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Surviving Fire Entrapments

Comparing Conditions Inside Vehicles and Fire Shelters

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7E62P87–Vehicle Entrapment

Contents

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Introduction

Since early in the days of wildland fire suppression, mechanized equipment has played an increasingly important role. Engines have become especially popular, providing transportation, water (and now foam), and a wide range of equipment for ground firefighters. This dependence on motorized equipment is not unique to the United States. Australia, Spain, Portugal, and France are just a few of the countries where engines are an important part of the fire suppression arsenal.

As engines are more widely used, the risk that fire will burn over the engine increases. Protective clothing and equipment (such as the fire shelter) are well accepted in the fire community. A wide range of opinion has been expressed concerning the protection an engine might afford during a burnover.

In recent years firefighters have been entrapped in their engines during a number of incidents. They have been forced to make instantaneous decisions about their best chances for survival: in an engine, or in a fire shelter.

✦ In 1958 on the Wandilo Fire in Australia, 11 firefighters were trapped in a fast-moving bushfire: three survived and eight died. Of the three survivors, one laid in the wheel rut on the sandy road, and the other two stayed in the engine cab until it caught fire.

✦ In October 1985, three Santa Barbara County firefighters abandoned their engine when the plastic lights and gauges melted and the front and side windows cracked from the heat. They went into fire shelters and survived uninjured.

✦ In 1987 on the Crank Fire in northern California, firefighters took shelter in their engines until the intense heat began melting components inside the cab. They left the engines and used their fire shelters as protective capes when they fled the burn area.

✦ In 1990 on the Wenatchee Heights Fire in central Washington the local fire chief attempted to ride out a burnover in the cab of an engine. When the heat became so intense that it blew out the engine's front windshield, he was forced to leave the engine and run through open flames, suffering third-degree burns over much of his body.

✦ In 1993 during a Santa Ana-condition firestorm in southern California, firefighters attempting to take shelter in their engines were burned because they were unable to get inside the engine quickly enough.

✦ In 1995, a fast-moving grass/sagebrush fire near Boise, ID, trapped two rural volunteer firefighters in the cab of their engine. Neither firefighter had a fire shelter, and both died in the engine.

✦ In 1995, many engines were destroyed by a fast-moving timber fire on Long Island, NY. All firefighters abandoned their engines and survived (Figures 1 and 2).

Figure 1—This engine burned during the 1995 fires on Long Island. Although many engines were destroyed, all firefighters escaped without injuries.

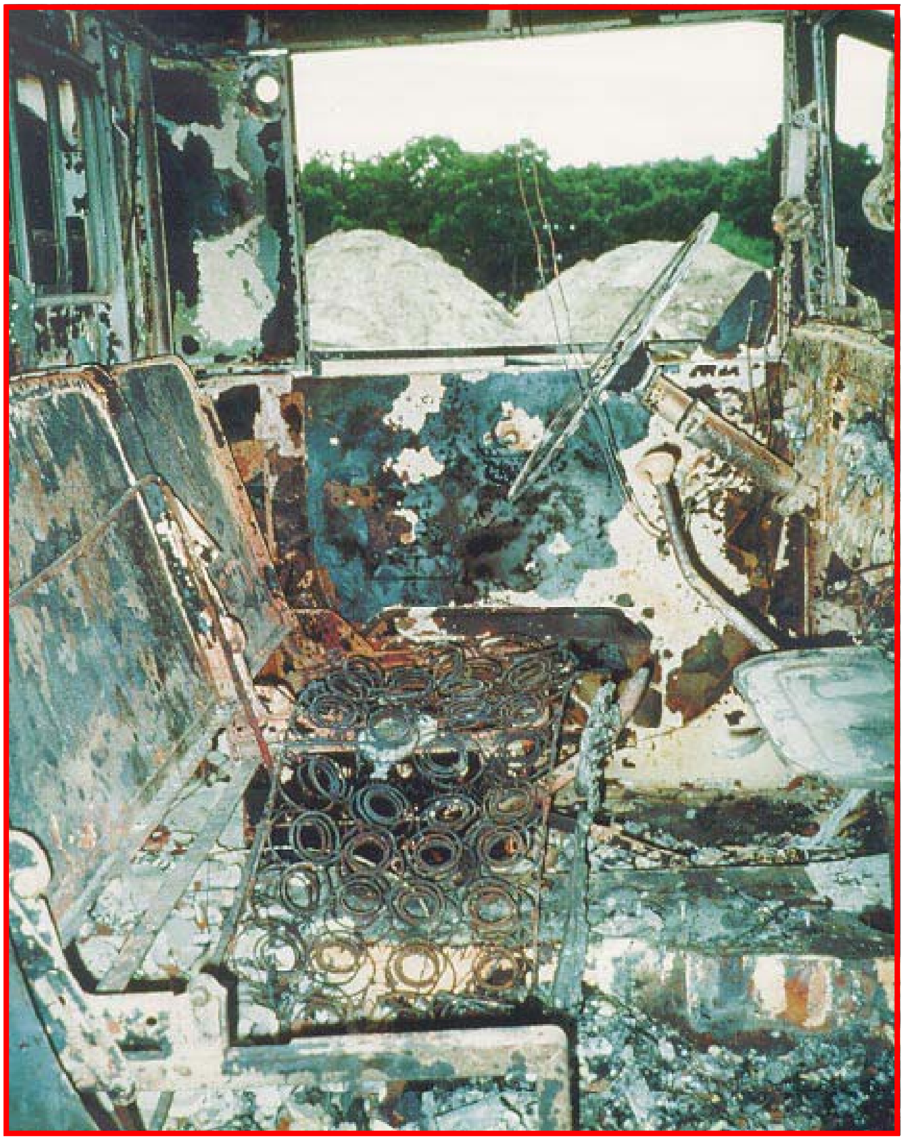


Figure 2—The cab interior of the same engine burned during the 1995 fires on Long Island.

✦ In 1996 on the Calabasas Fire in southern California, firefighters seeking shelter in their engines were at risk when the flame front curled around the vehicle, reaching firefighters who were seeking shelter behind the engine.

In October 1995, the Missoula Technology and Development Center in Missoula, MT, began a 1-year study to compare conditions inside a fire shelter and inside an engine under identical fire conditions; cooperators in this study included the Florida Division of Forestry, Los Angeles County Fire Department, Montana Department of Natural Resources and Conservation, and the Intermountain Fire Sciences Laboratory.

Objectives

The study was designed to quantify the conditions that existed inside the cab of an engine and inside a fire shelter—at the same time—during a wildfire burnover (Figure 3).

The specific factors to be measured included:

✦ Air temperature in the immediate vicinity of the engines and shelters, at levels from 6 to 108 inches (15 to 274 cm) above ground level

✦ Radiant heat flux levels in the immediate vicinity of the engines and in fire shelters, 3, 6, and 9 feet (0.9, 2, and 3 m) above the ground

✦ Air temperatures within the cabs of the engines, measured every 6 inches (15 cm) from the floor to the ceiling

✦ Surface temperatures on the outside and inside surfaces of the standard fire shelters and prototype stainless steel fire shelters (Figure 4)

✦ Air temperatures within the fire shelter, 1 inch (3 cm), and 12 inches (30 cm) above the ground

✦ Gas compounds released by heat and burning in the engines and fire shelters.

Video and still photographs would be taken of the fire conditions affecting the test vehicles and the fire shelters, including video footage taken inside the cab of the engines. These photographs would be used for technology transfer.

There is no intention on the part of MTDC or the WO Fire and Aviation Management in this study to set policy to determine whether firefighters should remain in a vehicle or deploy a fire shelter—rather, the study should provide as much quantifiable data and observations as possible so managers can formulate policies that apply specifically to their agencies.

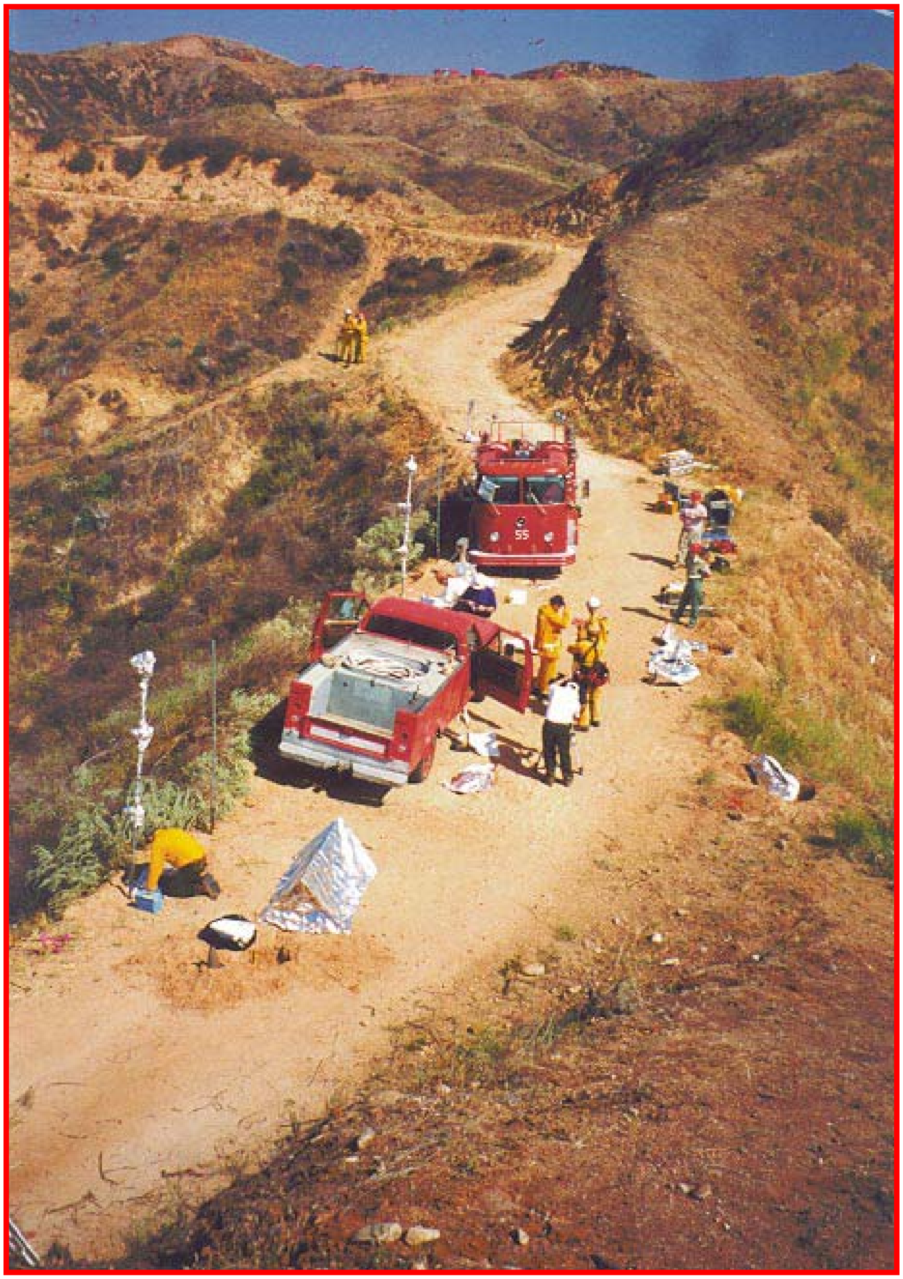


Figure 3—Layout for the June 5 burn in Los Angeles County.

