COMPARATIVE TESTING ON FIRE EXTINGUISHING IN THE WIDE-BODY AIRCRAFT ENGINE SIMULATOR WITH OZONE-FRIENDLY PENTAFLUOROETHANE IN COMPARISON WITH HALON 2402 AND 1301

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INTRODUCTION

Aircraft fire protection research and design is a very specialized field of endeavor. Activities in this area are typically performed by a select community of fire researchers, and the preponderance of such work is performed at a few very specialized experimental and test facilities. The unique nature, characteristics and issues related to aircraft fire protection distinguish themselves from more conventional fire protection research and development pursuits. Among these are the strong emphasis upon the minimal weight and space impact to the aircraft (as is common with all aerospace systems), the requirement for rapid detection and extinguishment to prevent the immediate threat a fire directs to an intolerant airframe already taxed to maximum performance in flight, and the very specialized operating conditions present in these potential fire zones and developed during the fire. These conditions include relatively high speed air flow directed through heavily cluttered compartments, with varying air temperatures from -60 °C **up** to 150 °C, and localized hot operating components that may reach temperatures of 800 °C. These fire zones are present in aircraft in the annular region surrounding the core of the engine and encased by an outer shroud (or engine "nacelle"), other voided compartments in which a fuel source, such as fuel or hydraulic lines or a fuel reservoir is present (as well as potential ignition sources), and within the fuel system itself under differing conditions. Extinguishing systems that are required in operate in such applications must feature reliable, rapid detection in the fire zone, remote activation of a stored, pressurized container(s) of extinguishant which is then rapidly (within one second, in most cases) transported via plumbing to the fire zone, and total dispersion within the cluttered fire zone instantaneously to assure a fire is quickly extinguished before the extinguishant is diluted by the ventilation airflow and is transported out of the fire zone. Such extinguishants must disperse (or "total flood) under adverse cold temperature conditions (typically requiring gasification of the extinguishant or sophisticated distribution networks) and mix with the airflow to penetrate stabilized fire reaction zones and disrupt the sustained fire in a few seconds before the extinguishant supply is exhausted.

These special conditions and performance has to be well understood by fire researchers and system designers to accommodate these phenomena in analysis and bench scale experiments. Special facilities have been built to recreate these conditions in full scale dimensions to incorporate the synergism of these parameters and to perform full-scale verification. These facilities feature large airflow capabilities (with temperature and pressure conditioning), hot operating surface simulations, and realistic fuel release rates and conditioning, as well as ballistic projectile initiation for military applications in some cases. Such facilities include the Aircraft Engine Nacelle Test Facility (AENTF) and Aircraft Survivability Test Facility (ASRF) at Wright-Patterson Air Force Base, the HIVAS Facility at the U.S. Naval Weapons Center, and engine and cargo bay fire test facilities at the U.S. Federal Aviation Administration Technical Center. Other substantial development and research activities have been underway for decades by both British government and industry institutions in the field. Recently, the search for new replacements for Halon fire extinguishants has involved development work from countries such as Sweden, Norway, Italy, Canada and Israel, to name several. The other traditional aviation design "powerhouse," the Soviet Union, had not participated historically with the Western community in the development of such capabilities and in the sharing of data and design concepts. In years past it has often been debated in the Western aviation community as to what capabilities and knowledge existed in the Warsaw Pact countries in the field of aviation fire protection, since the sophistication of their other aviation designs and accomplishments were obvious. The recent end of the Cold War and the emergence of Russia is an independent entity has opened new avenues for communication, cooperation and lessons learned in this field. In August of 1993 Mr. Michael Bennett of the U.S. ***Air*** Force participated in the First International Conference on Aircraft Fire Safety, sponsored by the Advisory Group for Aviation Research and Development (AGARD), which is associated with the North Atlantic Treaty Organization **(NATO).** The meeting was hosted by the Central Aerohydrodynamic Institute (TsAGI) in the greater Moscow, Russia area. Mr. Bennett presented a paper on the search internationally for Halon substitutes for aviation fire protection, and research underway at his organization in Wright Laboratory at Wright-Patterson Air Force Base. While at the meeting Mr. Bennett discussed relevant issues in this area with Russian aviation design specialists. In these discussions Mr. Bennett became aware of a nearby facility that was purported to conduct full-scale aviation fire experiments similar to those at facilities in the United States. Through hasty arrangements Mr. Bennett was soon able to visit this site at the Zvesda Design Bureau, and meet the director of fire research, Dr. Alexander Klimenko. The airflow facilities were found to be very similar to those in the United States and resembled a hybrid of the facilities mentioned earlier. Prominent Russian aircraft were present for testing, much like the Air Force aircraft tested at the Wright Laboratory facilities. In discussions between Mr. Bennett and Dr. Klimenko, it was found that many observations and design techniques (including the consideration of various concepts such as solid propellant gas generators) were common between the two communities, although no prior contact or data transfer had been made, but in many cases very different system design and experimental philosophies existed. In particular, the distribution system configurations, extinguishant types and charge pressures, procedures **for** initiating the systems during emergencies and techniques used to simulate the different fire events in the laboratory are examples of areas where the two philosophies were very different. The merits of using fire extinguishing systems on single engine aircraft were debated, as well as the potential of new **fire** protection concepts. It was agreed, however, that much progress could be made in furthering knowledge and capability in the field if Mr. Bennett and Dr. Klimenko, and the two communities in general, could continue to communicate and exchange ideas during this remarkable opportunity in history to do so. Subsequent visits occurred and the interchange was kept intact for the next few years.

