DEVELOPMENT OF FIRE AND SUPPRESSION MODELS FOR DOD VEHICLE COMPARTMENTS: BACKGROUND, OBJECTIVES, AND METHODOLOGY*

Louis A. Gritzo
Sandia National Laboratories
Albuquerque, NM 87185-0836 USA

James R. Tucker
Wright Laboratories
Wright Patterson, OH 45433-7605 USA

Lawrence Ash
US Naval Air Systems Command
Patuxent River, MD 20670-1906 USA

ABSTRACT

A roadmap for acquiring the necessary understanding of cluttered compartment fire phenomena, and the development of practical, credible engineering tools for the design **of** efficient fire protection systems using best available agents, is presented in this document. The detailed objectives outlined in the roadmap include gaining the necessary understanding, developing models that can be used as tools, establishing performance metrics, defining and implementing optimization strategies, and integrating suppression system optimization with other compartment design/ retrofit considerations.

The strategy is to follow a logical progression from addressing basic airflow with multiple inlet/outlets and clutter, to environments including gaseous agents, condensed and solid phase agents. Technical challenges associated with addressing this class of problems includes (1) developing models for transport (including mixing) and burning in regions with small (approx. < 1cm) and intermediate (approx. 1 – 10 cmj scale clutter, (2) development of models for the transport of condensed and solid phase materials, including the interaction of these materials with surfaces, (3) characterization of typical droplet release conditions, and (4) characterization of effective suppression conditions for potential agents. Successful achievement of this strategy will include laboratory-scale experiments for model development and validation: full-scale experiments for global phenomena discovery and model validation under relevant, end-use conditions: and computational models to plan experiments, investigate phenomena computationally. and apply to actual problems. Activities presently in progress **as** part of the methodology described here are highlighted. Potential next steps will also he identified.

INTRODUCTION

Despite considerable efforts to define suitable alternatives, Halon 1301's highly desirable attributes have yet to be matched by agents with acceptable measures of toxicity, global warming potential, and ozone depletion potential. **A** complementary activity to the quest for the most effective halon-alternative agent is the development and use of practical fire and suppression models for system design and assessment in compartments designated as fire zones. These models provide another tool that can be used to improve, and perhaps even optimize, the performance of best available agents, thereby reducing the amount of agent needed and allowing the use of less effective (on a unit mass basis) agents. The benefit of these models to system testing has been presented in an earlier work [1]. End users include system manufacturers and DoD technical personnel working on the design optimization of new and retrofit systems.

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Recently, trends within the defense arena have emphasized the attractiveness of modeling and simulation. Although positive in the sense that a shift from a solely test-based approach to a joint model/test strategy will undoubtedly increase the value gained from related expenditures, the development of practical models prcscnts a significant challcnge.

The objective of this work is to assess the requirements, current status and framework for devclopment of compartment firc and suppression models for DoD applications. Specifically, the following three questions are addressed:

1. What arc the requirements of a model for it to be of greatest utility'?
2. How accurate and usable are present models'?
3. What technical issues need to he addrcssed to make existing models of greatest utility'?
4. How can these issues he addressed'?

Compartments in DoD systems that may become fires zones include aircraft dry bays, fuel tanks and nacelles. ground vehicle crew and engine compartments. shipboard machinery, and occupied spaces, ctc. The discussion that follows will he limited to general concepts expected to be pertinent, although in varying degrees. to all applications. Somc principal features of fires in these compartments arc presented in the following section.

GENERAL FEATURES OF COMPARTMENT FIRES

Typically. fires in DoD system compartments involve the burning of a hydrocarbon fuel as a spray (such as a punctured fuel tank or high pressure linc) or from a fuel pool or spill. The discussion presented here is based on the premise that the heat transfer from the fire to the system or items within the system is the principal hazard. An assessment of this hazard (as yielded by fire calculations) therefore defines the performance criteria (usually a minimum time) for a fire suppression system. The additional hazard posed by smoke or toxic gases may also he worthy of consideration.

