# HIGH TEMPERATURE ACCELERANT FIRES

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## INTRODUCTION

In the past decade, several bizarre, deadly arson fires have been reported in the Pacific Northwest and elsewhere across the country. These fires which have been dubbed "High Temperature Accelerant" (HTA) fires have been the nucleus of thousands of man-hours of investigation by the fire investigation and scientific communities. The cause of the extraordinary interest provoked by these fires centers around their unusual behavior. Early efforts at identifying HTA compositions and attempting to understand their fire dynamics were concentrated among fire investigators in the Seattle area. Because of increasing reports of similar fires in other parts of the country however, an expanded interest in this phenomenon is rapidly occurring.

This report aims to illustrate many of the previously known aspects of High Temperature Accelerant fires, and to explain what recent progress has been made in interpreting their behavior. It will also attempt to present the latest available information to assist investigators not only in recognizing an HTA fire, but also in locating and collecting the available evidence necessary to establish the corpus delicti. Further, it will review several suspected HTA fires in order to identify common factors among them and frequent misconceptions regarding their behavior.

Prior to beginning any discussion of HTA's, it seems prudent to first define what an HTA is and what it is not. Though no precise origin of the term "HTA" is known, it appears the expression was first used in the early stages of the Seattle Fire Department's investigation. It gained popularity when investigators believed that the fires they were seeing behaved much differently than would be expected. For instance, typical fires generally do not generate temperatures higher than 2,000°F (1,093°C). With such temperatures, finding damage such as melted steel or badly damaged concrete is unusual. Since investigators began finding such damage in the first of the now entitled HTA fires, a name was created to describe what was thought to be a new type of blaze.

This paper will use "HTA" in describing and discussing the various fires to be examined herein. In general, fires with nominal temperatures in excess of 2,500°F will be generally depicted herein as HTA fires. While such temperatures can be achieved with exotic organic fuel combinations or under special oxidation conditions, probably the most common way to attain these temperatures is burning a combustible metal fuel/solid oxidizer mix. While a more accurate name might be "High Temperature Fuel" fires, the currently familiar term of HTA will be used.

## CURRENTLY REPORTED CHARACTERISTICS OF HTA FIRES

Once Seattle fire investigators began to recognize patterns common to high temperature fire scenes, they attempted to further characterize the unusual aspects of the fires. The following is a summary of some of the recurrent properties they identified.

- One earmark of HTA fires is the appearance of intense white or nearly white flames often restricted to a relatively small area. These flames have been described as similar to an energized welding rod or a carbon-arc light. While in some instances, these bright flames were noted at the beginning of a fire, flare-ups have also been seen after a fire was well involved.
- Often accompanying the white flames are displays of white-hot pyrotechnic-like sparks emitted from the fire. Videotaped footage of at least one fire has captured this phenomenon as it occurred.

- As the name describes, HTA fires generate extremely high temperatures. This can be evidenced not only be appearance of white-hot flames, but also by the damage found in the aftermath. While some claims have been made that these fires attain upper temperatures of between 4,000°F to 7,000°F, a more reasonable upper limit is between 4,000°F and 5,500°F. Increases much past this point would generally require additional pressurization not present at building fires.
- Concrete subjected directly to burning HTAs can be extensively damaged. Unusually deep "spalling" may occur as well as a blue-green discoloration. In certain instances, concrete has melted, or has become so brittle as to be crushable with one's hands.
- In addition to extreme concrete damage, metals such as steel and cast iron have apparently melted or eroded in suspected HTA fires.
- Several of the suspected HTA fires in large, almost vacant buildings (with only structural fire loads) reached flashover in "unusually rapid" times. [While flashover can not be precisely defined, it is generally considered the point in a fire at which gaseous temperatures in a compartment reach between 500°C and 600°C (932° to 1,112°F). In this range, all

of the available combustible materials in a room typically ignite, given sufficient oxygen.]

- Another frequently reported occurrence in HTA fires is abnormally quick structural collapse. Estimates of the early roof and wall failures have been between 10 and 40 minutes. [As with defining "rapid flashover", classification of early structural collapse is obviously contingent on precise knowledge of when a fire started.]
- Another indication of an HTA fire is an apparent aggravation of flames by the application of water. Several fire companies have discovered while adding water to HTA fires, that the situation has worsened and created (at least the appearance of) a more intense, faster burning fire.
- Burn patterns found at several suspected HTA fires were similar to those associated with liquid accelerants fires. They are typically irregular in shape and often located near areas of greatest damage.
- Standard methods of forensic analysis of arson debris have failed to confirm the presence of liquid hydrocarbons in each of several samples taken from suspected HTA fires.

