NaHCO_3$(s) => CO_2 + NaOH(g)
- **R6**: NaOH(g) <=> NaOH(hvy_gas) (hvy_gas = heavy-gas approximation)
- **R7**: NaOH(hvy_gas) + HF => NaF(hvy_gas) + H_2O
- **R8**: $NaHCO_3$(s) + HF => NaF(hvy_gas) + H_2O + CO_2
- **R9**: JP-8 + O_2 => C (soot) + H_2O
- **R10**: C (soot) + O_2 => +CO_2

Kinetic Rate Coefficient for each equation is given in Arrhenius form (three-parameter)
Halon Kinetics includes HBr acid

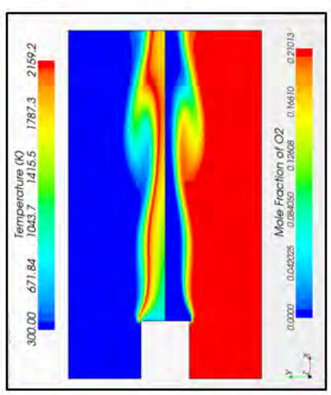
Selected Crew AFES performance criteria:

Parameter	Requirement	Simulation
Fire Suppression	Extinguish Flames without reflash	Y
Skin Burns	Less than Second degree burns	Y
Overpressure	Lung damage <11.6 psi; Ear damage $\leq$3.6 psi	Y
Acid Gases	Acid gas, 5 min dose ($HF + HBr + 2{\cdot}COF_2$) < 746 ppm-min	Y
Agent Concentration	<Lowest Observed Adverse Effects Level	Y
Oxygen Levels	Not below 16%	Y
Discharge Impulse Noise	No hearing protection limit < 140 dB	N
Discharge Forces	Acceleration $\leq$ 8 g and pressure pulse $\leq$10 psig at crew locations	N
Fragmentation	Ejected non-agent particles $\leq$300 micrometers	N

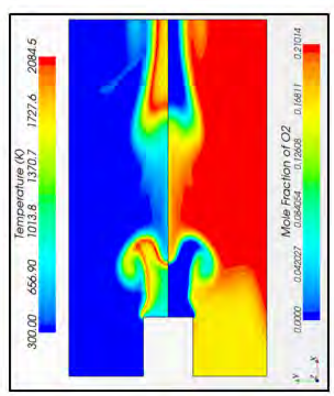
Cup-Burner Modeling (Determine Flame Extinguishing Concentrations)



Ref. NRL Paper (GMRES, 35 species, 217 reactions)



Uninhibited (Two-step Global Reactions)



Inhibited With Nitrogen (Two-step Global Reactions)

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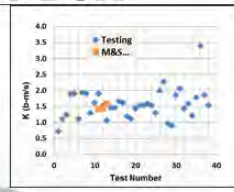
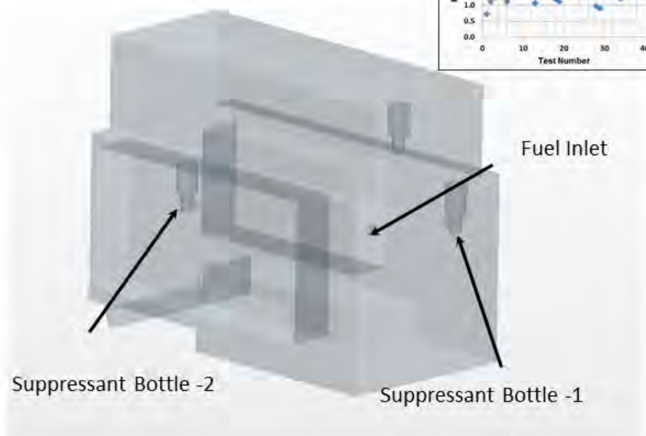
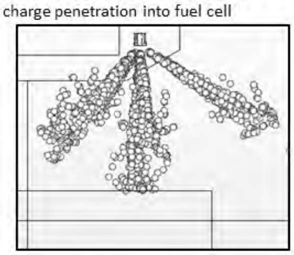
EXPLORATORY TEST BOX





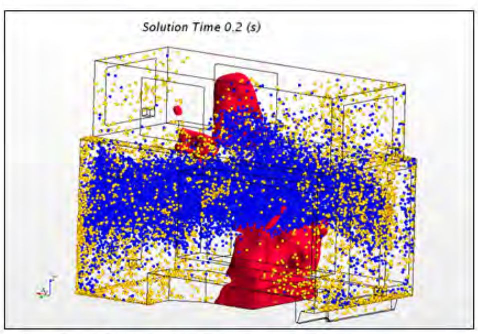
Fire Ball Generator

Fireball is based on a medium shaped charge penetration into fuel cell

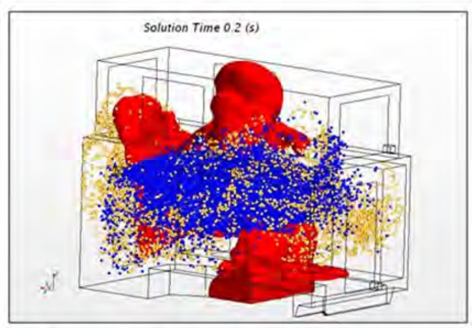


Reference: ***<u>Fire Extinguishing Agents for Protection of Occupied Spaces in Military Ground Vehicles</u>***

EXPLORATORY TEST BOX SIMULATIONS



Test Box (Successful Suppression)
Fire Ball (Red), SBC (Gold), HFC227ea (Blue)



Test Box (Failed Suppression)
Fire Ball (Red), SBC (Gold), HFC227ea (Blue)

Criteria	Above Design Conc.		Below Design Conc.	
	Test	Simulation	Test	Simulation
Overall	Pass	Pass	Fail	Fail
Extinguish Flames without reflash	YES	YES	YES	No
K Value	1.56	1.44	1.14	1.44
HF Acid (PPM)	<20	47	3975	NA
COF2 Acid (PPM)	<20	97	1550	NA
Oxygen Levels	17.4%	18.0%	16.5%	NA

Comparison of FM200 Concentration (Test & Simulation)

Peak concentration levels measured within the 1st 200 and 340 ms

			11. Two-Nozzle @ 45° HVAC off (test)		11. Two-Nozzle @ 45° HVAC off (simulation)	
Position			200	340	200	340
Driver	Nose					
	Knee					
Commander	Nose					
	Knee					
Right Rear	Nose					
	Knee					
Gunner	Nose					
	Knee					
Left Rear	Nose					
	Knee					
FBG	Front					
	Rear					

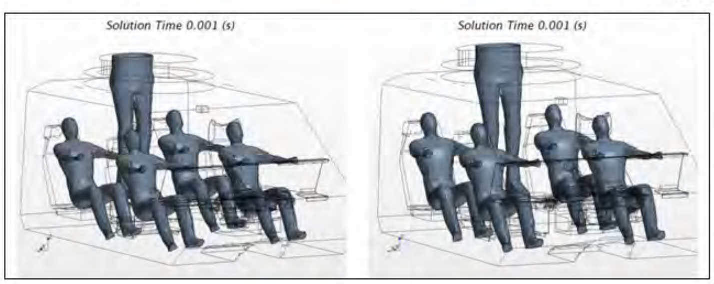
270 ms Criteria

- Peak > 8.7% : Good
- 6.7% < Peak < 8.7% : Acceptable
- 6.7% > Peak : Inadequate

Crew Compartment Nozzle Configuration Comparison

Configuration I

Configuration II



Nozzle Configuration Comparison
With HVAC Off

Comparison of Simulation with Test Data

Criteria	Configuration I 		Configuration II 	
	Test	Simulation	Test	Simulation
Overall	Fail	Fail	Pass	Pass
Extinguish Flames without reflash	YES	YES	YES	YES
Overall Pressure (psi)	0.59	0.48	0.35	0.31
Agent Concentration	Below LOAEL	Below LOAEL	Below LOAEL	Below LOAEL
HF Acid (PPM)	708	656	<20	96
COF2 Acid (PPM)	161	518	<10	169
Oxygen Levels	15.9%	15.9%	17.1%	17.2%

Typical measurements include high speed video, blast overpressures, temperatures and the chemistry of the atmosphere, in particular the combustion byproducts using Fourier Transform Infrared Spectrometer (FTIR)

Simulations done To-date for Crew Compartment

- With & without active air flow
- Fire Ball Generator (FBG) Location change
- Change nozzle parameters
  - number
  - location
  - discharge pattern
- Amount of agent & agent type
- Different clutter characteristics
- Hatch open vs closed scenario
  - RWS vs OGPK

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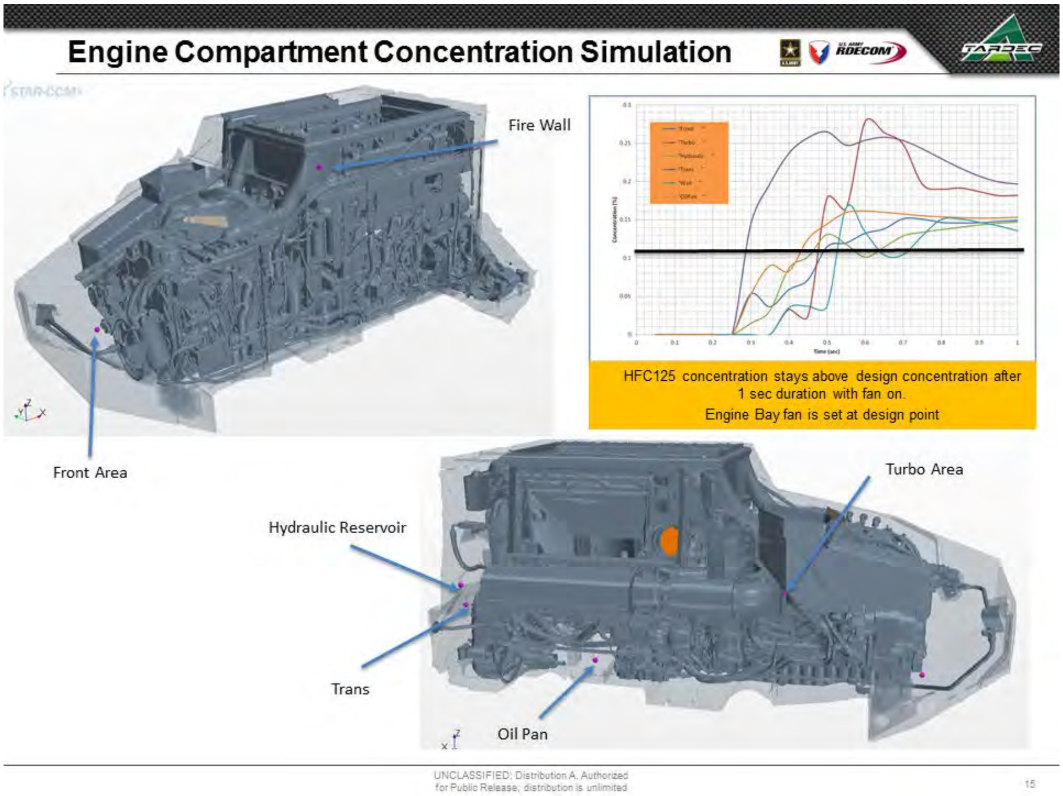
Engine Compartment Concentration Simulation
Fire Wall
HFC125 concentration stays above design concentration after 1 sec duration with fan on.
Engine Bay fan is set at design point
Front Area
Turbo Area
Hydraulic Reservoir
Trans
Oil Pan
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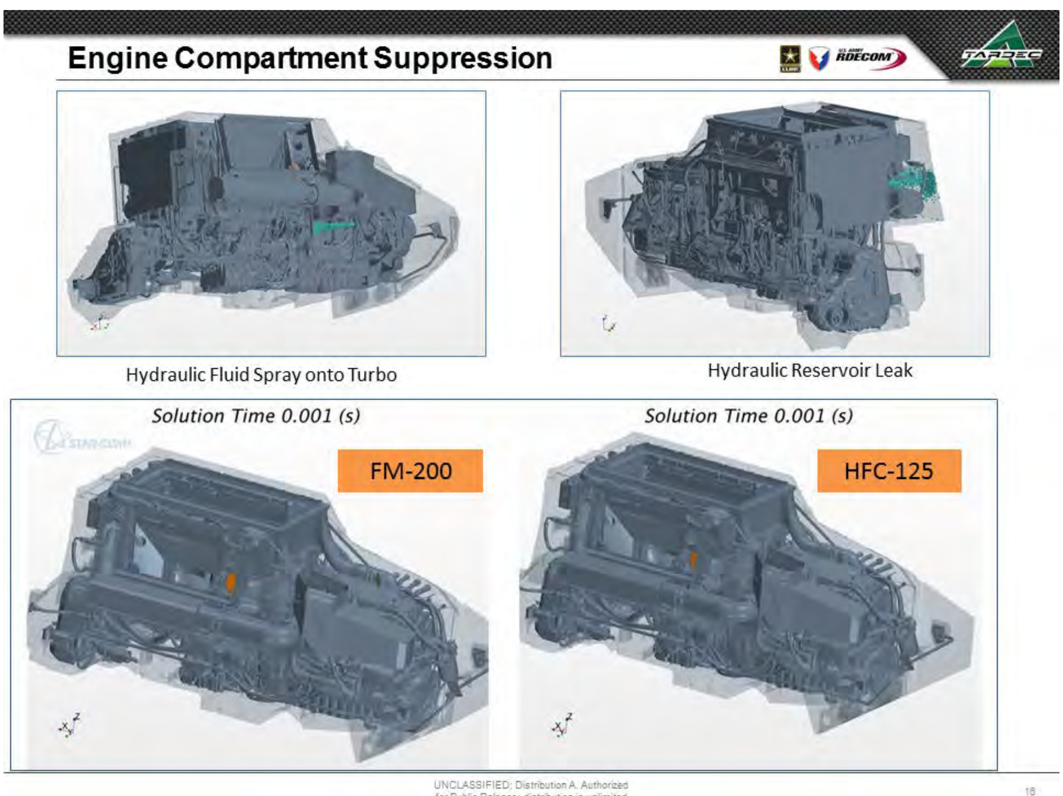
Engine Compartment Suppression
Hydraulic Fluid Spray onto Turbo
Hydraulic Reservoir Leak
Solution Time 0.001 (s)
FM-200
Solution Time 0.001 (s)
HFC-125
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Summary & Future Work

- Simulation Results Comparison with testing
  - Results are qualitative and to a extent, quantitative
  - Coarse grid implications (adjustment of activation energy, soot)
  - Suppressant Nozzle specification (cone angle)
  - Halon and Water+Potassium acetate validation is limited to-date

- Improve turn-around time
  - Status: 1-2 weeks for geometry preparation, 1 week for computation with DSRC HPC

- Atomization Specification (SWRI & ARL)
  - Scaling with Threat size
  - Phenomenological model

- Discharge of the suppressant (HAI effort)
  - Discharge Lag time, flow split etc.

- Nozzle Characterization effort (ADAPCO)
  - Droplet distribution
  - Velocity distribution
  - Cone Angle

US ARMY RDECOM U.S. Army Research, Development and Engineering Command

Fire Prediction Model V&V

ARL

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

Jamie Edwards

October 2015

US ARMY RDECOM

FPM Functional Capabilities

ARL

FPM models three damage mechanisms:

- Dry bay fires
- Spray fires
- Ullage fuel-air vapor explosions

Addresses single ballistic threat striking fixed-wing or rotary-wing aircraft as well as wheeled and tracked vehicles. Threats include:

- Fragments
- Armor-piercing incendiaries (APIs)
- High-explosive incendiaries (HEIs)
- Spark
- Hot surfaces
- Shaped-charge jets
- Lasers

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

2

FPM Functional Shortcomings

US ARMY RDECOM | ARL

FPM does not address:

- Large KE penetrators
- Explosions from multiple bombs or missile warhead fragments
- Explosively-formed penetrators (EFPs)
- Improvised explosive devices (IEDs)
- Long-rod penetrators

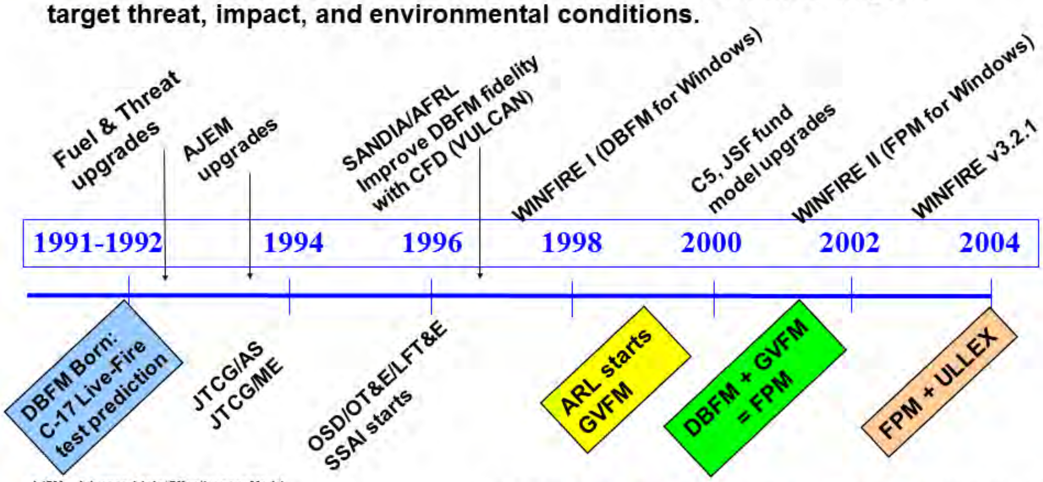
TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

3

Fire Prediction Model History

US ARMY RDECOM | ARL

Evolving each year, growing in physical capabilities, while retaining original objective – easy to use, fast running, and applicable to a wide range of target threat, impact, and environmental conditions.



