DETERMINING THE FEASIBILITY OF VULNERABILITY REDUCTION TECHNIQUES FOR C-130 WING DRY BAYS

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BACKGROUND

The C-130 Vulnerability Reduction Program (VRP) was established to address C-130 aircraft system vulnerability issues identified in a recently completed C-130H/J comparative vulnerability analysis. This analysis, performed by the Survivability/Vulnerability Information Analysis Center (SURVIAC), identified wing dry bay fires as the major ballistic vulnerability contributor and recommended survivability enhancement priority focus on dry bay *fire* protection. From this analysis, wing trailing edge, leading edge, engine area, and tip dry bays were shown to constitute the majority of the vulnerable area. Furthermore, it found active fire suppression to be the most promising technology to reduce this vulnerability. Therefore, investigation of fire suppression techniques in these dry bays, except for the wing tips, which are small compared to the other dry bay areas, was the focus of this C-130 VRP. C-130 VRP Phase I addressed C-130 wing dry bay vulnerability; Phase IA examined solutions for C-130 wing leading edge dry bay fire vulnerability; Phase IB addressed solutions for C-130 wing engine area dry bay fire vulnerability; and Phase IC examined solutions for C-130 wing trailing edge dry bay fire vulnerability.

OBJECTIVE

The test objective for C-130 VRP Phase I was to collect data to evaluate (replica test article) and demonstrate (production test article) the effectiveness of candidate fire extinguishing agents in extinguishing a ballistic threat-induced C-130 wing dry bay fire. Phase I evaluation and demonstration tests were conducted using pentafluoroethane (CHF_2CF_3), designated HFC-125 (Trade Name FE25), and solid propellant gas generator (SPGG) agents. The solid propellant agents consisted of an inert propellant (FS01-40) and a chemically active (PAC-3302) propellant.

To meet the test objective, it was expected that a large number of repeatable tests would need to be performed. The exclusive use of production test article assets was not practical for this approach. Production assets were not widely available and not easily repairable. Therefore, a replica test article was constructed for evaluation tests necessary to determine optimal fire extinguishing agent masses. The replica test article was designed to be robust enough to withstand a large number of tests and to provide a repeatable shotline. The subsequent use of production hardware for demonstration testing allowed for validation of the results obtained during the replica testing.

C-130 VRP Phase I was performed in the Aircraft Survivability Research Facility (ASRF) at Wright-Patterson Air Force Base (WPAFB), Ohio. Testing was conducted between August 1998 and September 1999, utilizing a replica wing section for evaluation tests and production outboard wing sections, removed from C-130H aircraft tail number 74-2063, for demonstration tests.

Test conditions were chosen based on a likely C-130 mission scenario. The chosen mission scenario simulates a C-130H aircraft in a high-speed (250 knots), low-altitude (1500 feet above ground level) egress from a drop mission. The aircraft is in straight-and-level flight with the flaps retracted, and the internal aircraft fuel load is 50%. Based on a 50% internal fuel load, the outer wing tanks are 66% full. As such, both the replica and production test articles (simulated and actual Main Tanks #1, #2, and #3, as appropriate for each test series) were filled to 66% full with JP-8 fuel for testing. The hydraulic system, bleed air system, and electrical system were powered at conditions reflective of the chosen mission scenario (temperature. pressure, flow rate, and electrical current) for several of the production demonstration tests.

The test series' Measure of Evaluation (MOE) assessed how effective the fire extinguishing agents were based upon:

- mass of agent required
- average time for each agent to extinguish a dry hay fire

The MOE was applied to each test to address the issue of fire extinguishing agent feasibility for achieving vulnerability reduction. The agent effectiveness for each test had to be quantified to meet the test objective. For each dry hay test article (replica or production) and each specific agent tested, the agent mass required to extinguish the fire was determined. An average time to extinguish a dry bay fire was also quantified. Another factor used to assess the agent effectiveness included whether or not re-ignition occurred.

TEST PROCEDURES

To apply the MOE, it was necessary to achieve a repeatable dry bay fire for each test. For this to occur, flammable fluid had to be introduced into the dry hay by the ballistic threat. The test shotlines were planned such that after penetration of the dry bay skin, the threat traversed the dry bay and penetrated an adjacent fuel tank below the fuel level line. An ignition source from the threat and sufficient oxygen were present for cornbustion to occur. These conditions were optimized to the extent possible to ensure fires were initiated on each test. A realistic threat, based on the scenario above, was used for the tests in the program. Some excursion tests with a larger threat were conducted to examine expected scaling effects.