**EARLY INVESTIGATIVE EFFORTS**

Attempts to recognize and understand HTA fires originated at the Seattle Fire Department after its first incident in January 1984. In the next four years, four more suspected HTA blazes impacted Seattle, culminating with the deadly Blackstock Lumber fire in September 1989 in which a Seattle Fire Lieutenant died. Subsequently, the Department embarked on an fervent attempt to educate firefighters throughout the country about the danger such fires pose. As part of their effort, they enrolled the voluntary assistance of top private, university and government scientists and engineers throughout the nation. Among the various agencies and companies assisting in the early HTA studies were:

**Sandia National Laboratory**

**Lawrence Livermore National Laboratory**

**Rocket Research Company (division of OLIN Corp)**

**Machine Design Engineers, Inc.**

**Weyerhauser Corp. Fire Technology Laboratory**

**Construction Technology Laboratory**

**University of Washington**

**California State University, San Jose**

**University of California, Davis**

**Washington State Police Crime Lab**

**Bureau of Alcohol, Tobacco & Firearms**

**California Department of Justice**

**U.S. Navy Research Laboratories**

**U.S. Navy Air Warfare Center, China Lake**

The resulting consultations and discussions between participants eventually led to a full scale HTA fire test in 1990. Subsequent to this test, Seattle Fire Department produced an educational videotape and distributed more than a thousand copies to fire departments throughout the nation. The impact of the videotape has been exceptional in raising the overall awareness of HTA. One effect was the generation of several more accounts by investigators in Washington, California, Illinois, Florida, Indiana, Pennsylvania and Canada of similar fires they had experienced dating back to 1981.

In addition to being the subject of Seattle Fire Department's educational efforts, HTA fire have also received substantial coverage by the national print and television media. Articles and programs featuring the fires have appeared in the **Wall Street Journal**, **CBS National News**, **Unsolved Mysteries**, **Firehouse** Magazine, the **State Peace Officers Journal**, **The National Fire & Arson Report**, and the **California Fire and Arson Investigator**.

## SUSPECTED HTA FIRES

Since the outset of the Carpet Exchange investigation in 1984, more than 20 fires around the country have been attributed to HTA. Table 1, compiled as of early 1994 lists possible HTA fires as surmised by the departments that investigated them.

Table 1

| Date | City | Name |
|---|---|---|
| 1/27/81 | Yakima, WA | Northwest Produce Warehouse |
| 9/11/82 | Spokane, WA | Tri-State Distributors |
| 9/16/83 | Yakima, WA | Artificial Ice Company |
| 9/16/83 | Yakima, WA | Clasen Fruit Company |
| 1/17/84 | Seattle, WA | Carpet Exchange |
| 3/25/84 | Bellingham, WA | Bellingham First Christian Church |
| 5/2/84 | Yakima, WA | Hansen Fruit Company |
| 5/23/85 | Woodland, CA | Cal-Wood Supply Company |
| 11/20/85 | Tacoma, WA | Advanced Electroplating |

| Date | City | Name |
|---|---|---|
| 11/30/85 | Seattle, WA | Victory Bumpers |
| 7/29/86 | Perry Township, IN | Comfort Inn Motel |
| 4/7/87 | West Chicago, IL | Crown Products, Inc. |
| 5/12/87 | Perry Township, IN | Buckcreek Lumber Company |
| 1/28/88 | Kitsap County, WA | Golden Oz Restaurant |
| 2/17/89 | Seattle, WA | Maritime Shipping Building |
| 9/9/89 | Seattle, WA | Blackstock Lumber Company |
| 10/29/89 | Del Ray Beach, FL | Patio Del Ray Restaurant |
| 1/10/90 | Winnepeg, Manitoba, CAN | Kirby Terrace Apartments |
| 3/21/90 | Lake Park, FL | E & H Boat Works |
| 3/1/91 | Orlando, FL | Central Florida Mack Truck |
| 4/19/91 | Sumner, WA | 13410-8th Street East |
| 6/29/91 | Sharon, PA | Galaxy Cheese Company |

| Date | City | Name |
|---|---|---|
| 7/16/91 | Woodland, CA | Adams Vegetable Oil Plant |
| 8/8/91 | Pitt Meadows, British Columbia | Purewal Blueberry Farm |
| 8/22/91 | Hebron, IL | Crown Industrial Products |

## PARTICIPATION BY THE BUREAU OF A.T.F.

In the past several years, media accounts as well as statements by investigators have reported a conclusion that a conspiracy is behind the use of HTA fires in arson-for-profit schemes. Despite the lack of any identified credible evidence to corroborate these claims, several questions have arisen in the law enforcement and fire communities as well as in legislative circles as to what can be done about the apparent problem in terms of a coordinated national effort. Because of the narrow jurisdiction of the various local agencies investigating the suspected HTA fires, expansion of their investigation into a widespread probe of possible links between fires was difficult. In an effort to minimize such a limitation, the Bureau of Alcohol, Tobacco and Firearms, the federal government's lead law enforcement agency in the fight against arson, was called upon by Congress for an opinion. It was decided, that to properly address the issue and to confirm or refute the veracity of media claims that "an 'arson-for-profit' group is responsible for fires ... that have killed two firefighters and caused millions of dollars in property damage" (1), a review of all suspected HTA fires and associated research efforts was in order. Although agents had participated in the investigation of Pacific Northwest fires since 1990, no nationally inclusive effort had been attempted.