AJEM = Advanced Joint Effectiveness Model
CFD = Computational Fluid Dynamics
DBFM = Dry Bay Fire Model
GVFM = Ground Vehicle Fire Model
JASPO = Joint Aircraft Survivability Program Office
JTCG/AS /ME = Joint Technical Coordinating Group for Air Systems, for Munitions Effectiveness
SSAI – Safety and Survivability of Aircraft Initiative
ULLEX = Ullage Explosion Model

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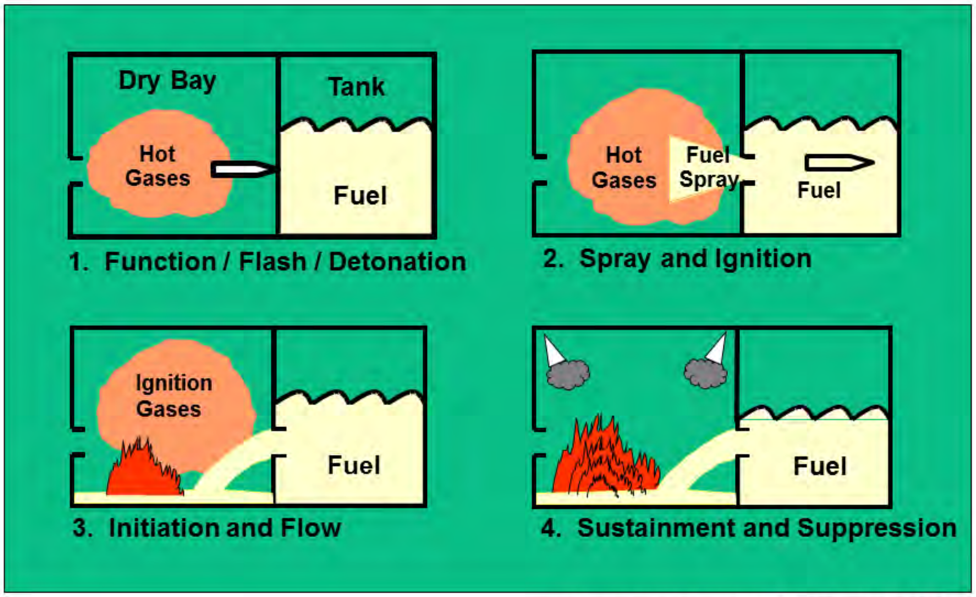
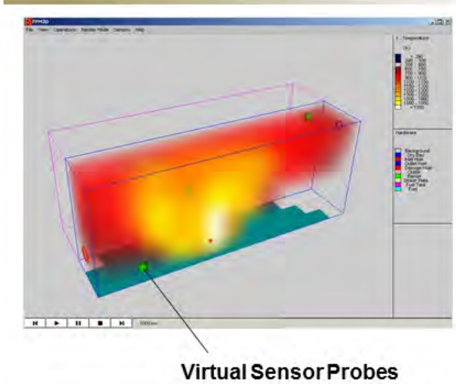
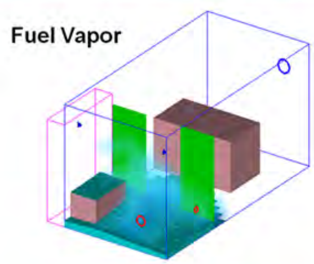
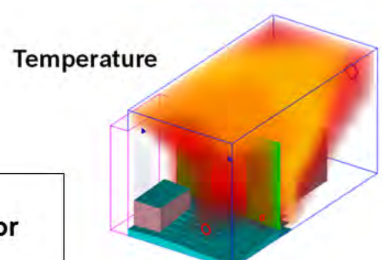
Dry Bay Fire Process



FPM 3-D Viewer







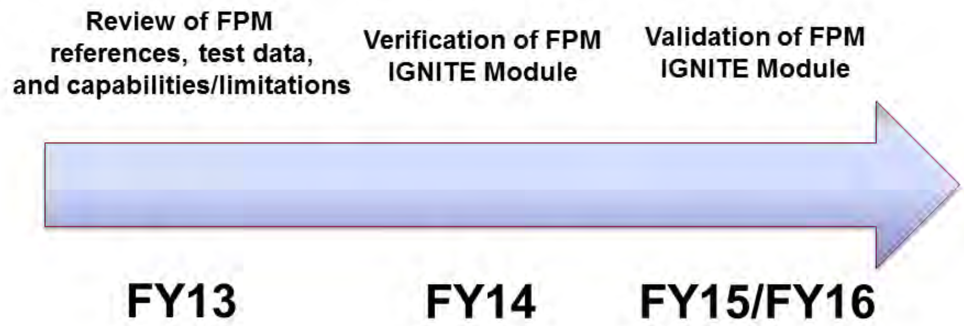
SURVICE Engineering's 3D Viewer

- Temperature
- Fuel Vapor
- Soot Volume

There is also WINFIRE, a GUI for Windows developed by Booz-Allen Hamilton

FPM V&V

- Joint effort funded through JASPO FY13-FY16 with participation from Army, Navy, Air Force, and SURVICE Engineering.
- Objective: Verify implementation of FPM IGNITE Module. Validate FPM IGNITE Module simulations against test data. Revise FPM IGNITE Documentation.



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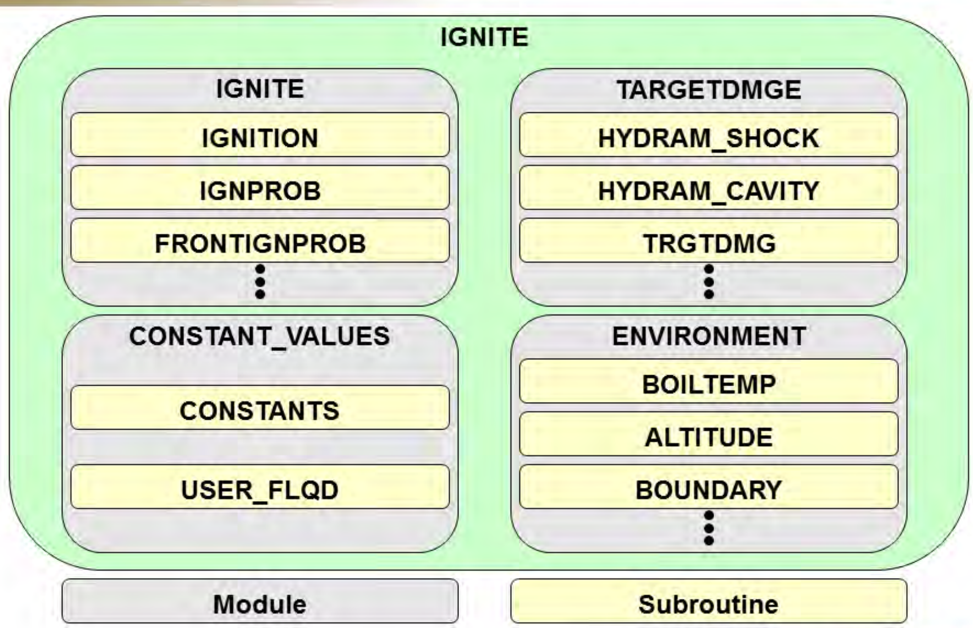
7

FPM V&V: Verification



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8

FPM Reference Grading Criteria

- **Reference Quality Considerations**
  - Accuracy: Is reference (in context of manual in-text citation) correct in concept and/or equations used?
  - Credibility: Has reference been peer reviewed/critiqued?
  - Relevancy: How well does reference apply to FPM topic of interest?
- **Reference Implementation Consideration**
  - Consistency: Does reference match analyst manual and code?
  - Context: Are all assumptions/limitations associated with references stated in analyst manual and/or commented in source code? Are user warnings in place that reflect these assumptions/limitations?
  - Clarity: Is reference information expressed as concisely and clearly as possible within analyst manual and source code?

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FPM Reference Grading Categories

QUALITY	IMPLEMENTATION
Fully Applicable No/Minimal assumptions	Good < 8 man hours to correct
Applicable Given assumptions and usage limitations	Satisfactory 8-40 man hours to correct
Not Applicable Limited applicability Extensive/unrealistic assumptions	Poor 40+ man hours to correct

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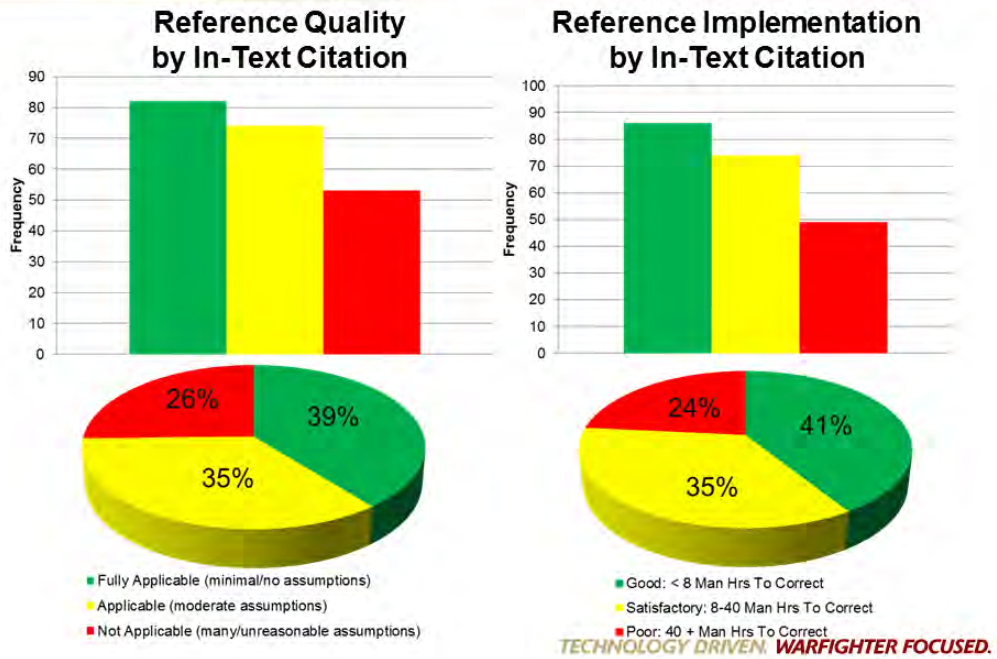
10

FPM Reference Grading Results



TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

User Warnings

- Added new module WARNING_UTILITY to notify user when:
  - Inputs exceed source data bounds
  - Scenarios of interest include substantial amount of unverifiable material
  - Unrealistic assumptions are associated with the simulations
- Displayed warnings in separate "RESULTS" file
  - Enumerates limitations of the simulation that was most recently executed
  - Contains most pertinent simulation info and outputs related to ignition
- Updated 4.2.1 User Guide and Analyst Manual (Now 4.2.2)
  - Describe V&V effort and new RESULTS file
  - Updated list of assumptions and limitations
  - More detailed warnings explanations
- Submitted over 30 SCRs for FPM improvements and documentation fixes in FY14 and FY15.

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Subroutine Grading Example

US ARMY RDECOM ARL

- **Statement Examples:**

```
PP=(PRFFNPRCNT(10)*PVBOILPAR/100.0)+(BNZNPRCNT(10)* &
        PVBOILARA/100.0)

IF (ABS(P-PP)/P.GT.0.02) THEN
```

- **Statement counts:**

Statement Category	Statement Count	% of Total Statements
Total Statements	19	100%
Statements w/ Errors and Ambiguities	8	42%
Statements w/ Immediately Correctable Errors Only	1	5%
Statements w/ Errors that Aren't Immediately Correctable	7	37%

- **Identified statements for sensitivity analysis**
  - Conflicts between source code and Analyst's Manual
  - Constant or logical rule of unknown origin
- **Submitted new SCRs**

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

Subroutine Grading Example

US ARMY RDECOM ARL

Module: IGITION_SOURCE
Subroutine: SPARK

Errors and Ambiguities

Statement Number: 1
Statement Error: 1 of 1
Original Statement: `VTGBD=(24400.*GAPSPRK)+(6530.*GAPSPRK**(0.5))`
Correct Statement: Unknown (one option recommended in resolution section)
Comment: Equation is similar (though not the same as) the average of the two equations presented in reference 4-1. These equations were assessed to be legitimate in reference grading report 4-1.1.
Resolution: Recommend using the actual average of the equations from the reference: VTGBD = 24418*GAPSPRK + 6370*GAPSPRK**(0.5), or using a regression on all available data. The later would be better but would require additional work. If sensitivity analysis reveals that the impact on the final answer is low, then recommend using the simple average and noting in the analyst manual that sensitivity analysis revealed that model outputs were deemed insensitive to this equation and therefore a simple average is sufficient. Whatever method is used, specify it in the analyst manual. Also note the ranges of the data used to derive this equation. Then update the source code with the new form of the equation.

- Needs correction
- Need to determine correct answer
- Needs sensitivity analysis

Statement Number: 4 and 16
Statement Error: 1 of 1
Original Statement: `CURR=VTGPS/(300.*GAPSPRK+RSTNCE)`
Correct Statement: Unknown
Comment: This seems to be an implementation of the 2nd equation in section "4.2.1 Spark Energy" from the Analyst Manual. It's difficult to determine if the code and manual are consistent given the lack of description in the analyst manual. There is no source listed for the equation in the analyst manual. It

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Sensitivity Analysis

Variable	Subroutine	Equation	Reason	Approach
FFFAAPI	FRONTIGNPROB/ FRONTIGNPROBD	IF ((1.75*FFFAAPI(IAPICAL,II)).GT. & (SLDST(IDB)-PENDRPL(IDB,INT(TIME/.001)))) THEN	Unknown source for 1.75	Drop 1.75 to 1.0 and check effects

None logic check	FRONTIGNPROB/ FRONTIGNPROBD	IF ((1.75*FFFAAPI(IAPICAL,II)).GT. & (SLDST(IDB)-PENDRPL(IDB,INT(TIME/.001)))) THEN
		PROBIGN(IDB,I,J)=1.0
		ELSE
		PROBIGN(IDB,I,J)=0.0
		ENDIF
			This check occurs within a loop and there is no check for Ignition Delay before defining PROBIGN	Use a write statement to see if PROBIGN flips

FRONTSMD/ FTDROPSIZE	IGNITION/ IGNDRPDST	IF (FTDROPSIZE(DROPBIN)**2.0.GT.0.01*0.001) THEN
		FTDROPSIZE(DROPBIN)=((FTDROPSIZE(DROPBIN)**2.0)-0.01*0.001)**0.5
		ENDIF
			This resets the DRPLSMD if it is greater than 31.62 microns	Comment it out and see what happens

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Validation Comparisons

- **Acquired validation data**
  - **API and fragment**
  - **Ignition Y/N**
  - **Flash timing**
  - **Fuel spurt timing**
  - **Fuel tank damage area**
- **Evaluated how to model test cases in FPM**
  - **No multiple frag holes**
  - **No sustainment data**
  - **No nonzero dry bay wall obliquities**
  - **API function definitions**
  - **Back face OR front face flash, not both**

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US ARMY RDECOM

Next Generation Fire Modeling

ARL

- New funding through JASPO starts FY15
- Objective: Establish a credible and validated dry bay fire assessment capability for API and fragment threats.
- Approach:
  - Decompose dry bay fire issue into functional areas, each falling under the oversight of a technical working group
  - Execute piece-wise test program
    - Understand underlying phenomenon and primary drivers of each functional area
    - Generate data for development of models and improvements
    - Generate data for model validation
    - Support development and execution of each subsequent phase of program.
  - Model improvement and development will occur concurrently with each phase of the test program.

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US ARMY RDECOM

Next Generation Fire Modeling

ARL

Penetration
- Ballistic limit (V50)
- Residual velocity and mass (Vr, Mr)
- Tumbling through bay
- Tank wall penetration and hole size(s)

Energy Deposition
- Flash/function location (back-face, front-face)
- Function type (API)
- Temperature and size time history

Fuel Deposition
- Quick dump
- Threat tumbling through fuel
- Cavitation, pressure
- Fuel spray into bay

Ignition
- Droplet vaporization
- Vapor mixing
- Vapor-air reaction

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Contact information

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james.e.edwards114.civ@mail.mil

Battery Safety in Abnormal Thermal Environments: Prospects and Potential Contributions.

John Hewson, Stefan Domino, David Ingersoll, Harry Moffat, Chris Orendorff, Josh Lamb,

April 30, 2015

Sandia National Laboratories

Exceptional service in the national interest

U.S. DEPARTMENT OF ENERGY   NNSA

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Energy Storage Safety/Reliability Issues Have Impact Across Multiple Application Sectors

Sandia National Laboratories

From Josh Lamb, 2541

2

Motivation

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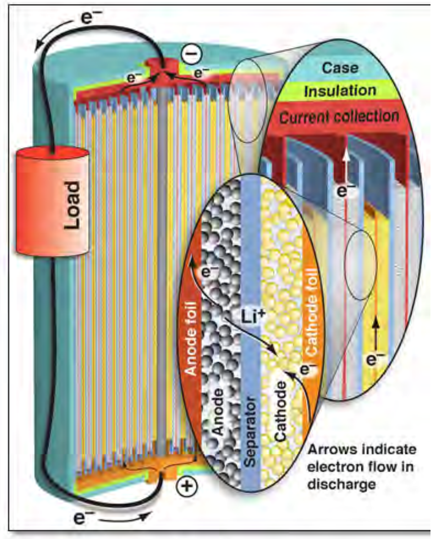
- Energy storage in electrochemical systems (batteries) is increasingly prevalent.
  - Energy storage facilities 3kWh to MWh scale.
  - Vehicle battery systems comparable to a 'gas tank' (50 kWh)
  - Laptops, etc., with 60 Wh.
- Potential hazards associated with stored energy couple with inexperience regarding safety and mitigation practices.
  - What are ignition characteristics?
  - What are hazards, both thermal and chemical?
  - What mitigation is appropriate?

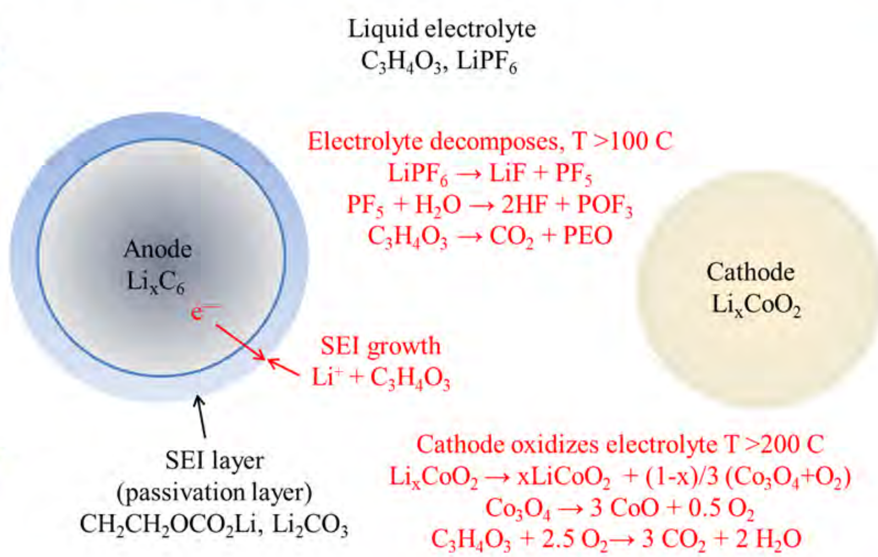


- Safety characteristics need to be evaluated; standards and best-practices need to be developed.

