

FSS 000150 R

Aviation Safety®

Four Dollars

June 1, 1986 Vol. VI

EXTRA AM
MAY 20 1986
WATER LIFE

Fire Fighting In Aircraft: Halon's Job

Fire is among an airman's most dreaded enemies. Any pilot sooner or later realizes that he sits in a sealed container full of flammable materials, with highly flammable gasoline, oil and brake fluid not far away, and with numerous sources of ignition around to start the blaze.

Many pilots have considered what they would do if an airborne fire got started. They probably would not have time to turn to the page in the handbook to find the checklist item "Fire Extinguisher—Activate (If Available)."

Actually, fire in the air is not very common. In one published study, of all accidents involving fire, less than six percent were fires while the aircraft was airborne. The study, covering the years 1976 through 1981, found 2,292 general aviation accidents involving fire among 24,954 total accidents during those years. Of the 2,292 accidents, 5.5 percent involved fire in the air, 2.4 percent involved airplanes that were on the ground at the time the fire broke out, and the balance—92.1 percent—were post-crash fires.

Fire on the ground, though, is a very real threat. The same study found that of 2,798 people on board these aircraft, some 1,146 (41 percent) were killed outright by the fire, while only 420 (15 percent) were killed by the crash. Another 739 people were listed as injured by either the crash or the fire afterwards.

Another study, commissioned by FAA in 1982, found that of 83 recorded incidents of in-flight fires in general aviation aircraft during the 1976 through

1981 period, some 86.7 percent of all non-impact related fires originated in the electrical system. A further six percent were caused by "smoking materials" (pipes, cigars, cigarettes).

Regulatory Vacuum

Faced with a fire, a pilot might turn to look for the "if available" extinguisher. He might find nothing, or he might find an extinguisher of the kind installed in many thousands of airplanes—and be very unhappy with the results when he tries to use it. With the clear and obvious danger which fire presents, especially in general aviation, what regulations are there pertaining to extinguishers? The unfortunate answer is: None.

This is especially ironic since, of the three major kinds of extinguishers commonly found in light planes (dry chemical, carbon dioxide, Halon), two have been declared by national fire ex-



tinguisher standards experts as *unsafe for use in an occupied aircraft*. Despite a slight toxicity concern, only Halon extinguishers are considered usable in a cockpit.

FAA has effected regulations on extinguishers dealing with large aircraft, turbine aircraft, airline and air taxi operations. But when it comes to John Q. Pilot and his Cessna 172, he's on his own. He is not required to carry a fire extinguisher, and if he does he can put anything he wants in his airplane.

For general aviation, the extent of FAA's action has been to issue an advisory circular (AC 20-42B). It is, as the name implies, advisory in nature and not regulatory. The AC continues to imply that dry chemical and carbon dioxide extinguishers are okay to use in a light-plane, despite "disadvantages."

FAA's "official position," however, is that "Halon extinguishers are the extinguishers of choice for GA aircraft," according to Thor Eklund of FAA's Technical Center at Atlantic City, New Jersey. And the choicest of Halon extinguishers is Halon 1301, in FAA's eyes.

Standard Equipment

Travels around any airport will show that most aircraft don't have any fire extinguishers at all, while those that do

The accident and safety report to pilots and aircraft owners

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often have one of the types which are actually dangerous to use in an aircraft.

The dry chemical fire extinguisher, one of the more common types, can be found clamped to the floor in many aircraft. Although they are effective against a fire, paradoxically, dry chemical extinguishers present serious hazards if used in an aircraft—hazards which may be more dangerous than the fire itself.

Dick Hill, fire safety program manager at the FAA Tech Center, told us, "We ran one test with a dry chemical extinguisher, and it pretty well fogs everything up. Based on the test I've seen, I wouldn't ever want to fire a dry chemical extinguisher in a [light aircraft] cabin."