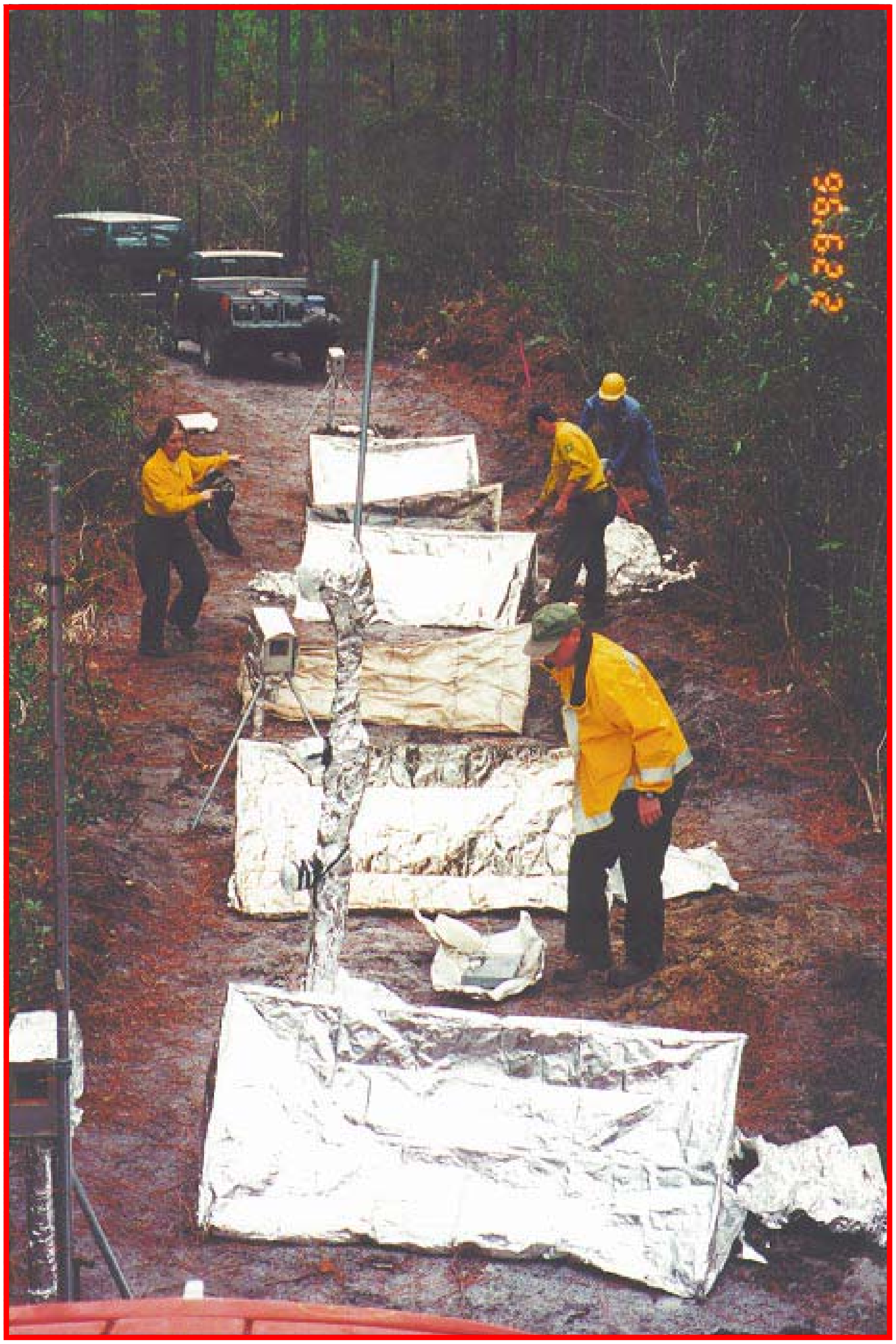


Figure 4—Several types of fire shelters were tested, including the standard Forest Service fire shelter and prototypes from MTDC and a private firm.

Previous Studies of Vehicle Burnovers

Although engines and other vehicles have been used in fire suppression for many years, surprisingly little has been written about firefighters becoming entrapped in engines. Many of the early field studies took place in Australia. Australians continue to study the safety of firefighters entrapped in their vehicles (Figure 5), as well as the safety of the general population as they attempt to flee from rapidly spreading bush fires.

In a 1972 report, *Studies in Human Survival in Bushfires*, Cheney reported that temperatures within a few feet of the ground and within a few feet of trees up to 35 feet (11 m) tall were lower than 120 ˚F (49 ˚C). In vehicle tests, car windows blocked half the radiant heat, but occupants would have still received severe burns to their bare skin. Within 4 minutes after the test fire was ignited, temperatures inside the vehicle reached 390 ˚F (199 ˚C). The roof lining and rubber seals burned, filling the cab with thick, dense smoke. Plastic and rubber material used in the interior lining smoked, causing “severe discomfort; tyres were caught alight by severe radiation heating; and 8 to 10 minutes after peak radiation, the engine compartment caught alight and burned strongly.”

In a 1995 personal communication, Cheney recounted his experience on a bush fire during 1965 when the Australian version of the fire shelter was being developed. He believes he took additional risks because he had a fire shelter, that it was very hot and uncomfortable inside the shelter, and that he would have been safer if he had stayed in his vehicle.

In an April 1996 article, *New Fire Tactics for New Car Fires,* Bill Gustin discusses the hydrocarbon-based synthetic materials now used to reduce vehicle weight. He says that these materials produce thick, toxic smoke, “a witches brew of toxic gases.” He also discusses the possibility of explosions from tires, batteries, hollow drive shafts, and components of the air-conditioning system. The plastic fuel lines used in newer vehicles carry gasoline at 15 to 90 psi. An electric fuel pump pumps gasoline from the tank to the engine. If a fire causes the fuel line to leak, gasoline will be under pressure, resulting in a sudden, intense fire fed by a spray of atomized gasoline.

Fuel tanks can no longer be vented to the atmosphere because of environmental concerns. Instead, vapors are pumped into a charcoal canister in the engine compartment. Excessive pressure from the heat of a fire could cause the fuel tank to leak along a seam, spilling fuel to the ground, increasing a fire's intensity. Fuel tanks made of polypropylene are lighter than metal tanks, but would melt more quickly.

Figure 5—This engine burned during the 1990 Toolara Fire in Australia. Three firefighters were trapped, one of whom was badly burned when he ran for safety. The other two men stayed in the vehicle, spraying themselves with water until the tires caught fire. Then they too ran for safety.

Cooperators

The Missoula Technology and Development Center depended heavily on the cooperation of wildland fire agencies, locally and across the country, to conduct a study of this complexity and scope.

The availability of engines that could be destroyed when subjecting them to the full effects of direct flame was critically important. In response to requests over the Internet, personal contacts, and interagency contacts throughout the wildland fire community, surplus engines were identified at the Florida Division of Forestry, Los Angeles County Fire Department, and the Montana Department of Natural Resources and Conservation. These engines enabled MTDC to fully implement the test plan as designed, with the engines and fire shelters exposed to a flaming front of fire for varying durations in a variety of fuel types.

Figure 6—Cooperators provided vehicles used in the tests, such as this engine and pickup provided by the Florida Division of Forestry.

Once engines were available, suitable sites had to be found where prescribed burns could be ignited under conditions similar to an engine burnover without damaging the site. Several of the agencies that contributed engines to this study also offered areas where burns could be conducted that met all of the criteria: where engines could be easily accessed and observed, where fire could impact both engines and shelters simultaneously, and where the risk of fire escape was minimal. The Florida Division of Forestry (Figure 6) and the Los Angeles County Fire Department offered burn sites that met these criteria. Both agencies had surplus engines available nearby. In Florida, lands of the Lake Butler Forest Unit of the Georgia-Pacific Corporation were selected. In Montana, the Beaverhead National Forest offered a site where we could to test the engines from the Montana Department of Natural Resources and Conservation.

Because the purpose of this study was to quantify the effects of flame and heat on the engines and fire shelters, scientific procedures had to be used when measuring:

✦ Air temperature outside and inside the engines and the shelters

✦ Radiant heat levels on the burn site

✦ Potential off-gassing from the various materials in the engines and shelters.

Dr. Bret Butler of the Forest Service's Intermountain Fire Sciences Laboratory in Missoula provided valuable expertise gathering and processing much of the data discussed throughout this report.

Preparing all the equipment, vehicles, and instrumentation for the test burns was labor intensive. Several smokejumpers from the Forest Service's Aerial Fire Depot in Missoula, MT (detailed to MTDC), helped complete these tests. In addition, the MTDC employees who helped implement the test plan were: Jim Kautz (photography), Lynn Weger (gas chemistry), Loren DeLand and Dave Gasvoda (instrumentation), and Ted Putnam and Bob Hensler (fire shelters and PPE).

Test Procedures and Methods

Because the study's objective was to quantify conditions in an engine compared to a fire shelter, test procedures and methods had to realistically measure the critical factors in a fire entrapment.

A study plan developed by the staff at MTDC was given wide review by cooperators, Forest Service fire specialists and researchers, and other fire specialists in the United States, Canada, and Australia. The final version of the study plan is in Appendix A.

Vehicles were positioned in or adjacent to fuels as they would normally be configured in a typical wildland setting:

✦ In the grass fuel type, they were placed in the middle of the fuels, with no clearing.

✦ In the brush and timber fuel types, engines were placed on roads, immediately adjacent to the fuels, but not in direct contact with them (Figure 7).

Fire shelters, both the Forest Service's standard model and a stainless steel prototype, were erected in front of or behind an engine, using tent framing to keep them erect. Weights along the inside edge of the shelter simulated a firefighter holding the edges to keep them from rising during the burnover. These shelters were adjacent to the fuels, rather than in a preferable deployment site as far from the oncoming fire as possible. This ensured that the data gathered were fully comparable to that obtained from the engines.

Instrumentation on the sites included two poles 9 feet (3 m) tall outfitted with thermocouples every 6 inches (15 cm). Data were recorded on Campbell Scientific data loggers, providing vertical temperature profiles on the burnover site. Radiometers were placed at the front or rear bumpers of the engines and on poles (Figure 8) to measure radiant heat flux. In the passenger side of the cab, 4-foot (1-m) thermocouple "trees" were outfitted with thermocouples every 6 inches (15 cm). The data were recorded on Campbell Scientific data loggers.

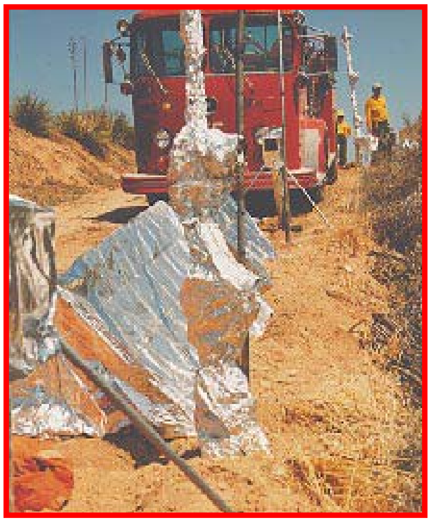


Figure 7—Both vehicles and fire shelters were placed right beside fuels. Firefighters would normally set up their shelters farther from the fuels, but the test compared fire shelters and vehicles under the worst conditions.

Figure 8—Radiometers on these poles measured radiant heat flux.

The fire shelters had thermocouples attached at the foot end, on the shelter's inside and outside skin. Thermocouples were placed at the head end of the shelter, 1 inch (3 cm) and 12 inches (30 cm) above the ground to measure air temperatures in an entrapped firefighter's critical breathing zone.

Both the engines and fire shelters had gas collection devices (Figures 9 and 10) placed inside to measure gases that could be harmful or fatal to an entrapped firefighter. The breakdown of materials inside the engine cab, such as the volatilization of petroleum-based plastics and sound-deadening materials inside the door panels, were a special concern, as was the off-gassing of the fire shelter adhesive that bonds the aluminum foil to the glass cloth. Detailed documentation of the gas collection system used on these burns—and on the gases collected—can be found in Appendix B.

Personal protective clothing (Figure 11), equipment, and other items commonly used by wildland firefighters were laid out near the fire shelters to visually evaluate their protective value during an entrapment. Items included the standard Forest Service Nomex shirt and trousers; leather firefighter gloves; hardhat; military-issue flight suit; and various outer garments such as brush coats, FR coveralls from Canada and Australia, and shirts from various cooperators. Clothing was tested as though it were on a firefighter. Five-gallon water bladders were filled with water and covered with 100% cotton undershirts. The shirts and jackets (or flightsuits) were placed over the undershirt. The bladder filled out the garments and simulated a heat sink, not unlike that of the human body. While some of these items were not instrumented, we felt visual observation of damage would offer valuable lessons for firefighter training. Specialized fireproof video photography equipment (Figure 12) was developed to take closeup shots of the fire's effects on the engines and shelters. These boxes were designed to withstand temperatures as high as 2300 °F (1260 °C) for extended periods (see Appendix C).

Figure 10.

Figures 9 and 10—Gas collection devices sampled gases inside vehicle cabs. Instrumentation was buried inside ammunition boxes so that it would survive the fire.

Figure 11—Personal protective clothing was laid out to observe the fire's effects on it.

Figure 12—Video cameras were set up inside specially designed fireproof boxes to observe the fire from several vantage points.

Test Results

Specific burn tests were conducted on three sites between February and July 1996:

✦ Lake City, FL (February 1996)—in cured bunchgrass, and matted grass and thatch (NFFL Model 3):

✦ Valencia, CA (June 1996)—in 2- to 3-foot (0.6- to 0.9-m) tall chamise with a cured grass understory (NFFL Model 4):

✦ Beaverhead National Forest, MT (July 1996)—in lodgepole pine slash (NFFL Model 12).

Figure 13—The Florida burn was not intense enough and did not burn for long enough to seriously test survivability inside either the shelters or the vehicles.

Florida Burn

At Lake City, FL, two surplus vehicles were selected for testing: the first was a standard wildland engine; the second was a standard pickup truck used for carrying a crew, with a slip-on pump and tank unit in the back.

The first burn was conducted on February 27, 1996, on an open, grass-covered field that had dry, cured bunchgrasses 30 to 36 inches (76 to 91 cm) tall, with a 2- to 4-inch (5 to 10 cm) mat of cured grass and thatch on the ground. The burn was in late afternoon with a 3- to 5-mile per hour wind. It was over in less than 1 minute, and had neither the intensity nor the duration to seriously test the survivability of the shelters or the engines (Figure 13).

Despite the brief duration and low intensity of this burn, some meaningful data were gathered:

✦ The peak air temperature was 650 ˚C in front of the engine and 950 ˚C in front of the pickup truck, as measured by the thermocouple trees.

✦ In the grass fuel type, air temperatures decreased as the height above ground level (AGL) increased.

✦ Air temperatures inside the engine cabs cooled more slowly than air temperatures outside after the burnover.