3

Some sources of energy in a Li-Ion battery

Sandia National Laboratories



4

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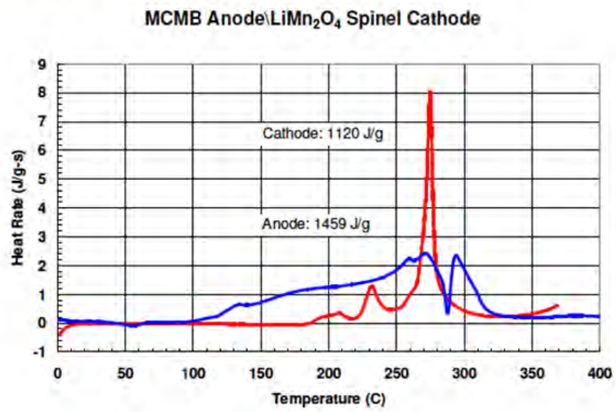
Thermal runaway is associated with anode reactions followed by cathode reactions

Sandia National Laboratories



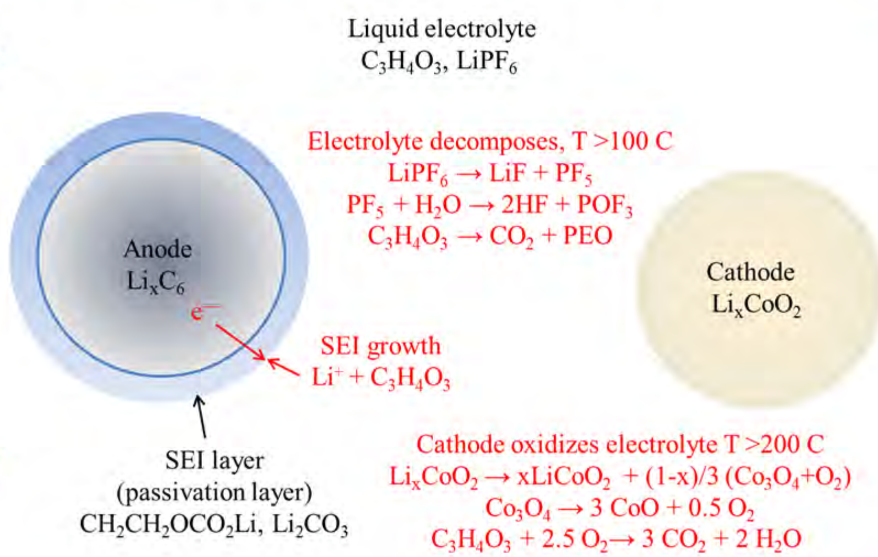
ARC measurements from Pete Roth

- DSC and ARC results suggest that the first step involved in thermal abuse is the breakdown of the SEI layer, exposing Li/C to the solvent.
- Further heating leads to oxygen release from cathode and reaction with electrolyte.

5

Some sources of energy in a Li-Ion battery

Sandia National Laboratories



6

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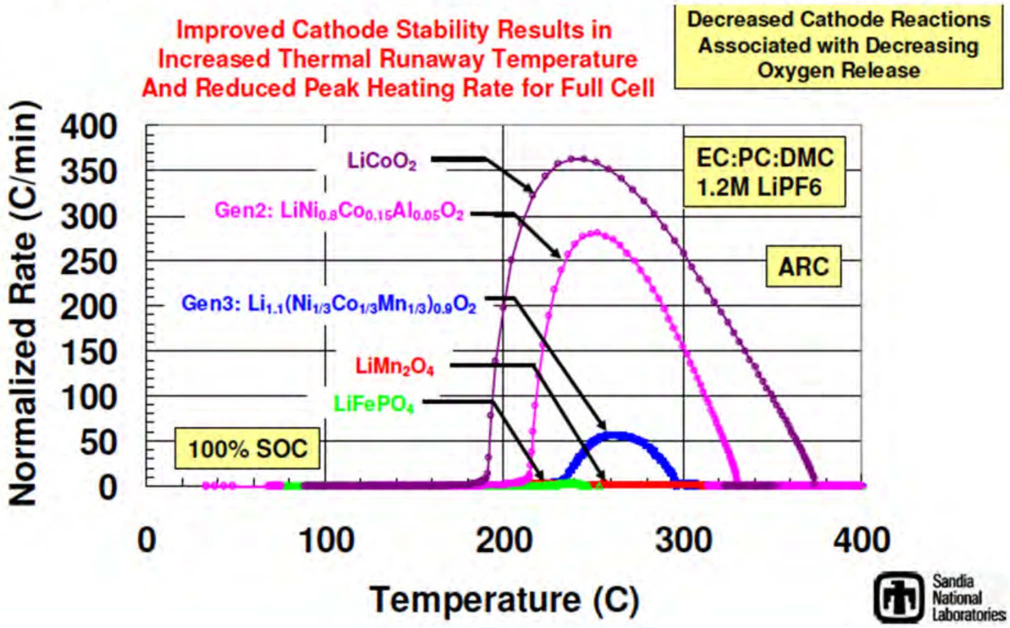
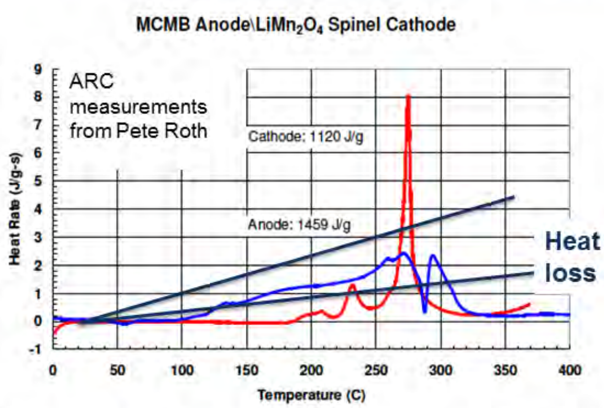
Reactivity is heavily dependent on active materials and electrolytes (ARC results from Pete Roth)



Thermal runaway occurs if heat release exceeds heat losses



- Increasing battery scale reduces heat losses, lower ignition temperature
- Active suppression/mitigation can increase heat losses, raise ignition temperature.
- Some low temperature degradation should be detectable.

8

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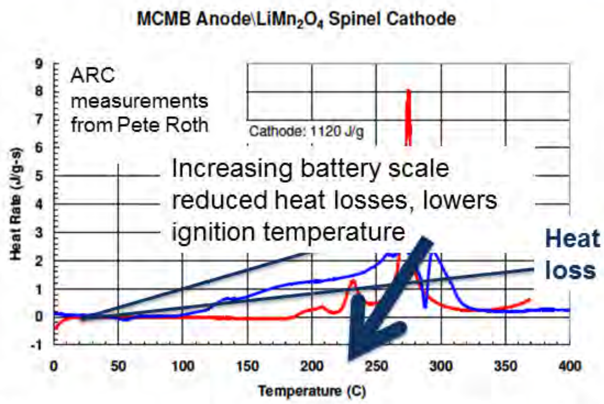
Thermal runaway occurs if heat release exceeds heat losses



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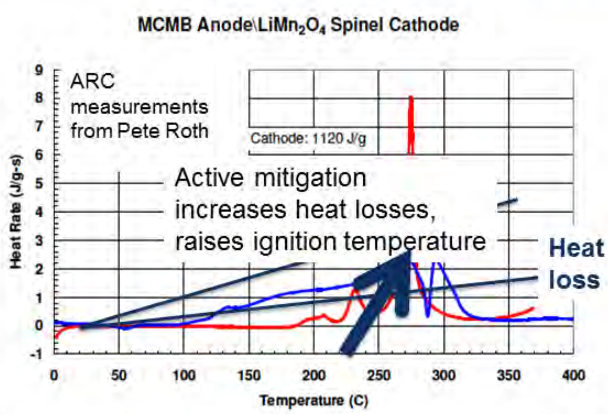
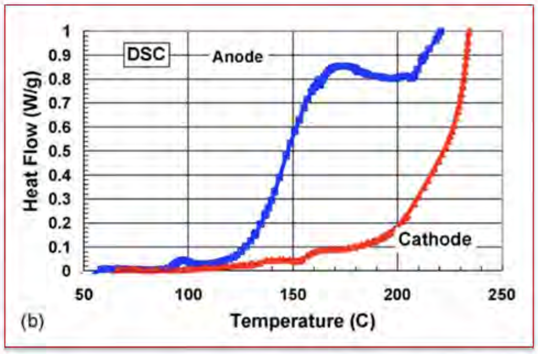
Thermal runaway occurs if heat release exceeds heat losses



- Increasing battery scale reduces heat losses, lower ignition temperature
- Active suppression/mitigation can increase heat losses, raise ignition temperature.
- Some low temperature degradation should be detectable.

Thermal runaway is associated with anode reactions followed by cathode reactions



Abraham et al. J Pow Sources 161, 648 (2006)

- DSC results suggest that the first step involved in thermal abuse is the breakdown of the SEI layer, exposing Li/C to the solvent.
- Further heating leads to oxygen release from cathode and reaction with electrolyte.

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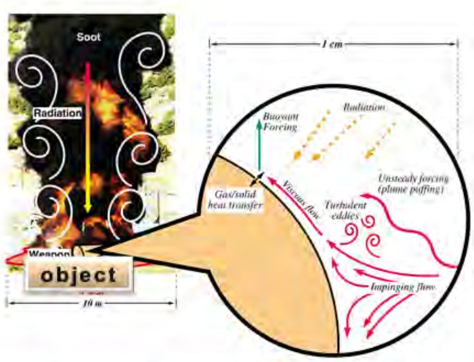
NW and battery safety application space overlap

Goal: Leverage the large DOE-NNSA Investments in Sierra-Mechanics Integrated Code simulation tools developed at SNL under the Advanced Scientific Computing (ASC) program for Science-based Stockpile Stewardship by applying these tools to battery safety analysis



Heat transfer mechanisms in a fire

Physics:

Turbulent fluid mechanics (buoyant plumes)

Participating Media Radiation (PMR)

Reacting flow (hydrocarbon, particles, solids)

Conjugate Heat Transfer (CHT)

The simulation tool *predicts* the thermal environment and object response

Stationary storage application

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Use Case: Hawaii Lead Acid Batter System on Fire

- Racks of lead acid batteries and power conditioning system inside the building
- No emergency response (Hawaii is a closed water system)

- In what context could we imaging a computational capability being useful?

Relevant geometries

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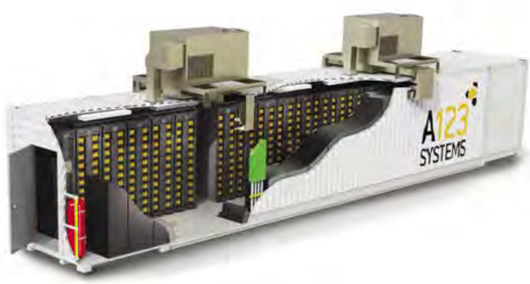

Plug-and-play Lithium Ion trailer

power conditioning system

racks of batteries

Lead acid Alaska facility designed to replace back-up diesel

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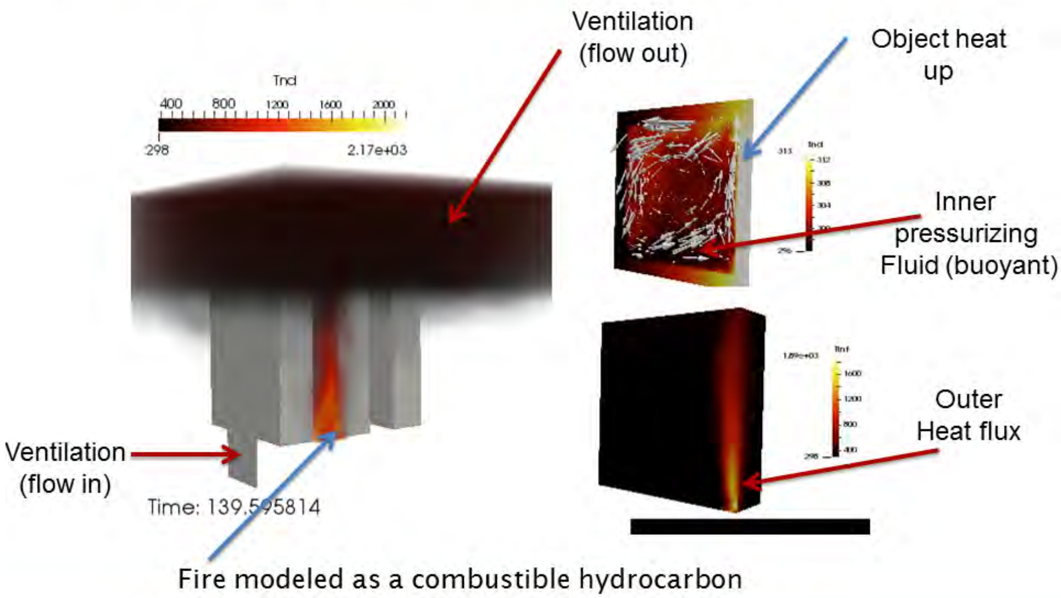
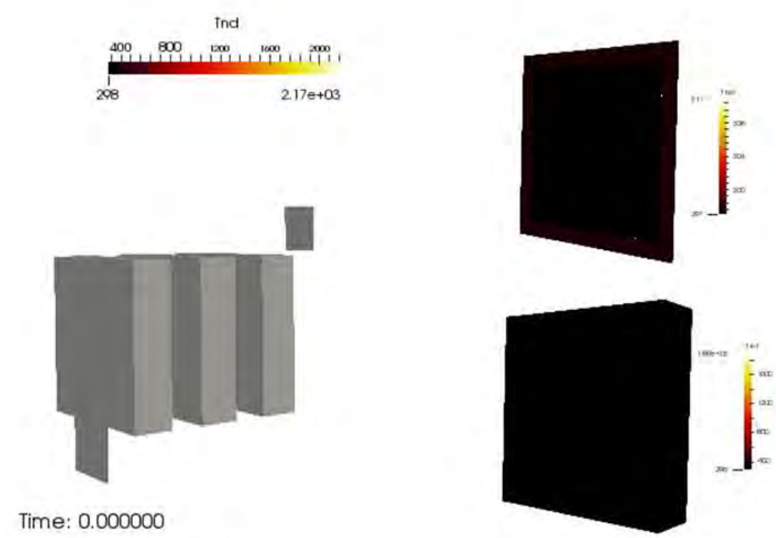
Applying Sierra codes to battery fire scenario

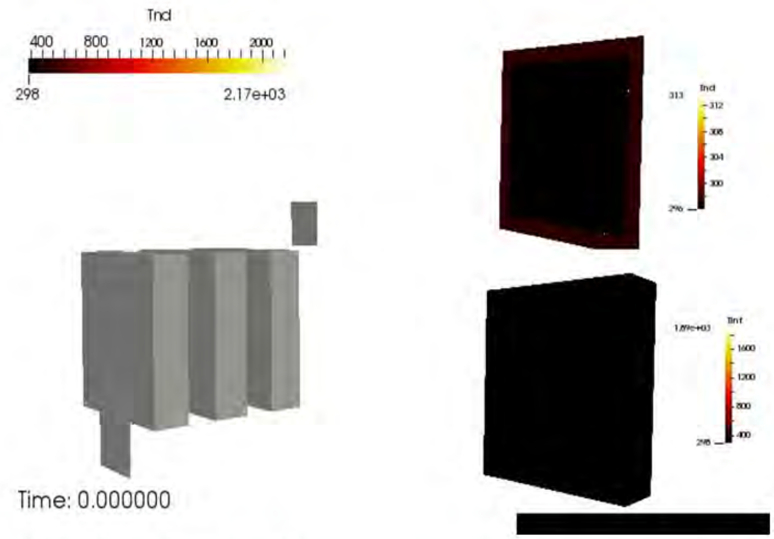


Ventilation effect on fire plume dynamics (1/3)



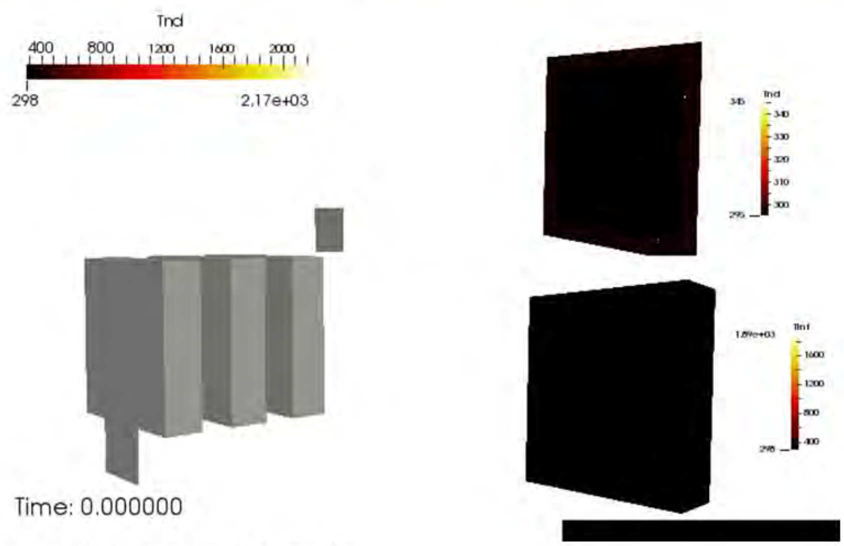
No Ventilation

Ventilation effect on fire plume dynamics (2/3)