It's the serious obscuring of the pilot's vision which is the danger of dry chemical extinguishers, Hill explained. The FAA test showed that the dry chemical powder will coat the interior of the aircraft—instruments, windshield, and occupants. "There have been instances we found in the accident/incident records where someone has fired a dry chemical extinguisher in a plane and everything has fogged up and they crashed," he said.

Even if the aircraft is still under control when the powder settles, the pilot may be virtually blind. According to poison experts we consulted, the chemicals which make up dry chemical extinguishants—there are five in common use—are all eye irritants. They will cause heavy tearing and blurring of vision if they get into the eye. The chemicals also cause a person to gag and cough.

Another side effect of the dry chemical extinguishant is that it may have both conductive and insulatory properties. One of the country's chief sources of fire extinguisher specifications is the National Fire Protection Association. NFPA standards state that dry chemical extinguishers "are not recommended for use on aircraft . . . because of the possibility of forming an insulating layer of chemical on delicate electrical contacts which could affect flight controls and navigational equipment." NFPA further states that "dry chemical, discharged in an area, may also clog filters in air-cleaning systems" (i.e., the vacuum system filters in an aircraft).

A slight change in the conditions can produce another problem with dry chemicals—conductive properties. NFPA standards indicate "the use of dry chemical extinguishers on wet energized electrical equipment may aggravate electrical leakage problems. The dry

chemical in combination with moisture provides an electrical path which can reduce the effectiveness of insulation."

Yet another problem is the corrosive nature of the powder discharge. In many applications (most notably computer rooms), dry chemical extinguishers have been banned—not because they don't put out the fire, but because they will destroy the equipment they are protecting. Although it should never be considered a reason to let a fire go unfought, a person using a dry chemical extinguisher on an aircraft panel can practically count on the avionics to be rendered useless. One aircraft salvager refused to let reporters try a dry chemical extinguisher in a wrecked fuselage, because the chemical would have corroded the remains into truly worthless junk.

With all these disadvantages, it's clear that dry chemical extinguishers have no place in an aircraft. Those who find themselves the owner of one would be well advised to station it near the family barbeque and get something else for their airplane.

Freezer Burn

Some pilots might look into their aircraft and spot a carbon dioxide (CO₂) extinguisher. But they shouldn't heave any sighs of relief yet. Those CO₂ units hold other hazards which make them unacceptable for aircraft.

Carbon dioxide extinguishers, like the dry chemical units, put fires out by depriving them of oxygen. CO₂ does not "saponify" like dry chemical, however, and leave behind a mess to smother the remaining fire. Instead, CO₂ provides cooling to get the material below its ignition temperature. (CO₂ comes out of an extinguisher at around -110 degrees Fahrenheit.)

Unfortunately, the amount of CO₂ needed to snuff out the fire will very likely snuff out the occupants as well. NFPA figures show CO₂ concentrations of 34 percent are needed to extinguish a gasoline fire. But CO₂ concentrations of only nine percent can cause unconsciousness, while 20 percent can be lethal.

As with dry chemical, CO₂ comes out as a cloud. The physical discharge consists of white vapor and carbon dioxide snowflakes. The vapor will obscure vision, but fortunately doesn't last very long. And those CO₂ snowflakes (they're "dry ice") flying around the cockpit can

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Aviation Safety (ISSN 0277-1764) is published twice monthly by Belvoir Publications, Inc., 1111 East Putnam Avenue, Riverside, Conn. 06878. Robert Englander, Chairman and President; Donn E. Smith, Executive Vice President; Michael Pollet, Vice President, Corporate Counsel; Richard B. Weeghman, Vice President; Jeffrey Spranger, Vice President; Stanley Person, Vice President, Finance. Second Class postage paid at Riverside and at additional mailing offices.

Subscriptions: \$48 annually (24 issues). Single copies are \$4.

Bulk rate subscriptions for organizations and educational institutions are available upon request.

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Postmaster: Please send Form 3579 to *Aviation Safety*, PO Box 958, Farmingdale, NY, 11737

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cause severe burns if they contact exposed skin.