✦ Maximum heat flux was 70 kW/m^2, decreasing with the height above ground level.

✦ Fire shelters subject to the burnover showed no visible signs of damage, although the stainless steel prototype shelter had some discoloration.

✦ Air temperatures inside the shelters were 20 to 40 ˚C lower at 1 inch (3 cm) AGL than at the thermocouple 12 inches (30 cm) AGL.

✦ Temperatures less than 3 feet (0.9 m) above the ground surface were 1000 ˚C, with a heat flux of 8 kW/m^2.

✦ Personal protective equipment laid out in the fuels suffered varying degrees of damage: the Military Nomex flight suit was badly damaged, as was the FR cotton brush coat. The standard FS Nomex shirt and trousers showed signs of the heat, but were not destroyed. They would have offered some protection from serious burns (Figure 14).

A second burn was planned in a heavier palmetto-galberry fuel type (NFFL Model 7). Heavy rains prevented us from conducting the burn as planned.

In summary, this burn served as a good "shakedown" for the procedures and techniques used in future tests, but it was not long enough or hot enough to develop meaningful data about the differences between the protection offered by a fire shelter and an engine cab.

Figure 14—The change in color of the pants shows the effect of heat. Water bags inside the fire shirt and upper pants served as a heat sink, keeping them from becoming as hot as the pant legs.

Los Angeles County Burns

At Valencia in Los Angeles County, CA, two vehicles were available for the burnover tests: the first was a “Crown” structural fire engine, the other was a pickup patrol truck that had previously been equipped with a slip-on pumper unit. The Crown engine had hose in the hose bed, and a ladder hung on the side as it would normally be configured.

Two burns took place on June 5 and 6, 1996, in dry, cured grasses 12 to 24 inches (30 to 61 cm) tall, with a 2- to 3-foot (0.6- to 0.9-m) chamise brush overstory (NFFL Model 5). Air temperatures were approximately 32 ˚C, with wind speeds of 5 to 10 miles per hour (8 to 16 km per hour) during the burns. Flame lengths averaged 12 to 20 feet (4 to 6 m), with short periods (less than 30 seconds) where lengths were 20 to 30 feet (6 to 9 m).

The June 5th burn took place on slopes averaging 70%. The engines, fire shelters, and PPE were on a road near the top of the slope (Figure 3, page 3). Flames came in direct contact with the engines and shelters, since they were positioned at the road’s edge to receive the maximum effect of the flaming front (Figure 15).

This burn occurred in heavier fuels and on a day with higher air temperatures than the Florida burn. It produced a significant amount of meaningful data:

✦ Air temperatures measured in the free air outside the engines peaked at 1000 ˚C between 48 and 60 inches (122 and 152 cm) AGL.

✦ Radiometers measuring heat flux at the 3-, 6-, and 9-foot (0.9-, 2-, and 3-m) levels recorded a maximum heat flux of 70kW/m^2 for periods less than 10 seconds, and long term fluxes of 15 kW/m^2; the levels decreased as the height above the ground increased from 3 to 9 feet (0.9 to 3 m).

✦ Temperatures measured inside the engine cabs ranged from 60 to 85 ˚C.

✦ Outside skin temperatures on the standard fire shelter were 430 ˚C at the Crown engine and 180 ˚C at the patrol engine. Inside the shelter adjacent to the Crown engine, temperatures ranged from 150˚C at 1 inch (3 cm) AGL to 220 ˚C at 12 inches (30 cm) AGL.

✦ Items of personal protective clothing laid out beside the engines and shelters showed serious degradation from the intense heat during the burnover. A difference of less than a foot (30 cm) from the fire made a significant difference in damage to the clothing (Figure 16).

✦ On the stainless steel shelter, outside skin temperatures reached 520 ˚C, with the inside skin temperatures reaching 220 ˚C. Inside temperatures were 160 ˚C at 1 inch (3 cm) AGL and 250 ˚C at 12 inches (30 cm) AGL.

✦ The personal protective equipment laid on the ground showed varying degrees of damage from the combination of direct flame contact and radiant heat.

✦ Neither fire shelter showed any visible sign of heat damage.

✦ The Crown engine showed these signs of damage:

–Windows cracked in the cab.

–The 4-inch (10-cm) cotton-jacketed, rubber-lined hose in the exposed bed on the back of the engine melted in some places and began dripping.

–The mud flap on the rear tire caught fire (Figure 17).

–The exterior ladder hanging outside the engine was badly scorched.

Figure 15—This image (taken from video) shows the intensity of the June 5 burn in Los Angeles County.

Figure 16—These items of personal protective clothing show the effects of the June 5 burn in Los Angeles County. Note the difference made by being just a few feet from the edge of the roadway.

Figure 17—Mudflaps are just one of the flammable items on the engine's exterior.

–The brake line at the rear of the engine burned through, rendering the engine immovable because the air brakes locked.

✦ Windows were cracked on the patrol engine and the paint was scorched. The cab filled with heavy smoke, even though nothing burned inside the cab. Video footage filmed inside the cab showed heavy smoke within 1 minute after fire reached the engine.

✦ The heat lasted longer inside the engine cabs than it did inside the fire shelters.

The table at right shows the levels of six gases in a vehicle and in a fire shelter.

The second burn in Los Angeles County was on June 6th, the next day. Weather conditions were nearly identical, but the slope, aspect, and fuel loading were different. The engines were positioned at the head of a small draw with 35 to 45% slopes (Figure 18). Some chamise brush was cut and piled next to the engines and shelters to increase the fire's intensity and duration. Because of the topographic effect of some adjacent spur ridges, the flames were diverted from the engines and shelters.

Although the engines and shelters had less direct flame contact than expected, important data were obtained from the effects of the radiant heat load:

✦ Air temperatures outside the Crown engine reached a maximum of 700 °C at 60 inches (152 cm) AGL, and a maximum of 75 °C inside the cab (40 °C on the floor inside the cab).

GASES (parts per million)	Engine	Shelter
SO_2	18.7	4.4
HCN	0.0	0.0
Benzene	1.5	0.8
HCl	7.8	1.0
Toluene	13.6	6.3
CO	29.3	5.5

✦ The patrol engine (Figure 19) had outside air temperatures of 440 °C, with inside air temperatures of 280 °C at the roof. The inside door panel on the driver's side caught fire, leading to the high temperatures inside the cab of the patrol engine (Figures 20 and 21). Floor temperatures were 45 °C.

✦ The maximum outside skin temperature of the standard fire shelter adjacent to the Crown engine was 300 °C, with inside skin temperatures of 180 °C. Air temperatures stayed below 80 °C at both the 1- and 12-inch (3- and 30-cm) levels inside the fire shelter.

✦ The stainless steel shelter adjacent to the patrol engine had a maximum outside surface temperature of 360 °C, while the inside surface reached a maximum of 120 °C. The air temperature inside the shelter reached a maximum of 180 °C.

✦ Video footage showed that the cab of the patrol engine filled with dark smoke in less than 60 seconds. The driver's side door panel caught fire from radiant heat on the outside of the door;

✦ PPE and additional fire shelters—both the standard Forest Service version and the stainless steel prototype—were placed at the head of the small draw away from the engines and other shelters. We intended to subject these items to direct flame contact and the maximum radiant heat load. The effect of the terrain prevented direct flame contact. Temperatures inside the stainless steel shelter reached a maximum of 135 °C, while temperatures inside the standard shelter reached just 70 °C. The PPE laid out in the open, including FR cotton coveralls from the Northwest Territories of Canada and standard FS Nomex, reached maximum temperatures of 120 °C. The clothing showed no visible signs of damage.

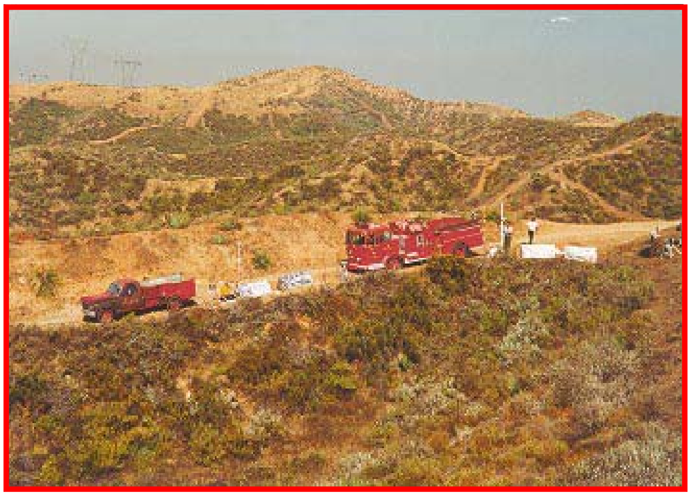


Figure 18—The engine, patrol engine, and fire shelters positioned for the second burn in Los Angeles County, June 6th.

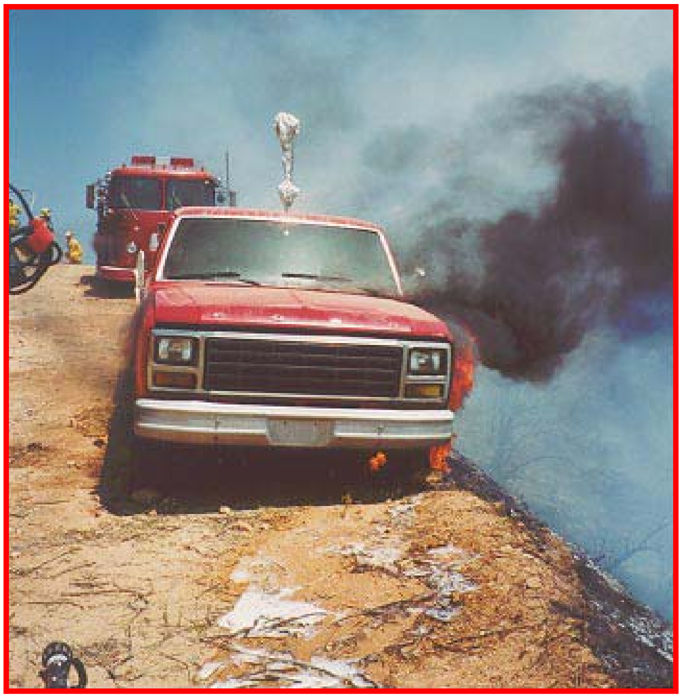
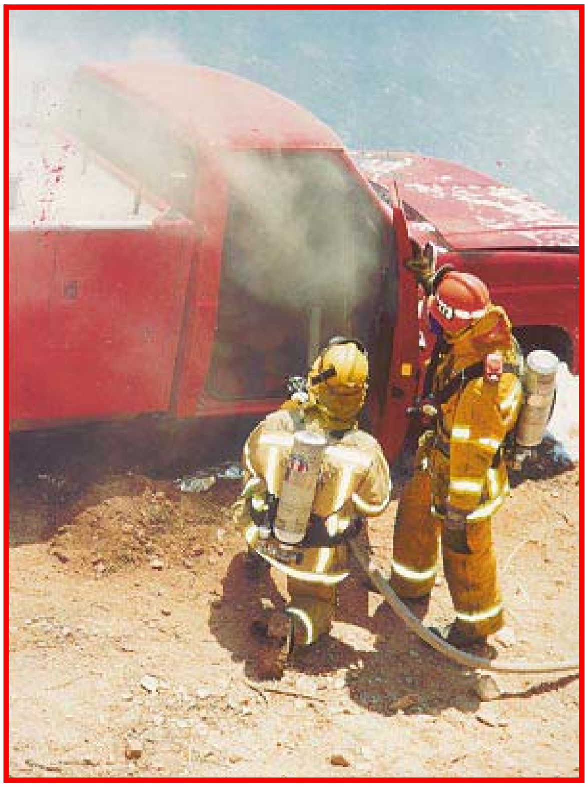
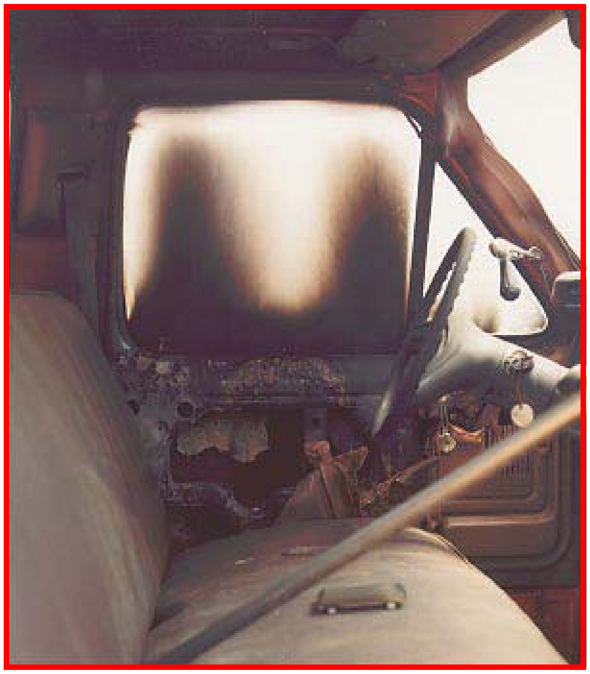