The most recent visit on-site at Zvesda Design Bureau (in April 1995) resulted in discussions regarding the pursuit of a formal research activity that would benefit from the expertise and facilities of both parties. The Air Force research team was at the time completing experiments at their full-scale engine nacelle fire facilities and developing design formulas to be used in sizing aircraft engine fire protection systems with the new non-ozone depleting extinguishant HFC-125. An innovative statistical experimental design process was used by the Air Force to require the minimal amount of experiments (and expense) in developing a design methodology that could be applied to the wide breadth of operating conditions. Such experimental conditions that were simulated were required to he relevant to helicopters, transport aircraft, fighters and bombers, as operated by the U.S. Air Force, Army and Navy, and commercial aircraft in support of the U.S. Federal Aviation Administration. This new process was used in concert with a new reconfigurable nacelle simulator design; thus the applicability of the results obtained to other experimental techniques and the variety of actual aircraft fire zones was uncertain, although every attempt was made to produce data that was realistic for as many **fire** scenarios and conditions as possible. Since the stakes were high to have a reliable design methodology (as the new extinguishing systems would be designed and fielded directly from this limited data set), it was desirable to have this data confirmed or adjusted by verification experiments on another realistic hut distinctively different engine nacelle experimental configuration and facility. The Zvesda facility at the time offered the only capability to generate such comparative data. In addition, the Air Force experimental configuration, while broad in variability, was limited in outer nacelle diameter to about 1.3 meters, which is sufficient for full scale simulation of all aircraft engine nacelles with the exception of large transport and commercial aircraft engines. While it was generally assumed that such results could be reliably extrapolated to the larger aircraft (particularly since the design output was scaleable by volume), there was no way previously to confirm such an assumption to assure that the increased surface area of the larger engines would not have some type of detrimental effect or have non-linearities when the boundary conditions of the statistical experimental design were exceeded. Another intriguing observation from the visits that merited further study was that the Russians used the high-boiling point Halon 2402 matched with a somewhat intricate plumbing system, released as a mist via small discharge orifices located along the plumbing and originating from a very high pressure storage bottle. Earlier Air Force designs had used the "high-boilers" Halon 1011 and 1202 with such systems (although at much lower pressures), hut these had been eclipsed for new designs in favor of the low boiling, superior total flooding Halon 1301, with a simple single (or dual) discharge orifice. This first opportunity to compare the merits of such different designs was a tempting prospect.

For the reasons just cited, an historic arrangement between both organizations was subsequently made over the intervening months to accomplish the following tasks: (1) to facilitate an internal verification of the engine nacelle fire protection design tools developed by the United States, experiments would he performed by an "outside" organization with a comparable but distinctively different simulation capability and approach, (2) the effects of a larger, more realistic engine nacelle on the final design recommendations would be assessed as they pertain to commercial and transport aircraft, and **(3)** to assess the diverse design philosophies and techniques between the Russian and American aircraft fire protection communities to observe any lessons or opportunities for improvement or exploitation by one or both parties. The Russian test fixture, an actual Tupolev *204* engine (with roughly twice the diameter of the *Air* Force simulator), was placed in an outdoor airflow facility that generated inflight airflow conditions via upstream operating jet engines and channeled the flow directly into the nacelle inlets. The experimental set-up and protocol, while similar in concept sufficiently to compare with data from the *Air* Force, had several novel features and techniques which were of interest to the **Air** Force for further study. A generally wide variety of conditions, fire locations, fuel types and extinguisher system configurations were studied. The effort was initiated in March 1996 via a contract through the Air Force European Office of Aerospace Research and Development, and experimentation was completed and a final report delivered by Zvesda in November 1996, completing the terms of the contract.

The results of the research project were surprising to both the Russians and their American counterparts, in terms of the performance of the **FE-25** fire extinguishant and the comparative results of the American and Russian-type systems and their ramifications. The US. *Air* Force was very pleased with the performance of the Russian researchers and the quality of the experimental work. This is particularly notable considering the substantial obstacles that were necessary to be overcome in initiating the work itself between the two military establishments and enduring the legal reviews that were required. The results, which are discussed in this paper, reveal several opportunities for exploitation that can pay off in better performing environmentally acceptable fire extinguishing systems for both communities. It is intended that the Air Force will seek opportunities for future collaborative efforts as circumstances permit. Most of all, the technical interchange and flow of ideas and experiences between the two parties was a very rewarding facet of the effort. The author would like to express particular gratitude to Dr. Klimenko of Zvesda Design Bureau for his hospitality on-site, his liberal sharing of knowledge and experience from his over forty years of aircraft fire investigations, and his diligence in executing the experimental work under significantly challenging conditions.

Date: 4/4/97 9:41:37 AM
From: Yru N. Batalov <npstarQnpstar.msk.su>
Subject:

Dear Mike,

Please, find below the text part of our joint paper. The tables and pictures will be sent to you by fax on Monday. Please, urgently send us your fax number since we could not contact you by fax.

Best regards,
Olga

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1. INTRODUCTION

The experience of real fire fighting shows that fire origin and development depend on a series of causes, and each cause lend special character to a process development. Aviation hardware failure or breakage as a rule becomes a cause fire, and that results in joining three factors: air (oxidizer), fuel and source of ignition, in the same time and material space.

Further development of the fire depends on both external conditions (speed, flight altitude and etc.) and conditions brought on with peculiarities of a protected object. With such variety of factors determining the character of fire origin and development, it is hardly possible to make definition of real aircraft fire.

Consideration of possible fires shall include the following physical parameters: the engine nacelle volume, its cross-section area and form, fuel type and its flow rate during a fire, air flow speed, temperature of air, fuel and structural elements, various hindrances contributing to **flame** stabilization and preventing even distribution of a fire extinguishing agent, and finally, dynamics of changes of all conditions in the process of fire development.