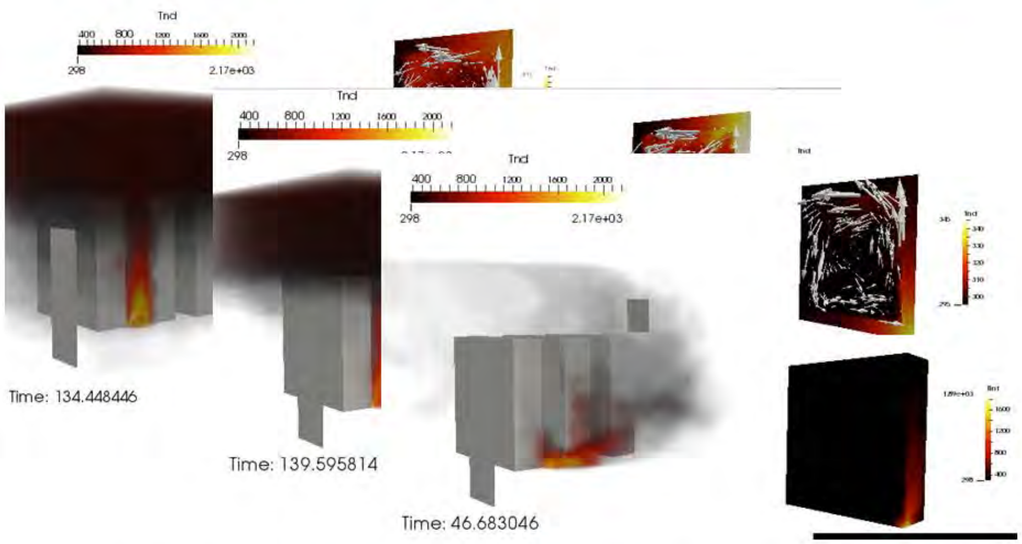
Ventilation is 1 m/s

Ventilation effect on fire plume dynamics (3/3)



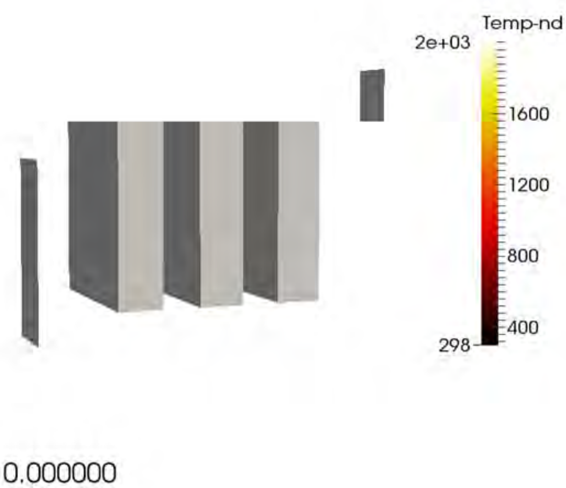
Ventilation is 10 m/s

UQ: plume dynamics



Three ventilation comparison still shot

Suppression of fires and thermal management



1 m/s Ventilation

Plumes and Hazardous Material Mapping – Concentrations as a function of time, distance, prevailing wind conditions

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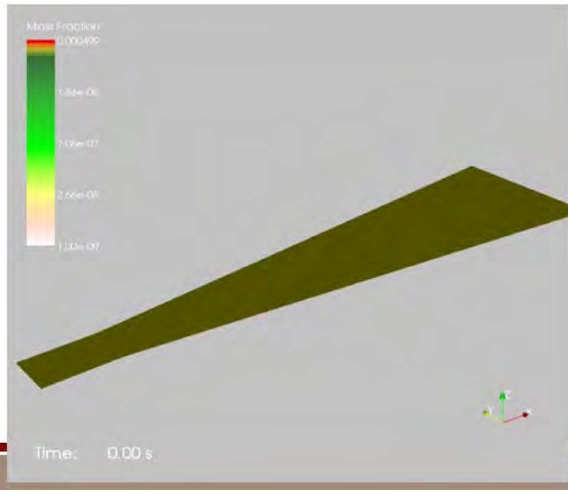
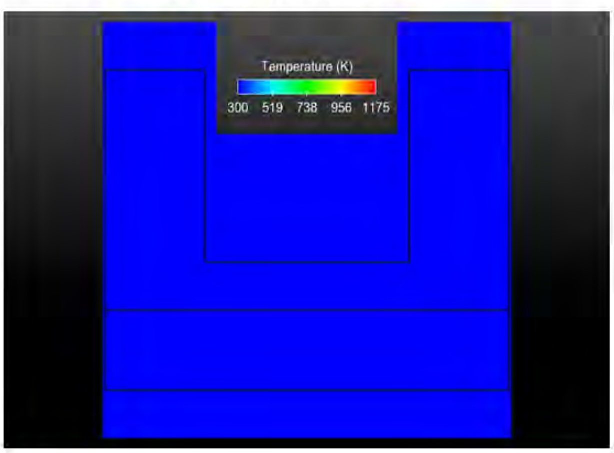
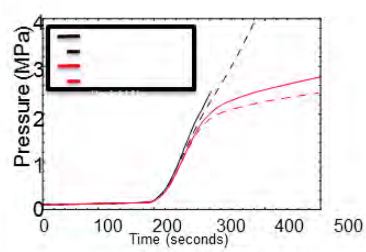


Modeling pressurization with solid combustion

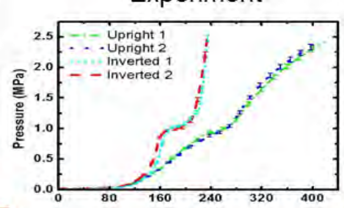
Sandia National Laboratories

Thermally decomposing foams.
Victor Brunini and Amanda Dodd



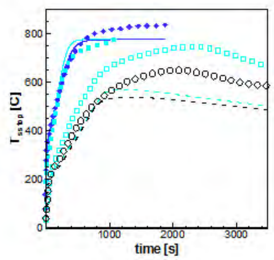


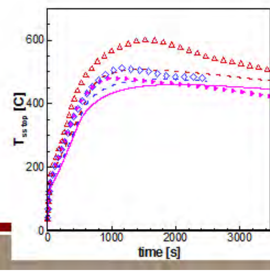
Experiment



Metal fires: Thermal dissipation and oxidation inhibition

- Sodium pool fires: modeling combined thermal dissipation and oxidation inhibition from porous oxides leads to better predictions.
- Suggests mitigation strategies.





Summary

- Thermal runaway is a significant risk and barrier to consumer acceptance.
- Sandia experience and investment in NW program has significantly overlaps battery thermal runaway challenges.
  - Fire modeling of fuels, reactive metals, organic materials, etc. Also passivation layers, reaction within pressurizing vessels, etc.
  - Hazardous products and plume transport (HF, H_2SO_4, metals like Pb).
  - Conjugate heat transfer : mitigation through heat dissipation, chemical inhibition and active suppression.
- Multiphysics code investment and experience.

Supporting capabilities

- UQ for accident environments.
- Sensitivity analysis to identify mitigation strategies.

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USN Lithium Battery Fire Test Summary

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John Farley – NRL Code 6186
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15 October 2015

ARL/TARDEC Fire Protection Information Exchange Meeting

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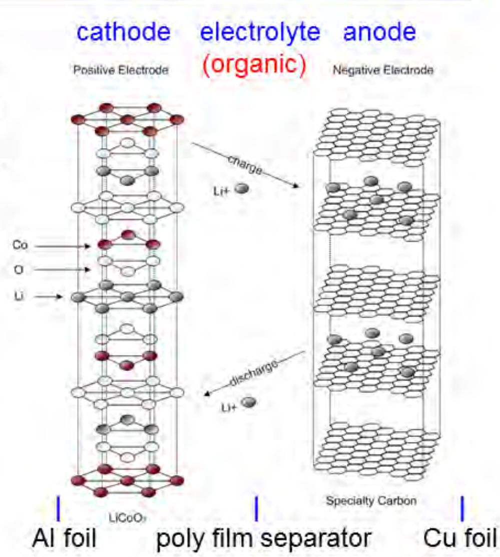
Lithium Batteries - 101

"**Lithium batteries**" are family of cells that consist of a lithium anode and a variety of different types of cathodes and electrolytes 3.6-4.2 V

Primary – Non rechargeable (Lithium Batteries)

Secondary – Rechargeable (Lithium Ion Batteries)

Testing and regulations make a distinction between the two but from a fire hazard perspective, my data suggests that there is only a limited difference.



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NAVSEA WARFARE CENTERS Carderock

Chemistries – Organic Electrolytes

Compound	CAS Registry Number	Molecular Formula	Flash Point	Boiling Point	Auto-Ignition Temperature	Heat of Combustion
Diethyl Carbonate (DEC)	105-58-8	$C_5H_{10}O_3$	25°C 77°F	126°C 259°F	445°C 833°F	−20.9 kJ/ml −5.0 kcal/ml
Dimethyl Carbonate (DMC)	616-38-6	$C_3H_6O_3$	18°C 64°F	91°C 195°F	458°C 856°F	−15.9 kJ/ml −3.8 kcal/ml
Ethylene Carbonate (EC)	96-49-1	$C_3H_4O_3$	145°C 293°F	248°C 478°F	465°C 869°F	−17.2 kJ/ml −4.1 kcal/ml
Ethyl Methyl Carbonate (EMC)	623-53-0	$C_4H_8O_3$	25°C 77°F	107°C 225°F	440°C 824°F	−19.2 kJ/ml −4.6 kcal/ml
Propylene Carbonate (PC)	108-32-7	$C_4H_6O_3$	135°C 275°F	242°C 468°F	455°C 851°F	−20.1 kJ/ml −4.8 kcal/ml
Tetrahydrofuran (THF)	109-99-9	C_4H_8O	−14°C 6°F	65°C 149°F	321°C 610°F	−31.2 kJ/ml −7.5 kcal/ml
Dimethylether	115-10-6	C_2H_6O	−41°C −42°F	−23.7°C 11°F	350°C 662°F	−51.3 kJ/ml −12.3 kcal/ml
1,3-Dioxolane	646-06-0	$C_3H_6O_2$	2°C 35°F	75°C 167°F	?	−24.4 kJ/ml −5.8 kcal/ml
1,2-Dimethoxyethane (Ethylene Glycol)	110-11-4	$C_4H_{10}O_2$	104°C 232°F	83°C 197.5°F	400°C 752°F	−21.3 kJ/ml −5.1 kcal/ml
Acetonitrile (Methyl Cyanide)	75-05-8	CH_3CN	6°C 42°F	81.6°C 179°F	524°C 975°F	−23.9 kJ/ml −5.7 kcal/ml
Thionyl Chloride	7719-09-7	$SOCl_2$	?	78.8°C 174°F	?	?

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NAVSEA WARFARE CENTERS Carderock

Cell Types/Construction

Button/coin cells
Cylindrical cells (A, B C, D)
Prismatic/pouch cells
(9V & computer)
Packs/groups of cells

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Battery Packs

Lithium-ion batteries 3.6-4.2V
Large number of cells in series and parallel (series voltage, parallel capacity)
18650 (AA) is the work-horse of the industry
Some USN – under water vehicles have thousands
The Tesla has over 8000 - 18650's

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Electrical Vehicle Testing

Video

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Initiating Events

- An internal manufacturers defect (material defect, construction, contamination).
- Physical damage (battery damaged during assembly, shipping handling).
- Electrical abuse (short circuits, charge/discharge range).
- Overcharging the battery.
- Exposure to heat (100°C-200°C).

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Physical Damage

Video

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Overcharging

Video

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Testing Overview

Navy Approach

Navy Technical Manual **S9310-AQ-SAF-010**, Navy Lithium **Battery** Safety Program Responsibilities and Procedures – Cell/Battery Level

Navy Technical Manual **SG270-BV-SAF-010**, High-Energy Storage **System** Safety Manual - Application

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Testing Overview

Hundreds of tests – approaching $1M in batteries

Over 30 different manufactures/cell types
- 25+ Commercial cells
  - (A123, Panasonic, Sony, E-one Moli, Ultralife, K2, etc.)
- 5 Military specific cells (Saft, Dow-Kokam)

Battery Casualty Characterization Tests
- Gas Production/Species
- Heat Release Rate

Hazard Mitigation Tests – Quantification/Mitigation/Suppression

Williams, F. and Back, G., "Lithium Battery Fire Tests and Mitigation", NRL/FR/6104-14-10,262, 25 August 2014

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Reaction Descriptions

- **Venting/Off gassing electrolyte without a fire**
  - **Flammable and toxic**
- **Road flare effect**
  - **Ignites surrounding materials**
- **Steady burn**
  - **Ignites surrounding materials**
- **Flash fireball**
  - **Ignites surrounding materials**
- **Explosion due to exposure to high heat**
  - **All bets are off**

Reactions are chemistry, construction and SOC driven

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Products Testing

5 m^3 (177 ft^3) Enclosure/Pressure vessel
Electrochemical Sensors and Optical Methods
Gas Chromatography-Mass Spectroscopy/Infrared (GC-MS/IR)
Summa Canisters, Sorbent Tubes and Impingers

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Products Testing

Venting Scenario

Species Formula	Species Name	Average % by Volume
CO	Carbon Monoxide	21.8733
CO_2	Carbon Dioxide	19.6233
N_2	Nitrogen Gas	29.4800
O_2	Oxygen Gas	0.1400
H_2	Hydrogen Gas	20.5600
CH_4	Methane	3.1543
C_2H_6	Ethane	0.5557
C_2H_4	Ethylene	2.9527
C_3H_8	Propane	0.0507
C_3H_6	Propene (Propylene)	0.3193
C_4H_{10}	Butane	0.0118
C_2H_2	Acetylene	0.0005
C_5H_{12}	Pentane	0.0052
C_6H_{14}	Hexane	0.0014
HF	Hydrogen Fluoride	0.002

Oxyhalides produce IDLH values of SO_2, HCl, H_2SO_4 and HF

30% N_2
20% CO_2
20% CO
20% H_2
10% C_xH_x

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Products Testing

Venting Scenario

Gas production is proportional to electrical energy (capacity)

160 L of gas per MJ of electrical energy

Lower Flammability Limit (LFL) ~ 10% by volume

Burning Scenario

Mostly CO_2, N_2 & H_2O, (HF)

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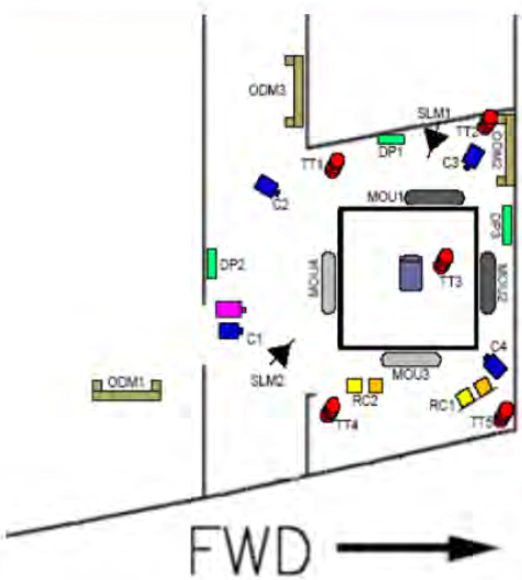
Heat Release Rate Testing



Standard Hood Calorimeters
100 kW NSWC-CD / JH
1 MW NSWC-CD / JH
5 MW NRL/CBD

Compartment Calorimeters
NRL/Shadwell

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Heat Release Rate Testing

Combustion energy is proportional to the electrical energy/capacity

Combustion energy is 6-10 times electrical energy/capacity

Shrink wrapping of individual cells can add 40%

Battery pack casings can add 200% thin plastic to
1000% heavy plastic cases

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State of Charge (SOC) Effects

Individual Cells

- Less than 30% SOC produces venting reactions
- Greater than 70% SOC produces flaming reactions
- 30%-70% reaction varies (no trend)
- Total gas released and HRR proportional to SOC

Packs

- Typically produce flaming reactions (unless O_2 limited)
- Total energy released fairly constant
- PHRR slightly higher for higher SOCs

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NAVSEA WARFARE CENTERS Carderock

Weapon System Battery

Video

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NAVSEA WARFARE CENTERS Carderock

Fireball

Video

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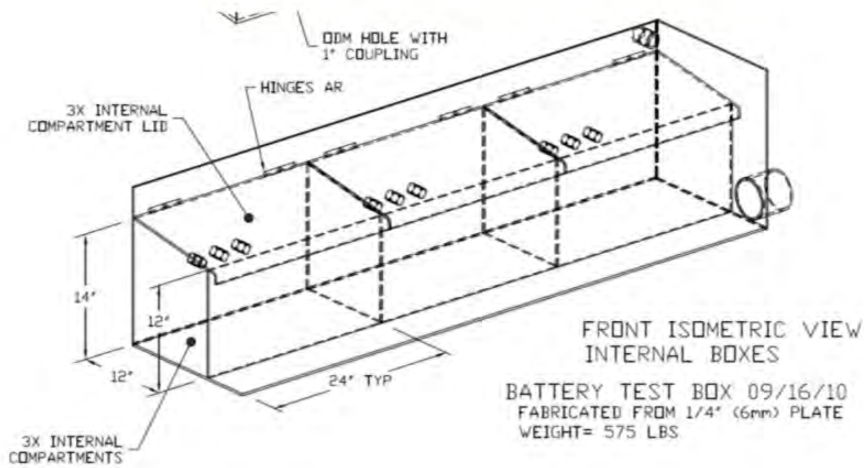
Battery Storage Locker



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Explosion

Video

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Battery Casualty Characterization

Hazard Parameter	Significant	Moderate	Insignificant
Explosion and Fragments	Will cause injury to unprotected personnel within the compartment of origin with compartment overpressures >1 PSIG or or release of any fragment with >15 ft/sec velocity or >20 ft-lb impact loading	Could cause injury to unprotected personnel in close proximity to the battery with compartment overpressures >0.25 PSIG or release of any fragment with >5 ft/sec velocity	Unlikely to cause injury (<0.05 PSIG overpressure) and no debris greater than 0.2 ft from battery
Fire/Thermal – HRR	PHRR > 100 kW for any duration	100 kW > PHRR >10 kW	PHRR < 10 kW
Fire – Fragments	Flaming fragments projected > 3 ft	Flaming fragments projected up to 3 ft	No flaming fragments
Aerosol Products	Loss of visibility within the compartment of origin and/or the production of explosive mixtures	Loss of visibility in close proximity to the battery (3 ft)	No loss of visibility
Gaseous Products (F)	Flammable concentrations within the compartment of origin	Flammable concentrations in close proximity to the battery	No flammable gases produced
Gaseous Products (T)	Toxic/hazardous concentrations within the compartment of origin for protected personnel	Toxic/hazardous concentrations in close proximity to the battery for unprotected personnel	No toxic/hazardous gases produced

PHRR = Peak Heat Release Rate (F) = Flammable (T) = Toxic

Mitigation

Water based solutions and gaseous agents

Performance objectives
Minimize the hazard to acceptable levels
- Minimize cell to cell propagation
- Complete gas containment