Development of models for fire and suppression requires a strong understanding of the phenomenological interaction between the flow field (including agent transport) and the firc field (including agcnt concentration required for complete fire extinguishment). To assist in focusing modeling and analysis cfforts, the broad spectrum offirc scenarios can be divided into two main classes to bc discussed below. The distinguishing feature bctwcen these two classes is the importance and coupling of the burning process to the overall fire phenomena. Scenarios where the hurning proccss is critical and therefore must be modeled require considerably more effort. This effort is a consequence of the complex aspects of turbulent combustion, soot formation and oxidation, and participating media radiative heat transfer, which must be considered to model the actual burning process.

Class I Compartment Fires

The first class of fire scenarios, referred to as Class I fires for purposes of this discussion, are cases where the fire presence and potential for fire suppression are largely uncoupled from the burning process. The suppressant dynamics are therefore largely independent of fire dynamics. These cases can occur in aircraft nacelles and wing leading edge dry bays where the momentum of air/fuel flow is significantly larger than the flow induced by the buoyancy produced in the flame zone. Class 1 fires also include the case where the fire size is small compared to the compartment and therefore the fire can be represented as a simple source of heat and smoke/ product release. Small fires in shipboard machinery spaces represent an example of such a scenario. These cases can be addressed using Computational Fluid Dynamics (CFD) models without detailed modeling of the burning region. The ability to suppress a fire in various regions of the compartment can first be evaluated based on agent concentration, as is presently performed in nacelle fire suppression system acceptance tests. Additional factors such as the ability to transport fuel/air to the region, and potential turbulent flame strain (due to velocity gradients) predicted by the turbulence model, can also be considered given the spatially resolved solution yielded by a CFD calculation.

Since a rendering of the flame zone is not provided by the model, the heat transfer from the fire (except in the far field) cannot be modeled. Several empirical correlations for heat transfer from fires in terms of total heat release are available [2], but these are limited to simple pool fires without interaction of local air flow (caused perhaps by ventilation systems) or objects/clutter. In these cases, successful suppression system design requires *a priori* knowledge of the criteria for maximum fire extinguishment time.

Class 2 Compartment Fires

In contrast to Class 1 fires where the flow field is uncoupled from the dynamics of the burning region, **Class** 2 fires represent cases where the flow field is largely determined by the dynamics of the burning region. In these cases, the fuel/air mixing that controls the burning and the suppressant dynamics are dominated by the fire-induced buoyant flow.

These cases require a rendering of the flame zone provided by CFD-based fire field models. The tight coupling between fuel air mixing, turbulent combustion, heat release. and buoyancy-induced turbulence must be reflected in addition to agent transport, flame strain, and fuel/air effects. Details regarding the challenge of representing the essential phenomena over the breadth of length and time scales have recently been investigated by Tieszen et al. [3].

MODELS OF FIRE AND SUPPRESSION

Background

Numerical models for the simulation of fire and suppression include algebraic models, empirical correlations, zone models, and CFD-based fire field models. The exact type of model to be used will depend on the application, including the user and the objective of the simulation. There are, however, some general requirements for all model types, and some basic physical features of fires in DoD system compartments that define which model is preferable for various applications. These requirements and physical features are discussed in the next two sections. The third section includes a description of some remaining technical challenges as well as a strategy to address them.

Requirements

First and foremost, results from these models must be sufficiently accurate so that they provide credible insight and guidance to the user. A tool that provides the wrong answer is worse than no tool at all. To provide credible results, these models must be able to represent the enormous complexity of actual systems. Models must also be sufficiently robust such that a “noli-expert” user can apply them. and limited in computational time to allow **a** sufficient numbcr of cases to bc addressed. For risk-based design. or Probabilistic **Risk** Analysis (PRA) models. the uncertainty in the prediction of the hazard posed by a fire scenario may he overwhelmed by the uncertainty in estimating the probability of occurrence of the scenario. In these cases, an increase in accuracy of the fire model beyond some limit does not provide a significant increase in the ability to quantify the risk.