Such multy-factor nature of the phenomena, which brings about the process of fire origin and development as well as makes it impossible to simulate fire in the airborne aircraft, calls for development of special approaches to physical modelling of the process which will allow **for** repeated simulation of the same conditions of the fire course and influence of fire extinguishing means on it in order to evaluate efficiency of fire extinguishing means and, particularly, halon alternatives.

"Minimum Performance Standards for Aircraft Engine and APU Compartment Fire Extinguishing Agent/Systems" developed by the International Halon Replacement Working Group allow for full and authentic simulation of real fire conditions in the engine. The appeal of selected test methods and test facilities, which make it possible to repeat the experiments in the set conditions many times, lies in completeness of their logic.

But, since this method is only a model of real fire, it cannot give an objective picture especially for f i e suppression in big engines such as those of Boeing **777** if the methods of gas dynamics and hydraulic similarity are not observed. Moreover, artificial and conventional character of the test facility does not make it possible to evaluate the effect of structure changes due to high temperatures on dynamics of fire development.

Simulation of flame and its suppression is an integral part of our research process: Bunsen burner of 10 mm diameter, vertical tube of 50 mm diameter, flat-flame burner of 150 mm diameter and simulation facility of 500 mm diameter.

More than 40-year experience in testing enabled the Russian specialists to develop the method to evaluate efficiency of fire extinguishing systems (FES) in reproduced (not modelled) conditions of real fire in flying vehicles because only in such a case, maximum reliability of results is achieved.

"Research, Development and Production Enterprise Zvezda" Joint-stock Company has wind tonnels which blow on a real aircraft or special test facility with the air flow rate of 500 km/in (see Fig.1). In these conditions, besides the engine compartment ventilation conditions, its temperature conditions and etc., we also reproduced external blow which makes it possible to conclude both about FES efficiency and structural means (leak-tightness) of cowling protection against fire, flame break through the air intakes and etc. Moreover, running of such tests onground under higher density of air and lower velocities of air blowing through undercowling space made these tests robust.

All former USSR aircraft and most of the Russian Federation aircraft have undergone such testing.

Totally about 100 aircraft and helicopters were tested, i.e. more than 5000 full-scale fires were organized under conditions which, as it was said above, practically reproduced the real ones. These efforts resulted in the methods for FES certification according to requirements of military and civil customers [1]. The data obtained **also** allowed the designers to minimize FES weight parameters and meet reliability and effectiveness requirements [2].

Those who worked out a joint test program for FE-25 (C_2HF_5), one of halon alternatives, found it tempting to run testing according to an agreed program at the RD&PE Zvezda's test facilities, the more so, that great inormativity and high objectivity of the full-scale fire tests with proven test procedures held out a hope that the whole effort cost would not exceed reasonable expenditures of the parties and will be adequate to the results obtained.

The FE-25 agent was considered as an alternative to ozone depleting bromhydrocarbons because ozone depleting potential (ODP) of bromhydrocarbons used in aviation is 3-16 and that of FE-25 agent is 0. The FE-25 agent seems to be the most preferable among other potential alternatives because its boiling point (-48.5 deg.C) is the closest to Halon 1301 boiling point (-57.5 deg.C). Halon 1301 is the major fire extinguishing agent used in the fire extinguishing systems of US aircraft, both military and civil [3]. Boiling points proximity defines high convergence between thermodynamic characteristics of FE-25 and Halon 1301. Therefore, even if FE-25 will not be selected as the fire extinguishing agent for aircraft onboard FES, it can be successfully used as a simulator for cold hydraulic tests, tests to measure concentrations in the compartments, i.e. for running the whole complex of aircraft FES qualification tests [4]. During this tests, the extinguishing chemical compounds are ejected into the Earth atmosphere in great quantities.

2. TESTING OF THE FIRE EXTINGUISHING SYSTEMS

2.1. Test Methodology

A power unit with an engine simulator was selected for the FE-25 comparative test program. The engine includes all components and structural elements which effect on the fire propagation and extinguishing process.

The power unit (PU) was assembled on the flight pylon and attached to the aircraft wing mock-up. The whole test facility was assembled on the frame support which made it possible to transport the facility and locate it in the required position in front of the aerodynamic facility (ADF) nozzle.

Figure 1 shows geometric parameters of the PU test facility and ADF nozzle portion.

The PU test facility was equipped with a flight FES which had undergone qualification testing with Halon 2402 ($C_2F_4Br_2$), and an emergency FES which had two phases of 3...4-fold Halon resource (each).

A remote control panel was used to control all the test facility systems and monitor the FES operation.

There was a certain difficulty in running the FE-25/Halon 2402 comparative tests caused by the fact that Halon 2402 boiling point is much higher than that of FE-25. However, the proven flight system for Halon 2402 distribution in the nacelle and the FE-25 distribution system made according to the same recommendations provided for almost similar agents supply rate.

The conditions for organization of a robust fire were selected, tested and registered basing on the analysis of the results obtained in the previous tests at this test facility and in accordance with recommendations made in the Russian normative documents [1]. To organize a robust **fii,** the TC-1 aviation fuel, the **MK-8** oil or the AMg-10 hydraulic liquid were supplied to the fire zone with operating parameters, concerning pressure and temperature, in quantities providing for the air excess coefficient of 0.6 **(70...**100 g/s).

The fires were run in accordance with the following time schedule.

0	3 s	13 s	23 s
Fuel supply actuation	Igniter actuation	FES actuation	Fuel supply switch off

Except for some details, this time schedule is consistent with the recommendations of the International Halon Replacement Working Group. The fire duration of 10 seconds prior to FES actuation was selected by **us** on the basis **of** the recommendations on fire extinguishing for crewmembers [6]. Besides, in order to provide smooth change of the fuel-air concentration in the compartment, the fuel supply was switched on smoothly that, to our opinion, assured fire suppression reliability.