Accordingly, beginning in early 1994, ATF set out to collect as many fire reports as possible for the suspected HTA fires. Additionally, where videotape, photographs and other data was available, it was also gathered and examined. (It should be noted that there was little visual material available for many of the fires. Where visual review was part of the analysis, it will be noted). It was acknowledged from the start that a review at such a late date would not likely conclusively determine whether or not the fires were actually caused by an HTA. Nevertheless, it was determined that such an analysis might identify useful correlations or discrepancies between the investigations. These might then aid in establishing whether the fires were consistent with any particular modus operandi as has been suggested.

Once the limited information was received, the author, a Certified Fire Investigator familiar with the nuances of HTA behavior, systematically reviewed the various reports and original findings of the investigators on scene after each fire. Subsequently, several telephone conversations were held with many of the investigators in an attempt to clarify ambiguous or confusing points. These conversations were not only with the authors of the various reports, but also with other investigators that might have also investigated the same fires. This was done in order to gather as many opinions as possible as to the fire causes. In addition to cause and origin reports, as many witness accounts as possible were reviewed to attempt and recreate the investigative information available at the times of the original investigations.

A brief synopsis of information gathered from these reports and the above mentioned conversations is included in this study. Where discrepancies exist, they are discussed. While this review was intended to critique this information, the names of the various investigators are not listed in order to eliminate any appearance of personal criticism. The aim of this review is not to castigate, but to expand the base of knowledge about high temperature fires so that future investigations might have an increased probability of pinpointing the cause of high temperature damage, and, if arson is involved, to apprehend those responsible.

Prior to beginning an examination of the suspected HTA fires, discussions of the various high temperature fire tests are in order. Additionally, a review of the chemical principles that apply to two examples of metal combustion (representative of the likely bulk of HTA mixtures) is included, as is a reassessment of the role of radiation in fire growth. Such information must, after all, be relied upon in conducting any thorough and thoughtful evaluation.

## REVIEW OF HTA FIRE TESTS

In the last ten years, several HTA fire tests have been conducted with the hope of identifying investigative leads to be used in tracking the arsonist(s). These tests varied from simple "backyard-experiments" to very complex scientific inquiries. While there may have been additional examinations of which the author is unaware, the following discussions of HTA research represent much of the work done relative to this pursuit.

### FULL SCALE THERMITE TEST

Shortly after the Carpet Exchange fire in 1984, Seattle investigators learned of a series of arson fires in Reno, Nevada in 1979 in which thermite compositions known as **CADWELD** and **THERMOWELD** were used as the accelerants. The chemical makeup of the Reno accelerants were, at least in part, consistent with the debris collected at the Carpet Exchange. The following year, a full scale fire test was conducted by the Seattle Fire Department. The test took place in a vacant two story, wood framed house. In it, 126 pounds of **DUWEL**, a commercial thermite mixture, was used as the accelerant. The purpose of the test was, in part, to try and visually duplicate the results of the Carpet Exchange fire. Accordingly, scientific instrumentation was not used to collect test data.

During the test, the **DUWEL** was poured unconfined on the concrete floor and ignited. Fire reportedly quickly breached the roof and within thirty minutes the house collapsed. No fire suppression was attempted. According to observers, the fire appeared unlike that seen and filmed at the Carpet Exchange. While greater damage was caused by the **DUWEL** than would have been expected from a hydrocarbon accelerant, the fire's intensity did not reach that seen at the Carpet Exchange. The damage included slight melting of one piece of steel angle iron, and a blue-green discoloration of concrete.

## PUYALLUP FULL-SCALE TEST

In 1989, the Seattle Fire Department experienced two more suspected HTA fires, the Maritime Shipping Building and the tragic Blackstock fires. After the death of the Seattle firefighter, the investigation resumed at a feverish pace. Several scientists and engineers asked by Seattle F.D. to examine the HTA data, stated they believed the HTA fuel was likely a mixture of combustible powdered metals and solid oxidizers, similar to the constituents of solid rocket fuels. Subsequently, in early 1990, two series of small scale tests were conducted to narrow the choice of fuel/oxidizer mixes from a myriad of possibilities. In these tests, small amounts of various mixtures were burned and the results were qualitatively analyzed.