Two classes of models are generally required to cover the analysis needs for a particular application. Detailed, CFD-based fire field models provide the best possible rendering of the physical phenomena associatcd with the turbulent tlow field. the burning (i.e., turbulent combustion), soot production, and heat transfer. Most all physical phenomena (such as turbulence, soot production) in the components (i.e., submodels) rendered by these models represent current areas of active research. The submodels are therefore rudimentary in nature but are expected to be representative of the essential features of the modeled process. Detailed assessment of the accuracy of these models is difficult and costly to perform due to measurement challenges and complications in designing experiments to isolate the relevant physics. Physical submodels therefore remain largely unvalidated.

CFD-based field models generally require resolving the geometry on a computational mesh. These models then strive to obtain solutions to the relevant governing equations by solving discrete forms of these equations obtained using the mesh. The user must therefore have the necessary configuration information required to construct a mesh of the compartment. Limits to the numher and shape of the grid elements must be considered. The mesh is usually generated by an “expert user” who is familiar with the ability of the model to obtain a accurate solution for a given mesh. Ideally, one would continue to refine the mesh until a fully converged solution is obtained, but rarely is there sufficient time for multiple large-scale simulations. The expertise of the modeler is therefore of primary importance. Although the need for a mesh required to render the flow involves considerable effort, it is the only way (with the exception of vortex-based tlow models that still requirc a surface mesh) to obtain a spatially resolved characterization of the tluid flow. Computational times on workstations can be on the order of **a** day to a week.

The computational requirements of CFD-based fire field models make them intractable for use in probabilistic assessments of parameter studies. Thercfore, various system–specific engineering fire models have been developed that require computational times on the order of minutes instead of hours. In general, these models include empirical correlations and solve mass and energy conservation equations over large control volumes (as opposed to solving discretized equations on a mesh). Due to the challenges of solving the Navier-Stokes equations, they do not provide any detailed modeling of the flow. Since spatial resolution is not obtained, there is no difference. for example. between fire predictions for cases where the tlow enters the bottom or the top of **a** compartment. Further improvements of thcsc models are underway to capture some of these features without losing the computational advantage of a simple control volume-based approach.

METHODOLOGY FOR MODEL DEVELOPMENT AND APPLICATION

Comprehensive validated models of fire and suppression models are not presently available. One methodology for acquiring the understanding necessary to develop thcsc models, which involves using the models in their present state (to provide some immediate utility), is presented here.

The process is divided into several steps. The description of each step includes an overview of the relevant technical issues. In cases where the technical issues can not readily be addressed using existing models, concepts for model development are presented.

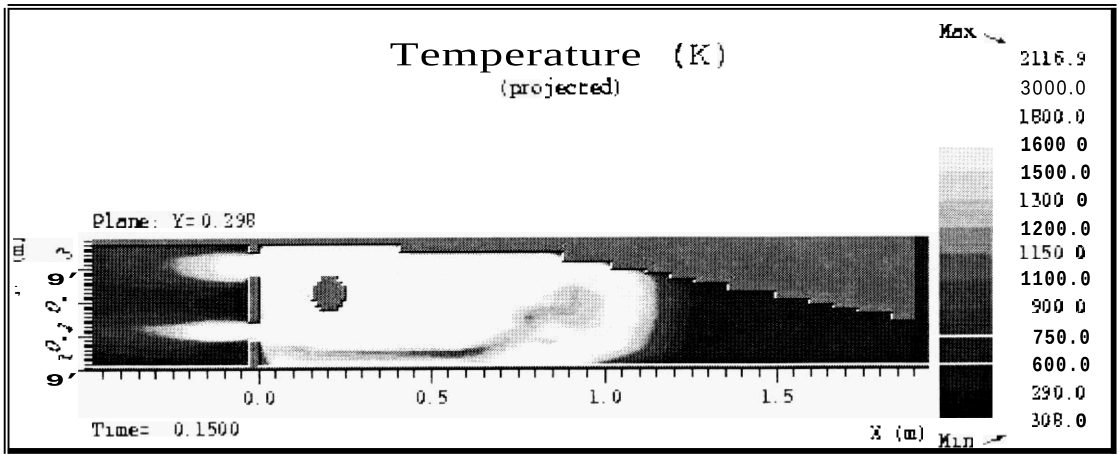
Step 1: Assess Capability and Utility of Current Models