The jointly worked out test methods included definition of the FE-25 minimum quantity for fire extinguishing in three typical zones of the compartment:
Zone 1 with air flowing through the compartment with maximum velocity - V max;
Zone 2 with air flowing through the compartment with minimum velocity - V min;
Zone 3 with average parameters of the air flow through the compartment, i.e. a fire shall be organized practically in the whole nacelle - V aver.

The specific places for fuel supply in order to organize fire were selected on the basis of previous (qualification) tests, since in the process of more than 150 test run, we managed to specify the fuel flow rate and supply direction which provided for the robust fire.

The typical fires selected in such a way were registered, and further their identity was controlled with thermocouples and other measuring instruments.

Totally there were planned 50 demonstrative (in the pass/fail sense) experiments. But in the process of program running, we had "overmasting" desire to perform some comparative tests with Halon 1301. Thus, we run more than **60** full-scale fire tests including 5 adjustment tests. Due to program time and scope limits and in order to satisfy expansion of fire types (variation of fuel supply zones and fuel types: aviation kerosine, oil and hydraulic liquid, usage of Halon **2402** and 1301 for comparative testing and the **US** and Russian systems to supply the agents into the compartment), the authors of the project had to confine themselves only to 3 positive results for definition of the efficiency limits.

We believe that this formal deviation from the FAA recommendations (4 extinguished fires out of 5) effected the results reliability in no way. For fire extinguishing, we used the Russian FES featuring the perforated circular tubing (95 holes of 1.5 mm diameter) and the **US** FES featuring two atomizer modules each having 3 holes (10, 5.5 and 10 mm diameters). To eject the fire extinguishing agent, we used flight spherical and cylindrical fire extinguishers with the pyroheads developed by RD&PE Zvezda. For the fire extinguishers, we selected the coefficient of volumetric filling - 0.65, the charge pressure at the room temperature - 75 kgf/cm2 for FE-25 and Halon 1301, and 100 kgf/cm2 for Halon 2402. With equilibrium solution at room temperature [5], such norms of charging make it possible not to exceed the fire extinguisher operating pressure of 150 kgf/cm2 at maximum point (80 deg.C) of the fire extinguisher operating temperature range, and not to drop below 30...40 kgf/cm2 at the minimum temperature of -60 deg.C, that is rather effective for long pipe lines.

2.2 Test Results

The results of the fire tests are given in Table 1. Column 7 gives fire extinguishers' capacity at the efficiency level for this test run, and column 9 gives the corresponding masses of the agent.

In test runs 6 through 8, fire extinguishment at the limit was achieved with 8 liter bottles charged as 7-liter bottles (such size does not exist). Comparing test runs #0, 1 and 12 where the TC-1 fuel fires organized in the same ones were extinguished, one can observe the advantage of gaseous agents over the liquid one under conditions of a short pipe line used in these tests.

Evaluation of FES efficiency will be more objective if we give the laboratory data on the extinguishing capacity on the heated vertical glass tube where pre-mixed mixture of the TC-1 fuel, air and agent was fired with a torch [7].

Table 2

Agent	Volume % concentration of the agent in the peak of combustion (reduced to 20 deg.C	Volume % concentration of TC-1 in the peak of combustion	Weight concentration of the agent, g/l (reduced to 760 mm Hg)
Halon 2402	2.5	2.8	0.27
Halon 1301	4.2	2.8	0.26
FE-25	7.25	2.8	0.365

These values differ from the results obtained at a cup burner with n-heptane fuel, but they are more accurate in reflecting the case with real aviation fuel.

But even in these tests for a fire extinguished with Halon 2402 in **a** 2-liter fire extinguisher, we needed a 3-liter fire extinguisher to suppress the fire with FE-25.

Low fire extinguishing capacity FE-25 was partially compensated by its even distribution in the compartment and filling of the "shadowed" areas of the compartment. Comparing FE-25 and

Halon 1301 (test runs #6 and 12) which are close in their physical properties, it is obvious that for FE-25 we need a fire extinguisher 3.5 times bigger than that for Halon 1301 (owing to higher efficiency, high density and lower boiling point of Halon 1301). Comparing the results of the tests with different agent distribution systems shows that "atomiz" system does not provide sufficient FE-25 distribution in the compartment, and, as a result, has lower efficiency if compared to the "perfor" system.

3. DETERMINATION OF ACID PRODUCTS OF FE-25 AND HALON 1301 DECOMPOSITION

Owing to its ODP=0, pentafluoroethane (FE-25) like as other fluorocarbons (FC) and hydrofluorocarbons (HFC) is recommended as ecologically sound Halon alternative by the Montreal Protocol Technical Committee on Halons [8]. But it is known that FC and HFC at high temperatures can decompose "thermally and evolve high toxic by-products, mainly fluorohydrogen. Therefore, testing of FES for aircraft engine nacelle with the use of FE-25 can lead to the environments pollution. Investigation of the FE-25 decomposition products was performed in various large-scale tests **[9,** 10], but in this test program we took an opportunity to determine acid products of decomposition in real fire tests of the wide-body aircraft power plant.

3.1 Methods for Determination of Acid Products

It is important to emphasize that among various decomposition products HF is the most convenient analytical object since in a water solution it forms a medium-strength acid ($Ka=6.8 \times 10^{-4}$) which desiccates totally at concentration below 0.0001 mole/l. Then the acid content can be registered by two factors: H+ -ions activity measured with a glass electrode, and F- -ions activity measured with fluoroselective electrode. **As** the concentration increases, the acid dissociation level decreases, therefore, the activity of the a.m. ions does not represent its concentration. In this case, it is necessary to preliminary neutralize the acid, then only F- -ions activity can be used as a measure of acid concentration.