Armed with the data from the small scale tests, participants conducted a full-scale incendiary burn on March 25, 1990 in Puyallup, Washington (2). The test was conducted in an empty, one story commercial building with 14 foot ceilings and approximately 30,000 square feet floor space. The main structure was heavy-timber construction with 6 x 8 inch columns and 8 x 28 inch gluelam beams. The roof was composite tar and gravel on a 4 x 6 inch tongue and groove wooden deck. The accelerant consisted chiefly of aluminum powder and various oxidizers, along with diesel added to minimize the possibility of static ignition. In all, the amount of fuel used at various places in the building was about 462 pounds.

Prior to the fuel ignition, scientists and engineers instrumented the building with numerous thermocouples, calorimeters, gas analyzers (oxygen, carbon dioxide and carbon monoxide), and pressure transducers. Additionally, fire investigators placed several samples of construction materials near the accelerant to observe its effects on them.

Though not all of the incendiary material was initially ignited, the results were nonetheless astounding (3,4). At about one minute into the fire, a set of glass doors were forced open from an interior pressure rise of about 80 pascals (approx 0.01 psi). Seconds later, a "spill" of the mixture that had been poured onto the floor self-ignited. At 1 minute and 25 seconds (1:25) into the fire, smoke obscured the front of the building. Flashover appeared to take place at 2:00 minutes and at 2:25 the front windows began breaking and hot fuel-rich gases poured out of the openings, sending flame plumes well above the roof. At 3:00

minutes, it appeared as if the incendiary mixture had burned out. No water was applied until 5:20.

Ceiling temperatures began climbing immediately, until at about 80 seconds, they peaked at between 400°C and 700°C. Temperatures then fell for 20 seconds to between 250°C to 400°C when they then began rising again dramatically. Within 20-40 more seconds, ceiling temperatures reached above 1,100°C. Elsewhere, smoke layer gases rose, temporarily fell and then peaked again at the same times discussed above, ultimately reaching temperatures near 1,300°C.

An analysis performed by Sandia National Labs showed the radiant heat flux measured near the accelerant initially pulsed at about 25-30 Watts/cm$^2$. Shortly thereafter, it stabilized at near 15-25 W/cm$^2$. Sandia also showed that the heat flux near the ceiling remained low until about one minute into the test. It then climbed to between 3 and 5 W/cm$^2$ for about 25 seconds and then fell to near zero for 20 more seconds. At flashover (2:30 minutes), it had climbed to a peak of near 19 W/cm$^2$. Lawrence Livermore Labs measured the heat flux 5 feet above the floor on the south wall. There, it slowly rose to about 1 W/cm$^2$ at 2:00 minutes and then climbed quickly to a short-lived peak of about 16 W/cm$^2$ at flashover, 25 seconds later. [For comparison purposes, one should consider that most fire scientists accept that a consistent radiant heat flux of approximately 2 $W/cm^2$ will typically produce flashover.]

A review of oxygen sensor data shows that about 90 seconds after ignition, $O_2$ levels dropped from 21% to 10%. At about that time, the glass double doors in the south were forced open. The interior $O_2$ concentrations then rose again to a peak near 19% thirty seconds later at 2:00. A second, more rapid reduction began at 2:00 when levels plummeted to less than 3% near the time of flashover and fuel extinction. Subsequently, levels again began rising to ambient (4). In this instance, the relatively quick return of oxygen to normal levels is likely due, in part, to the fact that the test building had several large display windows that failed near the time of flashover leaving large openings through which hot gases could escape and outside air could return.

This test and these measurements clearly demonstrated the destructive potential of combustible metal fuels when used as accelerants (3,4,5). In a very short time, a relatively small amount of fuel had driven the temperatures of the combustible materials in the structure to well beyond their ignition points. The fire in the near-empty building reached flashover in about two-and-one-half minutes. Typically, if ordinary fuels were used, flashover would have taken about 30 minutes for a similarly sized building. For a typical residential room, reaching flashover would take about 5 minutes (4).

The temperatures and heat fluxes produced in the test were much greater than those likely with typical cellulose or hydrocarbon fuels. Conventional fuels and accelerants would be expected to generate flame temperatures of only about 800°C (1,472°F). Additionally, they would likely only produce a maximum heat flux of about 5-10 W/cm$^2$, about one third of that measured.

At Puyallup, the nominal fuel composition was approximately 462 pounds of a mixture of ammonium perchlorate ($NH_4ClO_4$), heat treating salts (mostly sodium and potassium nitrates and nitrites), aluminum, and diesel. Maximum (theoretical) flame temperatures for this fuel were calculated by the U.S. Navy's **TIGER** computer code (7) to be about 2,200°C (3,992°F). The corresponding heat release rate (assuming a uniform burn rate for three minutes) was approximately 3.5 megawatts (million watts). Considering that the accelerant mix was fuel rich and that ammonium perchlorate served as the chief oxidizer, an abundance of hydrogen would have been produced in the combustion reaction. If that hydrogen completely burned in the fire plume, computer predictions were that the heat release rate could have potentially reached 7.0 megawatts (3,7).

