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13. CONCLUSION

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13.1 Background

This report presents the results of two years of research in support of the objective to identify and make ready for use the optimal near-term fluid to replace halon 1301 for in-flight fire suppression in aircraft engine nacelles and dry bays. At the time the work presented in this report was begun, the Technology Transition Team of the sponsors, the Air Force, Army, Navy, and FAA, had selected the following candidates for consideration:

Engine Nacelle	**Dry Bay**
C_2HF_5 (HFC-125, pentafluoroethane)	C_2HF_5 (HFC-125, pentafluoroethane)
C_3HF_7 (HFC-227ea, 1,1,1,2,3,3,3-heptafluoropropane)	CF_3I (trifluoroiodomethane)
CF_3I (trifluoroiodomethane)	C_3F_8 (FC-218, octafluoropropane)

The NIST research results in Part 1 of this report were directed at helping to reduce each of these lists to a single chemical. The results in Part 2 are to assist in the development of engineering design criteria and suppressant system certification.

13.2 Knowledge to Help Select the Optimal Currently-Available Alternate Fire Suppressant

13.2.1 Fire Suppression Efficiency

Most of the laboratory-scale information was reported in Grosshandler *et al.*, (1994). From the deflagration/detonation tube results presented here, FC-218 provides the most consistent performance over the widest range of fuel/air mixtures and tube geometries. CF_3I has the greatest positive impact at low addition levels, but shows non-monotonic behavior of combustion wave speed and shock pressure at higher levels. HFC-125 produces higher peak pressures than either CF_3I or FC-218, but the more moderate conditions investigated in the current study do not yield the excessive overpressures note previously.

Also presented here are comprehensive fire suppression efficiency measurements in a turbulent spray burner. CF_3I was found to be more efficient than either HFC-125 or HFC-227ea. However, at elevated temperature of 150 °C, the three chemicals performed equally on a mass basis.

13.2.2 Stability During Storage

There should be no problems with designing long-term storage capability for any of the four agents.

- The stability of HFC-125, HFC-227ea, and FC-218 was excellent after storage for 48 weeks at 150 °C and 4.2 MPa in the presence of a range of possible metals for use in the storage bottles: Nitronic 40, Ti-15-3-3-3, C4130, and Inconel 625. In all cases, there was no noticeable loss of agent, and no new spectral features appeared in the post-exposure analyses.

- Samples of CF_3I were observed to be stable at 23 °C for 52 weeks in the presence of the same metals. However, during exposure at 100 °C and especially at 150 °C, some CO_2 and an unknown chemical appeared whose concentration increased with exposure time. Identification was by the appearance of a sharp peak at 950 cm^{-1} in the spectrum of the degraded CF_3I. The peak appeared in all of the samples, and was not significantly affected by the nature of the metals present. It did not appear when moisture or metallic copper (reputed to retard the degradation of iodides) were added to the storage atmosphere at 150 °C. Our efforts to identify the product chemical from its telltale peak have been unsuccessful. The degree of CF_3I degradation was small, even if extrapolated to a 5-year storage time. However, should this unknown chemical be toxic, its presence might be an additional reason for care in discharging CF_3I in occupied areas.

Each of the four chemicals is compatible with a choice of materials for the storage containers: elastomers, lubricants, and metals.

- The compatibility of the four candidate suppressants with organic materials potentially found in fire suppression systems was evaluated by swelling experiments. Seven elastomers and three greases were exposed to each of the agents at pressures up to 5.86 MPa and temperatures up to 105 °C. The tests measure the extent to which the agent dissolves in the material, a behavior that is undesirable if excessive. Each agent caused only relatively minor swelling in at least three of the elastomers and at most moderate swelling in the greases. HFC-125, FC-218, and CF_3I all showed only limited solubility in two of the greases.

- The long-term stability of the seven elastomers was evaluated using compression set measurements and tensile testing of o-ring materials. Exposures in CF_3I were performed to 58 weeks, and the other three agents were tested for times as long as 74 weeks. The testing temperature was 75 °C. Compression set evaluates the resistance of the elastomers to excessive permanent deformation, and the results showed that at least two elastomers are compatible with each of the candidate agents. Tensile testing was performed to evaluate the retention of mechanical strength of the elastomer. However, these results were inconclusive due to large variability in the data. The testing also showed anomalous behavior of the CF_3I, suggesting some agent degradation.

- After immersion of five types metal coupons (Nitronic 40, Ti-15-3-3-3, C4130, 304 stainless steel, and aluminum alloy 6061-T6) for 12 months at 150 °C and 5.86 MPa in each of the four candidate agents plus halon 1301, the mass changes for these alloys were relatively minor, although some slight pitting was observed, particularly on the C4130 steel. In addition, CF_3I showed some small interaction with three of the metals, none with Nitronic 40, and significant interaction with C4130. Under the same conditions at 20 °C, little or no interaction was seen except for three pairs: halon 1301 with the aluminum alloy, and CF_3I and HFC-125 with the C4130 steel.