Another analytical side effect can be observed during chemical interaction between HF and the metal surface of the sampler in presence of water with forming of simple and complex fluorides. Therefore, prior to measuring F- -ions activity, it is necessary to break down this complexes, e.g., by precipitation of metal hydroxides in ammonia medium.

The extent of Halon 1301 thermal decomposition was evaluated by the content of HBr and HF which were defined by the method of Br- -ion potentiometric titration with silver nitrate, and the content F-ions was defined with fluoroselective electrode.

In order to sample gas, ***6*** samplers were attached to the engine cowling in the points of gas exit (gills and joints) from the undercowling space (see Fig. 1). **Four** samplers (Sl-S4) were located on the starboard, one sampler (S5) - on the top and one sampler (S6) on the portboard (it is not seen in the figure). The samplers are one liter cylindrical vessels made of stainless steel with remotely controlled solenoid valves. **A** short line of stainless steel was connected to each sampler. The end of the line was directed to a place of gas exit, forward to incoming flow. The "dead" volume of the sampling line did not exceed 0.5% of the sampler volume. Prior to sampling, the sampler washed in distilled water, dried under the temperature of 120...180 deg.C during hour and evacuated down to residual pressure of 1 mm Hg.

The measurements showed that it took not more than 1.5 s to fill the sampler with a gas sample after opening of the solenoid valve. The fire suppression is completed in about the same time period. Every time the valve opening signal was sent in a second after agent supply since the concentrator of the decomposition products decreased by an order of magnitude in **3** seconds (see test #41).

Upon completion of the experiment, the samplers were taken off, the valves were removed, and 20 ml of distilled water were introduced into the inner space. During 1 minute, the samplers were intensively shaken so that the acids were fully dissolved in water; 10 ml of the solution was taken and pH of the solution was measured with the i-120.2 ionometer. Then the glass electrode was change with the fluoroselective one, and ammonia hydroxide was added by drops to the solution till we had stable values of potential. We used the calibration chart to mark F- -ion concentration in the solution and further calculated HF content in the gas sample (in mg/m3). **We** evaluated the level of thermal decomposition taking into account the total mass of the agent, volume of the air flowing over the engine during fire suppression and average molar concentration of HF.

3.2. Results of the Analyses

Table 3 shows major initial and calculated parameters for some of the experiments on the engine fire extinguishing with the use of the Russian and US systems to supply the agent (FE-25). The analysis of these data leads to the following conclusions.

With thermal action under conditions of open flame we observed noticeable FE-25 decomposition with forming of HF (sampling points from 1 to 4). The content of HF was negligible or was nor registered at all in the top portion and portboard of the engine undercowling space (S5 and S6) where the fire was not intensive.

Maximum HF concentration reached 80000 mg/cm3 in some points such quantity can pollute with fluorides the air space in the area exceeding 10000 m2 with air layer altitude about 5 m (according to the norms accepted in Russia, maximum allowable concentration of HF in the working zone air is 0.5 mg/m3). When FE-25 was supplied with the US type FES, acid products of decomposition are formed 1.5-2 times as much.

The extent of FE-25 thermal decomposition ranges from a few hundredth of percent to a few unities of percent; moreover, this parameter hardly depends on the total mass of the agent, but it greatly increases under conditions of unextinguished fire. There is a simple explanation of this effect: the time of thermal effect on the agent increases under unextinguished fire conditions.

Halon 1301 extinguishes the fire quicker and with a smaller quantity if compared to **FE-25** that corresponds to his lower extent of thermal decomposition it should be noted that under conditions of full-scale tests, it is rather difficult to obtain rigorous quantitative data of **FE-25** thermal decomposition due to effect of many quick-changing parameters, such **as** average HF concentration in the air flow, extent of decomposition products delusion, agent share in the high temperature zone, moment of gas sampling and etc. The given agent decomposition extent has considerably speed in values which ranges from **0.5** to 1.0% for tests with unextinguished fire and from 0.07 to **0.2%** for tests with extinguished fire. But in any case, we can state that quantity of acid products of **FE-25** decomposition during engine fire extinguishing is much greater than in case of Halon 1301 usage.

4. CONCLUSION

The test results show the following:

The presented test methodology provides for a rather full and quick answer about **FES** and alternative agents efficiency.

Pentafluoroethane **(FE-25)** has both advantages and disadvantages. Therefore, it is necessary to continue search for efficient and ecologically sound Halon alternatives.

Acknowledgment

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CONCLUSION

For the configuration and operating conditions of the experimental engine fire simulator at Zvesda, the design model developed by the U.S. Air Force predicts a required quantity of HFC125 at 2.0 kilograms under worst case conditions. This mass requirement estimate assumes an optimal distribution of extinguishant in the fire zone. The fire experiment results at the Zvesda facility revealed a requirement of between 1.46 and 2.2 kilograms of HFC-125 under worst case conditions, using the Russian distribution network. A more refined estimate between these two extremes could not determined due to the limited number of experiments permitted. This result supports the viability of the U.S. Air Force design model by demonstrating its accuracy in predicting behavior and requirements in a simulator vastly different in configuration from that used by the U.S. **Air** Force in deriving the model. This also suggests that the model will be practical to **use** in designing fire extinguishing systems for other actual aircraft engines, as it was intended to do. The design model specifies a required HFC-125 concentration for a given application as the key certification standard; unfortunately, this quantity could not be measured during this program to verify the localized concentrations measured under extinguishment conditions. The American system configuration, in contrast, performed much more poorly than its Russian counterpart, which was reflected in the larger quantities required for its **use.** This increased requirement over the Air Force design model can be attributed to the reduction in distribution efficiency of the single point discharge design, which is a far departure from the optimized distribution that must be assumed by the design model.

