INVESTIGATION INTO HALON 1301 REPLACEMENTS: A WATER-BASED SYSTEM FOR THE AIRLINE LAVATORY APPLICATION

Dr. Mike Parsons
Pacific Scientific

Kay S. Swartwood
Harvey Mudd College

Project Team (Harvey Mudd College):
Kevin Bensel
Brenda Farmer
Matt Gardner
Grace Ho
Carmen Lee
Hanna Lee
Josh Mann

Faculty Advisor:
Dr. Sedat Serdengecti
Harvey Mudd College

I. PROJECT INTRODUCTION

Commercial airlines use Halon 1301 extinguishers on airplanes in the engine compartments, in the cargo bay, in the fuselage, for the auxiliary power unit, and in all lavatories. Over half of the new commercial airplanes are equipped with fire suppression systems by Pacific Scientific. Pacific Scientific is searching for a replacement agent for Halon 1301. The lavatory application requires the least amount of agent, and concern for the affected area, the lavatory trash bin, is minimal. This project takes the first step toward finding Halon 1301 replacements by focusing on the airplane lavatory application.

The replacement studied by this project is a water-based system. This system incorporates three known fire suppression agents – water, dry chemical, and inert gas -- into a complete fire suppression agent. The idea is to add a dry chemical to water and propel the solution with an inert gas. This paper discusses the research, testing, and results of the chemical selection process for a water-based system.

II. CHEMICAL SELECTION

The chemical selection focuses on dry chemicals in a solution with water. Dry chemicals not in solution, foams, and gases were not considered.

A. INITIAL RESEARCH

Extensive work into finding Halon replacements has already been published [1], [2], [3]. These works gave ideas for possible chemicals to test. Three requirements that a chemical must meet before being tested were established:

- not highly toxic
- not a contributor to ozone depletion or other negative environmental effects
- reasonable availability

Table 1 gives a list of the chemicals that satisfied these requirements.

Table 1. List of Chemicals

DRY CHEMICALS	MOL.WT.
acetic acid, potassium salt; $KC_2H_3O_2$	98.14
acetic acid, sodium salt; CH_3CO_2Na	82.03
aluminum sulfate: $Al_2(SO_4)_3$	342.14
ammonium dihydrogen phosphate; $NH_4H_2PO_4$	115.03
boric acid; H_3BO_3	61.83
chromium (III) acetylacetonate	349.33
potassium bromide; KBr	119.00
potassium chloride: KCl	*14.55*
potassium hydrogen carbonate: KHCO,	100.12
potassium iodide; KI	166.01
potassium sulfate: K_2SO_4	174.25
sodium chloride: NaCl	58.44
sodium hydrogen carbonate; NaHCO,	84.01
sodium tetraborate decahydrate; $NaB_4(H_2O)_{10}$	381.37

B. TESTING SETUP

Testing of the chemicals was performed outdoors. This is a worst-case scenario as the test fires are constantly fed with oxygen supplied by air currents. In a lavatory application, the oxygen supply in the trash bin will diminish, allowing for more rapid extinguishment as well as less smoke.

Testing results were monitored by change-versus-time plots using thermocouple readings. A videotape of the tests was also recorded.

Figure 1 shows a representation of the testing setup used for all chemical testing. A plastic garden weed-sprayer was used as a means of dispersing the solutions. The sprayer was hand-pressurized with air so that the solution dispersed in a heavy, cone-shaped mist. The fuel for the fires, a set number of dry paper towels, was loosely packed in a tin can. One type K thermocouple was located about four inches directly above the can. This placement is similar to that of the current extinguisher's temperature-activated dispersion tubes in the trash bin area. Another type K thermocouple was placed under the can to measure heat that the upper thermocouple would not detect.