The Puyallup test showed that the HTA mix produced white flames, massive amounts of smoke and rapid heat buildup (and flashover). Despite that impressive showing the fire never vented through the ceiling/roof. Additionally, the building suffered no collapse even though buckets of fuel were placed around support columns with the intention of maximizing damage to them. This contrast with actual HTA fires may be in part due to the vast heat loss through the broken windows and the relatively short period (5:20 minutes) between ignition and the start of fire suppression. In any case, once the high temperature fuel burned out at about 3:00 minutes, further heat damage would have been due to the continued combustion of the structural fuel load. Damage from the fire to building materials was somewhat severe. A steel plate near one fuel source was found buckled and melted along with an iron alloy display stand. A steel pipe placed where HTA fuel was poured on the floor did not melt, nor did installed HVAC equipment that had fallen into that area (5). Examination of the concrete revealed some spalling and a blue-green discoloration similar to those found at other HTA fires.

Forensic analysis of the fire debris at Puyallup was conducted by the Bureau of ATF's Western Regional Laboratory in

Walnut Creek, California, and the Washington State Patrol Crime Laboratory in Tacoma. The analytical methods used included organic extractions followed by capillary gas chromatography; visual microscopy and scanning electron microscopy; wet chemical analysis; infrared spectroscopy (FTIR); and x-ray fluorescence elemental analysis. These analyses were unable to identify the chemical composition of the test fuel. The Washington State Lab did report finding what it thought to be aluminum oxide present where the test fuel had been poured on the floor and ignited. The lab also detected traces of calcium, silicon, potassium, chlorine, sodium, iron, zinc, phosphorus, sulfur, nitrate/nitrite ions, and manganese, all substances arguably common to the fire scene.

[NOTE: While ATF forensic scientists participated in this test, no other ATF personnel were present. The previously reported data was graciously provided by the Seattle Fire Department and the participating scientists and engineers. This analysis of that data was subsequently conducted.]

## CHINA LAKE TESTS

In 1991, Seattle fire investigators began discussing the HTA phenomenon with personnel at the Fire Research Office of the U.S. Naval Air Warfare Center (formerly U.S. Naval Weapons Station), at China Lake, California. Since before the Persian Gulf War, the Navy had been aware of the destructive potential of rocket propellant fires. The destructive capability was unfortunately realized first-hand during an incident in which the U.S.S. Stark received two Exocet missile hits from an Iraqi warplane. The subsequent fire was devastating and much of the damage was attributed to burning rocket propellant from the missiles.

Accordingly, in 1991 and 1992, the U.S. Naval Research Laboratory directed a project to study the effects of burning propellants at a test site in China Lake. Upon learning of Seattle F.D.'s commitment to HTA fire research, the Navy invited fire investigators to participate in the tests. In February 1992, Seattle fire investigators joined by fire investigators from ATF and the California Department of Justice and an engineer from Sandia National Laboratories met at China Lake to take part in four rocket propellant test burns. Navy Fire Research personnel were also present as were engineers and technicians from Hughes

Associates, a fire engineering company contracted by the Navy to perform the overall study. Additionally, a television crew from CBS National News videotaped the tests.

The test burns were conducted in an approximately 20 foot by 20 foot steel building with a 10 foot high ceiling, built to simulate a shipboard compartment. The space was fitted with a movable 10 foot high steel door to alter ventilation. Additionally, adjoining spaces were constructed above and alongside to examine fire effects in adjacent compartments. The only combustible materials in the main space were samples of wood cribs and building materials supplied by Seattle fire investigators.

As in the Puyallup tests, numerous instruments were used to measure data such as temperature, radiation, pressure, gas concentrations, and gas flow velocities. The main compartment had been equipped with types K and S thermocouples, radiometers, fluid flow sensors, oxygen and carbon monoxide sensors, optical pyrometers, and pressure transducers by Hughes personnel. Many of these devices were located on "trees" (vertical arrays of sensors suspended between the floor and ceiling) at four evenly spaced locations near the center of the compartment. The fires were each monitored electronically as well as by still and video photography. In addition to Hughes instrumentation, Sandia National Laboratory provided calorimetry equipment to measure heat fluxes.