The American-style system required between 3.6 and 5.1 kilograms for extinguishment. Even with the excellent distribution characteristics of HFC-125, it is seen that the networked distribution system employed by the Russians can increase the performance dramatically -reducing extinguishant quantities even up to 6.4 Ibs. in some cases. Prior wisdom in the U.S. design community was that the increased weight of a more complex distribution network would offset the benefits of extinguishant mass reduction, but with the need for larger extinguishant quantities and systems for the Halon substitutes, such thinking must be re-evaluated.

The most surprising finding was that, with Russian system employed, the performance of HFC-125 matched the performance of Halon 2402 (which actually surpasses that of Halon 1301 comparatively), using the Russian test protocol. It is not understood as to what to attribute this performance parity, and more in-depth experiments might reveal discrimination in their performance. It could be that the networked system with the superior distribution characteristics of HFC-125 over Halon 2402 can overcome the fundamental efficiency differences between the two. This result may bode well for existing U.S. Air Force aircraft that already use similar networked distribution systems in concert with Halons 1011 or 1202 concerning the potential of using HFC-125 as a drop-in replacement for Halon in their systems, and should be explored further.

Much was learned by the American participants and sponsors regarding Russian design philosophies and experimental techniques in aircraft fire protection for the first time. It is clear that the Russian aircraft design community highly regards effective fire protection and fire safety principles in the sophistication of their design, the breadth of use of fire protection systems on aircraft (far greater than that in the West), and the knowledge they possess of their own propulsion systems and aircraft operation that leads to improved fire safety. As examples, it was learned that Russian designers have a high degree of knowledge of the hot engine surface behavior during fire events and extinguishant distribution designs, and novel techniques in testing to evaluate a wide array of fire conditions with minimal cost or fabrication. The Russian protocol of designing fire protection systems on actual engines exposed to actual air flow, with real fires used to optimize each design, is an acknowledgement of the need to design based upon realistic flow fields influenced by the presence of the fire, a commitment which has not been embraced by the West as yet. The expense to maintain this level of development, which is accepted by the Russian community, reveals their commitment to a high level of fire safety and priority in comparison to other design needs.

It is desired that future collaborative efforts could occur to build upon this historic collaboration. The Russian investigators have performed an admirable task in producing a body of work that required a marrying of two philosophies of research and design. The areas deemed worthy of additional exploration are a more in-depth assessment of the improvements that the Russian hardware and derivatives may offer, and a planned long term collaborative effort to optimize aircraft extinguishing systems using the best design knowledge and techniques from both communities.

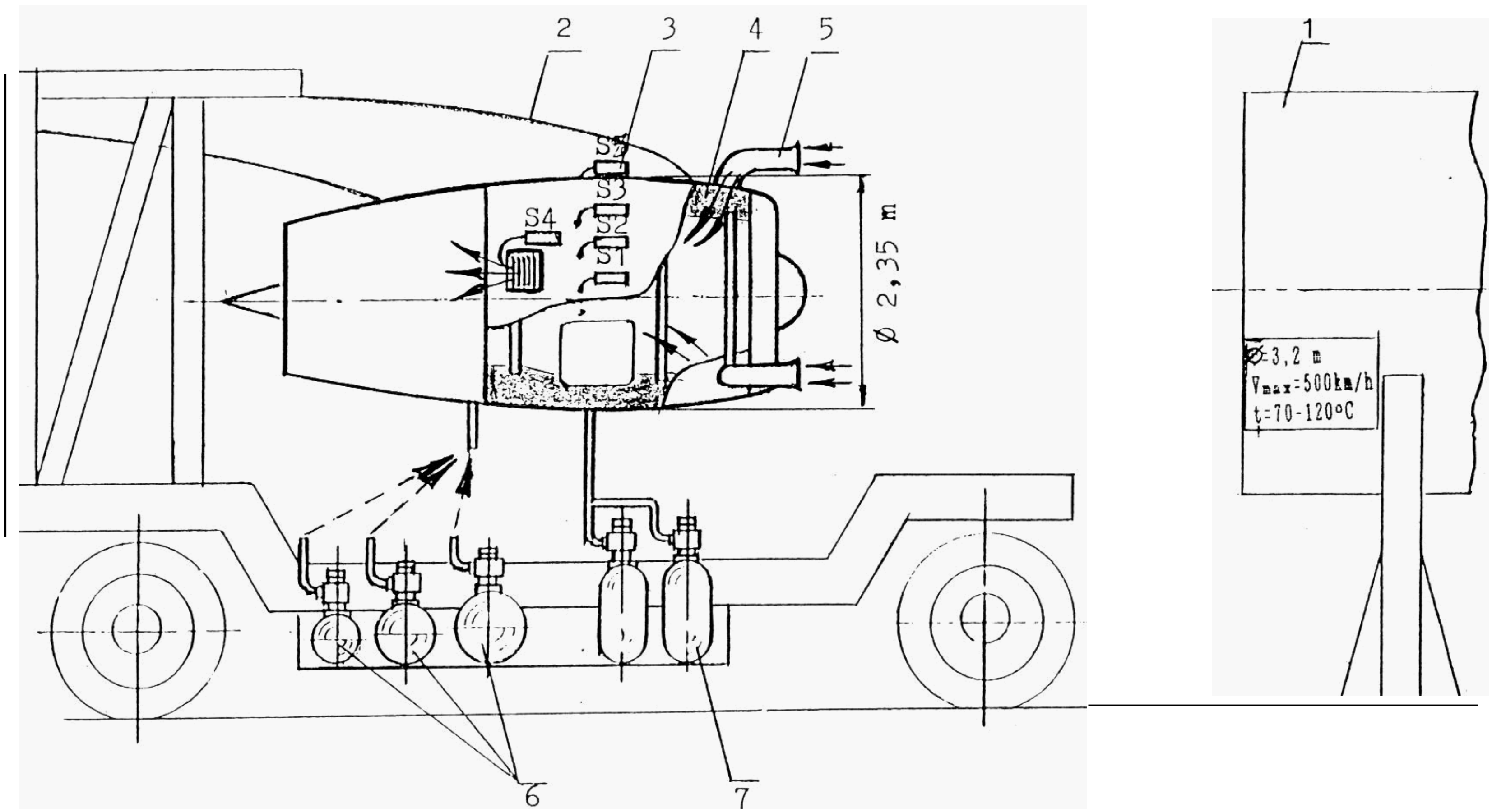

Fig. 1. Test facility for FES in the engine nacelle

1 - wind tonnel; 2 - wide-bidy aircraft engine; 3 - samplers; 4 - protected space under the engine cowling; 5 - air intakes; 6 - fire extinguishers with the tested agent; 7 - emergency FES.