The first step of the process outlined here is to assess the ability of present models to provide credible solutions to realistic problems. This process primarily involves the comparison of model predictions with experimental results. Present activities performed as part of the Safety and Survivability of Aircraft Initiative (SSAI), an initiative from the office of the Deputy Director, Operational Test and Evaluation/Live Fire Test and Evaluation, include two efforts to evaluate present models of fires in aircraft dry bays. The first is a comparison with well-characterized fire tests in a simple, uncluttered, 1 by 3 m rectangular compartment with a well-controlled fuel and air flow. The experimental configuration was designed using extensive pre-test calculations performed at Sandia National Labs using the VULCAN fire field model. The test series is scheduled to begin in early Fall of 1999 and will be performed at the Air Force Research Laboratory at Wright-Patterson Air Force Base. The purpose of these experiments is to understand the basic fire features in a simple geometry and perform comparisons with model predictions for a case with well-controlled boundary conditions and extensive measurements.

The second SSAI activity to assess the performance of current fire models is focused on the application of models to fire test scenarios in actual aircraft dry bays. This endeavor is designed to provide additional insight into the relevant phenomena in actual fires as well as to evaluate the practicality of applying the models to real-world scenarios. As part of this activity, calculations of three F14 dry-bay fire scenarios using the VULCAN fire field model were performed. The scenarios examined included a simple generic case, and two cases corresponding to fires in the F-14 lower dry bay for comparison with tests performed at Naval Air Warfare Center at China Lake. Inspection of the F-14 prior to the test did not yield any significant sources of ventilation air flow within the lower dry bay. Accordingly, calculations were performed for the limiting case of no venting. Observed fire phenomena during the test were not consistent with model predictions for the unvented case. Closer inspection revealed the presence of a vent between the lower dry bay and a large bay in the fore section of the aircraft. Furthermore, the damage hole was larger than expected. Subsequent calculations considering the presence of the vent. and the flow through the damage hole, were consistent with phenomena observed in the test. A cross sectional image of the results of the fire calculations, showing the propagation of the flame toward the vent on the fore end of the aircraft, is provided in Figure 1. Insight gained from reconciling model predictions and test results. as well as conclusions regarding the strong, but bounded, dependence of model calculations on specific configurations and boundary conditions, were provided as part of this joint testing and modeling activity.

Both of the above cases are expected to be Class *2* fires. That is, the compartment is sufficiently small and the inlet air momentum is sufficiently low for the flow field within the compartment (and hence the transport of a suppressant released at reasonably low pressure) to be at least affected (if not dominated) by the fire-induced flow.

Additional efforts have also been devoted to the modeling of ground vehicle crew compartment spray fires for the US Army. Calculations were performed for conditions corresponding to tests performed at the Aberdeen Test Center. These results showed very favorable agreement between model calculations of flame front propagation from an ignition source throughout the fuel-spray



Figurc 1. Cross sectional view of tlame zone in F-14 dry hay fire.

filled compartment. The fuel spray was modeled as a gaseous fuel release. In a manner consistent with this assumption. the model predicted slightly (–10%) slower rate of propagation than observed in the test video record. Efforts to compare thermocouple data with model-predicted temperatures highlighted the challenge in measuring gas/soot temperatures in spray fire environments due to suspected impingement of liquid droplets on thermocouples.