The WINFIRE dry bay fire model was used to evaluate potential shotlines for use in this test series. The PC-based model was developed in the C-I7 Live Firc Test and Evaluation Program and subsequently enhanced under the Joint Live Fire Program for analyzing the probabilities of sustained fire in a dry hay adjacent to a fuel tank. The model was used in the C-130 VRP to help set up and modify test conditions.

WINFIRE, based on a combination of combustion physics and empirical data, is able to simulate warhead fragments and API and HEI projectiles. It also enables an analysis of spark ignition by a severed electrical wire in the dry bay. The model can be used to analyze JP-4. JP-5, and JP-8 fuels. Alternatively. it can be used to analyze MIL-H-5606 and MIL-H-83282 hydraulic fluids.

Agent-related pretest predictions for this test program were restricted to estimating the amount of agent needed to suppress an induced fire. A design equation developed during Phase III—Establishment of Design Criteria Methodologies—of the Halon Replacement Program for Aviation (HRPA) was used to predict the amount of HFC-I 25 required for the dry bays to be tested in this program. The design equation derived during the Phase III test program is presented below:

$$\text{Mass of HFC-125} = (0.4467 + 0.04376 * \text{VOL} + 0.6174 * \text{SHOT} + 0.001022 * \text{EXT})^2 \qquad (1)$$

In this equation, VOL is the total zone (dry bay) effective volume in ft^3, SHOT is the shotline angle, and EXT is the external airflow rate in knots. The parameter "SHOT" equals 1 if the dry bay/fuel tank orientation is vertical (i.e., the fuel tank is above the dry bay with the projectile entering the dry bay from below on a vertical trajectory). It is 0 if the dry bay/fuel tank orientation is horizontal (i.e., the fuel tank is behind the dry bay with the projectile entering the dry bay from the side on a horizontal trajectory). This design equation is only to be used for situations involving input variables that fall within the ranges of the data used in its development. These limits are 11 ft^3 to 55 ft^3 for VOL, vertical or horizontal for SHOT and 200 knots to 400 knots for EXT. Outside these limits, the equation can be used by selecting the closest extreme value and proportionally scaling the mass [1].

The HRPA also produced a probabilistic bracketing approach to determine the optimum fire extinguishing agent mass for use in current and future aircraft [2]. Through several iterations and improvements, the "bracketing procedure" has been executed primarily in engine nacelle testing for the HRPA Broad Methodology, HRPA Phase II Aircraft Engine Nacelle [2], and F-22 Engine Nacelle [3] programs. Although no testing had previously implemented the bracketing procedure in aircraft dry bay areas, there was opportunity in the C-130 VRP to capitalize on the direct results and lessons learned of previous engine nacelle fire extinguishing agent effectiveness testing. Thus the bracketing procedure was used for the C-130 VRP Phase I evaluation tests in which HFC-125 was the fire extinguishing agent.

Based on a computed starting agent mass of HFC-125, tests were completed for one scenario with all other parameters consistent (i.e., one threat, one velocity, one temperature, etc.). The bracketing procedure is a step-by-step process that prompts after each test, "is the fire completely out?" If the fire is not out, the mass is increased by a given amount dependent upon how many runs have been completed at the current mass thus far. If the fire is extinguished, the bracketing procedure will then ask if this mass has been tested successfully five consecutive times. Once this goal is reached, agent mass was decreased for future tests.

Tests continue until a convergence interval of less than or equal to 10% is reached. This convergence interval is computed by taking the difference between the current and new masses and dividing it by the current mass. This mass then becomes the amount of HFC-125 to be used in demonstration tests.

Primex Aerospace Corporation provided the starting fire extinguishing agent mass and procedure used to determine the final mass for SPGG technologies. Primex initially estimated a starting amount of agent based on set of sizing charts developed in-house. The sizing charts are based upon the volume of the dry bay and extensive previous live fire test experience.