The extremely low temperature of a CO₂ discharge could also be lethal for avionics. A blast of -110 degree CO₂ on some hot radios will be a thermally shocking experience.

Another special hazard for CO₂ units is that of explosions. If the extinguisher gets too hot, from sitting in an enclosed area such as an aircraft out on the ramp in the sun, the safety disc should rupture and empty the extinguisher before it explodes.

But according to a publication from the National Association of Fire Equipment Distributors (NAFED), CO₂ extinguishers may explode anyway—sometimes because of defects in the cylinders, and sometimes because double safety discs have been installed. NAFED cites a case where a CO₂ cylinder corroded internally and exploded in an auto repair shop. The bottom section of the extinguisher “sliced completely through both sides of an auto chassis; the large [upper] portion skyrocketed 1/8 mile away after tearing through a heavy wood truss roof.”

Pilots should be unwilling to have such a potential bomb in their aircraft, and the other problems associated with discharging a CO₂ unit in the cockpit add impetus to getting CO₂ out of airplanes.

As with dry chemical units, NFPA standards now state, “For occupied spaces on aircraft, carbon dioxide extinguishers *shall not be used.*” [Our italics—Ed.]

Better Ideas

With CO₂ and dry chemical extinguishers out of the picture (and hopefully out of the airplane), what can pilots look to for fighting fire in an aircraft? Is there something that will kill the fire, but not the airframe or the airmen? In the opinion of many, ranging from FAA to NFPA, Halon extinguishers are the way to go.

In the early 1980's, a new kind of hijacking hit the scene—people would carry a flammable liquid onto the aircraft and threaten immolation. FAA, alarmed at this new trend, started looking hard at hand-held fire extinguishers. FAA commissioned a study of hand-held extinguishers which found that Halon extinguishers were the most effective available, particularly when compared to others on a weight basis.

FAA's efforts were given new impetus following the tragic fire aboard Air Canada's Flight 797 which killed 23

In informal tests, the small 12-ounce aerosol can of Halon 1211 performed very well on a flame coverage about four inches square on top surface of seat foam, but did not do as well on this embedded blaze.



passengers. The NTSB, in the course of its investigation, recommended to FAA that, “tests have demonstrated vividly that the performance of hand fire extinguishers with the Halon extinguishing agent is significantly superior to the performance of carbon dioxide, dry chemical or water type hand extinguishers and that safety will be enhanced by replacing the latter types of extinguishers with the Halon type.”

Pretty strong words, but NFPA had even stronger words. In their 1984 revision of their standards, NFPA states that CO₂ and dry chemical “shall *not* be used.” The only types approved for use in the cabin are water-based agents and Halon.

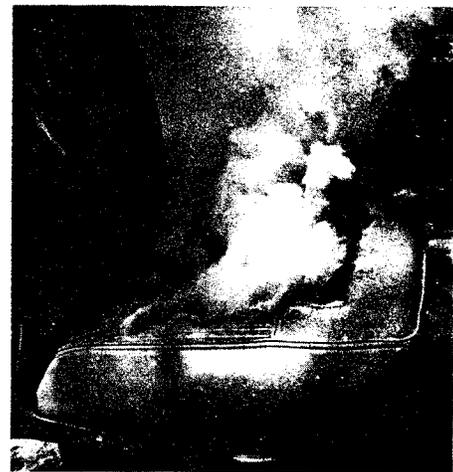
What Is This Stuff?

There are actually several types of Halon. They are denoted by numbers based on a military coding system related to their chemical composition. They are all about equally effective.

Although several types have been used in fire fighting, only two are in common use today—Halon 1211 (bromochlorodifluoromethane) and Halon 1301 (bromotrifluoromethane).

How these fight fires is not entirely known, but it is believed that they interfere with the combustion reaction by removing the free electrons needed for oxidation to take place. But with names like these, they certainly sound toxic, even dangerous. Could Halon be more of a hazard than the fire? Will it poison pilots who try to use it? These were the questions on FAA's lips as it debated the hand-held extinguisher topic.