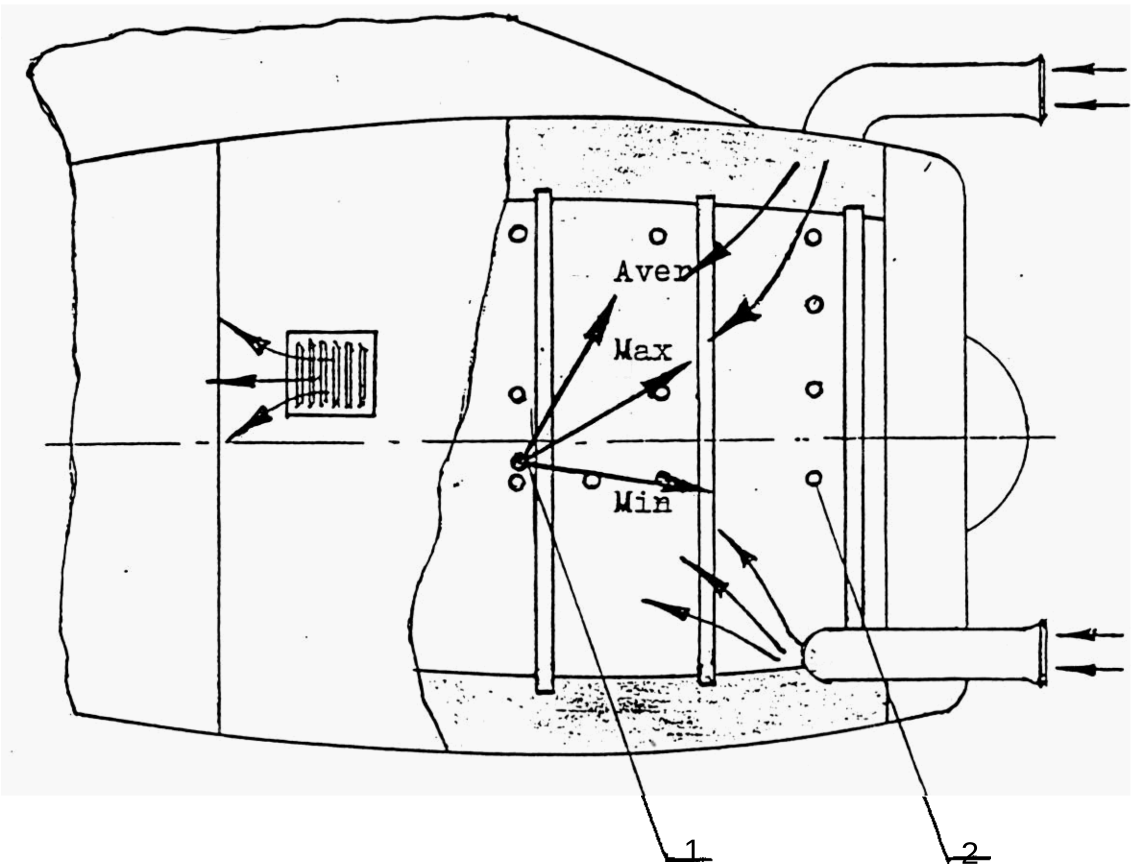

Fig. 2. Arangement of fuel atomizers and thermocouples in the engine nacelle.

1 - fuel atomizers (2 pcs)
2 - thermocouples (12 pcs)

The arrows show the directions of fuel supply which defined fire intensity.