Primex manufactures the SPGG units in six different sizes (105-gram, 189-gram, 210-gram, 347-gram, 420-gram, and 515-gram). The size and number of SPGG units were varied during evaluation testing to determine the actual threshold (minimum successful) amount. The sizes used were typical, but not exclusively, standard Primex production sizes. In addition, Primex staggered the timing of discharge of the agent from their units. Two discharge times typically were used when testing more than two units in a test. Based on the agent performance in the evaluation tests, Primex subsequently selected an agent configuration for demonstration testing in the production test articles. This configuration typically used an amount of agent larger than the threshold mass determined in evaluation testing.

All testing was perfomied at the 46th Test Wing's ASRF at WPAFB. Ohio. The ASRF is a live fire test site consisting of six test ranges designed to support the test and development of survivable combat systems. The C-I30 fire extinguishing agent testing was performed in upper Range **3** of the ASRF. Range 3 is one of only a few ballistic test facilities in the world with high-speed airflow capabilities — air flow up to 500 knots or greater can be achieved.

This test series focused on determining the agent mass required to extinguish a threat-induced C-130 wing dry bay fire. To meet this objective, it was necessary to minimize test variables. Therefore, mast tests utilized ***a*** computer timing systcm that discharged the agent at a predetermined delay time after the projectile impacted the test article. Delay times of 20 ms (Short Duration - SD) and 300 ms (Long Duration - LD) were used during testing.

Three steps werc required to satisfy data requirements. First, data that describe test conditions was collected. Next, data resulting from responses incurred by the test article and its surroundings during the test were collected. Finally, post-test results were derived after the test conditions and results had been collected and analyzed.

Instrumentation used in C-130 VRP Phase I replica and production testing was selected to enable an accurate characterization of the ignited fire and the effectiveness of the fire extinguishing agent. Criteria for the instrumentation (i.e., type and quantity of instrumentation devices, general location, range, and sampling rate) were chosen to ensure the test objectives were accomplished. Each test was recorded on videotape and documented with still photographs. Standard video cameras and miniature video cameras were used during each test to record fires and their reaction to the fire extinguishing agents.

DISCUSSION OF RESULTS

Each test involved a realistic aircraft configuration and environmental conditions, as well as realistic shotlines. An Armor Piercing Incendiary (API) projectile was the main threat tested. In a few cases, a High Explosive Incendiary Tracer (HEI-T) round was used. Airflow reflective of the chosen mission scenario (approximately 250 knots), which can either intensify or extinguish a fire, was utilized during this test series.

Using the bracketing procedure for HFC-125 tests in the replica test article, a final or optimum mass would be determined, which would then be selected for demonstration testing. Primex Aerospace estimated the initial SPGG agent mass and used its own in-house procedure to determine the final SPGG agent mass based on test results. Table I shows the number of valid tests and the fire extinguishing agent masses for each test series. Valid tests indicate those shots meeting the criteria established in test planning. Invalid tests were those tests where equipment malfunctions or other unforeseen circumstances failed to achieve the test program objectives.

TABLE I. SUMMARY OF TEST SERIES RESULTS – VALID TESTS.

	Replica Test Article		Production Test Article	
	# API Shots	Weight Selected (lbs)	# API Shots	Demonstrated Weight (lbs)
Wing Leading Edge				
HFC-125	28	2.16	5	2.16
SPGG*	10	0.93	4	0.93
Wing Engine Area				
HFC-125	17	2.8	2	2.8
SPGG	8	0.93	2	0.93
Wing Trailing Edge				
HFC-125	16		0	
SPGG	8	1.38	2	1.86

* Wing Leading Edge SPGG testing included FS01-40 and PAC-3302 agents.

WING LEADING EDGE RESULTS

Wing Leading Edge (WLE) fire extinguishing solutions based on HFC-125 or an SPGG active agent (PAC-3302) applied in the Outer Wing Station (OWS) 0.00 to 158.4 WLE dry hay are feasible for the shotlines and threats tested in this program. It should he noted that no attempt was made to optimize the agent distribution systems used in this program. Therefore, a direct comparison of masses among the different agents is not entirely valid. Also, the inert SPGG agent (FS01-40) was not fully evaluated in this program, since it became apparent PAC-3302 was performing better for this application.

Using the bracketing procedure, evaluation testing with HFC-125 resulted in convergence to an agent weight of 2.16 pounds. Thus, the HFC-I 25 quantity of 2.16 pounds was selected for demonstration testing. An excursion test of an API shotline through the powered bleed air duct did not extinguish the fire successfully at the 2.16 pounds mass. **A** second excursion test using 8.65 pounds, scaled upward for a larger threat, did not extinguish an HEI-initiated dry hay fire.