Well, the answers to these questions are yes and no. Yes, Halon can be toxic, but no it shouldn't be toxic in the concentrations expected over the time periods expected. Research on rats, dogs, and humans found that while Halon 1211 is



Although the Halon knocked out the flame, there was a lot of residual smoldering, with foul fumes.

more toxic than Halon 1301, the toxic effects are mild in the concentrations expected to be found after discharging a Halon extinguisher in a closed environment such as a cockpit.

NFPA standards state, “Halon 1211 has been studied in humans and found to produce minimal, if any, central nervous system effects at concentrations below four percent for exposures of approximately one minute duration. At concentrations above four percent, effects such as dizziness, impaired coordination, and reduced mental acuity become definite with exposure of a few minutes duration; however, these effects are not incapacitating for exposure of one minute or less. At concentrations of the order of five to ten percent there is the risk of unconsciousness and possible death if the exposure is prolonged.”

FAA considered the toxicity question. The Tech Center has been performing fire testing using a Cessna 210C and a Piper Comanche. Their findings: “We feel that for small, non-pressurized aircraft, Halon is safe and very effective. We're not so sure for pressurized aircraft because we haven't been able to do any

testing on those yet," explained FAA's Thor Eklund.

FAA tests placed the Cessna in a wind tunnel with the engine running. A Halon extinguisher was discharged in the cockpit and the concentration measured. The researchers found that the airflow through the cabin changed the air about once per minute, keeping both the concentration and the exposure time well below the limits.

The Comanche was placed outdoors and flight conditions were simulated. A fire was started in the cabin and a Halon extinguisher discharged to put it out. Again, the concentrations and duration were below the dangerous levels, and the fire was put out.

Which One?

There's a choice to make among the two types—Halon 1211 and Halon 1301. What are the differences between them? Given the choice, which should pilots buy?

Toxicity is a reasonable issue to consider. Halon 1211 is more toxic than Halon 1301. How much more toxic? Underwriters Laboratories, using a toxicity rating scale of 1 to 6—with 6 being the least toxic—has put Halon 1211 in toxicity Group 5a.

Halon 1301, however, is placed in Group 6. Thus, given the choice pilots should choose 1301 due to its lower toxicity. But the UL rating scale is rather abstract. What do the toxicity ratings mean in terms of physical effects?

Early studies by the Army Chemical Center found that the approximate lethal concentration of Halon 1301 was more than twice the value for 1211. In other words, it took twice as much Halon 1301 to kill, making 1301 half as toxic as 1211.

The Army also looked at the effects of

lower concentrations in terms of "anesthetic effects"—the concentrations at which the body starts to react. The studies found that a concentration of 320,000 parts per million of 1211 would produce "narcosis" in one minute, while the same concentration of 1301 took 15 minutes to produce an effect.

So, given the choice, we would recommend pilots choose extinguishers containing Halon 1301. FAA agrees. As the Tech Center's Dick Hill explained, "We would rather see 1301 in GA aircraft for two reasons. One is that in the neat form [i.e., unblended with other agents], 1301 has a much lower toxicity. The second reason is that 1301 comes out as a gas, whereas 1211 comes out as a liquid spray. The gaseous form of 1301 will allow it to penetrate better into areas like the instrument panel without having to aim the extinguisher directly at the fire."

Burned Halon

Another question which required serious examination was that of the toxicity of decomposed Halon. Because Halon breaks down when heated to temperatures over about 900 degrees Fahrenheit, researchers questioned whether the decomposition products would be hazardous.

NFPA tackled this question, and reached the following conclusions: "The decomposition products of Halon 1301 and Halon 1211 have a characteristic sharp acrid odor, even in concentrations of only a few parts per million. This characteristic provides a built-in warning system for the agent, but at the same time creates a noxious, irritating atmosphere for those who must enter the hazard following a fire [or those who must remain in the area]." Since the gases produced by decomposed Halon are very

acidic, the primary hazard is edema of the upper respiratory tract which can cause suffocation in severe cases.