Resulting Designs
- Pressure vessel storage containers
- Battery storage lockers
- Battery charging stations
- Battery storage and charging compartments

Predictions / Modeling

Fire Dynamic Simulator (FDS) – CFD Fire Model
Heating – Solids, heat transfer model

Modeling used to:

- Quantify the hazard (i.e. resulting conditions)
- Predict cell propagation
- Assess mitigation
- Design explosive gas extraction systems

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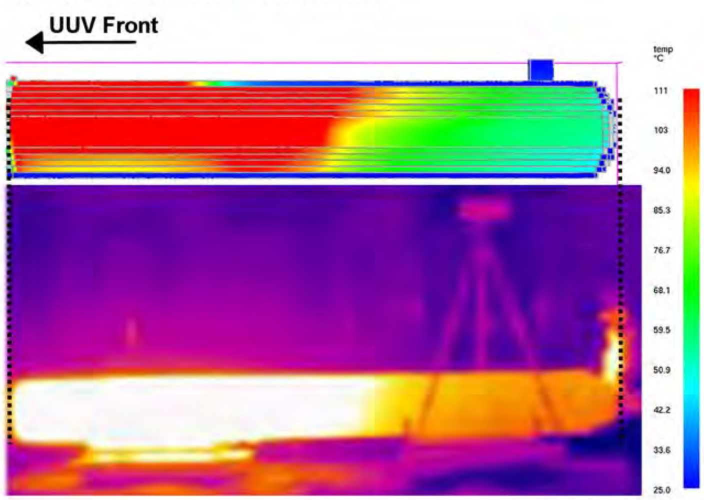
Predictions / Modeling

Internal Reactions/conditions



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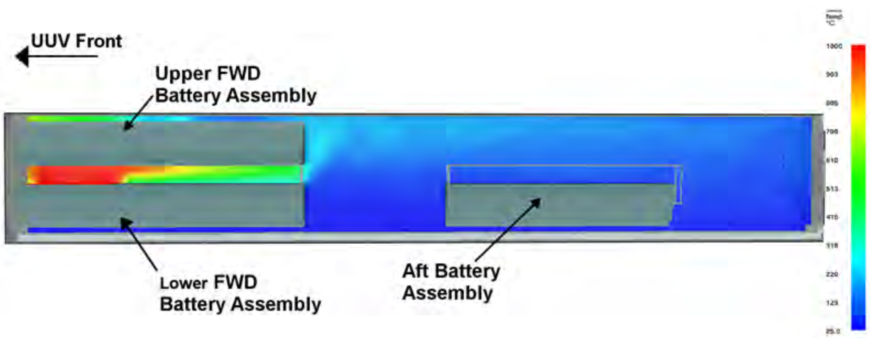
Predictions / Modeling



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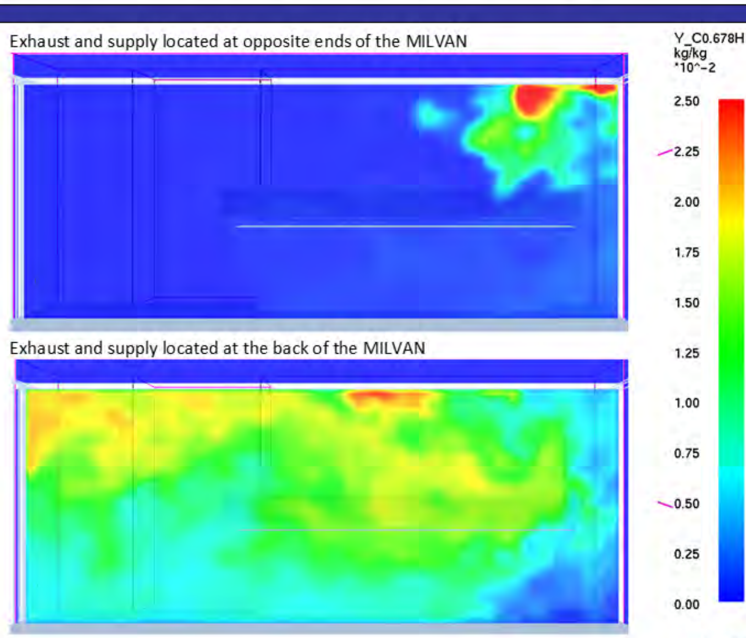
Predictions / Modeling



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Summary

USN has developed a database of hundreds of tests

Over 30 different manufactures/cell types
- 25+ Commercial cells
  - (A123, Panasonic, Sony, E-one Moli, Ultralife, K2, etc.)
- 5 Military specific cells

Battery Casualty Characterization data includes
- Gas Production/Species
- Heat Release Rate

Hazard Mitigation Tests – Quantification/Mitigation/Suppression

USN is using this data and analytical tools to predict reaction severity/conditions

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Questions?

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ARL

Li-ion Battery Vulnerability Assessment

J. Kevin Boyd
Travis J. Payne

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Introduction

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- The U.S. Army is looking to replace current lead-acid batteries with higher energy density lithium ion (Li-ion) batteries.
  - The electrolytes in Li-ion batteries are highly flammable.
  - Damage to a Li-ion battery from ballistic impact, shock, overcharge, etc. can cause thermal runaway in the battery resulting in the electrolytes reacting violently.
- TARDEC funded ARL to assess the vulnerability of two Li-ion battery chemistries and to evaluate a proof-of–principle fire suppression system.

Li-ion battery thermal runaway in a sealed battery compartment.

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Method

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The vulnerability of two Li-ion chemistries were evaluated. The batteries were subjected to overcharging to induce thermal runaway.

Lithium Nickel Cobalt Manganese Oxide (NiCoMax) and Lithium Iron Phosphate (LiFePo4), were evaluated in the open air and also in a sealed light-weight aluminum battery box.

- The batteries were charged at 260 amps and 30 volts.
- Time to first visible signs of thermal runaway ranged from 30 to 70 minutes.

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Observations

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– Both chemistries produced a significant amount of smoke/combustion by-products.
  - Battery surface temperatures of 600° F to 700° F were observed.
  - In a sealed battery box peak pressure of 4 psi was recorded.
– The NiCoMax chemistry reacted the most violently.
  - Visible flames were observed in addition to intense smoke.
  - Only smoke was observed with the LiFePo4.

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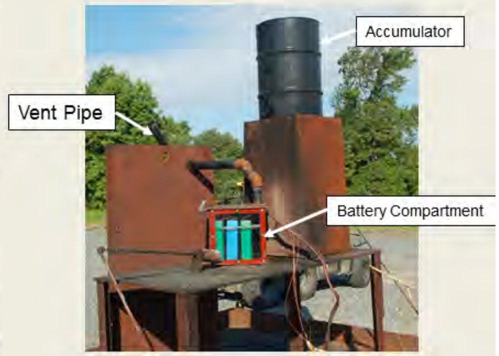
Fire Suppression System

A proof-of-principle fire suppression systems was developed to mitigate the response of thermal runaway in the batteries.

- The system consists of a ¼” thick steel vented battery compartment plumbed to an accumulator filled with a pressurized mixture of a potassium acetate (K-ace) solution and a fire fighting foam concentrate.
- The mixture of K-ace and foam concentrate was released at the first sign of thermal runaway.
  - In this evaluation visible smoke inside of the compartment indicated thermal runaway.



U.S. ARMY RDECOM ARL

Results

The violence of the reaction was significantly reduced with the fire suppression system.

- Some flames were visible inside the compartment but no flames breached the compartment.
- Even with fire suppression a significant amount of combustion products were produced.

NiCoMax thermal runaway reaction with the proof-of-principle fire suppression system.

Venting of the battery compartment.

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Conclusion

ARL

The two battery chemistries examined produced a significant amount of smoke and combustion by-products. Based on previous testing it can be assumed that these by-products are toxic.

If the batteries were collocated with the crew in a crew compartment, the by-products would quickly fill the crew space.

- Either chemistry would require a sealed battery compartment with the smoke/toxic fumes vented away from the crew space.
- The higher energy density NiCoMax chemistry would require a battery compartment robust enough to contain the reaction.
    - ¼” aluminum was initially used in our system and failed.
    - Fire suppression required pre-inerting the battery compartment with inerting fluid.

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The Power of the Future. Today.

Ultracapacitors – Rapid, Reliable, Safe Power

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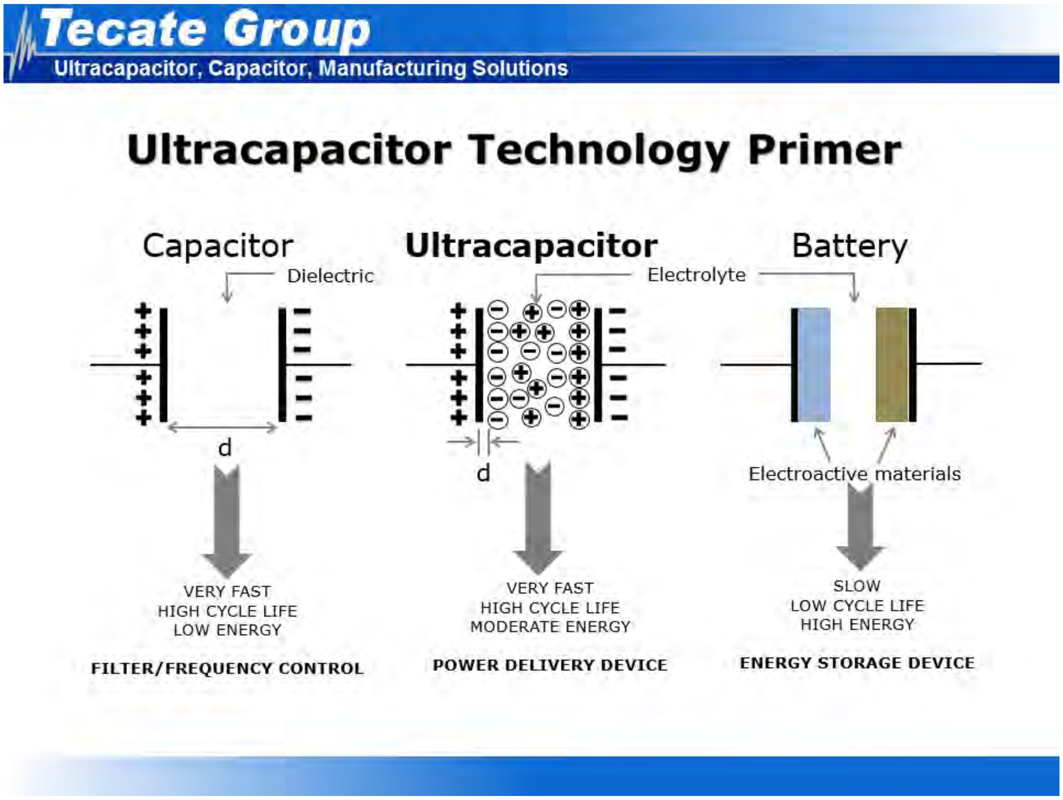
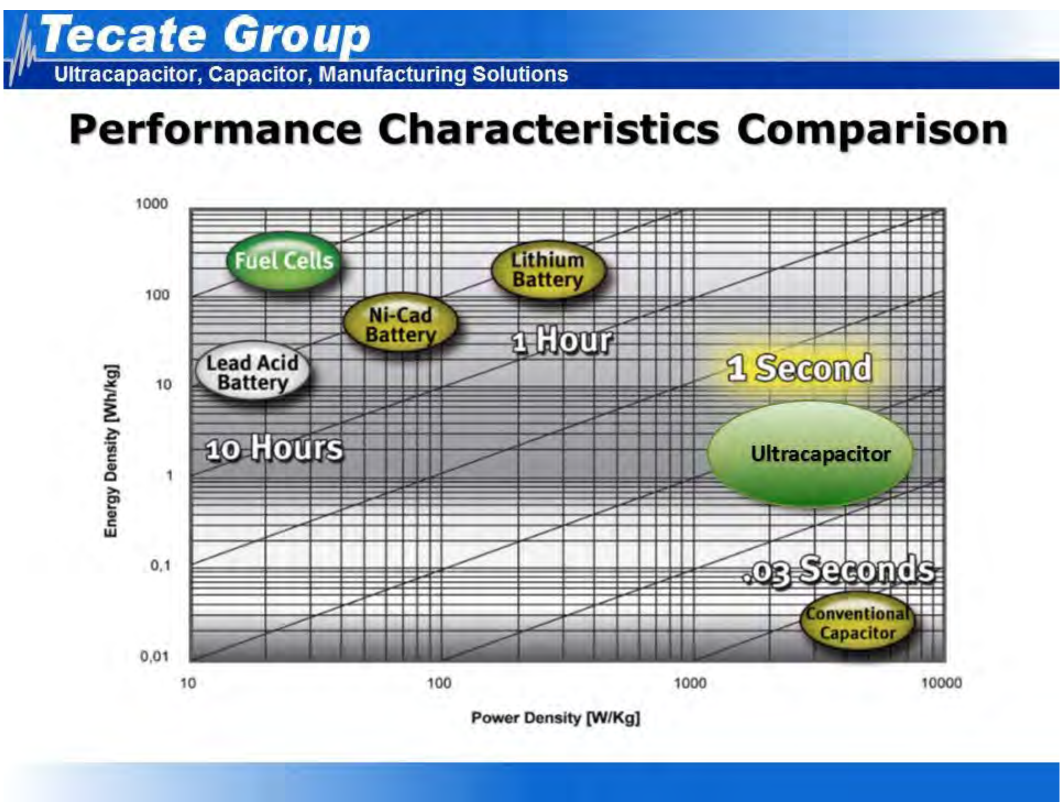
Introduction to Ultracapacitors

- Ultracapacitor, Supercapacitor, EDLC
- Power Delivery vs Energy Storage Device
- Store energy as electrostatic charge – NO chemical reaction
- Low sensitivity to number of charge/discharge cycles or discharge current
- Wide Operating Temperature -40°C to 85°C
- Light Weight





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Basic Components

- **Aluminum** – no safety hazards
- **Carbon** – no safety hazards
- **Paper** – no safety hazards
- **Polymers** – (ethylene propylene diene monomer) rubber seals - No safety hazards
- **Electrolyte**: acetonitrile, TMATFB

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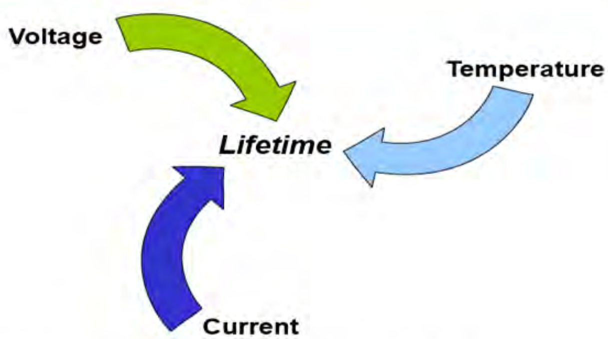

Electrical		**Mechanical**
Voltage		Vibration, Shock
Current		Temperature
Temperature		Humidity, Pressure

Venting of UC cells is generally benign and gives ample time to discontinue use upon detection

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Worst Case: Over voltage conditions produce the most significant rates of pressure increase within products depending on rate of charge (current)

Product Variables:

- Geometry
- Packaging Material
- Packaging thickness
- Internal free volume
- Electrolyte quantity
- Capacitor mounting methods

Condition variables:

- Over voltage level
- Rate of charge
- Capacitor mounting
- Temperature

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Ultracapacitor Safety

- Venting Cell Failure Progression
  - Step 1 – Functions as a non hermetic ultracapacitor
    - Small effects on capacitance and ESR
    - Timeframe – hours to weeks
  - Step 2 – drying out of electrolyte and contamination from ambient conditions (mostly humidity)
    - Dramatic effect on ESR
    - Timeframe – hours to days
  - Step 3 – open circuit conditions
    - Possible arc conditions if use persists

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Conclusions

- ACN is not more flammable than many common household products
- Fires involving ACN with ample supply of air will produce little if any HCN
- Any fire involving battery electrolytes will produce toxic gases
- Other materials burning (plastics, nylon, wool, foam, synthetic rubber, etc…) will also produce toxic gases including HCN

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Ultracapacitor Safety Considerations

The combination of materials, packaging design and product behavior require the following considerations for application design and differ from product to product

- Protection in the event of over pressure release (mechanical)
- Emissions/vapor exposure protection during compromise of packaging
- Exposure to combustion by products during fire

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Packaging Example

FEATURES

- Ruggedized Enclosure
- Active cell balancing
- Weight: <7.7 lbs.
- Deutsch DT15-6P connector
- Charge status indicator LED

APPLICATIONS

- Vehicle System Back-up Power
- Peak power handling
- Voltage Hold up

Stored Energy: >14.5KV when charged to 28VDC

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Safety and Reliability Summary

- Ultracapacitors safe and reliable when operated under normal conditions
  - Operation within specification
- Ultracapacitors safe when operated under adverse conditions with proper design considerations
  - Component design for extreme conditions
  - Appropriate implementation can assure safety

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Thank You

Brendan Andrews

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Engineering & Scientific Innovations

Intelligent Fire Protection System Technologies

Peter J. Disimile,
University of Cincinnati
and
David McGinnis
Engineering & Scientific Innovations, Inc.

Presented at the
US Army Research Laboratory
Aberdeen Proving Grounds
"Systems Fire Protection Information Exchange"
October 14th – 15th, 2015

Background Overview

- Current aviation fire protection strategies flood the volume of interest (i.e., dry bay or engine nacelle) with fire suppressant once agent discharge is activated.
- Time required to flood these volumes with a sufficient level of agent is relatively long and requires a large volume/weight of agent.
- Resulting Problems:
  - Long fire extinguishing time can result in significant fire and heat damage.
  - The need to carry large amounts of agent on board an aircraft; presenting additional weight and space issues.
  - Once the fire protection system activated all the agent is released. No agent remains for a relight or a second fire event.

An Ideal Solution

Therefore there is a need for an intelligent fire suppression system that can:

- Rapidly detect the presence of a fire.
- Validate the existence of a fire.
- Align the agent discharge nozzle with the fire event.
- Rapidly release the fire suppressant.
- Efficiently transport the agent to the fire zone and ensure the agent is effectively mixed within the fire zone.
- Once the fire is extinguished stop suppressant delivery and re-arm suppression system for a potential second fire.
- A unit should perform with both single phase and multiphase suppressants.

System Objectives

- The ESI Fire Protection systems are developed with several objectives in mind:

  1- Detect and Validate: Using a high speed electro-optics light emission from a fire can be rapidly detected and differentiated between light emissions produced by other sources (i.e., sunlight, electric sparks, high impact flashes, and functioning API's).