For evaluation tests using the replica test article and an API threat, both inert and active SPGG technologies were used. The active agent mass, which performed more effectively, achieved an SPGG threshold mass (i.e., the lowest mass that successfully extinguished a threat-induced fire) **of** 0.46 pounds (using two 105-gram units). However, Primex believed that four 105-gram units (0.93 pounds total mass) provided a higher confidence level, and the SPGG active agent at a mass of 0.93 pounds was selected for demonstration testing. In an excursion test, the four 105-gram units successfully extinguished a fire induced on an API shotline through a powered bleed air duct.

The HFC-125 demonstration testing used 2.16 pounds of agent. This amount was successful in extinguishing two of four valid API shots, but did not extinguish the fire in a test when the bleed air duct was impacted. An HFC-15 mass of8.65 pounds successfully extinguished a dry bay fire created in an excursion test using an HEI threat.

During demonstration testing, four 105-gram units (0.93 pounds) of PAC-3302 agent successfully extinguished three valid API-induced fires. A fourth API-induced fire involving the impact of a powered bleed air duct also was successfully extinguished.

The time to extinguish a fire was similar for both replica and production test articles for all agents. In general, either the agent extinguished the fire within a few tenths of a second after release or did not put it out at all. Fire-extinguished times (measured by watching internal minicam video) ranged from 0.1 sec to approximately 1.25 sec after agent release for all agents. Data for evaluation tests on the replica test article are shown in Figure 1.

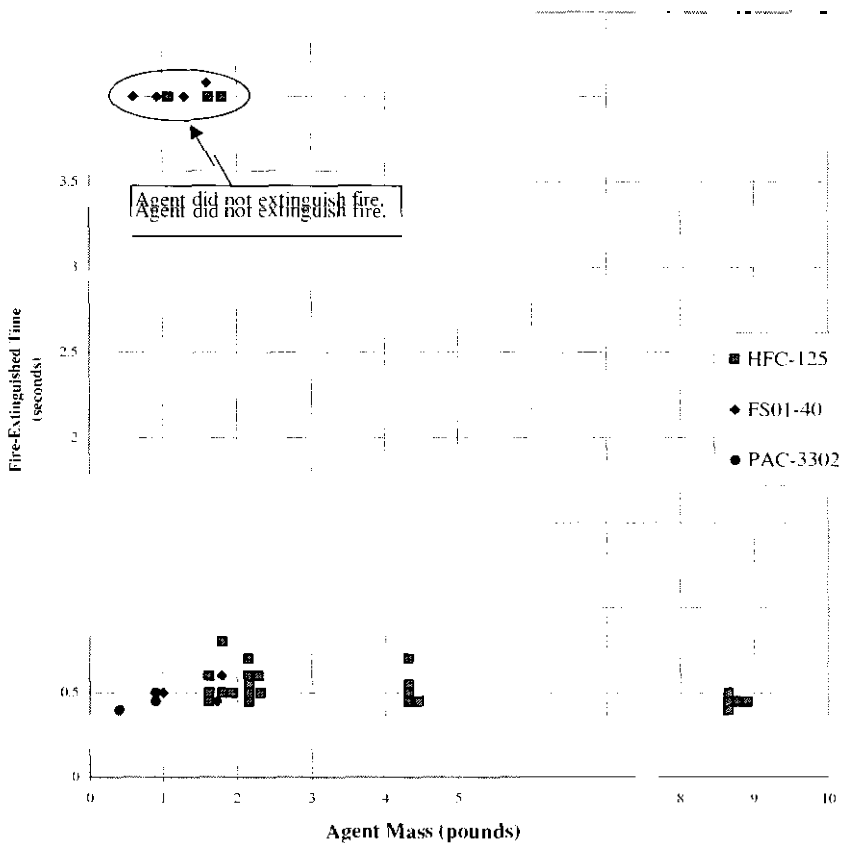

Figure 1. Phase IA evaluation tests fire-extinguishing times versus agent mass.

WING ENGINE AREA RESULTS

Wing Engine Area (WEA) dry bay fire extinguishing solutions based on HFC-125 and a SPGG active agent (PAC-3302) applied in the OWS 144.2 to OWS 214.6 WEA dry bay are feasible for the shotlines and threats tested in this program. It should be noted that no attempt was made to optimize the agent distribution systems used. Therefore, a direct comparison of masses among the different agents is not entirely valid.