FAA's researcher, looking at the available data on the decomposition characteristics of the two Halons, expressed the opinion that "for the small fire scenario it is likely that the fire will be extinguished rapidly with little agent decomposition, thus rendering the decomposed agent toxicity issue academic. For the large fire scenario, agent decomposition is expected . . . However, as seen in the tests conducted at the FAA Technical Center, measured levels of Halon 1211 decomposition products do not appear to represent a problem. Therefore, the decomposed agent toxicity issue is again rendered academic. Further, the likelihood is that *no other commercially available extinguishing agent in acceptable hand-held size could control such a fire.*" [Our italics.]

FAA's Hill explained that the Tech Center had looked at the question also, and got an answer rather indirectly. After testing several types of extinguishers on gasoline-soaked seats which had been set ablaze, "We found we got more [of the same toxic gases] firing a CO₂ extinguisher at a burning seat than we got firing a Halon at it, because the seat gave off the same toxic gases as decomposed Halon, and the CO₂ took longer to put out the fire."

In other words, while the Halon may decompose to produce toxic gases, the fire itself is producing much more toxic gas than the extinguishing agent could.

Under Pressure

Halon extinguishers don't leave a goopy mess after the fire. They don't obscure the vision of the pilot. They are slightly toxic, but not enough to snuff out the crew with the fire like CO₂ can. But since they are under pressure, can they explode like CO₂ extinguishers might?

Not according to several industry people we spoke with. Amerex, a manufacturer of Halon extinguishers, explained that the extinguisher containers are tested to about four times the pressure they experience in normal circumstances. To reach this pressure would require temperatures of around 280 degrees Fahrenheit, which are not likely to be encountered in most uses.

Hands-On Experience

Not content with dry studies, *Aviation Safety* went shopping for a representative



Large (2½-lb) Halon 1211 was powerful, killing the flames on this aircraft seat within about one second of application. Note Halon vaporizes to become a colorless gas, leaving a pilot's vision unimpaired.

sample of extinguishers and conducted some impromptu tests. Actually, we must stress that they were wholly unscientific and might be better called "demonstrations" rather than "tests."

We obtained a couple of typical aircraft seats, which is to say, a couple of typically flammable seats. The fabric has some flame-retardant qualities, but does support combustion once it gets started. The foam of the seats is very, very flammable, and when we lit up the seats with a match to foam exposed through tears in the fabric, we were rewarded by flames engulfing the seats in about 90 seconds.

We tried a small (12 ounces of Halon) extinguisher obtained from a pilot mail order house and, because we were concerned about the low-temperature propellant pressure of the Halon, we chilled it to eight degrees Fahrenheit before using it. The pressure was ample. It worked well—on a small fire. Once a seat became engulfed, it looked to us as though the 12-ounce bottle would never have a chance. (However, if the small size of the bottle means it will be kept instantly at hand, it may well be a life-saver because it nips a fire in the bud.)

We tried a couple of cheap (two for \$15 from a department store) dry chemical extinguishers and got the expected "instant whiteout" condition. Because the powder lies on a burning object and "saponifies it" (soaps it), it's very effective. But everyone in attendance agreed

Sequence shows effect of dry chemical extinguisher. It puts out a fire, but leaves a cloud of dust that coats an aircraft windshield, and attacks the pilot's eyes and throat. Dry chem extinguishers do not belong in airplanes.



they'd never want to be in an enclosed space when a dry chem unit went off.

We blasted off a 2-1/2-pound Halon 1211 and found the healthy flow not only knocked out the flames, but also blew some of the foam right out of the seat. This size unit is about as big as would be practical in a light airplane, and seemed certainly to have the "oomph" to put out a serious fire. However, we noticed a propensity of the foam in one of the seats to continue to smolder, changing its noxious gases from black to grey, after the Halon had killed the flames. With this deeply embedded seat fire, gallons of water seemed to do the job, but two hours later the seat was found smoldering again.