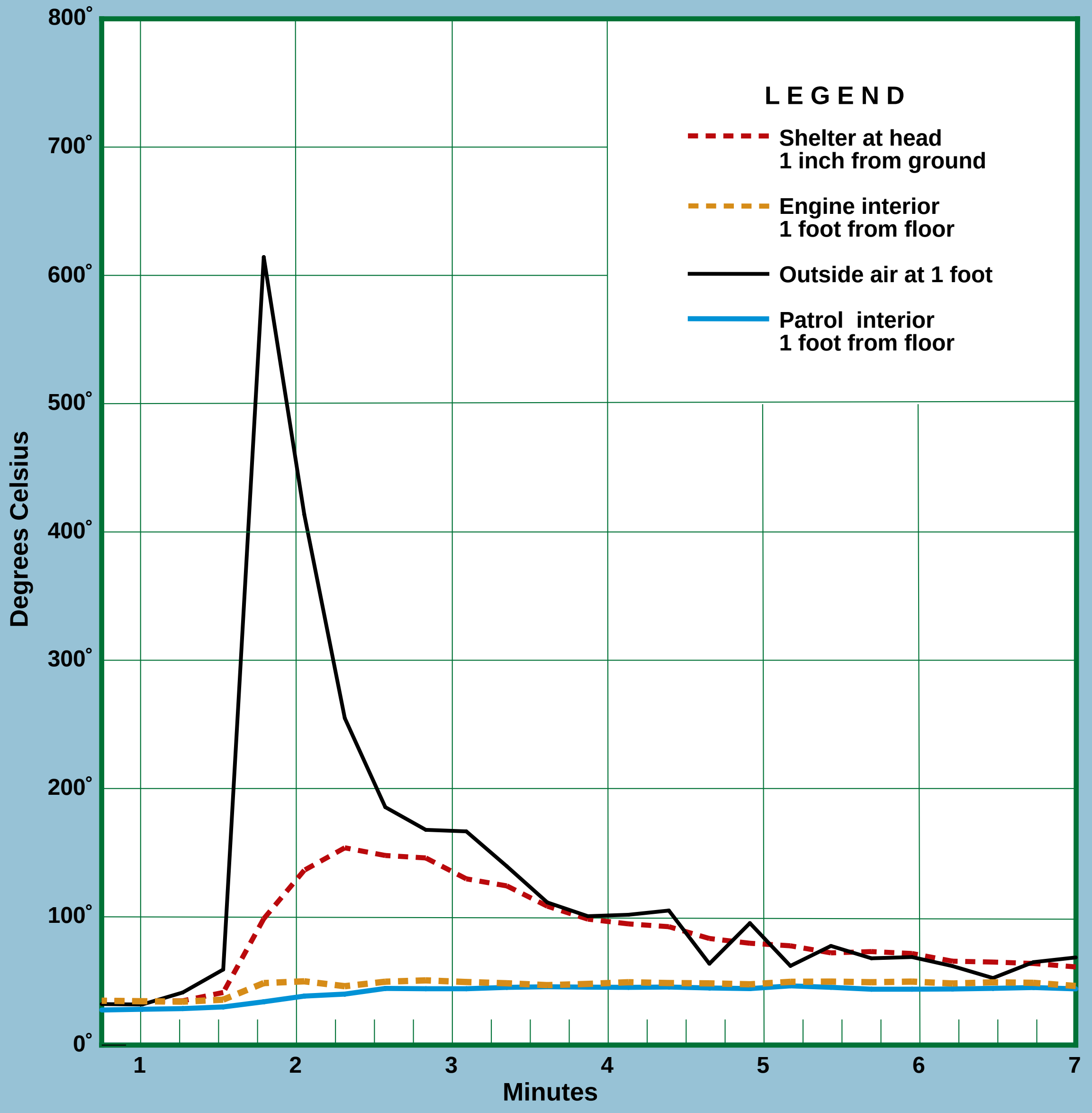
Figure 19—The patrol engine caught fire during the June 6 burn in Los Angeles County.



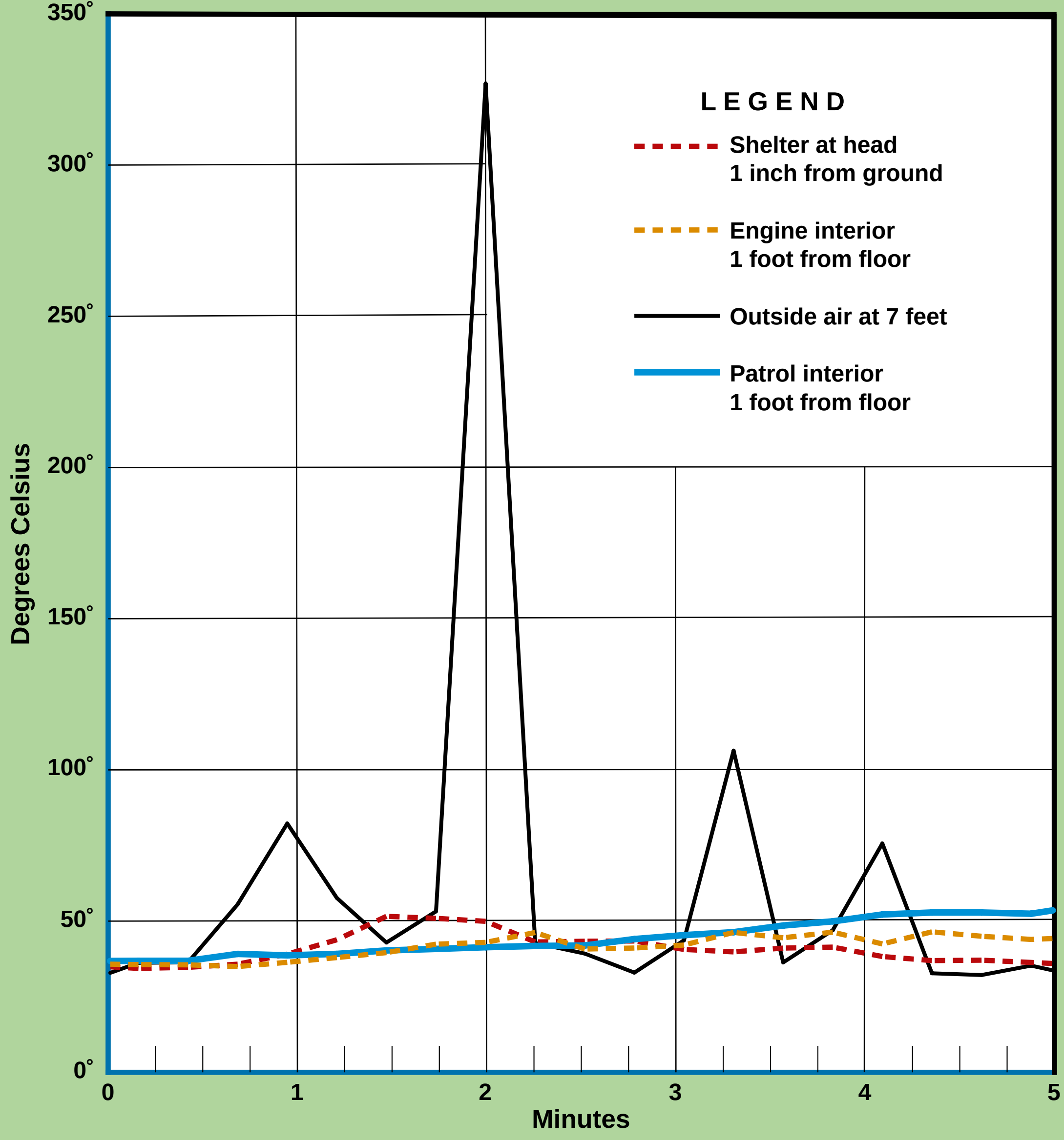


Figures 20 and 21—Firefighters put out the fire in the cab of the patrol pickup. Material on the inside door panel burned, emitting smoke that would have forced entrapped firefighters to leave the truck.

Los Angeles—June 5th



Los Angeles—June 6th



Montana Burn

The Montana Department of Natural Resources and Conservation supplied two engines for the test in southwestern Montana. One was a surplus military $2\frac{1}{2}$-ton truck that had been converted to an engine. It was similar to the engine that was burned over on the Point Fire near Kuna, ID, in 1995, killing two firefighters inside. The other was a crew carrier pickup that had been fitted with a slip-on fire tank and pump.

The test burn was conducted in late July in an area of thinned lodgepole pine slash that had been piled about 5 feet (2 m) high, 8 feet (2 m) wide, and 200 feet (61 m) long. Air temperatures that day were in the mid-70's (about 21 °C), with humidities in the low 20's. The engines, fire shelters, and PPE were laid out beside the edge of the slash piles to obtain maximum heat load.

An unforecast wind shift just before ignition prevented direct flame contact on the vehicles and shelters being tested (Figure 22). However, satisfactory results were obtained:

✦ Maximum air temperature outside the $2\frac{1}{2}$-ton engine was 400 °C, while temperatures inside the cab exceeded 700 °C. The inside of the engine cab caught fire (Figure 23) and burned, resulting in the higher temperatures.

✦ The crew cab truck outside air temperatures were less than 200 °C. Air temperatures inside the cab exceeded 250 °C because the interior caught fire.

✦ Surface temperatures on the fire shelter at the rear of the $2\frac{1}{2}$-ton engine reached 150 °C, although they generally


Figure 22—Wind prevented flames from directly contacting vehicles during the test burn near Dillon, MT.


Figure 23—Even though flames did not directly contact the $2\frac{1}{2}$-ton truck, its cab caught fire.

remained in the range of 100 to 150 ˚C. Inside surface temperatures remained below 100 ˚C, except for a momentary spike to 140 ˚C.

✦ Air temperatures inside the fire shelter at the rear of the $2\frac{1}{2}$-ton engine were only 40 ˚C at 1 inch (3 cm) AGL and 75 ˚C at 12 inches (30 cm) AGL. The shelter had no visible damage.

✦ The stainless steel prototype shelter in front of the crew cab engine had outside surface temperatures of 250 ˚C, and inside surface temperatures of 220 ˚C. The free air temperature inside the stainless steel shelter at 12 inches (30 cm) AGL was 105 ˚C; the thermocouple at 1 inch (3 cm) AGL was faulty and did not record.

✦ The radiometer at the front of the crew cab engine measured a radiant heat flux of 170 kW/m^2, with a prolonged level (longer than 6 minutes) of 130 kW/m^2; the heat flux decreased with the height above the ground.

✦ The radiometer at the front of the $2^1/_2$-ton engine measured a peak radiant heat flux of 150 kW/m^2 at 9 feet (3 m) AGL.

✦ The cabs of both engines filled with thick smoke. Within a few minutes after the burn was ignited, the interior of both cabs caught fire from the radiant heat.

✦ Protective clothing and equipment was instrumented with thermocouples and laid between the fire shelters and the engines. The items selected (trousers, shirts, flight suits, and coveralls) were placed over a 5-gallon water bag that had been covered with a 100% cotton T-shirt (see *Test Procedures and Methods*).

–Nomex trousers recorded an outside surface temperature of 160 ˚C and an inside temperature of 20 ˚C, with no visible damage to the trousers.

–A Nomex fire shirt recorded an outside temperature of 100 ˚C, and an inside temperature of 70 ˚C, with no visible damage.