For evaluation tests, the bracketing procedure resulted in selection of 2.1 pounds of HFC-125 for use in demonstration tests on the production test article, however, an error was discovered in the bracketing algorithm. Correction of this error resulted in a change of the HFC-125 weight to 2.8 pounds for demonstration testing. This quantity was successful in extinguishing an excursion test with an HEI threat-induced fire, while a similar test with 1.4 pounds was not successful.

The threshold SPGG active agent mass determined in WEA dry bay fire evaluation tests was 0.46 pounds. Based on the agent performance over all the evaluation tests, Primex selected the quantity of 0.93 pounds (420 grams) total mass (two 210-gram units) for evaluation tests since it provided a higher confidence level. The total agent mass of 0.93 pounds was successfully used on an excursion test involving an HEI threat.

The HFC-125 agent mass of 2.8 pounds was successful in extinguishing fires in two API tests with the production test article. The final HEI production test using 2.8 pounds of HFC-125 was not successful in extinguishing an HEI threat-induced fire.

Two 210-gram SPGG units (0.93 pounds) of PAC-3302 active agent were used for demonstration testing, and these were able to successfully extinguish the two API-induced fires produced with the production test article.

The time to extinguish a fire was similar for both the replica and production test articles. In each case, if the agent was successful, the fire was typically extinguished less than 1 sec after projectile penetration with typical times being close to 0.6 seconds. Extinguishing times (measured by reviewing internal minicam video) ranged from 0.6 sec to approximately 2 sec after release for all agents. Data for evaluation tests on the replica test article are shown in Figure 2.

WING TRAILING EDGE RESULTS

Wing Trailing Edge (WTE) dry bay fire extinguishing solutions based on at least a SPGG active agent (PAC-3302) applied in the OWS 0.0 to OWS 158 outboard WTE dry bay are feasible for the shotlines and threats tested in this program. It should be noted that no attempt was made to optimize the agent distribution systems used. Therefore, a direct comparison of masses among the different agents is not entirely valid.

Testing of HFC-I25 with the WTE dry bay commenced with the agent-release delay times (300 milliseconds) used in the previous phases. However, given the much greater internal dry bay airflow in the WTE dry bay compared to the other two dry bays, it became apparent the delay time for agent release was excessive. The quantity required to extinguish the fires reliably had reached 19.84 pounds using the bracketing procedure and was near the limit that the two adjustable volume fire extinguishers could hold. Thus, it was decided to return to the 0.020-sec agent release delay time used in baseline testing in the program. At this point only a limited amount of time remained to complete all WTE testing. Therefore, it was not possible to fully accomplish the bracketing procedure for HFC-125 with the 0.020-sec delay time and reach a convergent agent mass. Test results indicated the final HFC-125 mass, determined by fully employing the bracketing procedure, would probably have resolved to a mass above 4.96 pounds, but less than or equal to 7.44 pounds. Testing of HFC-125 ceased after two successful API threat tests with 7.44 pounds. Since a fully optimized mass was not determined, it was decided not to perform demonstration tests on the production test article with HFC-125.