- Slow strain rate tests of the five above agents with Nitronic 40, 304 stainless steel, and Ti-15-3-3 at 150 °C and 5.86 MPa showed no difference from metal samples immersed in inert argon. The one exception was CF_3I and the titanium alloy. Two of these three titanium samples fractured distinctively early, indicating potential incompatibility between the two. At 20 °C all the agents were similar to argon (an inert gas) in their effects on the metals.

13.2.3 Safety Following Discharge

- While accidentally-discharged CF_3I will decompose under both normal outdoor and indoor lighting, laboratory measurements and dispersion modeling show that the concentrations of potentially toxic photolysis products (HF, COF_2) are not likely to be sufficient to hinder prompt escape. HFC-125, HFC-227ea, and FC-218 are not photosensitive to normal lighting.

- The production of HF (during fire suppression) from all four of the chemicals can now be predicted. The principles for this have been verified using HF concentration data from laboratory flames and room fires. Fires in dry bays are suppressed sufficiently quickly that only small amounts will be formed regardless of which of these agents is used. For engine nacelle fires, the model developed here predicts that HFC-227ea, HFC-125 and FC-218 would produce similar amounts, while the more efficient CF_3I would produce far less. Exposure to surfaces heated by the fire would produce more HF from CF_3I than from the other three chemicals.

- Samples of aircraft materials (6061-T6 aluminum alloy, Inconel alloy 718, Inconel alloy 903, 410 stainless steel, titanium alloy Ti-8-1-1-1, titanium grade 5 alloy, Haynes alloy 188, and a 3501-6/AS4 graphite-epoxy composite) that might be located near or downstream of an engine nacelle fire were immersed in 1 % or 10 % aqueous HF and then stored at 100 % relative humidity for 30 days at 22 °C. In both cases, no significant corrosion occurred after the initial exposures to the HF.. However, actual deployments in service will contain particulates and/or other compounds that could significantly alter the corrosion behavior of these alloys.

- The excessively high overpressures previously observed when HFC-125 suppressed high speed combustion waves in a deflagration tube do not occur under conditions more typical of those observed in the live-fire dry bay tests at WPAFB. The data indicate that none of the three candidates should be eliminated from consideration based on this criterion.

13.2.4 Discharge Performance

- All four of the chemicals can be expected to discharge and disperse well from their storage and distribution systems at temperatures near 20 °C.

- Data from this report and the prior work indicate that at the lower temperatures experienced during high altitude flight or cold weather operation, CF_3I and HFC-227ea, with their high boiling points, would not distribute as uniformly as the other two chemicals.

13.2.5 Recommendation

Based on the results available in October, 1994, we recommended the selection of HFC-125 as the optimal candidate for Phase III examination for both engine nacelle and dry bay fire suppression. FC-218 is not distinctively more efficient than the other chemicals and possesses an extremely long environmental lifetime. While CF_3I is the most efficient suppressant, being virtually a drop-in replacement for halon 1301 in some tests, it is unfavorable in three aspects. First, its inhalation toxicity in cardiac sensitization testing (performed elsewhere) is such that it is not usable in occupied areas. Second, at the time the decision was to be made, the stability and materials compatibility data were inconclusive. Third, its relatively high boiling point makes it less likely to discharge and disperse well (especially around obstructions) at the low temperatures encountered when flying at high altitudes or operating in cold weather. HFC-227ea has a similar boiling point, and thus would show similar behavior. This is the principal distinguishant from HFC-125, whose boiling point is far closer to that of CF_3Br. In other respects, the two HFCs are comparable in their performance measures. The knowledge that has accrued in the final year of the project has not changed our perspective on this recommendation.

During the fall, 1994 meetings of the Technology Transition Team, these data and the results of an extensive and carefully-constructed series of real-scale live-fire tests at Wright Patterson Air Force Base were discussed. The Team recommended HFC-125 as the candidate for Phase III evaluation for both applications.

13.3 Knowledge to Assist in the Development of Engineering Design Criteria and Suppression System Certification

13.3.1 Agent Discharge Behavior

The rate at which a suppressant will emerge from its storage container depends on the thermodynamic properties of the stored fluid and any pressurizing gas as well as the initial conditions in the container. Effective design of the suppression hardware requires quantitative performance measures for these chemicals.

- The computer code PROFISSY accurately calculates binary vapor-liquid equilibria within the storage bottle. This will aid hardware designers by providing useful and reliable data on the pressure/temperature characteristics of the selected agent/nitrogen mixtures.

- Laboratory data show that the nitrogen dissolved in the stored liquid agent significantly affects the agent discharge whether in a direct release system for dry bays or a piping system for engine nacelles.