The four tests each consisted of burning several large pieces of propellant ignited remotely. The propellants were either enclosed in a combustible tube-like casing, or simply molded, exposed, into a cylindrical shape. Although formulation of the fuel used at China Lake was not disclosed, it was described as a "heavily aluminized" mixture containing ammonium perchlorate ($NH_4ClO_4$) and some type of binder. The propellant was designed to be fuel-rich so that during actual rocket use, no excess oxidizer would be present to damage rocket nozzles. The specifics of each test are shown in Table 2.

**China Lake HTA Tests**

Table 2

| **Test #** | **Total Fuel (lbs)** | **Configuration** | **Burn Time** | **Vent Area** |
|---|---|---|---|---|
| 315 | 162 | 3 - 54# blocks uncased fuel | < 60 secs | 20 sq. ft |
| 316 | 224 | 3 - 73# cased | Approx | 30 sq. ft |

| Test # | Total Fuel (lbs) | Configuration | Burn Time | Vent Area |
|---|---|---|---|---|
| | | blocks | 2 mins | |
| 317 | 300 | 6 - 50# blocks uncased fuel | Approx 1 min | 50 sq. ft |
| 318 | 300 | 2 sets of 2 - 75# cased blocks | 2 min 15 secs | 30 sq. ft |

General observations indicated the Navy's fuel appeared every bit as destructive as that used in the Puyallup test. As seen before, the temperature rise in these fires was remarkable. In test 315 (the first test), 162 pounds of uncased propellant was burned in one corner of the compartment. The 10 foot high door was opened two feet. Thermocouples trees (#1, 2, & 3) each positioned about 6 to 8 feet from the fuel experienced a rise of more than 800°C in 10 seconds (**figures 1-3**). About 3 feet from the fuel (at tree 4), the 10 second rise was 1,000° and 1,400°C at 5 and 9 feet high, respectively (**figure 4**). Within one minute of the completion of the short burn, temperatures at the same sensors dropped to about 200°C. At the main door to the compartment, temperatures at 3.5 feet and below, rose about 900°C in the 10 seconds and then dropped in as quick a time to near 100°C (**figure 5**). These temperatures were quickly affected by the inflow of cooler air at the lower portions of the vent. Higher in the same vent, where hot gases escaped the compartment, temperatures remained near 800°C for the duration of the burn (**figure 6**).

As for the radiant heat measured during this test, thermal heat flux trees showed rises of about 25 $W/cm^2$ in less than 10 seconds and then reductions almost as quickly to around 7 $W/cm^2$ (**figures 7-8**). Further declines then slowed to a rate of about 8 $W/cm^2$/minute.

In test 316, 224 pounds of cased fuel was burned in three piles arranged around the compartment. Additionally, common building materials including samples of concrete cylinders, a nearly 10 inch x 10 inch x 3 foot wood timber, and aluminum bar stock were directly exposed to the plumes from the cased fuel. The compartment door was opened three feet wide. In this test, temperature rises were less dramatic than in the first test. For the first 15-20 seconds, temperatures climbed rapidly to between 500° and 700°C (**figures 9-10**). The continued rise then slowed, peaking at the 90 second mark between 900° and 1,100°C where they stabilized until the burn concluded near the 2 minute mark. Though measurements at the different trees varied slightly, the data curves were similar. As in the first test, vent temperatures followed a comparable pattern.

With regards to heat fluxes, initial rises were, like those of the temperature data, slower than in test 315. Radiometers near where the wooden beam and concrete cylinders interrupted the flame plume (at trees 3 and 4), showed increases of only about 5 W/cm$^2$ in 15-20 seconds (**figures 11-12**). Fluxes then stabilized at each location for about 80 seconds until they quickly rose to about 10 W/cm$^2$. Both areas then experienced heat flux declines over the next minute to near zero. Near the aluminum sample (tree 2), the initial rise in flux was close to 10 W/cm$^2$ followed by an 80 second slight decrease and then a pair of pulses to near 20 W/cm$^2$ (**figure 13**). Like trees 3 and 4, this array also showed a drop in flux to near zero in the next minute. The remaining tree (number 1) located furthest from the building material samples recorded the highest heat fluxes (**figure 14**). There, initial 15 second pulses reached about 17 W/cm$^2$ followed by an 80 second decline to 10 W/cm$^2$. The second rise reached 25 W/cm$^2$ and again, the flux dropped to near zero within another minute.

In test 317, 300 pounds of uncased fuel (six 50 pound blocks) was burned in scattered locations through the compartment. A wall segment constructed of two layers of 2x construction lumber sandwiching a 1/2 inch thick sheet of gypsum board, similar to fire walls at the Blackstock Lumber Company, was also placed in the compartment. The door was opened five feet in this test. Within 10 seconds of ignition, temperatures climbed to between 800° and 1,200°C (**figures 15-17**). Though some thermocouple trees measured slight decreases after the initial peak, temperatures for the most part stabilized or dropped just slightly for the next 30-45 seconds. They then began about a one minute decline to near 200°C where they remained for the next several minutes.