  2- Locate Fire Zone: Two approaches are considered:

  i) pre-specify potential local fire zones,

  ii) pre-specified a general protection area where multiple fire zones exist.

  3- Effective Agent Discharge: Maximize the efficiency of a fire suppressant to reach, penetrate, and effectively mix within a fire zone. This requires the specification of the maximum fire size and the required standoff distance.

Self-Contained FPS Performance

Rotorcraft Engine Nacelle Demonstration

- Tests were performed in a full-scale rotorcraft engine nacelle fire simulator under 100 kts forward flight conditions.
- High speed nacelle air flow rate: 4.53 kg/s = 10 lbm/s
- JP-8 spray fires were positioned at one of three pre-defined fire locations; as noted by the manufacturer.
- The measured steady state fire temperature approached 1100 °C.
- Agent delivery was driven by compressed air.
- Detection & actuation system required 5 vdc (4 N cell batteries).
- Current prototype weight is just over 12 ounces when pressurized.
- SCFPS performance exceeded current systems using several agents, including SPGG's

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Self-Contained FPS Performance

Rotorcraft Engine Nacelle Demonstration

Air @ 60 psi delivering < 0.2 oz (5.7 g) of agent.

Fire Extinguished @ t = 128 ms

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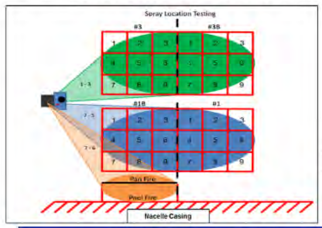
Smart FPS Performance
Rotorcraft Engine Nacelle Demonstration

- Smart FPS tests performed in the nacelle fire simulator under 100 kts forward flight conditions.
- JP-8 spray and pool fire scenario's were tested:
  - spray fires burning @ 8 GPH
  - pool fires (6" x 9" in size), capable of burning for several minutes were placed beneath the engine core.



- A single fixed Smart FPS is used.
- Flame out in < 475 msec with < 0.5 oz (14 gm) of a potassium bicarbonate based agent.

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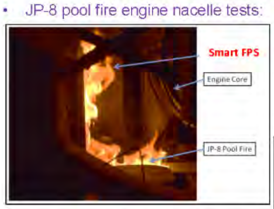
Smart FPS Performance
Rotorcraft Engine Nacelle Demonstration

- JP-8 pool fire engine nacelle tests:



- A 6" x 9" pool of JP-8 was positioned 34 degrees off the smart nozzle centerline and placed beneath the engine core.

- All fires were electrically ignited.
- The Smart FPS was maintained in the same physical location as that used in the spray fire tests.
- All fires were successfully extinguished.

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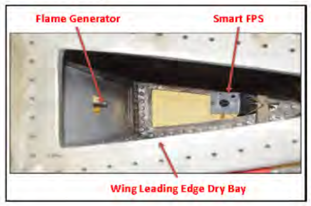
Smart FPS Performance

Wing Leading Edge Demonstration

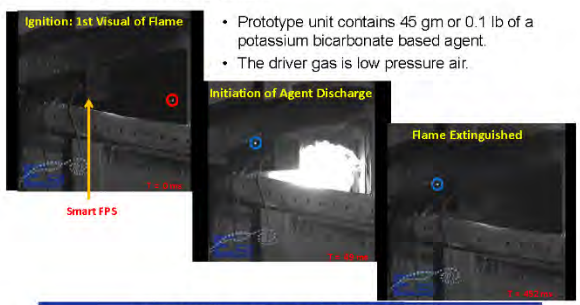
- Using a full-scale section of wing leading edge, JP-8 spray fire tests were conducted.
- Fires were ignited at different positions above and below the discharge nozzle centerline and at different locations along the leading edge.



Smart FPS Performance

Wing Leading Edge Demonstration

- A typiical test is against an 8 GPH spray fire within a wing leading edge under 1000 cfm internal airflow.
- Prototype unit contains 45 gm or 0.1 lb of a potassium bicarbonate based agent.
- The driver gas is low pressure air.



Smart FPS Performance

Wing Leading Edge Demonstration

- The "Smart Fire Protection System" has been successfully demonstrated in two full scale fire simulators:
  - Rotorcraft engine nacelle and
  - Wing leading edge dry bay.
- JP-8 pool and spray fires were detected, located, and successfully extinguished in all cases.
- JP-8 Spray fires as large as 8 GPH were used in most tests.
- All flame extinction times were less than 475 ms.

Note:

1- Current prototype weights 4 lbs. (includes 0.1 lbs. (45 gms) of agent).

2- The "Smart FPS" only requires aircraft electric and any low pressure driver gas.

System Comparison

A quick comparison between the Smart FPS (SFPS) and the Self-Contained Fire Protection System (SCFPS).

	SFPS	SCFPS
Requires an external source of agent	Y/N	N
Requires aircraft electrical power	Y	N
Fire detection/validation time	<110 ms	<10 ms
Flame out time (tests to date)	<475 ms	<300 ms
Fire locating capability	Y	N
Multiple location protection	Y	N
Multiple discharge capability	Y	N
Field deployable	N	Y
Rechargeable	Na/?	Y

Chemours

Development of Zero ODP, Low GWP Clean Agents

Mark L. Robin, Ph.D.
The Chemours Company
mark.l.robin@chemours.com

ARL-TARDEC Fire Protection Information Exchange Meeting
US Army Research Laboratory
Aberdeen Proving Grounds, MD
Oct 14-15, 2015

Total Flooding Agents

- High mass efficiency
- Chemically inert
  - *No reaction with water, common solvents*
  - *No reaction in humans*
  - *Long term storage stability*
- High volatility
  - *bp -70 to + 40 °C*
- Electrically non-conducting
- Low toxicity
- Cost effective

Chemours

Fire Suppression Properties of Total Flooding Agents for Occupied Areas

Property	Halon 1301	FM-200®	Novec™ 1230	TF- 1
Class A MDC, % v/v	5.0	6.7	4.5	5.6
Class B MDC, % v/v [a]	5.0	8.7	5.9	6.9
Class C MDC, % v/v	5.0	7.0	4.7	6.3
Relative mass efficiency, heptane hazard	0.48	1.00	1.26	1.00
Relative mass efficiency, Class C Hazard	0.60	1.00	1.25	1.00

Based on laboratory-scale Testing

Mass Efficiency:

Halon 1301 > Flooding Candidate 1 ~ HFC-227ea > Novec 1230

→ Higher mass required

Chemours™

Toxicological Properties of Total Flooding Agents for Occupied Areas

Property	Halon 1301	FM-200®	Novec™ 1230	TF-1
4h LC_{50}, ppm	>800,000	>800,000	>100,000	>231,000
CS NOAEL, % v/v	5.0	9.0	10.0	10.0
CS LOAEL, % v/v	7.5	10.5	> 10.0	12.5

Chemours™

TF-1: Total Flooding Candidate 1

Suitable for the protection of normally occupied areas containing Class A, Class B, and Class C hazards

- *4h LC_{50} > 23.1%*
- *CS NOAEL = 10%*
- *CS LOAEL = 12.5%*
- *MDC Class A = 5.6%*
- *MDC Class B = 6.9%*
- *MDC Class C = 6.3 %* ← 95% Clean Agent Applications

Chemours

Physical & Chemical Properties of Total Flooding Agents for Occupied Areas

Property	Halon 1301	FM-200®	Novec™ 1230	TF-1
Chemical Formula	CF_3Br	CF_3CHFCF_3	$CF_3CF_2CF(CO)-CF(CF_3)_2$	Proprietary
Boiling point (°C)	-58	-17	49	31
Liquid density (g/cm³ @ 25 °C)	1.54	1.38	1.72	1.3
Chemical Reactivity	Low	Low	High	Low

Volatility : Halon 1301 > FM-200 > TF-1 > Novec 1230

Increasing Ease of Evaporation ←

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Environmental Properties

Experimental Data
- **Infrared Absorption Spectrum**
- **OH Reaction Temperature Dependent Rate Coefficients**

Climate Impact Metrics
- **Radiative Efficiency (RE)**
- **Atmospheric Lifetime (*t*)**
- **Global Warming Potential (GWP)**

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TF-1: Atmospheric Lifetime & GWP

$k(272\ K) = 3.2 \times 10^{-13}\ cm^3\ molecule^{-1}\ s^{-1}$
$[OH] \sim 1 \times 10^6\ molecule\ cm^{-3}$

Lifetime = ~36 days

Including other loss terms would lead to a shorter lifetime

Global Warming Potential (GWP)

Chemical Transport Model (CTM) calculation
to determine corrected RE (Hodnebrog et al., 2013)

GWP(100 year time-horizon) ~2

Chemours

Environmental Properties of Total Flooding Agents for Occupied Areas

Property	Halon 1301	FM-200®	Novec™ 1230	TF-1
ODP	10	0	0	0
Atmospheric Lifetime, years	65	34.2	0.02	0.10
GWP (100 y ITH)	7140	3220	1	2
VOC	No	No	Yes	No

Chemours™

Clean Agent Development

Streaming Agents

- High mass efficiency
- Chemically inert
  - *No reaction with water, common solvents*
  - *Long term storage stability*
- Liquid or high bp gas
  - *bp -10 to + 40 °C*
- Electrically non-conducting
- Toxicity
  - *Equal to or better than Halon 1211 or HCFC-123*
- Cost effective

Chemours™

Physical & Chemical Properties of Streaming or Non-Occupied Area Agents

Property	Halon 1211	2-BTP	Streaming/ Non-occupied Area Candidate 1 (SC1)	Streaming/ Non-occupied Area Candidate 2 (SC2)
Chemical Formula	CF_2BrCl	$CF_3CBr{=}CH_2$	Proprietary	Proprietary
ODP	3	0.0028	0	0
Atmospheric lifetime (y)	16	0.02	TBD	TBD
GWP (100 year ITH)	1890	0.26	< 10 est.	5
Boiling point (°C)	-4	34	31	18
Liquid density (g/cm³ @ 25 °C)	1.8	1.65	1.38	1.3
Chemical Reactivity	Low	Low	Low	Low

Chemours

Fire Suppression Properties of Streaming or Non-Occupied Area Agents

Property	Halon 1211	2-BTP	Streaming/ Non-occupied Area Candidate 1 (SC1)	Streaming/ Non-occupied Area Candidate 2 (SC2)
Class A MDC, % v/v	5.0	?	5.6	4.8
Class B MDC, % v/v	5.0	6.1	7.3	6.2
Class C MDC, % v/v	5.0	?	6.3	5.0
Relative mass efficiency, heptane	1.0	1.3	2.0	1.0
Relative mass efficiency, Class A	1.3	?	1.9	1.0

Candidate 2 exhibits a mass efficiency equal to or superior to that of Halon 1211 and a mass efficiency superior to that of 2-BTP

Chemours

Toxicological Properties of Streaming or Non-Occupied Area Agents

Property	Halon 1211	2-BTP	Streaming/ Non-occupied Area Candidate 1 (SC1)	Streaming/ Non-occupied Area Candidate 2 (SC2)
4h LC_{50} , ppm	31,300 to 100,000	> 20,000	> 102,900	120,000
CS NOAEL, % v/v	0.5	0.5	1.25	2.50
CS LOAEL, % v/v	1.0	1.0	2.50	> 2.50

Candidate 2 exhibits toxicity profile superior to that of Halon 1211 and 2-BTP

Chemours

Development of Zero ODP, Low GWP Clean Agents

•Total Flooding Candidate Developed

- •ODP = 0
- •GWP = 2
- •Low chemical reactivity
- •Suitable for normally occupied areas

•Two Streaming Candidates Developed

- •ODP = 0
- •GWP = 5 (SC2) ; GWP <10 (SC1)
- •Low chemical reactivity
- •Completed small scale fire tests, tox tests, physical properties
- •Candidate #2 mass efficiency = Halon 1211; superior tox to Halon 1211, 2-BTP

Chemours

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FUEL SYSTEMS

Thermal Injury Prevention Strategy (TIPS) Information Briefing

15 October 2015

Nick Twardokus – Director for Ground Programs,
Robertson Fuel Systems

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Agenda

- Who is Robertson Fuel Systems?
- Why Thermal Injury Prevention Strategy?
- What is Thermal Injury Prevention Strategy?
- Thermal Injury Prevention Strategy Goals
- Congressional Language

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Who is Robertson Fuel Systems?

The Company

- Saves lives by containing fuel to prevent post event fuel fed fires in otherwise survivable crash/blast/ballistic /fragmentation events
  - Crashworthy
  - Ballistically tolerant self sealing
  - Fragmentation & Blast tolerant
- Produces survivable fuel systems for aviation & ground platforms
  - Auxiliary fuel systems
  - Primary fuel systems
- Self funds all development efforts; offers products for sale at firm-fixed catalog prices
- Founded TIPS

The Founder

Dr. S. Harry Robertson
Robertson Aviation Founder,
CEO Emeritus, Robertson Fuel Systems, LLC

- Distinguished military pilot
- Instructor in flight safety/accident investigation
- Researcher in aircraft crashworthiness
- Co-author - U.S. Army Crash Survival Design Guide
- Hall of Fame Member
  - Army Aviation
  - National Aviation
  - International Aerospace
- Founded Robertson Aviation in 1976

If the event is humanly survivable the occupants should not perish from a fuel fire

3

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Why Thermal Injury Prevention Strategy (TIPS)?

- Over 800 GWOT burn victims
  - Data from 2008 US Army Institute of Surgical Research Burn Center Letter
    - http://www.usaisr.amedd.army.mil/burn_center.html
  - Over 6% deaths from burn injuries
    - Does not include deaths from multiple injuries
- Far reaching consequences
  - Physical and psychological impact on the individual and the organization when such consequences are avoidable.
    - Recruiting and retention impact
  - Severe materiel and equipment loss impacts
  - Aggregate cost to the military occasioned by such losses of personnel and equipment

Ask soldiers what they fear most, and many will reply, "burning."

4

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What is Thermal Injury Prevention Strategy?

- Bringing awareness and action to preventing thermal injuries
  - Focus attention on TIPS to get key decision-makers and strategists to emphasize the elimination of preventable thermal injuries
- The TIPS Consortium
  - Companies and agencies with technology, products, and research associated with thermal injury treatment and prevention
  - Current members
    - Robertson Fuel Systems – Tempe, AZ
    - Meggitt Rockmart – Rockmart, GA
    - Southwest Research Institute – San Antonio, TX
    - FireTrace – Scottsdale, AZ
    - Global Safety Labs – Tulsa, OK
    - TenCate Protective Fabrics – Union City, GA
    - Hutchinson Rodgard – Buffalo, NY
    - GKN – Tallassee, AL
    - Continuum Group Inc. – Washington DC
- Open to all sharing the TIPS Vision
  - No preferred solution, not a business approach
  - Government, Medical Community, OEMs welcome

5

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Thermal Injury Prevention Strategy Goals

- Official update to thermal injury data
  - Current established baseline
- Congressional language
  - Establish ground platform standards and requirements for thermal injury prevention
- Make TIPS part of TARDEC Survivability initiatives
- Increase Consortium Membership
- Find venues to display/exhibit/expand TIPS

6

Congressional Language

- **2014 NDAA Language:** *Thermal injury protection in combat and tactical vehicles*

The committee understands that the U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC) has established an occupant centric survivability program, with a goal of examining technologies that can significantly protect against vehicle occupant casualties. The committee supports this effort.

In the committee report (H. Rept. 112-479) accompanying the National Defense Authorization Act for Fiscal Year 2013, the committee directed the Director, TARDEC to provide a report to the congressional defense committees that outlined the status of the Army's evaluation of occupant centric survivability systems for combat and tactical vehicles. The committee has reviewed the report and has concerns regarding the development and application of systems that could be used to prevent thermal injury. The committee notes that technologies like fuel containment, fire retardants, fire suppression, fire prevention, and personal fire protection may improve occupant safety as well as vehicle survivability. These technologies are currently being applied in a limited scope. While the committee commends this effort, it believes that additional analysis over current thermal injury survivability requirements is still required.

The committee directs the Director, U.S. Army Tank Automotive Research, Development and Engineering Center to provide a briefing to the Senate Committee on Armed Services and the House Committee on Armed Services within 60 days after the date of the enactment of this Act that outlines the advisability and feasibility of establishing objective and threshold survivability operation al requirements for thermal injury prevention in ground combat and tactical vehicles. The committee expects the briefing to include, but not be limited to: fuel containment; fire retardants; fire prevention; fire suppression; and personal protection.

7

Congressional Language

- **2015 NDAA Language:** *Report on thermal injury prevention*

The House bill contained a provision (sec. 1068) that would require a report on prevention of thermal injuries to occupants of military vehicles that result from overmatching ballistic threats.

The Senate committee-reported bill contained no similar provision.

The agreement does not include this provision.

We are interested to learn how the Army is aggressively investigating innovative technologies to prevent or mitigate the risks of thermal injury to occupants of combat and tactical vehicles that can result from overmatching ballistic threats. Accordingly, we direct the Secretary of the Army to provide, not later than March 31, 2015, a briefing to the Committees on Armed Services of the Senate and House of Representatives on the Army's related technology research and development plans and investment strategies for thermal injury prevention, as well as occupant centric survivability systems in current and future combat and tactical vehicles.

8

The TIPS Consortium is larger than any one company or any one technology. Thermal injuries affect us all and we owe it to the soldiers, Marines, airmen, and sailors who are in harm's way to ensure that they do not suffer devastating burns and the lifelong impacts that these injuries represent. We hope that others feel the same way and will join us in this worthy endeavor.

QUESTIONS?