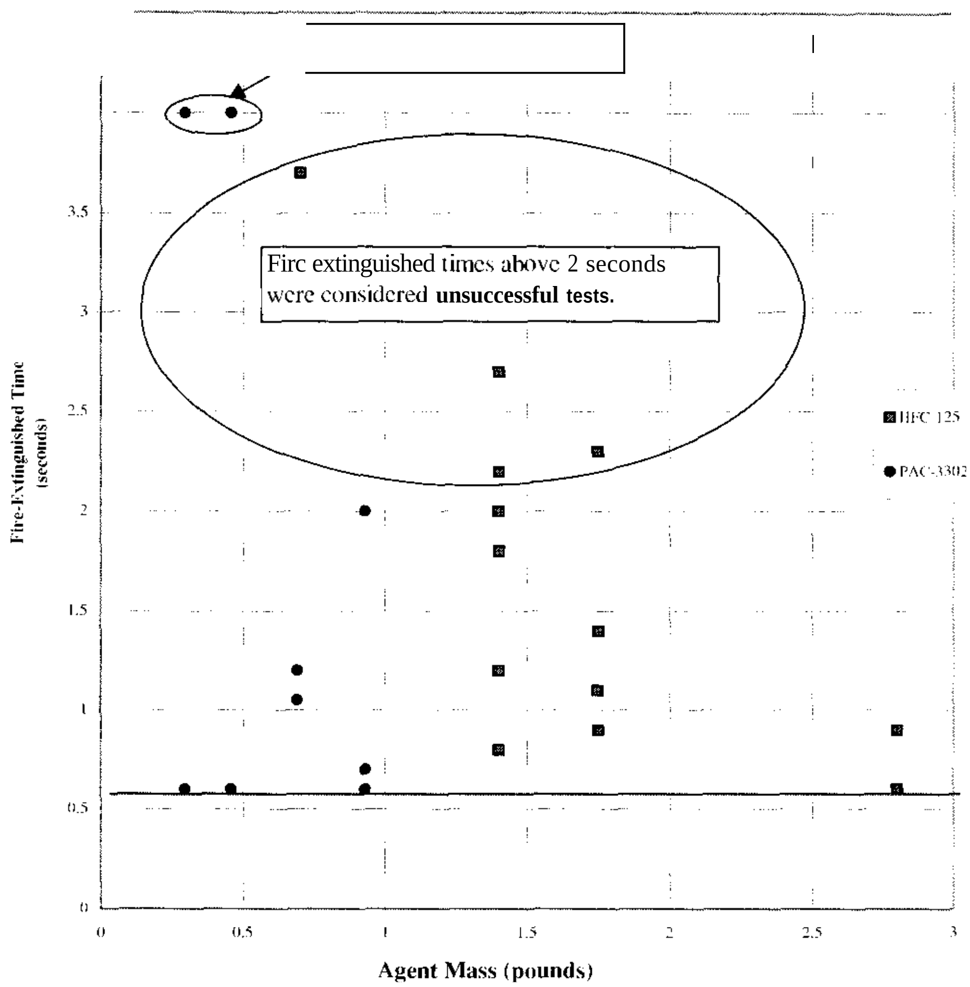

Figure 2. Phase IB evaluation tests fire-extinguishing times versus agent mass.

Evaluation tests commenced with SPGGs and an agent release time of 0.020 sec was used in these tests as for the later WTE HFC-125 tests. The threshold (lowest successful) active agent mass was 0.93 pounds (420 grams) for SPGG evaluation testing. Two variations of the 420-gram weight were successful in extinguishing the fire: the majority of the tests used four 105-gram units, and one test used two 210-gram units. Based on the overall WTE testing, Primex believed that 1.38 pounds (four 157-gram units—628 grams total mass) provided a higher confidence level and selected this quantity for subsequent demonstration tests.

For demonstration tests on the production test article, SPGG testing was accomplished by distributing the agent from four different locations. An initial test with 1.38 pounds was not successful. In a follow-on test, four 210-gram units (1.86 pounds) were used and successfully extinguished the API-induced fire. **A** final test with an HEI threat was successful in extinguishing a weak fire produced when the projectile failed to function fully.

Based on WTE dry bay replica testing, the agent release delay time was found to be an important parameter influencing the success of the agent in extinguishing a fire in the dry bay. If the fire was allowed to burn too long before agent was applied, the fire escaped the WTE dry bay through the seam between the flap and the lower WTE skin. Once the fire escaped from the dry bay, it was likely to remain an external attached fire, and no amount of agent would be successful in extinguishing it.

The time to extinguish a fire was similar in both the replica and production test articles for both of the agents tested. In general, either the agent extinguished the fire within a few tenths of a second after the release or did not extinguish the fire at all. Extinguishing times (measured by watching internal minicam video) ranged from 0.2 sec to approximately 1.0 sec after agent release for all agents. Average fire extinguishing times for shorter agent release delays were about half the times for longer agent release delays. Data for evaluation tests on the replica test article are shown in Figure 3.