In both of the above investigations of fires in DoD compartments, the comparison of model predictions and test results raised several questions pertaining to differences in the two sets of information. The quest for answers to these questions provided considerable additional insight and an improved understanding of the relevant technical issues. Neither activity, however, provided more than a basic level of confidence in the models. More rigorous evaluation, as presented in the next section, is therefore required to gain true confidence in model results.

Step 2: Rigorous Evaluation of Ability to Model Flow Field

As most cases, and for all Class I fires. prediction of the air and/or fuel flow is critical for the successful modeling of fires and fire suppression. Aircraft engine nacelles are among the most challenging applications for characterizing the air flow. The nacelle design typically includes air flow, either via an external scoop or other vent air, for cooling purposes and to avoid the build-up of detonable fuel mixtures. In general, this "engineered" air flow has sufficient momentum to dominate the buoyancy produced by burning. The dynamics of a fire within an aircraft engine nacelle are therefore typically dominated by the features of the designed air tlow. A large number of components are located within this region, resulting in a complex, cluttered geometry that further challenges the ability to model fires.

Presently, aircraft survivability and suppression system proving tests are performed under conditions intended to replicate the nacelle air flow while the aircraft is in tlight. Test fixtures, such as the Aircraft Engine Nacelle (AEN) Facility at the Air Force Research Laboratory (AFRL) at Wright-Patterson AFB in Dayton, Ohio. have been constructed to represent the long, slender, geometries typical of aircraft nacelles. Extensive sets of experiments and live fire tests (with varying degrees of complexity in the internal geometry) have been conducted to evaluate the performance of suppression systems and strategies. These tests and experiments have provided significant insight into the essential and salient features of successful systems, and serve as the basis for present system acceptance. However. the results from these tests, particularly when fire extinguishment (as opposed to simply the presence of agent) is the focus, are often difficult to understand due to the lack a well-characterized flow field.

Due primarily to geometric complexities, efforts to characterize the flow field in engine nacelles using computational fluid dynamics (CFD) have been limited to simplified cases. Calculations performed to date include analysis performed by Hamins et al. [4] of agent transport in the extensive set of tests performed at the AEN facility for the Halon Alternatives Program [5,6]. Marginal agreement between calculational results and experimental data was obtained. In some cases, opposite trends were observed in the calculations and experimental results. Additional calculations for a smooth F18 nacelle geometry with agent release via solid propellant gas generator were performed by Lopez et al. [2]. Results from this analysis were consistent with trends observed in data from simulator tests at the Naval Air Warfare Center at China Lake. Sufficient data were not available to rigorously validate the model predictions.

Given the limited available data, and the difficulties encountered in validating model calculations for simplified cases with the same inherent features as actual nacelles, a comparison of experimental data with model calculations for a simplified nacelle geometry is currently in progress. Reduced (1/4) scale experiments (to allow access of appropriate diagnostics) of the flow from an inlet to a smooth slender annular geometry and out a single outlet, will be performed at AFRL. Although fully developed flows in annuli are well understood, the development of those flows with different inlet conditions has yet to be addressed.

Experiment design will be guided by pretest calculations, such as presented in Figure 2. Flow conditions will he Reynolds number scaled to match the extensive set of experiments performed in the AEN facility as part of the Halon Alternatives Program. Calculations will be performed and compared with experimental data at multiple cross sections within the flow field. Once confidence in the model and measurements and a confirmed understanding of the flow field have been obtained for this general class of problems, complex configurations more representative of actual aircraft nacelles will he addressed. These cases will include multiple inlets and exits and multiple gases (to evaluate agent transport and mixing).