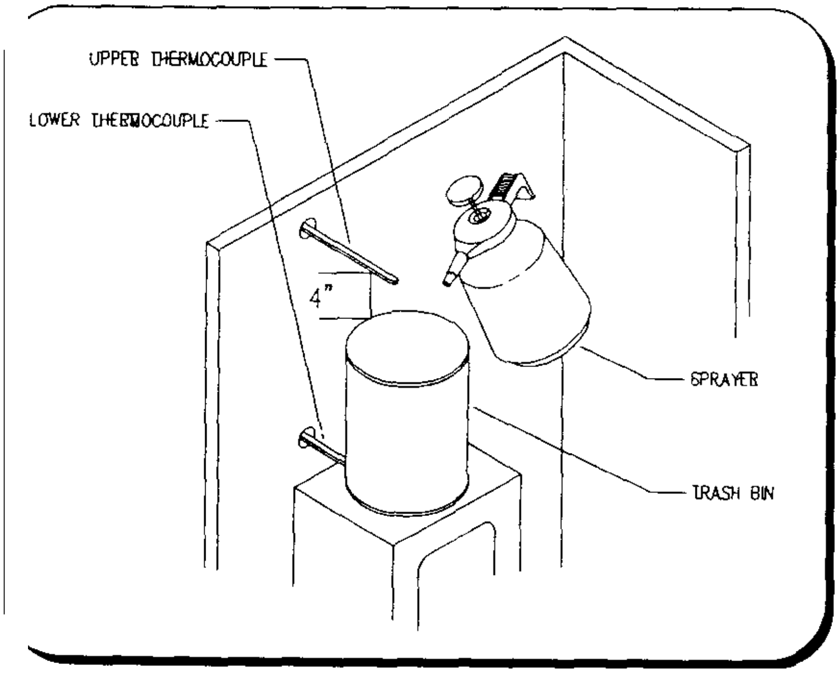

Figure 1. Chemical Testing Setup

C. ELIMINATION TESTING

Water was first evaluated as a standard by which to compare all chemical solutions. The efficiency of each solution was evaluated relative to water, based on the following three parameters:

- concentration of chemical in solution
- temperature change (cooling of the system)
- production of smoke

The concentration of the solution was varied. Evaluation of smoke production was based on observing whether or not the agent created an excessive amount of smoke.

The controller was started at the same time a match was dropped in the can of paper towels. When the change in temperature above the fire reached 300°C, the chemical solution was sprayed over the entire area of the can. Spraying continued for a designated amount of time. Data was taken for at least another minute to see if the fire re-ignited.

It was not difficult to reduce the list of chemicals to three candidates – aluminum sulfate, potassium iodide, and sodium chloride – that performed significantly better than water and warranted further and more detailed attention. Many of the chemicals tested, traditionally associated with good fire suppression performance, did not perform well in solution. A list of the chemicals eliminated from testing, along with the reasoning behind the elimination, is found in Table 2 on the next page.

The final three chemicals – aluminum sulfate, potassium iodide, and sodium chloride – were put to further testing.

Table 2. Chemicals Eliminated From Testing

CHEMICAL	REASONS FOR ELIMINATION
Acetic acid, potassium salt	Did not extinguish fire well at all, possibly due to carbon in the chemical acting as-fuel.
Acetic acid, sodium salt	Did not extinguish fire well at all, possibly due to carbon in the chemical acting as fuel
Ammonium dihydrogen phosphate	Did not extinguish fire well at lower concentrations. Very nauseous smoke.
Boric acid	Did not extinguish fire well at lower concentrations.
Chromium (III) acetylacetonate	Not soluble in water. Note: Did work very well at small concentrations.
Potassium bromide	Not as effective as a similar chemical, potassium iodide. Note: Did work relatively well at lower concentrations.
Potassium chloride	Very nauseous, black smoke. Note: Did work relatively well at lower concentrations.
Potassium hydrogen carbonate	Did not extinguish fire well at lower concentrations.
Potassium sulfate	Did not extinguish fire well at lower Concentrations.
Sodium hydrogen carbonate	Did not extinguish fire well at small concentrations. Did even worse as concentration was increased.
Sodium tetraborate decahydrate	Did not extinguish fire well at all. Very expensive and heavy chemical.

D. FINAL TESTING

The three final chemicals were tested extensively. Every test was repeated sixteen times; it was determined that at this number of runs, consistent results could be achieved despite the random nature of fire. To further structure the process, eight of the runs were bottom fires (match dropped to bottom) and eight were top fires (match placed on top surface).