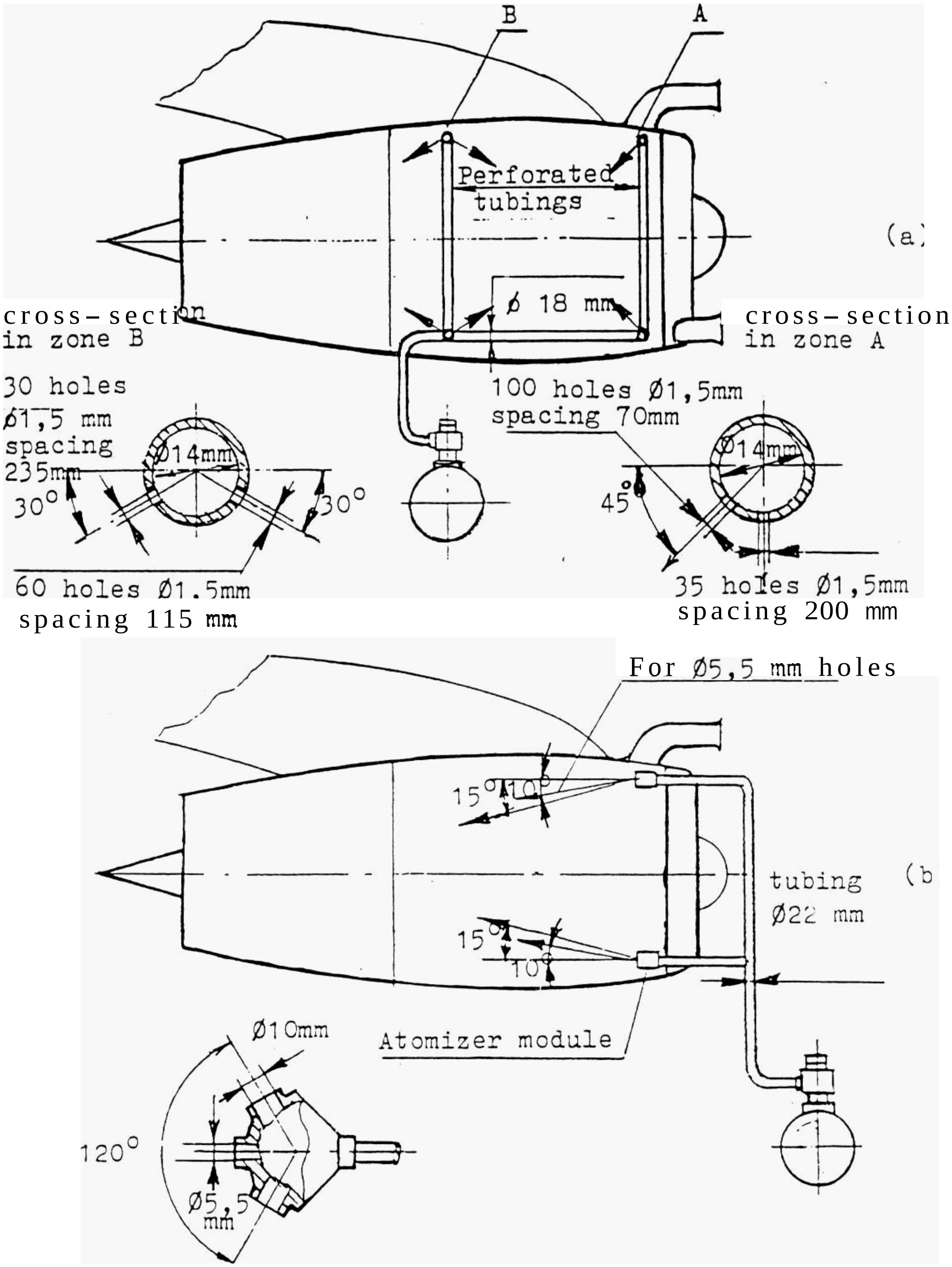

Fig. 3. Fire extinguishing systems (FES)

(a) flight FES with perforated circular tubings (Russian type)

(b) FSS with two atomizer **nodules** (US type)

Table 1. Fire extinguishment test results

#		Fire features					Extinguishment features						
Test run	Experiment	Fuel type	Fuel flow rate, cm^3/s	Max temp., ° C	Fire intensity	Fire ext-r capacity, l	Agent	Agent mass, kg	Fire exting-r pressure kgf/cm^2	Fire exting-r discharg time, s	Agent supply system
1	2	3	4	5	6	7	8	9	10	11	12
0	1-5	TC-1	76	850	max	2	2402	2.82	100	0.9	perfor
1	6-14	TC-1	76	850	max	3	FE-25	2.2	75	1.1	perfor
2	15-23	TC-1	76	550	min	3	FE-25	2.2	75	1.0	perfor
3	24-29	TC-1	76x2	700	aver	4	FE-25	2.93	75	1.25	perfor
4	30-35	АМГ-10	75	650	max	3	FE-25	2.2	75	1.05	perfor
5	36-41	MK-8	75	700	max	3	FE-25	2.2	75	1.0	perfor
6	42-47	TC-1	76	800	max	7(8)	FE-25	5.16	75	1.35	atomiz
7	48	TC-1	76x2	750	aver	7(8)	FE-25	5.16	75	1.35	atomiz
8	49	TC-1	76	550	min	7(8)	FE-25	5.16	75	1.3	atomiz
9	50-52	АМГ-10	75	650	max	6	FE-25	4.4	75	1.2	atomiz
10	53-54	MK-8	75	650	max	6	FE-25	4.4	75	1.2	atomiz
11	55-60	MK-8	75	700	max	5	FE-25	3.66	75	1.1	atomiz
12	61-66	TC-1	76	800	max	2	1301	1.2	75	0.6	atomiz

Table 3. Results of analyses of gas samples taken during tire extinguishment in the undercowling space of the power unit

Test #	Agent mass, kg	FES	HF content, mg/m^3 T1	T2	T3	T4	T5	T6	Agent decomp mole %	Test result*	Remark
FE-25											
38	1.09	perfor	3500	4800	900	450	-	-	0.69	-	
39	1.45	perfor	2500	7700	3200	7200	-	-	1.14	-	
40	2.2	perfor	500	1100	550	950	-	-	0.11	+	
41	2.2	perfor	105	280	20	300	-	-	0.03	+	Sampler opening in 3 s
42	2.2	atomiz	20000	20000	2400	10000	160	40	1.9	-	
44	3.6	atomiz	80000	80000	4000	16000	3200	80	4.0	-	
45	4.4	atomiz	20000	3200	1600	2400	600	80	0.5	-	
43	4.4	atomiz	4000	680	320	680	200	68	0.1	+	
46	5.2	atomiz	8000	1600	1000	1800	360	160	0.2	+	
47	5.15	atomiz	1600	650	400	1200	380	120	0.07	+	
48	5.16	atomiz	2000	1200	1080	2200	200	320	0.11	+	
Halon 1301											
61	0.9		120	110	20	-	4	80	0.06	-	F-ion
62	0.9		400	270	<100	-	<100	<100	0.06	-	Br-ion

* "-" fire **is** not extinguished
"+" fire is extinguished