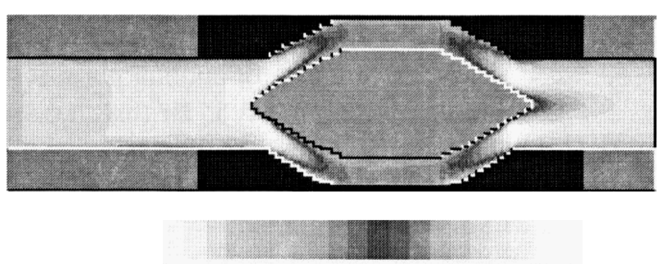


Figure 2. Sample calculation (compressed in axial direction) of flow in nacelle-type geometries.

All actual DoD compartments include significant clutter. An example of the spectrum of different sizes of this clutter for an F14 dry bay is shown in Figure ***3***. Compared to many applications, such as some engine nacelles, the compartment in Figure **3** is sparsely cluttered, e.g., large regions of open space can he observed. Even for this case, the clutter varies in size from

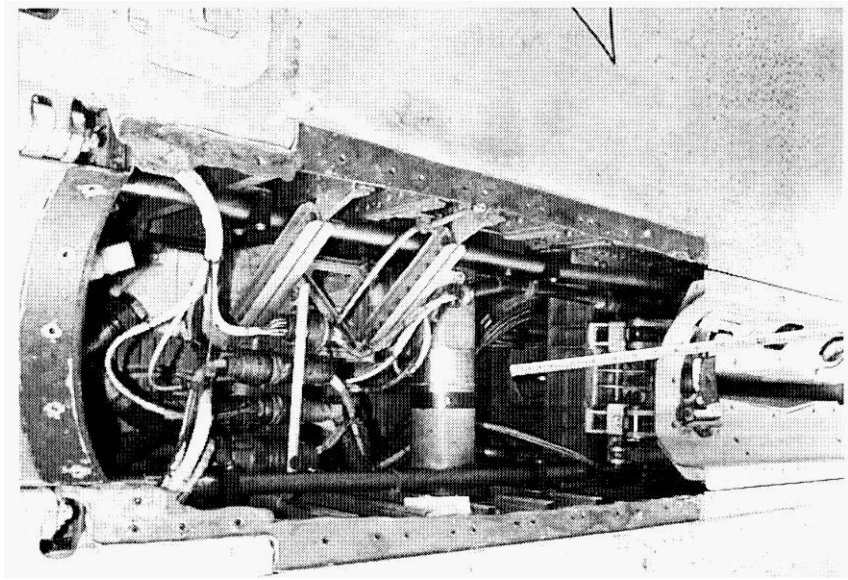


Figure 3. Sparse clutter in F14 lower dry hay.

large objects to individual and groups of small items such as wires and wire bundles. For *a* given air flow. the variation of clutter sizes results in *a* spectrum of Reynolds numbers. The combination of these interactions. including the mixing induced by the clutter and "downstream" effects. requires that the system be evaluated at full scale. These effects define the character of the fire as well as the transport and effectiveness of suppression strategies.

The ability to suppress a fire in a cluttered environment can be evaluated in terms of the ability for the agent to reach the reaction zone, and the ability of the fire to survive, given the local momentum (i.e., velocity) and scalar (i.e., temperature, concentration) fields. The enduring suppression of a fire requires that local suppression be achieved globally.

It is therefore necessary to address both the transport of the agent (including mixing) and an evaluation of local effectiveness on length scales well below the size of *a* computational mesh used to model momentum and scalar transport.

The treatment of clutter requires the development of new models. One option for the development of these models **is** presented here. In this approach, clutter is treated using separate models for ***(a)*** momentum and mixing, (b) turbulence, and (c) combustion and suppression effectiveness. Clutter consisting of objects with sizes helow the grid scale are characterized within each computational cell by an approximate void fraction (i.e., porosity or open space). a characteristic length scale of the objects (say, the diameter of the wire), and an orientation to address multi-dimensional effects. Momentum transport for clutter with length scales much smaller than the grid and sufficiently small porosity can be treated by the Darcy equations for llow in porous media. Clutter on the boundaries can he treated *as* surface roughness. or by an effective momentum restriction. It is also important to treat the effect of clutter in the region downstream, or adjacent to the object.