The first task in final testing was to find the optimum concentration of each solution. Each chemical was tested for a range of concentrations in solution within the water solubility of each chemical. Table 3 on the next page shows this range for each chemical. Due to cost considerations, aluminum sulfate hydrate was used in place of aluminum sulfate during the final testing. Preliminary results showed similar performance between aluminum sulfate and its hydrate.

CHEMICAL	TESTING RANGE (moles/liter)	OPTIMUM (moles/liter)
Aluminum Sulfate	0.01 - 2.001	0.05

The ranges shown in Table 3 were tested with a procedure similar to the elimination testing. Again, the controller was started at the same time a match was dropped in the can of paper towels. When the change in temperature above the fire reached 200°C, the chemical solution was sprayed on the fire. (The decision to lower the temperature of activation was made to achieve a higher number of successful, and therefore more consistent, runs.) After a designated time, spraying was stopped.

The concentration of each solution was considered to be optimum when increasing the molarity of the solution did not significantly increase its fire suppression performance. These decisions were made through visual analysis. The optimum concentrations, shown in Table 3, are 0.05 $Al_2(SO_4)_3$, 0.25 KI, and 1.0 NaCl.

Upon determination of these concentrations, the solutions were subjected to different types of tests. The differences in these tests were time of application (at what temperature application of the solution began) and amount of solution applied (how long solution was sprayed). Four different tests and sixteen runs of each test for each chemical solution were performed. The parameters for the four tests are as follows:

- TEST 1: activation at 200°C, 15 seconds applied
- TEST 2: activation at 150°C, 15 seconds applied
- TEST 3: activation at 200°C, 25 seconds applied
- TEST 4: activation at 150°C, 30 seconds applied

The variation in tests was used to better determine the strengths and weaknesses of each solution. Summaries of the performance of the solutions with respect to these different tests are found in the discussions on the visual and decay constant analyses.

Using the data and videotapes from the final testing, the solution with the best fire suppression performance was found.

E. FINAL TESTING DATA ANALYSES

The most important analysis in determining the best chemical solution for fire suppression was the visual analysis. Visual analysis gave a good feel for the relative performance of each solution. **A** decay constant analysis was also performed on the data to supplement the visual analysis. Discussion and results for each analysis follow.

1. VISUAL ANALYSIS

Visual analysis is analysis by visual inspection. During each chemical testing run, the performance of the solution was observed and evaluated. All relevant observations were recorded in a chemical testing lab book. **Also,** the solutions were reviewed on a relative basis through the video taped recordings of each run.

Table **4** shows results for the final chemical testing through this analysis.

CHEMICAL SOLUTION	VISUAL ANALYSIS RESULTS
0.05M aluminum sulfate	Worked very well at times and very poorly at others. Worked better at higher activation temperatures. Frequently allowed significant amounts of smoldering that often lingered long after solution was applied. Major concerns: inconsistency and smoldering.
0.25M potassium iodide	Worked adequately at times but never worked really well. Changing activation temperature and amount applied did not significantly affect performance. Smoke was extremely nauseous during almost every run. Major concerns: mediocrity and smoke.
1.OM sodium chloride	Worked well at times and adequately at others. Worked better at higher amounts applied. Major concerns: none.

The best performance by any single run was with aluminum sulfate solution, but this same solution also resulted in many of the worst runs. Potassium iodide was relatively consistent, but it never gave outstanding performance. Sodium chloride had by far the most consistent fire suppression performance relative to the rest of the chemicals tested.

2. DECAY CONSTANT ANALYSIS

For the decay constant analysis, the focus was on the temperature change-versus-time plots. Figure 2 shows a run with water, used as a representative plot for a chemical testing run. The horizontal axis is time in seconds. The vertical axis is change in temperature in °C as measured by the thermocouple located above the fire.

After the agent is applied to the fire, there is a distinguishable curve. This curve can be approximated by an exponentially decaying function:

$$f(t) = A * \exp(-t / \tau) + B$$

where t is time, A and E are constants, and $1/\tau$ is the decay constant. The larger the decay constant, the more effective the agent is at cooling a burning system. Using values of $1/\tau$ for each solution, it was determined which solution cooled the fire most quickly and, therefore, most efficiently.