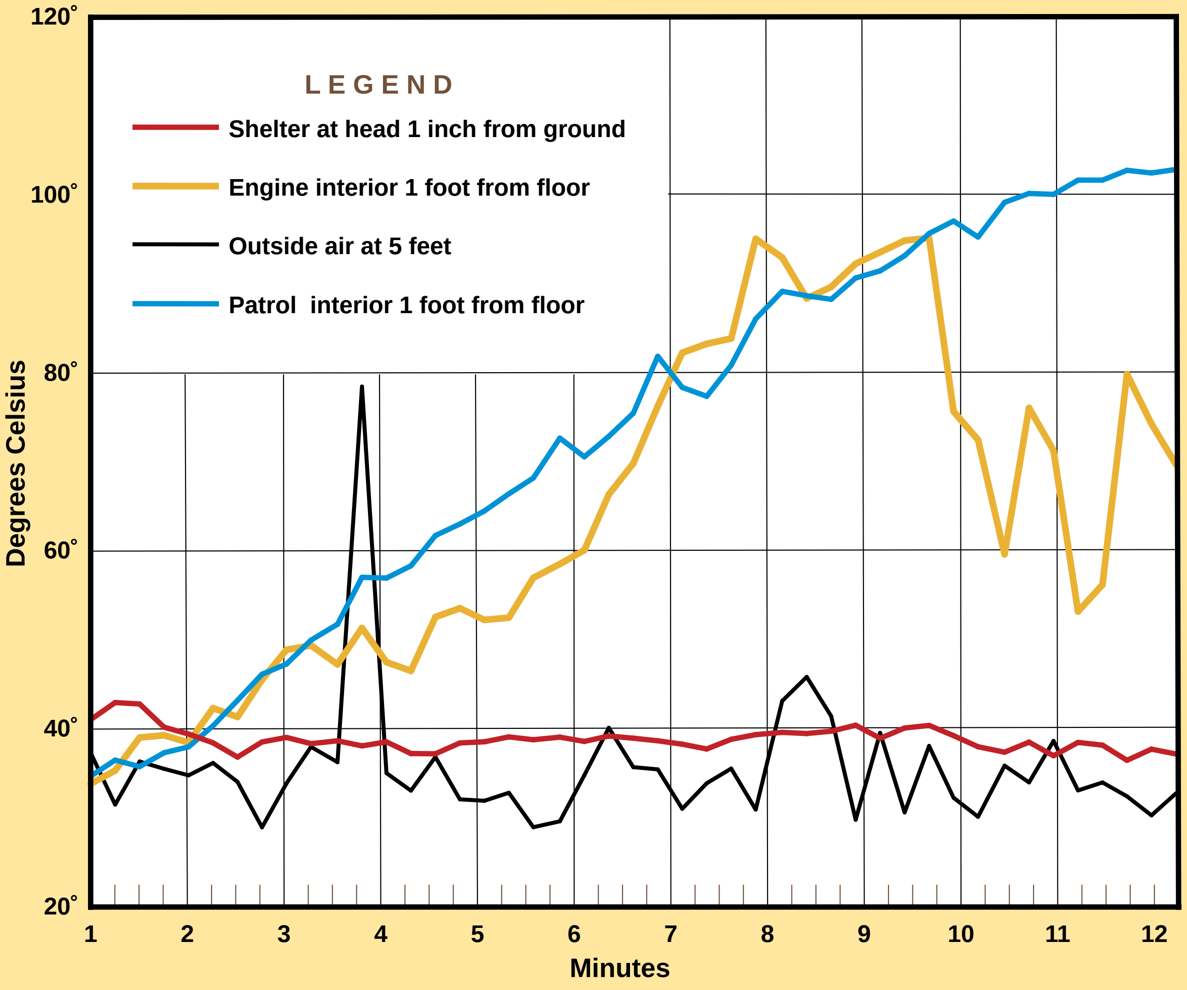
–Although the Nomex had some heat discoloration, it retained its structure and did not break apart or catch fire.

–FR cotton coveralls from the Northwest Territories were not instrumented, but they were laid out immediately adjacent to the Nomex shirt. They were partially consumed by fire ignited by radiant heat.

–A GSA firefighter's hardhat (Model 5100-P) was placed on the ground beside the fire shelter in front of the crew cab engine. It showed significant melting for about 5 inches (13 cm) from its edge, but the rest of the helmet showed no melting or damage (Figure 24).

Figure 24—This hardhat shows the difference a few inches can make at ground level. The hardhat melted where it was closest to the fire, but wasn't damaged just a few inches away from the heat.

Beaverhead


LEGEND
Shelter at head 1 inch from ground
Engine interior 1 foot from floor
Outside air at 5 feet
Patrol interior 1 foot from floor
120˚
100˚
80˚
60˚
40˚
20˚
Degrees Celsius
1
2
3
4
5
6
7
8
9
10
11
12
Minutes

Discussion

This project's primary purpose was to gain quantifiable data on conditions in engine cabs and fire shelters under identical, real-life conditions. However, we made a number of qualitative observations that are relevant to survivability in an entrapment. They include:

✦ In most fuel types (besides grass and light brush), the temperature and radiant heat flux generally increase with the height above the ground. This is consistent with the principle that heat rises. This observation has special relevance considering the height of an engine cab compared to the height of a fire shelter.

✦ Heat from the passage of the fire front appears to be retained in the vehicles longer than in the fire shelter or other items of PPE, indicating that the metal in an engine may act as a "heat sink" (Figure 25).

✦ When fire comes up a steep sideslope, it appears to go over the top of an engine ***and*** under the chassis, creating an eddy on the back side that draws heat and flame (Figure 26). A firefighter taking shelter behind an engine parked on a steep slope would not be protected from heat or flame. This effect was demonstrated in October 1996 when a engine was burned over during the Calabasas Incident in southern California.

✦ Video footage shows that a large volume of smoke seeps into the engine cab, even when the cab's windows are tightly rolled up. This occurred under low-temperature conditions when the cab might appear to be survivable.

✦ When the outside doors of an engine cab are subject to high radiant heat loads, the petroleum-based plastics and sound-deadening materials in the door

Figure 25—Even after a fire has passed, a vehicle retains heat, acting as a "heat sink."

Figure 26—When a fire comes up a steep sideslope, it appears to go over and under the engine, creating an eddy on the back side that draws heat and flame.

panels and dashboard volatilize. The smoke generated by this volatilization may cause both short-term and long-term health effects on firefighters without respiratory protection, and will create conditions that force them from the cab into the fire area.

✦ During the moderate-intensity, short-duration exposure of the Los Angeles County tests, exterior components of the engines either caught fire or experienced some melting (Figures 27 and 28). Under higher intensity or longer duration exposures, the engine could catch fire and continue burning when conditions outside would be harmful to a firefighter attempting to leave the engine.

✦ For these tests, both the engines and fire shelters were placed in the area most likely to receive the highest exposure to the flaming front and the radiant heat flux. In a real-world fire entrapment, moving just a few feet back from the oncoming flaming front—especially on a road cut on steep slopes—appears to significantly reduce the effect of temperature and radiant heat flux on both the individual firefighter and an engine.

Figures 27 and 28—Items on an engine's exterior may catch fire during moderate-intensity, short-duration fires.

✦ Because of safety concerns during testing, the gas tanks on all the engines were empty. In an actual fire operation, damage to the fuel tanks during a burnover could increase the danger to firefighters in or near an engine.

✦ Observation of the exposed PPE indicated that under experienced radiant heat loads, the protective characteristics of the clothing and personal protective equipment appear to offer adequate levels of protection (Figure 29) for an entrapped firefighter who has neither a shelter nor an engine for protection.

✦ The temperature difference between the 1-inch (3-cm) and 12-inch (30-cm) levels in the fire shelters reinforces the need to encourage entrapped firefighters to get on the ground and to keep their face and mouth as close to the ground as possible, protecting their respiratory system.

✦ Since the test engines were drained of gasoline or diesel fuel, the engine's motors could not be left running during the burnover to assess the effect of reduced oxygen on engine performance. Experience during the recent Calabasas entrapment showed that an engine became "oxygen starved" and quit running in a burnover situation. Firefighters hoping to escape a burnover by driving away in an engine should consider this possibility.

✦ Under high heat loads, tempered glass in the cab's windows may break out. This may occur when the difference in temperature inside the cab and the temperature outside is only 4 ˚C. Consideration should be given to using safety glass for greater levels of protection.

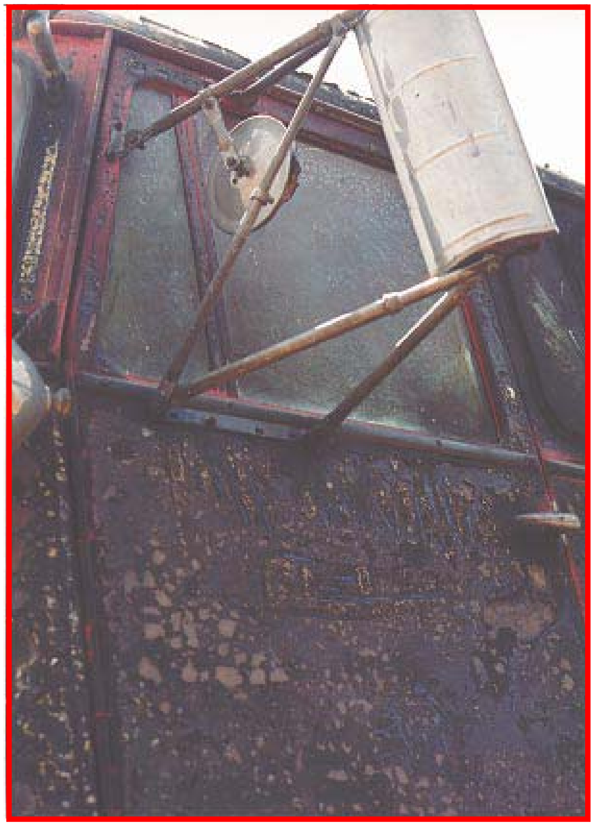


Figure 28.

In a real fire entrapment or burnover, the human dimension is a critical factor:

✦ What is the experience and training of the individuals involved? Does their frame of reference (experience) allow them to recognize the situation they are in, and make the appropriate response?

✦ Do the firefighters have knowledge of all the pertinent factors? In the Wenatchee Heights entrapment, Fire Chief Rick West thought he knew the fuel conditions (grass), but was unaware of the woody component from apple orchard trimmings. That fuel resulted in a high-intensity, long-duration flame front that compromised his safety in the cab of the engine. When he was forced to flee the engine, he suffered serious burns over much of his body.

✦ How much time is available for the critical decision? Can you get all the exposed firefighters into an engine cab safely in less than the 20 to 25 seconds needed to deploy a fire shelter?

✦ Have firefighters considered the need for an adequate Safety Zone early on during the fire suppression, or do they consider their engine or fire shelter to be their “Survival Zone?”

Figure 29—Even though the engine is on fire, the shelters and personal protective clothing are undamaged.

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About the Author

Dick Mangan has been Fire and Aviation Program Leader at MTDC since 1989. His major responsibilities include developing equipment for wildland firefighters, primarily personal protective equipment and equipment for smokejumpers. Dick serves on the National Wildfire Coordinating Group Fire Equipment and Safety and Health Working Teams, and is chair of the National Fire Protection Association's technical committee for wildland fire personal protective equipment. He is red-card qualified as an Operations Section Chief I and Planning Section Chief II, and serves as Operations Section Chief on a national Type 1 fire overhead team. Dick has a bachelor of science degree in forestry from Humboldt State University and more than 20 years experience on Ranger Districts and National Forests in Oregon and Washington. His last assignment before coming to MTDC was as Fire Staff Officer for the Ochoco National Forest in Prineville, OR.

Library Card

Mangan, Richard. 1997. Surviving fire entrapments: comparing conditions inside vehicles and fire shelters. Tech. Rep. 9751-2817-MTDC. Missoula, MT: U.S. Department of Agriculture, Forest Service, Missoula Technology and Development Center. 37 electronic p.

Describes tests in California, Florida, and Montana during which vehicles, fire shelters, and firefighters' personal protective equipment were purposely placed in the path of test fires. Temper-atures inside the vehicles, fire shelters, and surrounding air were measured at levels of from 1 inch to 9 feet above the ground. Radiant heat flux was measured in the immediate vicinity of the engines and in the fire shelters. The levels of six gases (sulfur dioxide, hydrogen cyanide, benzene, hydrochloric acid, toluene, and carbon monoxide) were measured in-side the vehicles and inside fire shelters. The tests showed that temperatures are lower within 12 inches of the ground (where a firefighter would be if lying in a fire shelter) than several feet off the ground (where a firefighter would be sitting in an engine cab). During several tests, plastic materials inside the vehicle caught fire, filling the interior with black smoke. Color photographs show the tests and their outcome.

Keywords: fire engines, fire fighting, fire shelters, protective clothing, safety devices, toxic gases.

Additional single copies of this document may be ordered from:

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Appendix A—Vehicle Entrapments Study Plan

MTDC Project #6287 Vehicle Entrapments

Conduct of Study Plan

PURPOSE

To evaluate factors (heat load, off-gassing) affecting wildland firefighters entrapped in a vehicle, compared to being in a fire shelter adjacent to the vehicle.

METHOD

Subject several instrumented test vehicles and fire shelters to direct flame contact in several different fuel types:

1. Southeastern U.S. Palmetto (NFFL 7)
2. Southeastern U.S. Sawgrass (NFFL 3)
3. California Chapparral (NFFL 4)
4. Grass-Brush (NFFL 2).

Fire shelters, both the current model (FS Spec. 5100-320) and various prototypes, will be set up in the immediate proximity of the vehicles to measure fire and heat effects both inside and outside the shelters.

Firefighter PPE will also be placed around filled 5-gallon water bags and laid in the same area as the shelters to assess visual indicators of heat load and fire effects.

REQUIRED MEASUREMENTS/ OBSERVATIONS

Both formal measurements and visual observations will be taken as part of the documentation of this study. These include:

1. Preburn fuel loading
2. Postburn fuel loading
3. Temperature thermocouples
    - Each 6 inches at 0 to 5 feet
    - Each 12 inches at 5 to 10 feet
4. Off-gassing inside vehicle with FASS packages (IFSL)
5. Heat flux radiometers.

PHOTOGRAPHIC DOCUMENTATION

Desired Photo coverage and support for this study includes:

1. 35-mm color slides of the setup and conduct of the burns, with postfire results of vehicles, fire shelters and other PPE
2. “Beta” video taping, same as above in number 1
3. On-tape interviews of participants during various stages of the burns, with emphasis on the interagency compo-sition of the participants
4. Aerial videos of burnover from helicopter.

WRITTEN DOCUMENTATION OUTPUTS

Written documentation of the burn results, and potential outputs from these burns include:

1. Levels of heat flux by duration
2. Data logger readings from within vehicle cabs
3. Technical report on the burns and results
4. Information articles for technical journals
5. Presentations and/or poster sessions for fire symposiums
6. Potential policy letter from WO-FAM on vehicle entrapments
7. Video production (6 to 10 minutes) on study and results for field.