9

Meggitt Polymers & Composites

Lessons Learned &Technical Capabilities to Meet Higher Level Threats

EAR

ECCN NUMBER: 9E610.b.14

Schedule "B": 8803.30.0060

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Lessons Learned &Technical Capabilities to Meet Higher Level Threats

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Meggitt Polymers and Composites

Lessons learned - Self-seal

- Self-seal technology has protected mission completion and "Get Home" fuel since WWII
- Self-seal fuel bladder constructions have been significantly improved resulting in thinner lighter weight solutions
- A significant amount of Self-seal technology has been successfully tested and deployed, allowing for mission completion without a detrimental loss of fuel that would leave the vehicle in a vulnerable position on the battle field
- Self-seal fuel bladder technology and performance can be applied directly to Ground Combat Vehicle (GCV) Fuel System Survivability
  - Work the same regardless of altitude, velocity
  - Are required by Mil-Spec to seal fully tumbled 14.5 mm exit wounds
  - Successfully tested entrance & exit wound seals for GCV external fuel system

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Lessons learned - Self-seal

- Meet stringent Army Aviation MIL-DTL-27422 threat requirements – offering significant increase in threat protection for GCV programs (kinetic threats)
  - Damp or dry seal in 2 minutes – 4 minutes at -40 degrees F
  - Entrance rounds straight, 45 deg. oblique, and full tumbled - entrance and exit
  - Round size up to 14.5mm and 20mm – 23mm successfully tested
  - 25mm tested – FTFS panel piece stuck in wound prevented seal
  - Adjusting the construction would seal higher level threats, i.e. 30mm entrance & exit
  - Subjected to 24 hour stand test following successful gunfire test - no leakage
  - Subjected to a sealant migration test – sealant does not "wash out"
- Fuel bladder performance is container dependent
  - Titanium creates entrance sealing issues and is unnecessary
  - Aluminum at 0.25" thick allows sealing performance for entrance and exit wounds
  - Other lighter weight materials (nylon, fiberglass) allow sealing performance
- Overmatching Threats (kinetic)
  - Fuel bladders overmatched by coring threats - FSP - Test results showed a cross sectional area reduction of 85%, significantly reducing fuel loss and fire potential
  - EFP/RPG sizes that overmatch are thwarted by modular fire suppression blankets

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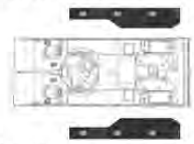
Lessons learned - Blast mitigation

- Bladder technology required to meet stringent Army Aviation MIL-DTL-27422 crash impact test requirements can be used to mitigate mine blast effects in GCV's
  - Crash Impact tested from a height of 65 feet
  - Completely full of water
  - Dropped onto a non-deforming platform
  - Unprotected (without a container) – no leakage



- Crash Resistant bladders were extensively tested, outlined in a 1966 report sponsored by the Army by a team of Goodyear Engineers & Harry Robertson resulting in Rev B of MIL-DTL-27422. Since then Meggitt has manufactured;
  - Over 75,000 crashworthy/self-seal and 20,000 self-seal bladders for aviation
  - ~4700 Bradley, 18 EFV, and 2 GDLS crashworthy self-seal bladders for GCV

- Applicability to GCV Fuel System Survivability – Full Scale Testing
  - Fuel bladders have elasticity that allows for crash impact tests to pass has helped to survive numerous blast tests
  - Internal Fuel Storage - Fuel bladder failures from mine blast testing has been benign, located on the bottom and has not resulted atomization of fuel
  - External Fuel Storage - Container failure resulted in fuel bladder extrusion and failure

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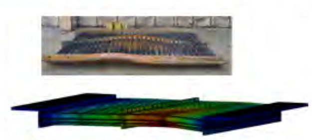
Lessons learned - Blast mitigation

- Fuel bladder mine blast performance is container dependent
  - Container failure must be benign to allow the fuel bladder to perform
- Overmatching Threats (ballistic, IED/RPG)
  - External Fuel Storage - Mine blast protection is a challenge (a new shield technology can mitigate this risk)





  - Passive, modular FTFS blankets eliminate combustion threats.

    - For new programs positioning the FTFS kit on the outside of the container with the self-seal bladder inside will provide the best protection without fear of breakage from routine road conditions encountered by GCV's
    - Positioning the FTFS kit on the outside of the container coated with the self-seal bladder materials will provide the best protection for legacy GCV programs where installing a bladder is impractical
  - Fuel bladder constructions can be adjusted to adapt to larger kinetic and ballistic threats generated by mine blasts, IED's and RPG's (currently classified in GCV specs)

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Current Technical Capabilities to Meet Higher Level Threats

» Design Considerations - A combination of technologies has been tested successfully creating a synergy that will provide GCV's with a significant improvement in higher level threat protection while reducing cost and weight
  - Fuel Bladder – Container design dependent
    - Less complicated shapes and less fittings will allow a less complicated fuel bladder design that will reduced cost, weight and threat vulnerability
  - Passive FTFS Blanket - Positioned on the fuel container exterior
    - Reduces cost (no hard tooling molds)
    - Multiple penetrations with continued performance of both blanket and fuel bladder
    - No hard materials to fracture and lodge into the fuel bladder wound preventing a seal
    - Lighter weight solution
    - Best FTFS blanket performance when positioned outside the container

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Current Technical Capabilities to Meet Higher Level Threats

» Design Considerations – Cont'd – Fuel system survivable performance is counter to the amour paradigm – to stop or react to the threat to avoid penetration
  - Backing Board - Used to keep the entrance wound clean and exit wound supported (essential for sealing)
  - Container - Improved fuel system survivability performance
    - Avoid titanium
    - Aluminum (0.25") has been proven for external tanks (steel also works)
    - Some vehicle fuel container locations would work well with fiberglass or nylon protected by a new blast shield technology
    - Container can be coated for pool fire resistance if required (successfully tested)
    - Container shape - angled on the bottom and high up on the vehicle for blast impact reduction and deflection
  - Blast Shield - Containers may incorporate bottom blast protection
    - Grill style shield has successfully protected a nylon fuel container coated with fuel bladder materials from a 13 lb C4 blast test. No shattering, no cracking and no leakage
    - Design is lighter than traditional armor and can be adapted to externally mounted fuel tanks

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Other Technologies and Recommendation

- Self-Seal - Low pressure fuel hoses can successfully seal against kinetic threats.
  - Threat sizes that overmatch the hose size would not be as successful
    - 1" diameter hose can seal a light machine gun round
    - A heavy machine gun round would not be expected to seal as well but would be expected to seal a larger diameter hose
  - This may prove useful for any exposed line inside or outside of the vehicle
    - This technology is currently flying on the Air Tractor 802 U
    - It is also used on the connection hose for the Robertson UH-1 aux system
  - This solution is light and cost effective
- Recommend de-classification of the GCV fuel systems
  - Established precedent - Army aircraft has an unclassified fuel cell specification – MIL-DTL-27422
  - De-classifying the GCV systems
    - Would allow an unclassified specification to be written to provide various increased threat level protection requirements that would be applicable to designated classes of vehicles
    - Allows designers to design vehicle specific solutions for threat requirements, adjusting and "dialing" into the threat requirements to "close the gaps"

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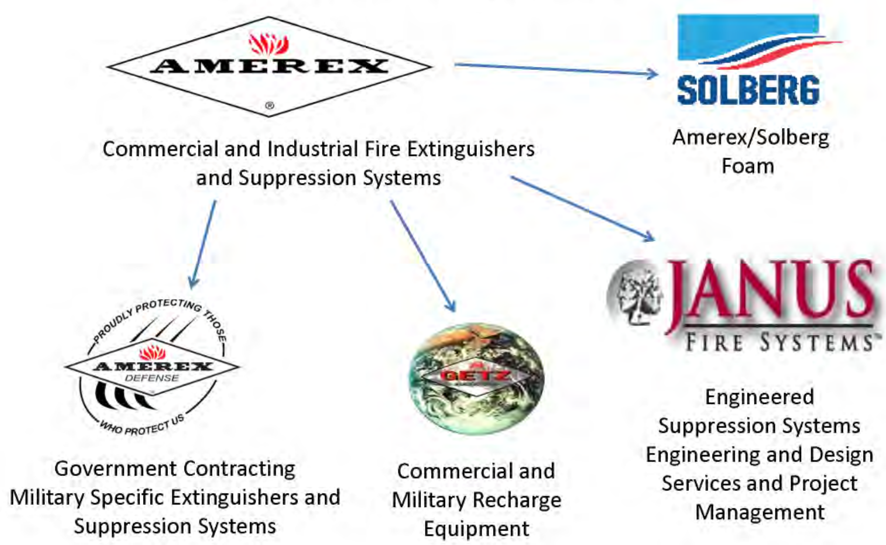
PROVIDING INNOVATION IN FIRE PROTECTION SINCE 1971

Amerex Corporation



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Amerex Corporation

- **Located in Trussville, Alabama (a Suburb of Birmingham, AL)**
- **500+ Employees**
- **390k sq. ft. Mfg. Space / 38k sq. ft. Office / 5k sq. ft. Indoor Test Facility with 900 sq. ft. Environmentally-Friendly Burn Room**
- **Financially Sound US Based Company (a Division of McWane Inc.)**
- **Production of up to 3.4 million Extinguishers and Suppression Systems Annually**
- **ISO 9001-2008 ISO 14001-2008 Certified**

Amerex Timeline

1971- Amerex Established in Trussville we begin to manufacture Hand Held and Wheeled Extinguishers

1990- Amerex introduces our Commercial Vehicle Fire Suppression Systems

1990- Amerex purchases Getz Manufacturing

1995- Amerex introduces our Commercial Kitchen Fire Suppression Systems

1999- Amerex is purchased by McWane Inc.

2001- Amerex introduces our Commercial Industrial Dry Chemical Fire Suppression Systems

2007- Amerex introduces CPS (Pre-Engineered Clean Agent Systems) using FM200 and Novec 1230

2008- Amerex establishes Janus Fire Systems our Engineered Systems company.

2010- Amerex establishes our Defense Division

2011- Amerex purchases Solberg Foam and establishes our Foam Division locations in Norway, Australia, Great Britain and the United States (Green Bay, WI).

Amerex Corporation Product Families - Commercial product offering

Commercial Kitchen Systems (1995)

Industrial Dry Chemical Systems (2001)

Pre Engineered Clean Agent Systems FM200 and Novec 1230 (2007)

VFSS Commercial and Industrial Vehicle Suppression Systems (1991)

Hand Portable Fire Extinguishers (1971)

Commercial and Industrial Wheeled and Stationary Units (1971)

PROUDLY PROTECTING THOSE

AMEREX DEFENSE

WHO PROTECT US

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Amerex Defense Product Family

- Crew Compartment Explosion Suppression Systems
- Engine AFES conventional Dry Chemical and Aerosol Generators
- Tire and Wheel Well EFES both Dry Chemical and Liquid Agents
- Liquid Cooling Egress Systems

Typical Crew Compartment AFES

Typical Aerosol Engine AFES

Amerex Defense Product Family cont.

Manual and Automatic Engine, Transmission and External Systems; Dry and Liquid

Wheeled and Stationary Units

Dry Chemical

CO2

Novec 1230

Halon 1211

Specialized Stationary Units both Liquid and Dry Chemical

Halotron

Foam

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Why Run ‘***Pre-Aberdeen***’ Fires / Concentration Tests at Amerex?

- Each program we encounter has specific design challenges in terms of vehicle configuration and available hardware mounting locations. We have the capability to rapidly mock-up test modules and test on-site at Amerex, or at vehicle OEM location, as needed.
- Crew cab discharge tubing length, configuration, UV/IR optical detection location and nozzle design are all validated together against fire-out time requirements.
- Agent concentration sampling tests validate internal crew cab volumes to balance effective fire extinguishment with concentrations safe for crew members.
- These live fire tests provide crucial system design validation prior to performing formally-witnessed Aberdeen fire tests, thereby vastly ***decreasing overall system development time and reducing program risk***.

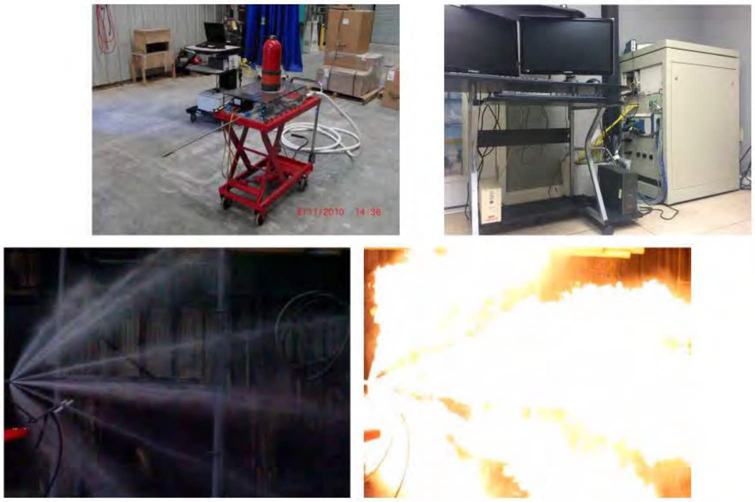
Testing Capabilities: Dedicated Test Building for Military Applications

Amerex Defense Test Building and Lab

5,000 sq. ft. Test and Prototype Shop

900 sq. ft. Burn Room

Data Acquisition and Fireball Generator

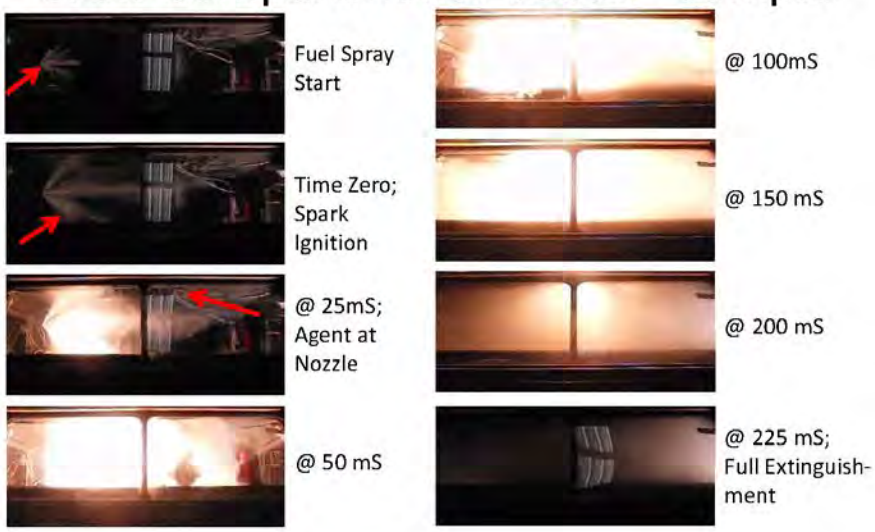


Data Acquisition

Our Data Acquisition Capabilities Include, but are not limited to:

- Nozzle Pressures
- Cylinder Pressure Decay
- Discharge Noise Levels
- Acceleration Forces
- Fire Detection Time
- Fire Out Time
- Agent Distribution Confirmation
- Agent Concentration Data (Six Point Analyzer)
- High Speed Video Recording

Testing Capabilities:
Crew Compartment Fireball - Sample



Testing Capabilities

Wheel Well and Tire Testing

¼ Scale Molotov

External and Under Chassis Fire Suppression Testing

Explosion Suppression and Slow Growth AFES Configuration

The Amerex Crew Compartment AFES was tested and qualified for use in the HMMWV program under the Spectronix name. Amerex entered into a License and Manufacturing agreement with Spectronix (now Emerson Electric) in 2008. Since that time, we have made numerous performance improvements via nozzle and discharge tube design enhancements. Our Crew AFES are currently installed in the Oshkosh M-ATV MRAP variant. Over 10,000 systems produced and fielded with current production ongoing.

Photo from Oshkosh Defense Website

"Proudly Protecting Those Who Protect Us"





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Summary

- Fire Suppression System that meets or exceeds all performance requirements
- Commonality of components between the TWV fleet.
- Interoperability
- COTS, fully tested, cost effective, combat proven system.
- Tested per MIL-STD-810G, MIL-STD-1275D, MIL-STD-461F.
- Strong onsite and office based support staff including engineering and field technicians.
- Ability to meet large quantity production demands. Produced 1000+ MATV Crew and Engine AFES per month plus met spare parts demand.
- ***<u>Complete Systems Approach</u>*: *Vertical Integration including Design, Development, Testing, Validation, Manufacturing, and Support.***

For More Information,
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SPECTREX INC.

"Slow Growth Fires : Detection-Testing-Spec"

ARL/TRADOC Systems Fire Protection Information Exchange Meeting

Oct. 14-15, 2015

Aberdeen, MD

Douglas Kulick, VP Military Systems , Spectrex INC. 510-487-8545

Introduction

- During the Iraq and Afghanistan conflicts we saw that the growth of fires from non-penetration events are deadly and need to be detected and extinguished just as effectively if not more as penetration events.
- These very hazardous cases of slow growth fires where studied in 2009 under a joint TACOM and Spectrex funded project and a series of tests. ATC utilized a British Aerospace (BAE) Tactical Vehicle Systems (TVS) Caiman Mine Resistant Ambush Protected (MRAP) to examine the performance and effectiveness of the manual and AFES installed. Systems tested comprised the troop compartment tested against slow growth pan fires.
- Thru discussion and presentation of these test results, our objective is to make the AFES community aware that all systems on combat vehicles need to address not only penetration high radiation events, but to detect and extinguish slow growth fires. The inclusion into future combats vehicle specs and test criteria to determine meeting such specs are essential for future vehicle AFES systems

2

MRAP FES Crew Survivability

PARAMETER	REQUIREMENT
Fire out	Extinguish all flames without reflash
Skin burns	Less than second degree burns < 2400 °F-s over 10 s or heat flux < 160 kJ/m²
Overpressure	Less than lung damage: 80 kPa (11.6 psi)
Agent concentration	Not to exceed LOAEL[a]
Acid gases (by-products)	See Species Incapacitation Table.
Oxygen levels	Not below 16 percent for 5 s average[b]
Toxic Gasses	See Species Incapacitation Table.