Experiments are required to develop and validate the models as well as the regime of applicability for each. For example, below certain limits the clutter will be too closely packed to sustain a flame. Combustion modeling is therefore not necessary in these regions, but the effect on mixing and downstream turbulence intensity needs to be considered.

In practice, the user would define computational cells with parameters to reflect the clutter parameters defined above. To keep analysis times tractable, the user would need to estimate the values of these parameters in view of the effort required to perform accurate measurement of compartment geometries.

Step 3: Evaluation/Development of Models for Condensed/Solid Phase Transport

Fires in DoD compartments often involve the transport of condensed or solid phase materials either due to the burning of fuels as a spray or the use of liquid and/or solid suppressants. Development in this arena is required for both Class 1 and Class 2 fires.

Including these liquid phase fuel/agent transport phenomena in models requires the accurate characterization of the release conditions either in terms of the state of the spray (including flux, size, and velocity distribution) or through models for the break-up of jets into droplets or dense sprays into smaller droplets. Some rudimentary versions of these models are available from the internal combustion literature and are presently being implemented in the VULCAN fire field model. Following release, droplet transport, including evaporation and droplet surface interaction, must be modeled. Among the greatest challenges is the modeling of surface combustion (i.e., the burning of fuel vapor near the droplet surface) due to the small length scales compared to the scale of the mesh.

Laboratory-scale experiments are best suited to support the development of models for small-scale phenomena (such as evaporation, surface burning, and surface interaction). The combined interaction of these phenomena. including the combined effects of liquid/solid and gas transport, must be evaluated at full scale to ensure appropriate matching of all relevant non-dimensional parameters. The presence of liquid/solid particulate matter may strongly influence the participating media radiative heat transfer field. Changes in the radiative property and temperature field will affect both particle evaporation and heat transfer from the flame zone.

Step 4: Development of Coupled Kinetics Model

Class *2* fires require modeling of the burning region due to the inherent coupling between heat release from the tire and the fire and suppressant dynamics in the compartment.

The ability to suppress a fire, given the presence of a gaseous agent in a specific region of the compartment, is driven by chemical kinetic processes. These processes are a function of the scalar field (temperature, gas concentration [including fuel. air, products, agent]), the local strain rate, and the local static pressure. Detailed chemical kinetics calculations are possible (although the reaction sets include considerable uncertainty) but not computationally tractable in the context of a combined physics calculation. Levels of conservatism (evaluated in the sense of ensuring the performance of a suppression system) can be achieved by disregarding secondary effects and modeling suppression based on laminar limits provided by cup-burner tests. The need to reduce weight requirements for agents is sufficient justification to explore the first steps in modeling these processes in a computationally efficient manner.

Models built from look-up tables to account for the influence of these parameters are currently under development [3]. The results are presently being compared with laboratory experiments [7].

CONCLUSIONS

The ability to perform practical, credible. modeling offire and suppression in DoD compartments will require significant technical development. Although the fundamental issues have been outlined here, fire phenomena are not thoroughly understood and therefore experiments for discovery (both lab- and full-scale) are needed. These experiments form the foundation for engineering models that must be developed in a manner consistent with the underlying structure of the system models. Once these models have been included, careful validation is required, both via well-controlled experiments (to validate the physics) and actual system tests (to validate applicability).

Although considerable effort is needed to obtain the end objective, many of the essential and salient features of fire and suppression in DoD compartment are captured by existing models. Comparisons of model calculations with experimental data to date illustrate the short-term utility of present models. Of the development areas identified herein, nothing appears to he intractable provided realistic expectations of accuracy and computational time are considered. Thus, practical tools for fire and suppression may he on the horizon, hut will require considerable effort to ensure appropriate development and sufficient validation.

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