EQUIPMENT

The following equipment items will be needed onsite for the conduct of the burns:

1. Vehicles (one engine and one pickup type per burn); provided by local cooperators
2. Fire shelters (current model and prototypes)
3. Data-loggers/gas monitors
4. Fire clothing (shirts, trousers, flight suits, coveralls)
5. Web gear, shelter cases, gloves, hardhats (for burning)

6. Flame lengths and duration

7. Visual indicators of damage to all vehicles and equipment.

LOCATION/TIMING

In order to obtain quantifiable data from a variety of fuel types and geographic locations, the following study site be used:

1. Northcentral Florida, in the vicinity of Lake City; the Florida Division of Forestry has agreed to provide excess vehicles at that location to subject to the test fires, as well as personnel to assist the MTDC crew.

2. Los Angeles County, California. Both LA County Fire and the California Department of Forestry have expressed an interest in participating in this study, and in providing surplus vehicles to be burned. Specific agreement needs to be reached with them. In addition, the California State Fire Marshal had expressed an earlier interest in this study, and will be contacted to see if his office will participate.

Proposed timing for the study burns:

Florida: February 23 to March 1, 1996

California: mid-April to mid-May, 1996.

PERSONNEL

The following positions will be needed to complete and document the conduct of these burns:

1. Project Leader (Mangan)
2. Fire Shelter Specialist (Putnam)
3. Instrumentation (Gasvoda/DeLand)
4. Photographer (Kautz)
5. Forestry Techs (Lee/Petrilli/Weger)
6. Cooperator Representative
7. Fire Behavior Analyst (local)
8. Engine crew (local)
9. Fire Instrumentation Specialist (Butler)

JOB HAZARD ANALYSIS—Attached

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Dan Francis
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California State Fire Marshal—
Hugh Council
Phone: (916) 262-1908

Appendix B—Characterizing Gases Generated in Vehicles and Fire Shelters

Introduction

As temperatures increase inside a vehicle cab or fire shelter, synthetic components may thermally degrade into other products by various chemical processes (mainly combustion and pyrolysis). These components include rubber, glass, different types of plastics (polyethylene, polyvinylchloride, acrylonitrile-butadiene-styrene, etc.), and other chemical compounds found in the vehicle's seats, side panels, dashboard, carpeting, floormats, tires, electrical wiring, batteries, circuit boards, and other components hidden behind the dashboard and under the hood. This "off-gassing" can release chemical products that may be toxic or dangerous at some levels. Concern has also been expressed about the chemical nature of the adhesives used in the fire shelter. Because of these concerns, the chemical quality of the air inside a vehicle cab and inside a fire shelter was studied during experiments in which prescribed fires burned over vehicles and fire shelters.

The First Field Test

For field tests scheduled in February 1996, special equipment was needed that could not only monitor the smoke and gas produced in the experiment but survive high temperatures and flame. Although many instruments are commercially available to measure chemical emissions, none is designed to measure emissions while a fire passes over them. The Fire Chemistry Research group of the Forest Service's Intermountain Fire Sciences Laboratory in Missoula, MT, has developed instrumentation that can collect samples while withstanding the hazardous environment of a fire. This instrumentation can collect particulate matter and gas samples, and monitor carbon monoxide and carbon dioxide in real time. Three of these Fire Atmosphere Sampling System (FASS) field packages were loaned to MTDC. In addition, "passive" Drager tubes were used to detect sulfur dioxide, hydrogen cyanide, and hydrochloric acid. These tubes monitored gases that were not monitored by the FASS package. Drager tubes are small, calibrated glass tubes packed with specific chemicals that change color in the presence of the chemical that the tube is designed to detect. The chemical's concentration can be calculated after comparing the amount of color change with calibration marks on the side of the tube. Passive tubes—unlike the more popular active tubes—have no mechanically drawn air flowing through them and operate on the principle of equilibrium diffusion with the surrounding air.

On February 26, 1996, this equipment was deployed on a cured bunchgrass/matted grass-thatch site at Lake City, FL, a day before the prescribed burn planned for the vehicle entrapment study. A FASS package was set up to monitor the air in each of the two vehicle cabs. The third FASS monitored the air inside a standard aluminum fire shelter.

The FASS had to be modified to fit in the vehicles and the shelter. The particulate-collecting "heads" were positioned where a human would be breathing inside the cab or shelter. After particulate is collected on filters in the head, pumps that deliver a flow of 2 liters per minute draw gases through inert Teflon tubing to collection canisters and real-time sensors. The real-time data are recorded on data loggers. The tubing is protected by a loose, flexible ceramic sheathing. The tubing umbilical exposed in the cab was threaded through an aluminum pipe to support the head and umbilical and to provide protection from the high temperatures. The aluminum pipe extended from the cab interior, through the cab floor, to the ground. The 50-foot umbilical (with Teflon tubes inside) was stretched from the lee side of the shelter or vehicles to the main body of the FASS package that holds the sensors, pumps, data loggers, and canisters. The lee side refers to the side of the shelters and vehicles opposite the fire's expected approach. The umbilical and FASS were buried after they had been assembled, calibrated, and armed. The aluminum pipe inside the shelter was slanted from the FASS head to the ground, roughly simulating the position of a human body lying in a shelter. After the arm plug has been pulled, these FASS packages activate once they sense a predetermined level of carbon monoxide. Carbon monoxide is a product of incomplete combustion that will always be produced in a fire. It is one of the first gases produced and its concentration spikes sharply early in any fire episode. The passive Drager tubes were hung inside the cabs and shelter where they were protected with high-temperature foil and tape. The tubes, like the FASS heads, were positioned in the approximate area where a human would be breathing.

A short-duration, low-intensity burn took place the next day. The results were disappointing. One package failed to trigger, while data from the other packages were negligible. The Drager tubes showed no color change. A second burn attempted a few days later in a Palmetto site was cool and spotty because of precipitation. Results were negligible and the Drager tubes indicated no color change.

This burn yielded two major conclusions. Future burns needed to be of high intensity and long duration. In addition, we learned that we needed to develop new compact, portable instrumentation to detect and measure acidic gases that could be generated.

New Equipment

New, simple equipment was developed to detect and measure the acid gases—hydrogen chloride, hydrogen cyanide, and sulfur dioxide (see table at right). Additional chemicals of interest were carbon monoxide, benzene, and toluene. Drager tubes would serve as the “sensors” in the instrumentation. Color changes in the tubes can be examined easily after a test.

Chemical	Predicted Color Change	Reaction Chemistry
Sulfur dioxide	Violet to yellow	SO_2 + pH indicator $\rightarrow$ yellow reaction product
Benzene	White to brown-green	$C_6H_6 + I_2O_5 + H_2SO_4 \rightarrow I_2 + CO_2$ + oxidation products
Hydrogen chloride	Blue to yellow	HCl + Bromophenol Blue $\rightarrow$ yellow reaction products
Toluene	White to brown	$C_6H_5CH_3 + I_2O_5 + H_2SO_4 \rightarrow I_2 + CO_2$ + oxidation products
Carbon monoxide	White to brown	$5CO + I_2O_5 + SeO_2 / H_2SO_4 \rightarrow I_2 + CO_2$ + oxidation products
Hydrogen cyanide	Yellow to red	$HCN + HgCl_2 \rightarrow HCl + Hg(CN)_2$
		HCl + Methyl Red $\rightarrow$ reddish reaction product

The new package used sorbent tubes in addition to the Drager tubes. These tubes generally are more accurate than the Drager tubes, but they show no color change and require laboratory analysis. Either real-time monitoring or a visual indicator like a Drager tube is needed to be sure that an experiment has produced the chemicals being studied. When both tubes are used, the Drager tubes can provide a coarse measurement while the sorbent tubes provide a fine measurement. Four types of sorbent tubes were used to measure sulfur dioxide, hydrochloric acid, hydrogen cyanide, and the b-tex compounds that include benzene, ethylbenzene, toluene, and xylene.

Both the Drager and sorbent tubes in this package require a constant gas flow to be delivered through the tubes, unlike the passive Drager tubes used in the first test. A system of pumps, flow controllers, tubing, and a valved manifold system supplied the air flow. Three pumps were required for each gas sampling package (Figure 1). A 12-volt pump pulls a steady gas stream of 2 liters per minute into the system through $\frac{1}{4}$-inch ID Tygon tubing. This pump was powered by a 12-volt Power Sonic rechargeable gel battery that had a lifetime of 8 hours under continuous usage. Excess gas flow is channeled to an exhaust port. From this main gas flow, two smaller pumps pull the required air flows through $\frac{1}{8}$-inch Tygon tubing to either the sorbent tube sampling train or the Drager tube sampling train. The tubes in each sampling train were arranged in parallel. Each tube has specific flow requirements that are controlled by a valved manifold. The flow across each tube is set by its associated needle valve on the manifold. The pumps pulling flow across each sampling train also can be programmed to adjust flow

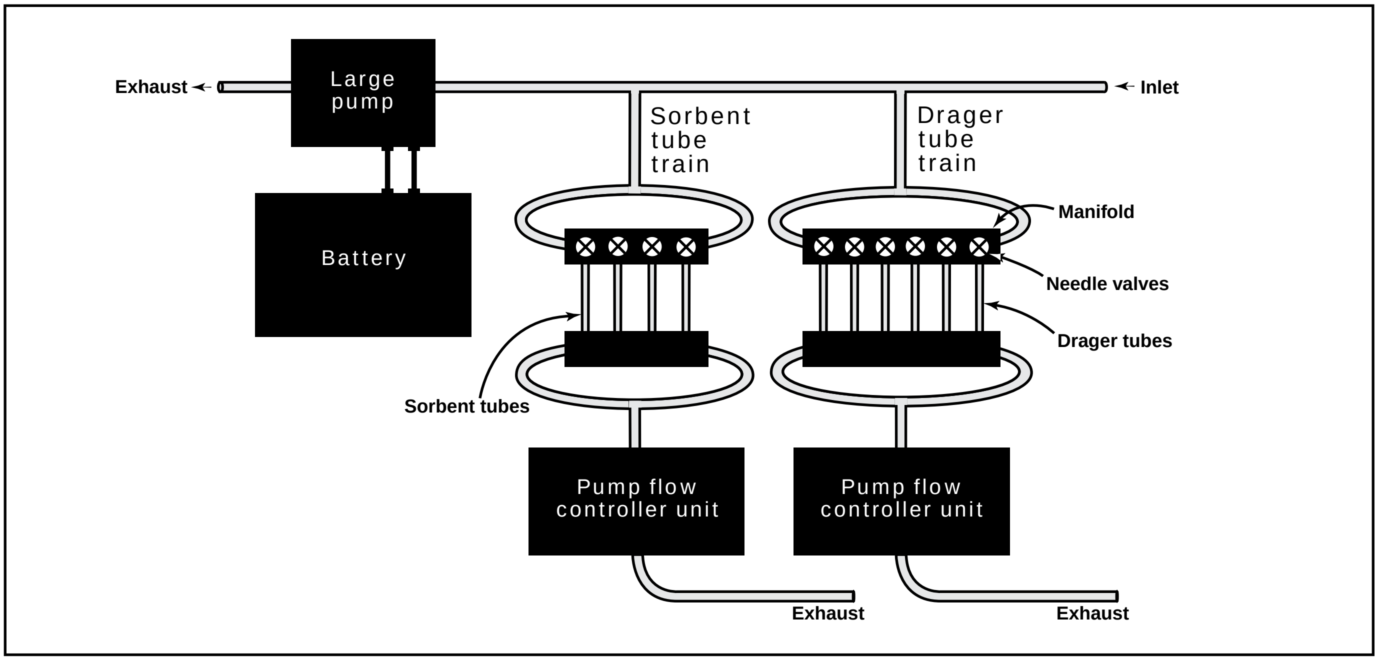

Figure 1—Schematic of the new gas sampling system used during the entrapment tests in California.

control. This guarantees delivery of a constant preset flow rate if the inline Teflon filter collects a great quantity of particulate or if there is a minor blockage (such as pinched tubing) in the system. Once gas has passed through the sampling trains, the gas is channeled to the exhaust ports.

Outer packaging and a long-distance flow delivery system (umbilical) were needed to help the instrumentation survive the hazardous fire environment. The components of the system were mounted on an aluminum sheet that slid inside an old steel military surplus ammunition box. The system was oriented such that the box sits on its side in the field or when working with the interior components. A Swagelok bulkhead fitting provided the connection for interior and exterior tubing. The exterior PTFE Teflon tubing was 24 feet long. A soft ceramic sheath protected it from high temperatures. The sheathing must withstand temperatures as high as 1400 ˚C where it is exposed in the vehicle cab and shelter. The umbilical was supported by an aluminum pipe that extended from the cab, through the floor to the ground. A piece of aluminum over the end of the pipe protected the umbilical and interior tubing while allowing gases to freely enter the tubing.

Field Tests With the New Equipment

The next field tests were during a prescribed burn in June 1996 near Valencia, CA. Two test vehicles were used. The smaller was a Ford “Patrol” Type 5 engine. It had a four-speed manual transmission with a 1-ton chassis manufactured between 1972 and 1976. The cab interior had a large amount of vinyl and plastic. The other engine was a Crown Fire Coach, Type 1 engine manufactured in 1968. It had less plastic and synthetic material in the cab. A dividing window enclosed the front of the cab. All holes and leaks due to age were patched and plugged to simulate a new or operational vehicle that had received regular maintenance.