- The storage bottle discharge model developed here, which incorporates nitrogen degassing, generally predicts agent discharge times to within a factor of two, but occasionally a factor of four. The only required input for the model is the initial conditions in the vessel.

- The prediction of the detailed structure of a highly transient flashing spray is still exploratory. Some very preliminary results are reported using state-of-the-art computer codes.

- For plumbed engine nacelle systems, a new, validated model can be used to facilitate transient pipe-flow calculations for two-phase flow.

- We have developed a flow chart to organize the use of these tools into a coherent process for optimal design of a new discharge system.

13.3.2 Engine Nacelle Fire Suppression Guidance

The selection of the mass of the alternative agent to be stored on an aircraft should be based on the amount needed to quench the worst realistic fire.

- For engine nacelles with ribs and other obstructions, experiments show that under similar flow conditions, a baffle-stabilized pool fire requires higher agent concentrations and longer mixing times than a baffle-stabilized spray flame.

- As anticipated, heating the air stream increases the mass of agent need for flame extinction. The system pressure and fuel flow had no significant effect on the mass of agent needed for suppression.

A step-by-step procedure has been developed that gives guidance in determining fire suppressant concentrations and discharge times for flame extinguishment. It shows the importance of agent injection duration, air flow and velocity, agent/air mixing mode, and fire scenario. A reasonable target concentration for an agent in the fire zone is that needed to quench the most flammable fuel/air mixture, ensuring both flame suppression and preventing re-ignition.

13.3.3 Real-Time Concentration Measurement

Determination of the dispersion of the suppressant following discharge requires measurements of its concentration that are well-resolved in both time and space. We examined two instruments in order to assess their ability to perform *in situ* measurements with the ~1 ms time resolution needed for dry bay applications. Neither performed well. Both were re-designed with the following results:

- An aspirated hot-film/cold-wire probe has been shown capable of recording simultaneous temperature and agent concentration measurements with high temporal (~1 ms) and spatial (~1 mm^3) resolution. However, the film is sensitive to velocity fluctuations and the small diameter, sonic orifice is readily clogged by small particles, leaving the probe unfit for practical use in its current version. There is a reasonable probability that these limitations could be overcome with further work.

- An infrared absorption probe (DIRRACS) with an incandescent source, narrow bandpass filter, pyroelectric sensor and an optical chopper can also record simultaneous temperature and agent concentration measurements. As developed, the air/agent mixture is observed as it flows between the source and the detector, a volume which manifests as a cylinder of 2.8 cm length and 3 cm diameter. Further, in its current design, the instrument response is sensitive to the flow velocity over it. Thus, this device also requires additional engineering to reduce both the sample volume and the flow dependence.

- A review of the sensing literature shows a number of alternative approaches, but none that could be accurately adapted to this application without a significant development and testing effort. The most promising are time-resolved mass spectrometry and mid- and near-infrared absorption combined with fiber optics to provide easy access and the needed spatial resolution.

13.3.4 Certification Guidance

- The mixing time for agent entrainment behind an obstacle is different under non-fire conditions than for fire conditions. A method for using the non-fire data to approximate the fire suppression concentration has been developed.

- HFC-125 closely replicates the physical and dispersion properties of halon 1301. Thus it is an excellent simulant for hardware development and can be used to certify those engine nacelle fire suppression systems that still rely on halon 1301.

13.3.5 Interaction with Metal Fires

In laboratory experiments, none of the four alternative chemicals nor halon 1301 showed exacerbation of burning of magnesium or titanium rods. It is not explicitly known why the flare-ups observed during the introduction of halon 1301 to real metal fires were not observed here. However, it may be useful to know that in the circumstances replicated in the laboratory tests, the alternative agents did not worsen the combustion relative to that with halon 1301 present.

13.4 Concluding Remarks

This report brings to a conclusion the laboratory-scale research and screening method development in support of the portion of the Department of Defense Technology Development Plan devoted to finding the optimal current replacement for halon 1301 for suppressing in-flight fires. The recommendation by the Technology Transition Team of HFC-125 for Phase III testing for both engine nacelle and dry bay use demonstrates the present state of this field: today's commercial technology only offers suppressants that are distinctly less acceptable than halon 1301. It will remain the task of a further search already about to begin, to find replacement fire suppression capabilities that truly serve DoD needs.

This study, reported here and in Grosshandler, *et al.*, (1994), should serve as a cornerstone for the new program. There is a high degree of consistency between results from real-scale fire suppression tests conducted at the Wright Laboratory and those results presented in these reports. This will enable the methods developed here to be used with confidence on future candidate suppressants. Similarly, the methods developed for characterizing new agents, their compatibility with materials, and their delivery toward a fire should also have broad application.

Finally, it is also our hope that the rigor of these two reports will serve as a model for future reports in this field. In a search that is likely to find its successes among many blind alleys, it is important that the methods used and the data obtained be thoroughly documented as guidance for successive research efforts.

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