We didn't have the opportunity to try a Halon 1301 unit, and we're not sure our informal test conditions would have revealed the difference between it and a 1211 unit anyway.

The 2-1/2-pound Halon 1211 unit cost us \$47 locally, and seemed well worth it. One "small" matter that could become big in an emergency was a strong plastic shipping strap that prevents the handle stop pin from coming out. There were no instructions to remove the strap after installation to make the extinguisher readily usable. It's debatable whether a pilot's adrenalin would give him the strength to snap the strap with his fingers.

The 12-ounce Halon cost only \$11.95 from Barry Jay Products, Menominee, Michigan—a price that would allow any pilot to carry one in his flight bag.

Mount 'em Up

Another consideration when choosing an extinguisher is the mounting method. There are some good ways, and some not so good, and some which shouldn't be in aircraft at all.

Among the ones which we heartily recommend against are plastic brackets. Some department-store units came with plastic brackets which were flimsy.

One such set of brackets we examined came out of the box slightly warped. The plastic strap which holds the extinguisher to the bracket was thin, and the tension loading which secured the strap led to its releasing easily on the slightest application of pressure on the catch.

Additionally, the bracket had holes for only two screws—one at each end. The screws to go in these holes were not provided, leaving the pilot to his own devices in deciding which ones to use.

Another manufacturer offers Halon extinguishers with velcro straps on the bracket. While these might be easier to operate, and don't spring open like the plastic ones, we feel that they are simply not strong enough for aviation applications.

By far the best mounting brackets are, fortunately, the most common—metal with a tension-loaded strap/catch combination. These offer ease of operation,

Halon Extinguishers Selected Manufacturers

Manufacturer	Weight of Halon (lbs.)	List Price	Manufacturer	Weight of Halon (lbs.)	List Price
Amerex Corp. 7595 Gadsden Highway East Trussville, Alabama 35173 (205) 655-3271	2½	\$73.00	Walter Kidde & Co. 1394 South Third Street Mebane, N.C. 27302 (919) 563-5911	2½	\$55.50
Barry Jay Products 1401 10th Avenue Menominee, Mich. 49858 (906) 863-4478	12 oz.	\$11.95	Martech, Inc. 3299 Southwest Ninth Ave. Ft. Lauderdale, Fla. 33315 (305) 463-3451	2.2	\$68.10
General Fire Extinguisher Corp. 1685 Sherman Road Northbrook, Ill. 60062 (312) 272-7500	2½	\$43.50	Metalcraft, Inc. 718 Debelius Ave. Baltimore, Md. (301) 485-0880	3*	\$89.95
	3	\$49.50		4*	\$109.95
	5	\$59.00			

**Refill cylinders are available for these extinguishers. The nozzle units can be screwed off and a new bottle screwed on. Three-pound refills—\$68.95, four-pound refills—\$89.95.*

security. Holding the extinguisher, and the straps, to stand up to the strains of flight.

One set of metal brackets we looked at featured a hanger to support the neck of the extinguisher, as well as the strap and catch to hold it. The bracket had eight screw feet drilled in it. Again, however, it did not include the screws.

Since most extinguishers under three pounds in weight are about the same size (three inches in diameter), pilots may be able to purchase a metal mounting bracket for extinguishers which don't have them. We feel that the metal brackets with the single catch are superior to the others, both in terms of security and ease of operation.

Owning It

Once purchased and installed, extinguishers should not be forgotten. Like most other items associated with aviation, they do need periodic inspection.

Most NAFED members we consulted stressed that perhaps the single most important key to a reliable extinguisher is regular maintenance. One dealer told us Halon extinguishers should be "broken down" once a year. This, he explained, requires discharging the extinguisher, inspecting it, and refilling it.