The vehicles, shelters, and test instrumentation were deployed on June 5, 1996, for a prescribed burn scheduled that day. The vehicles and shelters were situated on the outer edge of a road near the top of a ridge. The hillside below the road had a 70% slope. The vegetation was primarily chamise and sage, fuels known for their volatile oil components. Some cut vegetation was piled in open or sparse areas near the road to provide a continuous fuel source and help create an intense, long-duration fire.

The gas detection system was deployed in a standard aluminum fire shelter and in the Ford Patrol. The umbilical was supported by aluminum pipes inside the vehicle cab (Figures 2 and 3). The remainder of the umbilical stretched across the road to the gas sampling package, which was on the cut bank side of the road. The instrumentation was on the lee side of the vehicle and shelters with respect to the direction of the fire’s expected approach. Before the fire, gas flow across each tube and across the whole train was calibrated. A BIOS dry calibration, piston-type flow meter was used for the calibrations. As close to ignition time as possible, the flow controller was programmed, the pumps were started, and the umbilical and gas box were buried.

The fire was ignited below the road at the bottom edge of the burn unit and swept up the slope to the vehicles and shelters. The fire was more severe and of longer duration than either Florida burn. Instrumentation survived the experiment with no damage. The shelters and vehicles also appeared to have sustained little if any damage. The gas sampling units were retrieved, the pumps were stopped, and the Drager tubes were examined. All the tubes except the hydrogen cyanide tube showed some color change. All experimental tubes were removed and capped. A

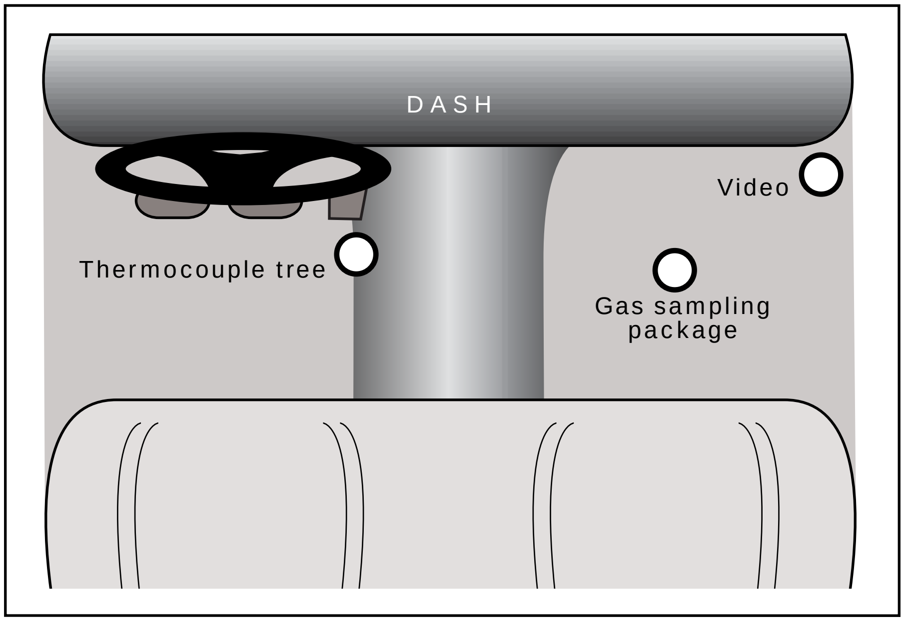

Figure 2—Overhead view of the instrumentation positions in the cab of the vehicle. The aluminum conduit with wiring or tubing inside was fitted through these holes and served as support and protection.

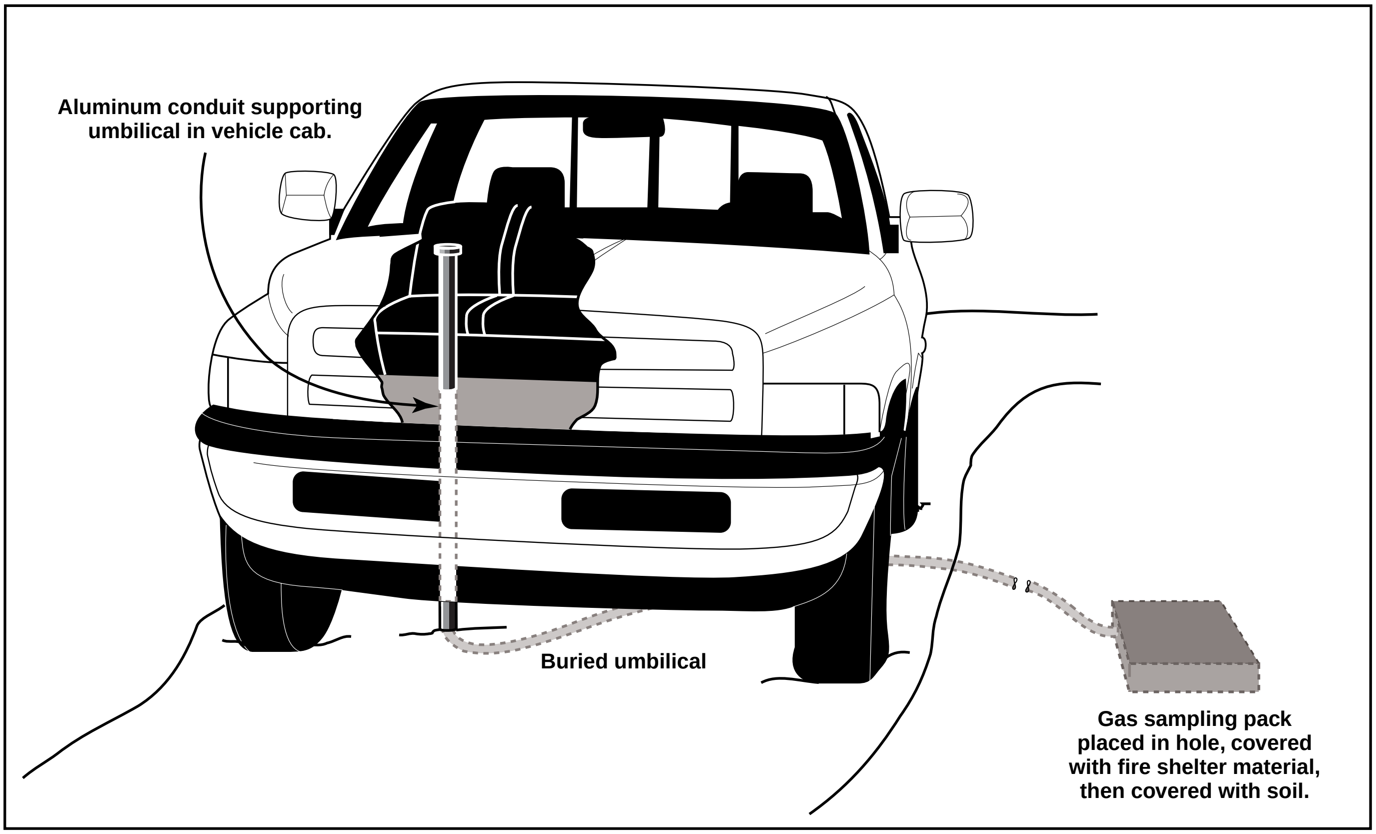

Figure 3—Cutaway view of the gas sampling assembly inside the aluminum conduit in the cab of the vehicle, and underground.

postfire calibration test was run with another set of Drager and sorbent tubes. The Drager tubes were examined and the following results were obtained:

GASES (parts per million)	Engine	Shelter
SO_2	18.7	4.4
HCN	0.0	0.0
Benzene	1.5	0.8
HCl	7.8	1.0
Toluene	13.6	6.3
CO	29.3	5.5

These numbers are derived from calculations applied to concentrations taken from visual examination of the calibrated Drager tubes. New Drager and sorbent tubes must be used for each fire as the reagents are chemically changed, rendering further readings inaccurate or unreliable.

A second prescribed burn took place the following day. The same vehicles were used. No structural damage and very little cosmetic damage (a few paint blisters) had occurred to the vehicles during the first fire. The second site had a higher fuel loading that promised an even more intense and longer fire event. The shelters and vehicles were positioned next to the edge of a road crossing the burn unit as in the first experiment. This road was on the east side of the draw. Some vegetation was cut and piled in bare and sparsely vegetated spots below the vehicles and shelters to obtain a continuous fuel source.

The gas sampling instrumentation was deployed inside the Ford Patrol and standard aluminum fire shelter exactly as it had been the day before. After calibration and as close to the time of ignition as possible, new Drager and sorbent tubes were fitted into the equipment, the pumps were started, and the equipment was buried.

After the fire was ignited, a wind change prevented flames from engulfing the shelters and vehicles. Thermocouple data revealed that the temperatures during the June 6 burn were somewhat higher than during the burn the day before. Those temperatures also lasted longer, an important condition for thermal degradation of materials in the vehicles and shelters. After the fire, smoke continued to rise from the interior of the patrol. When the door was opened, thick, dense, black, sooty smoke billowed out of the cab. This smoke was very black and sooty compared to the brown smoke that had collected in the cab during the first fire. The inside panel of the driver's door was smoking. The synthetic materials on the door panel on the fire side of the cab appeared to be thermally decomposing. Other synthetic materials hidden under the hood may have been in a similar condition.

The Drager and sorbent tubes were collected and capped. A postcalibration test was performed on the equipment. All the Drager tubes except the hydrogen cyanide tube showed a color change. Results from the fire were:

GASES (parts per million)	Engine	Shelter
SO_2	19.8	6.6
HCN	0.0	0.0
Benzene	39.2	11.3
HCl	21.2	9.0
Toluene	26.6	8.7
CO	102.1	50.0

Because no color change was recorded in the hydrogen cyanide tubes for either field experiment, concentrations were zero or undetectable as measured by the Drager tubes. In both experiments, all chemicals other than hydrogen cyanide were detected in both the shelter and the vehicle. Concentrations were higher in the vehicle cab. The concentration of sulfur dioxide was slightly higher during the second burn. The concentrations of benzene, toluene, hydrochloric acid, and carbon monoxide all were significantly greater during the second burn, particularly inside the vehicle. Data from the sorbent tubes for both burns were negligible and unreliable because of pump failures.

The final field test was on July 24, 1996, in the Beaverhead National Forest near Dillon, MT. Two surplus vehicles, a 1955 2½-ton, 6x6 Reo and a 1972 ¾-ton 4x4 (club cab) Dodge pickup, were positioned on an old logging road next to a windrow of lodgepole pine slash. Fire shelters were placed near the vehicles. The dry, densely piled slash and midsummer weather conditions would normally produce an intense fire with a long duration.

One gas sampling system was positioned inside the newer Dodge pickup while the other was placed inside the standard aluminum fire shelter. Some modifications were made to the gas sampling system. Teflon tubing in the umbilical was replaced to ensure the system's purity. Internal plumbing was changed so that one pump flow controller unit was pulling across both the Drager tube and sorbent tube trains. A temperature label was slipped inside the Tygon tubing to monitor gas temperature at the entrance of the gas sampling package. Check valves were added at strategic points to prevent backflows that could contaminate the system or sample tubes. New Drager and sorbent tubes were placed in the collection unit after a calibration test.

The windrow of fuel was ignited. The wind changed direction and flames did not engulf the sides of the vehicles and shelters as expected. Sooty, dark smoke did collect in the vehicle cabs.

After the fire, the boxes were retrieved, the tubes were removed and capped, the postfire flow calibrations were performed, and the Drager tubes were examined. The sorbent tubes were sent to the Clayton Environmental Laboratory for analysis. Each yielded the results shown in the two tables below.

Prefire and postfire calibration data indicated that the sorbent tubes still had flow problems. With such a problem, concentrations could be off by a factor of 10. Although concentrations may have been off, all test chemicals were detected by the sorbent tubes. The concentrations of benzene and toluene were the highest among the gases studied, whether they were measured by sorbent or Drager tubes. Gas concentrations were higher in the vehicle than in the shelter except for hydrogen chloride, where the difference was minimal and the concentrations were low.

DRAGER TUBES GASES (parts per million)	Engine	Shelter
SO_2	3.1	2.9
HCN	0.0	0.0
Benzene	53.0	0.0
HCl	7.7	4.8
Toluene	403.5	0.0
CO	18.7	0.1

SORBENT TUBES GASES (parts per million)	Engine	Shelter
Xylene	3.8	< 0.10
HCN	1.2	< 0.09
Benzene	5.1	< 0.08
HCl	0.4	< 0.60
Toluene	8.10	0.30
Ethyl Benzene	0.96	< 0.06

This test had mixed results. Benzene and toluene appear in concentrations that are nearly as high if not greatly higher than concentrations produced in the California burns. Concentrations of sulfur dioxide, hydrochloric acid, and carbon monoxide were lower than those detected in the California field tests. Temperature data obtained from the thermocouples show that this fire had the longest duration. The temperatures peaked slightly below those of the second California burn but were sustained at higher temperatures for a longer time.