Heat fluxes readings at all radiometers but one, rose swiftly to 25 W/cm$^2$ (**figures 18-21**). The lowest measured flux which peaked at 17 W/cm$^2$, was at the tree closest to the wall section. While most readings dropped over the next 15 seconds to between 5 and 12 W/cm$^2$, they then rose again briefly to near 10 to 15 W/cm$^2$ before rapidly sinking to near zero within 30 seconds.

Test 318 consisted of burning two 150 pound blocks of cased propellant with the compartment door opened three feet. Temperatures increases were the slowest of all tests. While peak temperatures reached between 1,000° and 1,100°C (**figures 22-23**), the total rise took just less than two minutes, considerably slower than before. Cooling of the compartment to the 200°C level (at where each test seemed to stabilize post-burn), also took the longest time, about two minutes at each tree.

Radiant heat fluxes for test 318 also showed the slowest increases. After initial increases to about 5 $W/cm^2$ in about 30 seconds, most readings tended to stabilize for about 50 seconds. Then, sudden increases to between 10 and 20 $W/cm^2$ occurred followed by some instability during the next 45 seconds (**figures 24-26**). At each tree, the final rapid decrease began just after 2 minutes into the test.

Despite similarities between peak heat flux data at China Lake and Puyallup, it should be noted that the main heat flux peak measured at Puyallup by Lawrence Livermore personnel occurred at the time of flashover. It was not the initial pulse in heat flux caused by just the HTA combustion. Sandia's equipment did measure that initial pulse adjacent to the fuel at Puyallup. The data showed the flux was initially 25 to 30 $W/cm^2$ followed by a drop to 15 to 20 $W/cm^2$. Those measurements were distinct from a later rise in radiant heat due to the flashover of the building.

At China Lake, Sandia measurements of the heat flux in test 317, adjacent to the uncased propellant charge was near 75 $W/cm^2$ (35). This was nearly three times as high as the peak fluxes at

Puyallup. The flux 10 feet away (as measured by Sandia) was about 25 $W/cm^2$. A Sandia engineer also estimates that the heat flux in test 318 adjacent to burning cased propellants reached 90 $W/cm^2$+(

*he China Lake tests, an interesting phenomenon was observed for the first time in HTA tests. As mentioned previously, the Navy's test facility contained no appreciable combustible materials except for small wooden test cribs. It was observed after each test that once the propellant burn concluded, some of the cribs, though somewhat charred, were not burning. On at least three occasions, the cribs were observed for several minutes after the incendiary burned out. In each test, it took about two minutes before each of the cribs had burst into flame.

An apparent explanation for this behavior is that shortly after ignition, the hot combustion gases forced much of the atmospheric oxygen from the chamber. Examination of oxygen concentration data generally shows rapid drops in the available oxygen in each test.

In test 315, the oxygen percentage at all but two sensors dropped within 15 seconds to less than 2% (**figures 27-30**). At the 9 foot level on trees 2 and 3, the level dropped to near 11%. Percentages remained low until near the conclusion of the propellant burn when they then again rose. The average length of time that oxygen levels were below 10% (the point at which flaming combustion is often considered to cease) was about 50 seconds.

Once the oxygen levels fell in test 316, they did not remain as stable as in test 315 (**figures 31-34**). After the initial drop, most sensors measured the levels near 10%. Deviations in the low concentrations measured as much as 5% between sensors until completion of the burn 2 minutes into the test. The approximate time that most levels remained below 10% was about 110 seconds.

The drop in test 317's oxygen levels mimicked those in test 315 (**figures 35-38**). The initial decrease was to near 0% at all but three sensors. The 9 foot sensors on trees 2 and 3 again measured the oxygen level near 10% - 12%, while at 5 ee #3, it dropped to between 4% and 5%. Again, levels remained low until near the end of the burn. The time below 10% $O_2$ concentration at most points in the compartment was about 60 seconds.

The oxygen depletion in test 318 behaved similar to the temperature and heat flux increases in that it occurred more slowly than in any of the other tests (**figures 39-42**). While levels at most sensors eventually bottomed out at below 3%, it typically took 75-90 seconds to do so. Then, the time period that levels remained below 10% was nearly two minutes, the longest of all four tests.

There were similarities in the rates and amounts of oxygen depletion during tests 315 and 317, and in tests 316 and 318, as well as similarities in the duration of the test burns. Though more analysis is called for before conclusions can be made, it is obvious the burn rate of cased fuel packages was slower than that for the uncased fuel. One might expect, as in typical fires, the higher the available surface area of a fuel, the faster it will be consumed, particularly if ambient gaseous oxygen assists in the combustion. Such a theory might explain the quicker and more complete oxygen depletion during the uncased fuel burns at China Lake. Another explanation might simply be that with the slower rates of temperature rise experienced during cased fuel burns, expansion of the gases in the compartment would also be expected to occur more slowly, thus enabling ambient oxygen to remain inside longer.