"Couldn't this get a little expensive?" pilots might ask. It can, costing as much as \$15 to \$20 for a breakdown. But some NAFED members have equipment which helps to keep the price down by capturing the expired Halon and refilling the extinguisher with its original contents.

Why go through the trouble of getting an extinguisher broken down each year? One dealer explained that Halon can eat the seals on the valve assembly of the extinguisher, allowing it to leak out over time. Breaking down the extinguisher allows the seals to be replaced with fresh ones to preclude seal erosion—which

may lead to an empty extinguisher.

The same dealer admonished extinguisher owners not to rely on the pressure gauge to keep tabs on the condition of the extinguisher. "Years ago, NAFED brought 10,000 of these pressure gauges to OSHA to prove to them that the gauges were unreliable. They spread these out on the floor, and even though none of them were connected to anything, each and every one showed a full charge—the needle pointing into the green range," he explained.

Another periodic maintenance point is hydrostatic testing. This involves pressurizing the extinguisher with water to a pressure of five-thirds of its service pressure. For example, a CO₂ extinguisher with a service pressure of 195 psi would be tested to a pressure of 390 psi. Hydrostatic testing for Halon extinguishers is only required every 12 years under NFPA standards, though. Other types, like CO₂, require hydrostatic testing every five years. Dry chemical extinguishers vary in the hydrostatic test requirement. Depending on their construction, intervals of either five or 12 years apply.

After Using

Can the extinguisher be reused? It all depends on the type and brand of extinguisher. Some can be refilled and reused, others can't.

Many dry chemical types are intended to be disposable. One use, and it's all over. Others can be recharged, but it may not be worth it. As one NAFED dealer explained, the extinguisher may have only cost \$10, but the recharge could run up to \$15 or \$20, making this type of rechargeable extinguisher disposable.

Halon extinguishers vary in terms of rechargeability. Most NAFED dealers can refill a Halon 1211 extinguisher. A NAFED spokesman explained, "In

almost any major city, there should be at least one distributor who can refill those."

But Halon 1301 extinguishers are a different story. While they can't be recharged, they can be refilled. Metalcraft, the only manufacturer of 1301 extinguishers, explained that DOT regulations prohibit reusing of 1301 cylinders, thus they cannot be recharged. But Metalcraft has designed the extinguishers so that the head and valve assembly can be unscrewed from the empty extinguisher and screwed into a new cylinder. A company spokesperson explained that this allows a pilot to carry several refill cylinders and, when one has been used, he can simply toss out the old cylinder and screw on a new one, maintaining his protection against further fires.

But since there are so many variances among extinguishers, the best advice concerning refilling a Halon extinguisher is to check with a NAFED dealer or the manufacturer.

Up in Smoke?

While fires in aircraft are not very common occurrences, they do crop up often enough that pilots should have a plan of action and some measure of protection against them. The plan of action can generally be found in the handbook, or pilots should make one of their own.

But a good (Halon) extinguisher should be found in every aircraft, and anything else is just too dangerous to have in an aircraft, in our opinion. Given our choice, we would choose a Halon 1301 extinguisher. They're dependable, the least toxic of the two Halons available, have very good extinguishing ability, and are not subject to some of the temperature restrictions which the Halon 1211 extinguishers have. However, we'd certainly take the 1211 if the 1301 was not available.

From Safety Board Files

Piling Up Problems

Some flights just seem to be a chain of problems, with one hazard being cured, or ended, only to have another crop up. A 51-year-old, ATP-rated pilot had

struggled her way through just such a flight, only to have the Cessna 303 Crusader she was flying run off the end of the runway at North Carolina's Hickory Municipal Airport. The February 12, 1984 accident left the Crusader with

substantial damages, but the pilot and her five passengers were unhurt.

The 7,614-hour pilot had logged some 110 hours in the Crusader, all of it as pilot in command. Her ratings included instructor tickets for single- and multi-