The concentrations derived from the field tests may underestimate the true chemical concentrations. Correction factors were made for the excess amounts of flow before ignition. It is impossible to visually judge when gases are no longer being produced at the end of the experiment. Air volume is measured to the time the system is stopped, whether that air contains gases or not. That may flush and dilute gases in the sample tube.

Discussion

From 1960 to 1975, the average amount of plastics in vehicles increased from 25.9 to 129.5 pounds. This trend has continued. Today the average vehicle contains over 200 pounds of plastic. Barbara Levin has compiled a literature review (Levin 1987), *The Chemical Nature and Toxicity of the Pyrolysis and Combustion Products of Seven Plastics*. Seven plastics were documented to produce over 400 chemicals. All seven plastics (Table 1) could generate carbon monoxide, and six of the seven could generate benzene and toluene. The table shows some of the data from her literature review.

Many plastics, including those commonly found inside motor vehicles, can produce the chemicals detected in these field tests. The flash ignition and decomposition temperatures (Table 2) for some of these plastics are in the range of temperatures reached inside or near the cabs of the vehicles (Table 3) during the tests. Long polymer chains decompose in the presence of heat or flame, producing chemicals of lower molecular weights such as hydrogen chloride, hydrogen cyanide, and similar chemicals.

Smoke, ranging in color from dark brown to dense sooty black, accumulated in the cabs of all the test vehicles during each of the field tests. Even after the June 6 burn was over, the Patrol continued to generate this smoke. This provides some evidence that the smoke was generated from some of the vehicle's synthetic components. In the early stages of decomposition, styrene polymers and acrylonitrile-butadiene-styrene (ABS) characteristically generate black, sooty smoke rich in aromatic polymers.

Table 1—Gases produced by seven plastics.

GASES PRODUCED BY SEVEN PLASTICS					
	Benzene	**HCl**	**HCN**	**Toluene**	**CO**
Rigid polyurethane foam	✓	✓	✓	✓	✓
Polyester	✓			✓	✓
Polyvinyl chloride	✓	✓	✓	✓	✓
Polystyrene	✓			✓	✓
Nylon	✓		✓	✓	✓
Polyethylene	✓	✓		✓	✓
Acrylonitrile-butadiene-styrene			✓		✓

Table 2—Flash ignition and decomposition temperatures for six plastics.

FLASH IGNITION AND DECOMPOSITION TEMPERATURES		
	Flash ignition temperature (˚C)	**Decomposition temperature (˚C)**
Polyethylene	341-357	340-440
Polyvinyl chloride	391	200-300
Polystyrene	345-360	300-400
Acrylonitrile-butadiene-styrene	466 (self ignition)	300-400
Nylon	421	300-350
Rigid polyurethane foam	310	

Table 3—Temperatures reached in the outside air, inside a vehicle cab, and inside and outside a fire shelter during three tests.

TEMPERATURE COMPARISONS INSIDE AND OUTSIDE				
	Location	June 5 (˚C)	June 6 (˚C)	July 24 (˚C)
Vehicle:	Outside	1000	440	< 200
	Cab ceiling	< 85	280	250
	Cab floor	—	45	—
Shelter:	Outside surface	430	300	150
	Inside surface	150	180	140
	Inside 2 inches AGL	150	< 80	40
	Inside 12 inches AGL	220	—	75

Carbon monoxide can be produced as a byproduct of the thermal decomposition of many plastics. It is also a product of incomplete combustion and is produced in any wildfire. A portion of the carbon monoxide detected may have come from smoke produced by natural fuels. Sulfur dioxide may be produced by thermal degradation of tires. Some tires were undamaged during the first California burn but caught fire during the second. During the Montana burn, tires burned on the side facing the fire and smoked on the other side. Concentrations of sulfur dioxide were highest during both the California burns, even though the tires generally did not burn or smoke. Industrial processes in the state may have contributed to the concentration of sulfur dioxide. Baseline data before the experiment could have helped determine the ambient concentration of sulfur dioxide on the day of the burn.

The fire shelter contains no plastics to serve as a source for these chemicals. However, all chemicals except hydrogen cyanide were detected in the fire shelter. Hydrogen cyanide is a component of the adhesives used in the shelter. This chemical was not detected by the Drager tubes and was only detected in small quantities in just one experiment by the sorbent tubes. The proximity of the shelters to the engine may have contributed to concentrations of these compounds. The swirling winds may have transported the chemicals to the air near the shelter and mixed the gases there. Pinholes and pores in the shelter material may have allowed the gases to enter. Smoke may have gone under the fire shelters. This is unlikely because heavy chain weighing down the inside perimeter of the shelter appeared undisturbed after each experiment. The lowest concentration of all chemicals except toluene was recorded during the Montana burn, when the wind was moving the fire's smoke away from the vehicles. The questions raised by these results might be answered if an additional gas sampling unit were deployed inside the burn unit to measure ambient gases near the shelter and vehicle.

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—Lynn Weger has worked on fire projects at MTDC since 1996. She graduated from the University of Montana with a B.S. degree in chemistry in 1987 and began working at the Forest Service's Intermountain Fire Sciences Laboratory the following year.

Component List

The following is the list of components used to assemble the gas sampling system.

Diaphragm pump, 5x4x2$\frac{1}{2}$ inches, 12 volt dc, 1.5 amps	KNF Neuberger, Inc.
Rechargeable gel cell battery, 7$\frac{3}{4}$x4$\frac{1}{2}$x2$\frac{1}{4}$ inches, 12 volt, 8 amp hours	Power Sonic
Tygon tubing, large size $\frac{1}{4}$-inch ID, $\frac{3}{8}$-inch OD, $\frac{1}{16}$-inch wall	Cole-Palmer
Tygon tubing, small size $\frac{1}{8}$-inch ID, $\frac{1}{4}$-inch OD, $\frac{1}{16}$-inch wall	Cole-Palmer
HDPE fittings, high-temperature resistance, various shapes	Cole-Palmer
Manifold, 12-port black anodized aluminum	Clippard Minimatic
Brass needle valves, 10-32 male	Clippard Minimatic
Brass fittings (plugs, hose barbs, pipe to hose)	Clippard Minimatic
Teflon tape	Cole-Palmer
Alpha constant-flow air sampler	Dupont
Temperature labels	Omega
Drager tubes	National Draeger, Inc.
Sorbent tubes	National Draeger, Inc.
Teflon tubing, 0.190-inch ID, 0.250-inch OD, 0.03-inch wall	Cole-Palmer
Voltrex ceramic sleeve packing, 1 inch x 25 feet, $\frac{1}{32}$-inch wall	SPC Technology
Bulkhead Swagelok fitting	Idaho Valve and Fitting
Aluminum plate 13x16$\frac{7}{8}$x$\frac{1}{4}$ inches	scrap
Steel surplus ammunition box, 17$\frac{1}{4}$x 7$\frac{5}{8}$x14$\frac{1}{8}$-inch wall	scrap

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Appendix C—Insulated Boxes for Protecting Video Cameras

Four camera systems were designed and built to provide video documentation of tests in which instrumented fire shelters and vehicles were burned over by simulated wildfires. A wildfire is able to reach temperatures of 1093 °C for short periods and 815 °C for longer times. Each system uses a video camera (no recorder) in an insulated box with a video tape recorder and battery in another box buried underground.

The camera is a Sony SSC-DC30 with a threaded "C" mount that accepts various lenses. Lenses from 3.5 to 50 mm are available. This camera requires a 12- to 18-volt, 4.5-amp current and outputs a standard NTSC video signal.

The recorder is a Sony Hi8 camcorder (CCD-TR700). The camera portion of this unit is not used. The video signal from the SSC-DC30 camera is fed directly into the video tape recorder. The camcorder requires a 6.5-volt, 2-amp current.

One battery powers both units. The battery is a 14-volt, 5-amp-hour Gates Cell that is fused. The camera is powered directly from the battery; the camcorder uses an adapter to reduce the voltage.

The insulated box, made of 16-gauge stainless steel (Type 306), has tripod mounts welded on the bottom. The insulation inside the box is 1-inch thick ceramic board. This ceramic has a continuous-use temperature of 1260 °C. Its thermal conductivity at 815 °C is 0.95 BTU inches Hr °F Ft^2.

The window for the camera is a thermopane design using Corning Vycor glass on the outside and a hot mirror on the inside. The Vycor glass is 96% silica and 4% boric oxide. It can be used continuously at 898 °C and intermittently to 1298 °C. This glass has a high resistance to heat shock. It can be heated to 900 °C and plunged into ice water without breaking. The inner glass is a dichroic mirror that transmits 90% of visible light (400 to 700 nm) and reflects 98% of the infrared light (wavelengths greater than 700 nm). The metal coating on the glass faces the outside of the box. This prevents radiant energy from heating the camera.

The Sony SSC-DC30 camera uses 4.5 watts of power. This will generate heat that raises the temperature inside the insulated box 0.0033 °C per second or 24 °C in 2 hours. The resulting temperature would be higher than the maximum recommended temperature of 52 °C. To keep the camera cool, 16 ounces of blue ice is frozen and placed under the camera mount. The power and video cables connecting the camera to the battery and recorder are routed through woven ceramic sleeving that is routed through steel conduit. The conduit is then wrapped with ceramic blanket (rated for continuous use at 1300 °C) and the assembly is wrapped with aluminized fire shelter material.

The camera must be within 5 to 10 feet of the subject. If the camera is farther away, smoke is likely to obscure the subject. The camera is mounted on the aluminum base plate, placed in the insulated box, and connected with a coax cable to the Tektronics waveform/video monitor. The Tektronics monitor becomes the viewfinder. The waveform is used to adjust the camera exposure. After the exposure has been adjusted, the monitor is disconnected and the camera is connected to the video camcorder/video tape recorder (VTR). The recorder can record for 2 hours.

Instructions for the Video Camera Systems

1—Freeze the blue ice 2 days before use (some freezers will not freeze the ice overnight).

2—Bolt the tripod legs to the box with ¼-inch bolts. Insert the power cable and the coax cable into the box one at a time. Connect the insulated conduit to the bottom of the box.

3—Choose the camera location and set up the boxes. The wide-angle camera lenses allow the camera boxes to be within 5 to 10 feet of the subject. This is important because smoke can obscure the subject. *Cameras inside vehicles must use the 3.6 mm Computar lens.*

4—Mount the camera on the aluminum channel with a ¼-inch flathead bolt. Connect the power cable. Connect the coax cable to "video out" using a right-angle BNC adapter.

5—The switches on the back of the camera are:
DC 12V—*off and on*
MODE—*B*
WHT BAL—*ATW*

6—The switches on the side of the camera are:
SHUTTER SPEED—*2*
AUTO IRIS—*video*

When using the Computar lens (black), plug the lens cable into the lens terminal.
CCD-IRIS—*off*
AGC—*off*

When using the Angenieux Lens (silver):
CCD-IRIS—*on*
AGC—*on*

7—The battery box is placed in the ground (not too deep at first, because dirt tends to fall inside the box before it is sealed). The power cable, the coax cable, and the remote control cable are fed through the hole in the lid. The hole is taped to prevent dirt from entering.

8—Connect the power cable to the battery. Connect the camcorder power cable to the battery and to the camcorder.

9—Connect the coax cable from the Tektronics monitor to the coax cable from the camera using a female-female phono adapter.

10—Turn on the camera and the Tektronics monitor. The PIX button shows the picture from the camera. The WFM button shows the waveform (exposure).

11—Focus the lens on infinity (the wide-angle lenses do not focus). The lens mount must be adjusted by loosening the Phillips screw (LOCK) on the side of the camera and turning the lens thumbscrew on top of the camera. Use the Tektronics monitor (PIX) to view the picture.

12—The Computar lenses have two adjustments:
ALC (automatic level control)—A (average), P (peak).
LEVEL (exposure)—High or Low.

To adjust the exposure, put the Tektronics monitor on WFM. The scale on the waveform is from 0 to 100%. It is okay to have some spikes above 100%, but if there is a solid line above 100%, the video is overexposed. *When setting up the camera inside a vehicle, the windows will be overexposed. After fire and smoke surround the vehicle, the exposure will be fine.* Start with the ALC in the middle and adjust the LEVEL. Inside the vehicle it is better to set the ALC toward A (average).

13—Disconnect the camera coax cable from the Tektronics monitor and plug it into the video jack (yellow) on the camcorder. Use a right-angle phono plug adapter. *The CCD-TR101 has a switch that must be set to input.*

14—Plug the remote control into the REMOTE jack. Then turn the camcorder power switch to VTR. *The power switch on the remote can turn the power on or off only if the power switch on the camera is set to VTR.* Insert a 120-minute tape. Look into the viewfinder to confirm that the video signal is coming from the camera. If it is not, check all power and cable connections.

15—Record some video by pressing the two REC buttons on the remote control. Rewind and play the tape. *The remote control will show the counter running and a round dot will display, confirming that the camcorder is recording.* The playback can be viewed in the viewfinder or by connecting the Tektronics monitor to the camcorder video jack.

16—Close the boxes and start recording just before the fire. Seal the camcorder box and the remote control in a plastic bag and bury them. *Be careful not to depress any buttons when burying the remote control.*

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