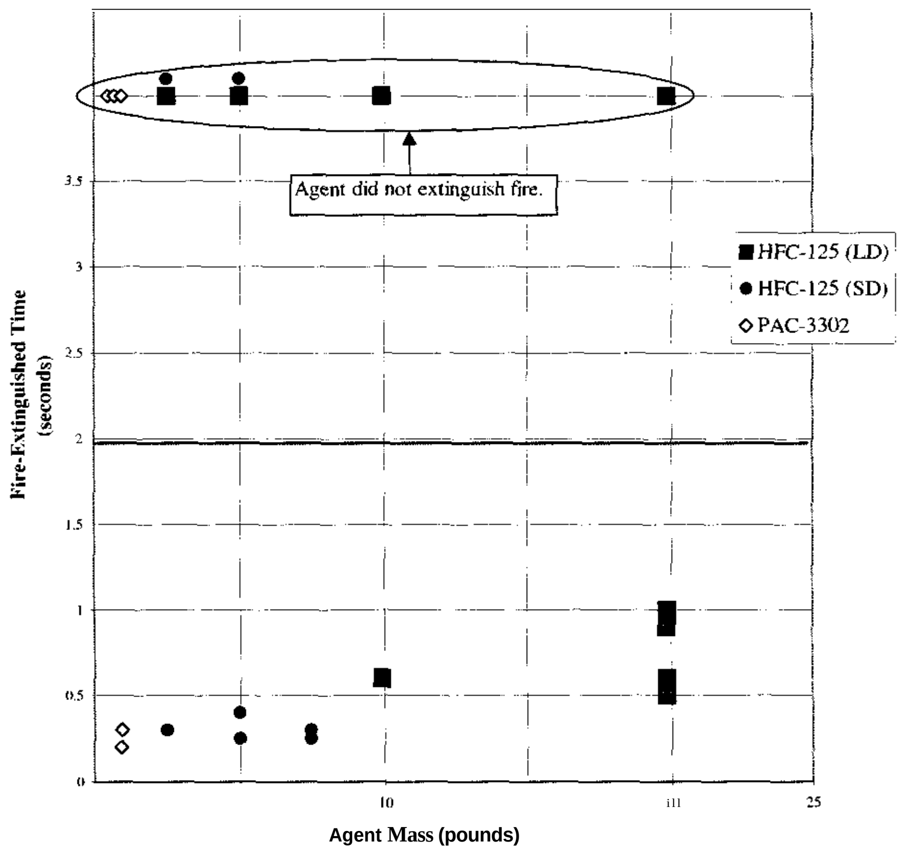

Figure **3.** Phase **IC** evaluation tests fire extinguishing times versus agent mass.

CONCLUSIONS

The primary purpose of the **C-130** VRP Phase **I** testing was to determine the feasibility of candidate fire extinguishing agents in extinguishing ballistic threat-induced fires in **C-130** dry bays. This feasibility was demonstrated. The data acquired from both evaluation and demonstration testing provides a baseline from which a production **C-130** fire suppression system could be designed, and the information developed during this test series could be used as inputs for any subsequent C-130 fire extinguishing system integration program.

If **a** system were to be designed for protection against a larger threat than the ones tested, additional internal dry bay airflow due to increased damage could be expected through lower skin damage, rear spar, or front spar damage. Introduction of additional internal airflow significantly increases the difficulty of extinguishing a threat-induced fire.

All tested fire extinguishing agents were capable of extinguishing threat-induced dry bay fires with a relatively low amount of agent. It should be noted that no attempt was made to optimize the distribution systems used in this program. Therefore, a direct comparison of masses among the different agents is not entirely valid. Because of the relatively low amount of agent required, other metrics such as total system weight, reliability. cost, maintainability, etc., may be dominant when choosing a C-130 fire extinguishing system. Some of these other fire extinguishing system metrics should be investigated in the implementation process.

One of the original measures of evaluation for this program was the time for an agent to extinguish the threat-induced fire. There did not seem to be a significant correlation between the amount (or type) of agent used and the time required to extinguish a fire. HFC-125 did, in general, demonstrate lower times-to-extinguish for higher successful HFC-125 masses. PAC SPGGs did not demonstrate as clear a trend. However, in general, testing showed that with sufficient agent mass, each agent tested extinguished the dry bay fires within approximately the same amount of time. The agent either extinguished the fire within approximately 1 sec after release or did not put it out at all.

During evaluation testing, two methods were used to determine the amount of agent to be used in the demonstration testing. The bracketing procedure was utilized to determine the optimum mass of HFC-125 required. Primex tested a variety of configurations and used their engineering judgment (in conjunction with their knowledge of past testing) to choose a configuration they believed would demonstrate 100% fire extinguishing system performance in all planned demonstration tests, while minimizing system weight and complexity (number of SPGG units) whenever possible.

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