[a] LOAEL = Lowest observed adverse effects level per NFPA-2001 (for HFC-227ea is 10.5 percent).
[b] Fire Survivability Parameters for Combat Vehicles Crewmen.
[c] Medical Evaluation of Nonfragment Injury Effects in Armored Vehicle Live Fire Tests," Walter Reed Army Institute of Research, September 1989

LFT&E Species

SPECIES	DOSE, ppm-min	
	0-PERCENT Incapacitation	100-PERCENT Incapacitation
CO + NO	37,250	62,750
CO_2	--	-
NO_2	125 (delayed)	375 (delayed)
	250 (immediate)	750 (immediate)
HCN	75	225
Acid halides[c] (HX)	746 (delayed)	2,237 (delayed)
	1,491 (immediate)	4,473 (immediate)
Acrolein	26	None available
Formaldehyde	150	None available

3

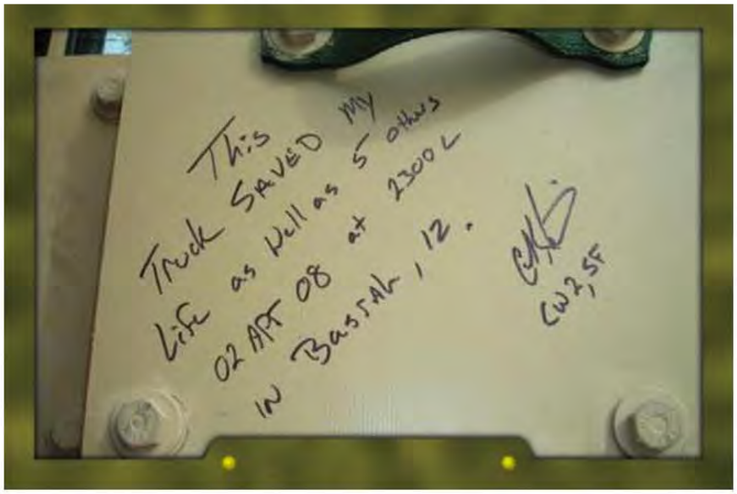
Overview

- Spectrex Inc. of Cedar Grove, NJ together with its affiliate Spectronix Ltd., of Israel have accumulated years of battle field and test/evaluation experience spanning over 30 years . Spectrex systems have had outstanding operation and combat performance in protecting and saving vehicles and crews . We have conducted numerous automatic fire extinguishing projects for tactical and combat armored vehicles, involving all stages from prototype integration testing and the qualification of operational systems.
- Spectrex Incorporated was the test sponsor through a cooperative effort with BAE's Caiman MRAP vehicle and the TACOM MRAP office.
- Testing was conducted via a private industry contract with Spectrex Incorporated with the U.S. Aberdeen Test Center (ATC), Aberdeen Proving Ground (APG) and under the U.S. Army Test and Evaluation Command (ATEC). ATC tested all parameters of testing and compiled the test report.

4

AFES Systems provide:

Soldier Survivability Vehicle Survivability
System Survivability



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Test Purpose

The tests where conducted on the British Aerospace (BAE) Tactical Vehicle Systems (TVS) Caiman Mine Resistant Ambush Protected Vehicle (MRAP) to examined the performance and effectiveness of the manual and AFES installed. The troop compartment was tested for Automatic AFES Detection of small slow growth fires as well as manual activation of the system.

In our experience, SLOW GROWTH FIRES are a deadly concern in all vehicles with an AFES system. Their detection and suppression is vital in all current and future Vehicles.

Within the Army and Naval Developers, it is essential to develop a uniform Slow Growth Fire SPEC and to flow that SPEC to the Test Community for a clear and concise verification testing to insure the SPEC is meet.

6

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Test Plan

The scope of the MRAP Caiman AFES testing was derived from the MRAP Caiman Troop Compartment Automatic Fire Extinguishing System Testing Detailed Test Plan (DTP), which included:

a. Crew compartment automatic detection and extinguishing capability for an 18-in. diameter unleaded gasoline pan fire.

b. Crew compartment automatic detection and extinguishing capability for a 1- by-1-ft unleaded gasoline pan fire.

c. Crew compartment manual extinguishing capability for an 18-in. diameter unleaded gasoline pan fire.

d. Crew compartment manual extinguishing capability for a 1- by 1-ft unleaded gasoline pan fire.

7

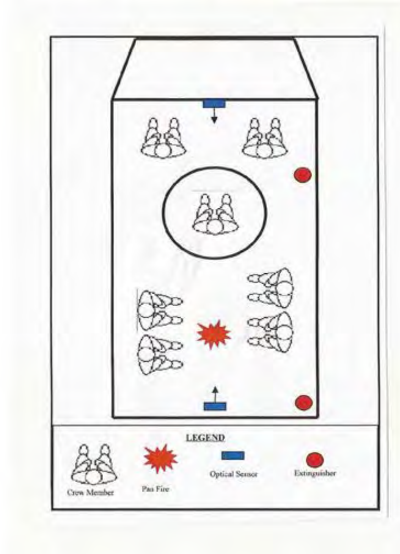
Test components

The crew compartment fire tests of the Caiman MRAP were conducted to assess the AFES performance against a challenging fire event. Two different size pan fires were executed: (1) 18-in. circular pan and (2) 1- by 1-ft square pan.

The pans were placed in approximately the same location for each crew compartment fire event. The AFES layout of the vehicle along with the pan fire placement is show in the next slide

8

Test vehicle fire pan layout



9

We save lives SPECTREX INC.

18 inch Fire Pan and 1′ x 1′ Fire Pan

10

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Instrumentation and Data Collection

- Instrumentation installed included high-speed video cameras viewing the driver's and crew's compartments. Heat flux gauges were installed on the face and the right hand of the crew surrogates.
- Fast response thermocouples were installed on the nose, chest, and right calf of the crew surrogates.
- Along with the mannequins that were seated during testing, a plywood mannequin was standing upright in the turret.
- BOP gauges were located on the face of the wooden mannequins

11

Conduct of tests

The crew compartment heating and ventilation system was operational, and set to the maximum speed. Doors were closed during the tests except for the rear access door and the gunner's hatch, with an objective gunner protection kit (OGPK) in place which remained open.

The rear access door was left open per guidance from Spectrex Incorporated. This represented a worst case scenario for the ability of the crew compartment AFES to extinguish the pan fires.

Significant space-occupying stowage items in the crew compartment, obstructions, and clothed mannequins were included during the crew compartment AFES tests. Surrogate components were installed for non-AFES components where necessary as long as they did not alter the function of the AFES or ventilation system.

Crew simulants wore only boots, battle dress uniforms (BDUs), helmets, and vests. External stowage was not installed.

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Test No. 1 – AFES Automatic 1′ x 1′ Pan

A 1′- by 1′ pan was placed at the rear of the vehicle in the crew compartment. The rear door and turret remained open during testing, while all other hatches and door remained closed. The vehicle was equipped with wooden crew members and stowage. The AFES was armed and discharged automatically without incident.

13

Test No. 2 20 sec manual activation

A 1′- by 1′ pan was placed at the rear of the vehicle in the crew compartment. The rear door and turret remained open during testing, while all other hatches and door remained closed. The vehicle was equipped with wooden crew members and stowage. The fire was allowed to burn for approximately 20 sec then the bottles were discharged manually. (20 secs was long enough to show dangers without test vehicle damage)

14

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Test No. 3 – AFES Automatic 18" Pan

An 18-in. circular pan was placed at the rear of the vehicle in the crew compartment. The rear door and turret remained open during testing, while all other hatches and door remained closed. The vehicle was equipped with wooden crew members and stowage. The AFES was armed and discharged without incident.

15

Test No. 4 – AFES Manual 15 sec. 18" Pan

An 18-in. circular pan was placed at the rear of the vehicle in the crew compartment. The rear door and turret remained open during testing, while all other hatches and door remained closed. The vehicle was equipped with wooden crew members and stowage. The fire was allowed to burn for approximately 15 sec then the bottles were discharged manually. (view in picture below shows why we only let it burn for 15 sec.)

16

Technical Analysis

- The Spectrex Incorporated crew AFES, mounted in the BAE Caiman vehicle platform, demonstrated that it was capable of extinguishing slow growth petroleum based fuel fires in the floor area of the crew compartment. When the crew AFES was allowed to function automatically, there were no injuries due to thermal, blast, or toxic fume effects.
- Had all manual fires been left for a longer period, vehicle damage and crew causalities were inevitable.

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Manual activation heat levels

- 1'x1' pan fire heat at crew closest to pan reached over 485 to 600 degrees Fahrenheit in 20 sec.
- 18" pan fire heat at crew closest to pan reached over 1473 degrees Fahrenheit in 15 sec
- No US Govt SPEC was available for these tests in 2009.
- Had any of the manual pan fires not been extinguished manually damage and crew burns would of be apparent.

18

Conclusions:

- Slow growth fires are vehicle and crew damaging if not detected and extinguished rapidly.
- All future Army and Naval vehicles would benefit with a unified SPEC for determining slow growth fires .
- A unified SPEC would have the test community test to verify the SPEC.
- Testing must be developed and instrumented to allow the testers, end users and developers to determine the unified SPEC has been meet.

U.S. ARMY TANK AUTOMOTIVE RESEARCH, DEVELOPMENT AND ENGINEERING CENTER

Vehicle Fires: Research and Effective Mitigation

ARL/TARDEC Fire Protection Technical Exchange Meeting
14-15 Oct 2015

Steve Hodges
Chair, SAE Fire Safety Committee
TARDEC Fire Protection Team
Alion Science and Technology, USA

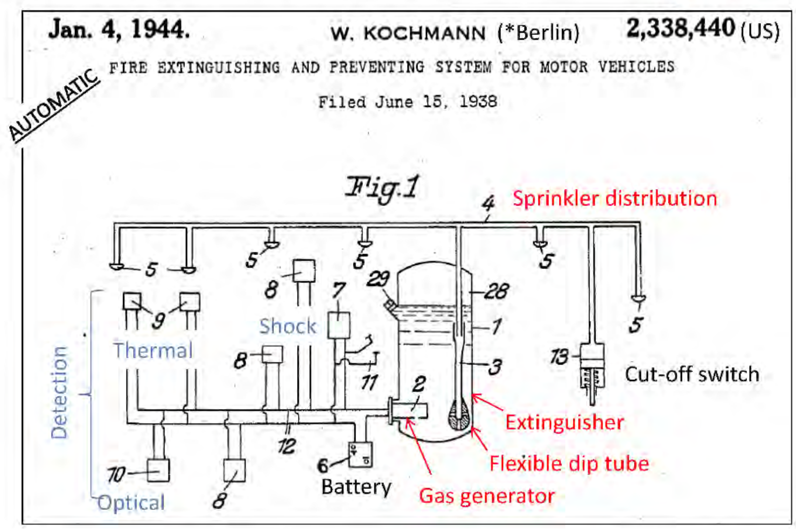
General Points

- This brief is an update of the keynote paper "Vehicle Fire Research – a Review," presented at the 2014 Fire in Vehicles (FIVE) Conference, Berlin, Germany, October 2014. Updated paper available on request.
- Fire safety is an important issue on any vehicle. Generally vehicle occupants and flammable materials are in close proximity and it is not always easy or practical for the occupants to move away in the event of a fire.
  - Post-collision fires are associated with a large fraction of vehicle accident fatalities due to fire. Overall, in the US, vehicle fire-related deaths account for approximately 10% of all deaths attributed to fire [11, 16].
  - Effective fire protection is different for different vehicles and accident scenarios, and depends the nature of fire threat(s) and whether the goal is
    - protection of asset,
    - life safety or
    - both.

First cars, first fires

"In 1891, John William Lambert built a three-wheeler in Ohio City, Ohio, which was destroyed in a fire the same year…." [1]

First patent for vehicle fire protection?



*Patent assigned to the US Alien Property Custodian [2]

Recalls and Research

1978 – Ford Pinto recall

"IN THE EVENT THE VEHICLE IS STRUCK FROM THE REAR, THE FUEL FILLER PIPE COULD DISCONNECT FROM THE TANK OR THE TANK COULD BE PUNCTURED IN THE FORWARD FACE. THIS WOULD RESULT IN FUEL LEAKAGE.... CONSEQUENCES OF DEFECT: FUEL LEAKAGE, IN THE PRESENCE OF A SOURCE OF IGNITION,COULD RESULT IN A VEHICLE FIRE AND SERIOUS INJURY TO PASSENGERS." NHTSA CAMPAIGN ID Number: 78V143000

GM C/K Pick-up truck saga

- 1973 – First saddle tanks outboard of frame
- 1992 – First widely publicized lawsuit regarding post-collision fuel fire injury
- 1993 – NHTSA call for recall (NHTSA EA92-041), GM rebuttal
- 1994 – Settlement: GM committed $51M to safety programs – including fire safety research (60 FR 13752)
  - Original papers filed as NHTSA dockets
  - SAE Fire Safety Committee formed in 2005
  - SAE Fire Safety Papers can be found at http://papers.sae.org/safety/hazards/ and at http://www.mvfri.org/

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Vehicle Fire Research Papers

- Statistical overviews of the highway vehicle problem [11, 16-19].
- The first post-collision fire created in laboratory conditions [20, 21].
- The first production automotive active fire protection system described [22].
- Hydrogen and fuel-cell vehicle safety standards and test protocols [23-28].
- Challenges in the fire protection of electric vehicles [12, 13]
- Studies of hot surface ignition of underhood fluids, summarized in [29].
- Flammability of plastics and the combustion byproducts of materials [30-32].
- The flammability of new and existing refrigerants [33, 34]
- Design trade-offs and cost-benefit analysis of fire protection [35-38].
- Relation of maintenance, design and/or features with fire safety [39-42].
- Vehicle burn tests; and correlation of oxidation patterns with fire origin [43].
- Active fire protection systems - discussed and evaluated [8, 10, 20-22, 44-46].

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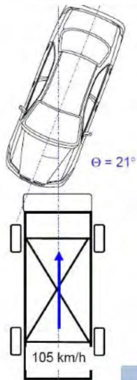
Vehicle Crash and Burn Tests



crash test to understand post-collision fires. [21]

vehicle mockup used to understand electric vehicles. [13]

Full-scale vehicle burn tests. [43]

Lessons Learned

- How can fire protection methods be effective in saving?
  - Lives
  - Assets
- We learn a lot from live-fire tests….
- But what do actual vehicle fires tell us?

Bus Fire – September 2005

"Explosions on a bus carrying elderly evacuees killed up to 24 people."

http://usatoday30.usatoday.com/weather/stormcenter/2005-09-23-rita-main_x.htm#

Highway Accident Report* Findings included:

•The accident motorcoach was mechanically unsafe because the right-side tag axle wheel bearing assembly lacked sufficient lubrication, which resulted in high frictional forces and high temperatures, causing the wheel bearings to fail and igniting the tire

•The tire fire, caused by an overheated right-side tag axle wheel bearing assembly, which ignited the tire, spread up the side of the motorcoach and burnt through the fiberglass sidewall above the wheel well and through the motorcoach windows, creating an entry path for the smoke and fire into the passenger compartment

*NTSB/HAR-07/01

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Bus Fire – 10 April 2014

"Someone kicked out a window on the bus, and many of those aboard squeezed through and ran for their lives to the other side of Interstate 5 before the vehicle exploded in flames." ... 10 people killed.

http://www.myfoxla.com/story/25220222/5-students-5-adults-dead-in-head-on-tour-bus-crash#ixzz2zWVzCCdd

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Similarities and Differences

Comparison of the 2005 and 2014 US bus tragedies

- Differences
  - Fire cause and origin
  - Passenger demographics
  - Passenger cargo
  - Maintenance issues
  - Driver factors

- Similarities
  - Egress issues
  - Combustible materials in vulnerable areas
  - No engine involvement
  - Current active fire extinguishing systems are unlikely to have had a significant effect [8, 10, 20-22, 44-46]

Risks inherent in new technologies

- Gaseous fuels, e.g., hydrogen [23-26]
- Electric vehicle batteries [14, 15]

The New York Times

Wheels

The Nuts and Bolts of Whatever Moves You

NOVEMBER 2, 2012, 11:57 AM

Mystery at Port Newark: Why Did 17 Plug-In Cars Burn?

By JOSIE GARTHWAITE

Amid all the damage left in Hurricane Sandy's wake is an automotive whodunit, or rather, what-dunit? What caused more than a million dollars-worth of plug-in hybrid vehicles, including 16 Fisker Karma luxury sedans, to catch fire Monday night at Port Newark?

Fisker Karma Fire In New Jersey (photo via Jalopnik)

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Military Vehicles

- Peacetime fires similar to civilian heavy-duty vehicles [7]
  - Fuel, hydraulic fluid, or lubricating oil component failures can lead to leakage of flammable liquids that are ignited by contact with hot surfaces and/or sparks,
  - Electrical component failures or corrosion can lead to overheated circuits that ignite wire insulation or oily contaminants and other combustible materials, and
  - Overheated brake components and trapped road debris can cause fires in the wheel well. Wheel well fires can also occur if a wheeled vehicle operates too long on ‘run-flats’ designed to offer temporary support when the main tires are deflated.
- Combat fires offer a unique fire protection challenge: explosion protection of an occupied area [53]

Layers of Survivability

Layer	Military Vehicle	Passenger Bus	Automobile
1	Fire power	Perform Maintenance	Collision Avoidance
2	Concealment	Avoid Road Debris	Minimize Impact Effects
3	Mobility	Emergency Egress	Restraints
4	Armor and PPE	**Fire Protection**	**Fire Protection**
5	**Fire Protection**		

Layers of Fire Protection

Layer	Military Vehicle	Passenger Bus	Automobile
1	Compartmentalization	Compartmentalization	Compartmentalization
2	Fire Resistant Materials	Fire Resistant Materials	Fire Resistant Materials
3	External fire protection	Automatic engine fire extinguishing system	*Underhood fire detection/suppression?*
4	High-speed, automatic fire extinguishing system	*Wheel well fire extinguisher?*	
5	Fire Resistant Uniforms		

Summary

- The close proximity of flammable materials and ignition sources make vehicle fires a significant risk and thus an important safety issue.
- Fortunately there are often means to mitigate the risks and damage caused by fire on a vehicle, but the optimum approaches vary by application.
- Many of the most effective design features that reduce the risk of fire on a vehicle, and/or mitigate the effects of a fire if it does occur, are the product of experience and extensive ongoing research and development.
- Advancements in vehicle development, which may inadvertently introduce new fire hazards, motivate continued vehicle fire research.

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Thank you

Disclaimer

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List of Symbols, Acronyms, and Abbreviations

3-D	3-dimensional
AFES	automatic fire extinguishment system
ARL	US Army Research Laboratory
ASA-ALT	Office of the Assistant Secretary of the Army for Acquisition, Logistics and Technology
ATC	US Army Test Center
CFD	computational fluid dynamics
DOD	US Department of Defense
EPA	US Environmental Protection Agency
FES	fire extinguishment system
FAA	US Federal Aviation Agency
FPM	Fire Protection Model
FR	flame-retardant
GWP	global warming potential
halon	halogenated hydrocarbon
HDRam	hydrodynamic ram
JANNAF	Joint Army Navy NASA Air Force
Li	lithium
NAVAIR	US Naval Air Systems Command
NRL	US Naval Research Laboratory
NSRDEC	Natick Soldier Research, Development and Engineering Center
ODP	ozone depletion potential
ODS	ozone-depleting substance

SCJ	shaped charge jet
SwRI	Southwest Research Institute
TARDEC	US Army Tank Automotive Research, Development and Engineering Center
TIPS	Thermal Injury Prevention Strategy
UC	ultracapacitor

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