The extent of the test curve approximated to the exponentially decaying curve was the twenty seconds after the peak. For example, referring to the sample plot shown in Figure 2, the approximation started at about 26 seconds (around 300°C) and continued for 20 seconds (to about 46 seconds and 70°C).

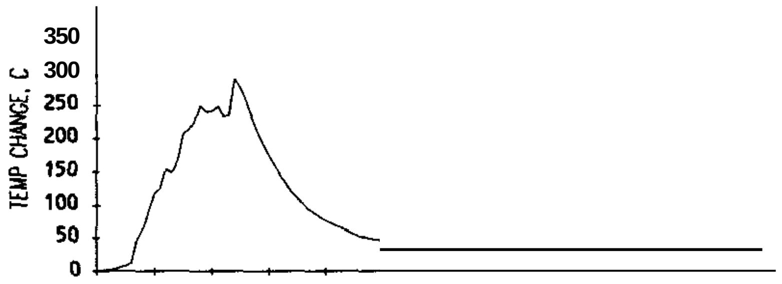

Figure 2. Chemical Testing Representative Plot:
Change in Temperature versus Time

Table 5 shows the results of the decay constant analysis. The different tests are the four tests previously described for final chemical testing. The mean and standard deviation of the decay constant for the sixteen runs of each test are shown.

Table 5. Decay Constants for Four Test Types

	TEST 1		TEST 2		TEST 3		TEST 4	
	mean	st.dev.	mean	st.dev.	mean	st.dev.	mean	st.dev.
0.05 aluminum sulfate	0.0505	0.0052	0.0453	0.0077	0.0510	0.0090	0.0596	0.0354
0.25M potassium iodide	0.0551	0.0059	0.0439	0.0076	0.0475	0.0041	0.0467	0.0070
1.0M sodium chloride	0.0634	0.0057	0.0483	0.0082	0.0550	0.0052	0.0472	0.0046
water	0.0519	0.0075	n/a	n/a	n/a	n/a	0.0454	0.0058

It was determined for this analysis that the effect of the thermocouple on the measured decay constants was small. The time constant of the thermocouple used is relatively **small,** 3 seconds compared *to* about 20 seconds for the temperature data, such that its effects are negligible. For an analysis that involves thermocouple and temperature data with time constants closer in magnitude, the effect of the thermocouple should be considered.

Aluminum sulfate has the best results for Test **4,** the second best for Test 2 and Test 3, and the worst – even worse than water – for Test 1. It also has very high standard deviations for the last two tests. These results support the visual analysis concern with the inconsistency of the performance by aluminum sulfate solution.

Potassium iodide has the second best results for Test 1 and third best for the last three runs. These results also support the visual analysis concern with the mediocre performance by potassium iodide solution.

Finally, sodium chloride has the best results for the first three tests and the second best for Test **4.** Again, these results support the visual analysis observation that sodium chloride solution has the most consistent results.

F. RESULTS

Chemical selection began with research into dry chemicals commonly associated with fire suppression. These chemicals were tested in solution and the resulting fire suppression performance compared to that of plain water. Three chemicals that performed significantly better than water were further tested, their concentrations optimized, and the testing data subjected to detailed analyses. Both visual and decay constant analyses showed 1.0M sodium chloride solution to be the most consistent fire suppressing agent for the given test conditions.

III. RECOMMENDATIONS FOR FURTHER STUDY

The results of the chemical selection were very promising. Testing of dry chemicals in solution should continue. It is suggested that further testing be performed in a controlled environment similar to that of the airplane lavatory. Testing should include a specific focus on the three final chemicals, especially on the aluminum sulfate solution which showed some of the best fire suppression performance and, if made consistent, would be a superior agent. The use of the decay constant analysis is recommended for a quantitative measure on the performance of different chemical solutions.

IV. REFERENCES

[1] Cote, Arthur E., Fire Protection Handbook, 16th ed., National Fire Protection Association: Quincy, MA, July 1990.

[2] Friedman, Raymond, Principles of Fire Protection Chemistry, 2nd ed., National Fire Protection Association: U.S.A., 1989.

[3] National Institute of Standards and Technology, NIST Technical Note 1279: Construction of an Exploratory List of Chemicals to Initiate the Search for Halon Alternatives, U.S. Government Printing Office: Washington, August 1990.