Because the temperatures throughout the compartment remained high after the burns, atmospheric oxygen did not immediately flow back inside in sufficient quantities to support combustion even though several square feet of venting existed. Once the oxygen was replenished, many of the cribs ignited since they were already at or above their auto-ignition temperature.

Most of the "forensic" efforts associated with the China Lake test involved visual observations of the building materials exposed to the burns. Of particular interest were the concrete cylinders. Though thorough petrographic studies of the samples have not yet been completed, summary examinations have been conducted by Construction Technology Laboratories in Skokie, Illinois. One effect which was much more evident than in other HTA testing was the melting of the concrete. Though no scientific data is available to quantitatively describe the composition of the cement or aggregate in the samples, a qualitative analysis is possible. Visible on the exposed sides of each cylinder that was positioned next to the fire plumes was a bluish-green melted layer, similar to glass. Cursory examination showed the thickness of the glass layers to be less than 1/4 inch on each of the cylinders. Another obvious outcome was that the concrete had weakened, becoming brittle and easy to crush. These results seemed similar to the kind of concrete damage reported in both HTA test fires and suspected HTA fires. Additionally, based on research conducted by Construction Technology Labs and others, the damage to the cylinders would tend to indicate the temperatures they encountered were in excess of 1,350°C. (8)

Examination of the wood timber and the wall segment placed in the test compartment also was somewhat cursory. The timber was Douglas Fir and the wall section was also constructed of a soft wood. Though positioned within a few feet of, and directly in line with the fire plume of a cased propellant block, the damage to the timber seemed relatively minor. The propellant is thought to have burned for nearly two minutes. An inspection of the wood showed charring of the wood was less than one half inch deep. Additionally, a round section of gray material believed to be aluminum oxide was found on the face of the timber. It has been suggested that this oxide layer might have acted as an insulator for the timber from the direct onslaught of the fire plume. As for the wall section, it too suffered surface charring, but the heat of the propellant burn alone was insufficient to penetrate the wood.

## Plymouth, Minnesota Full Scale Test

In 1993, scientists from Alliant TechSystems of Hopkins, Minnesota, a defense contracting company familiar with small missile systems (including propellants) contacted local fire investigators regarding reports they had heard about High Temperature Accelerant fires. Of particular interest to them were claims that finding evidence of the chemical makeup of such accelerants after they burned was apparently impossible. Collectively, the group concluded that, at a minimum, the topic was interesting and possibly worth investigation.

Later that year, the Alliant employees began formulating plans to conduct an HTA test along with fire personnel with the intention of not only monitoring the fire, but also in collecting and analyzing fire debris. One major goal was to collect and identify the components of the fuel. Alliant contacted participants of the Puyallup test fire regarding their test and the fuel used. Additionally, ATF fire investigators were contacted and asked to participate in a future full-scale test.

Subsequently, the scientists along with local fire investigators conducted several small scale test burns to try and optimize a mix suitable for a full scale test.

On March 5, 1994, the Alliant representatives, along with ATF Certified Fire Investigators, gathered in Plymouth, Minnesota to conduct two HTA burns in buildings scheduled for demolition. Though two buildings were burned, the principal test site was in an abandoned two story, wood frame building (known as the grainery) covered with galvanized steel sheeting on the roof and exterior walls. The grainery had approximately 386 square feet of interior space on each floor. The first floor had an 8 foot ceiling while the second floor was open to the roof with a maximum height of 13 feet floor to peak. The structure was built on a post and beam foundation and located about two feet above grade level.

The interior framing was exposed, revealing nominal thickness 2 x 4 inch studs and rafters, 1 x 6 inch floor planks and walls, and 2 x 6 inch floor joists. Also located near the center of the first floor was a 5 inch diameter log serving as a column to support the second floor. Under the steel roof sheeting were layers of cedar shakes over 1 inch thick planks. An open wooden stairway to the second floor was located along the south wall of the building, three feet inside the east wall.

An approximately 6 x 3 foot wooden-plank door near the south corner of the east wall served as the only entrance and exit. There were two windows on each of the first and second floors. The glass to the first floor windows (each 15 x 20 inches) was missing and the openings were partially covered with corrugated fiberglass sheeting. Glass in both second story windows was intact.

Unlike sites of earlier test fires, the grainery had a substantial amount of combustible material inside including cardboard, boxes of school books, plastic buckets, and rigid plastic chairs. The fuel load of these contents seemed typical for a dwelling that size.

The morning of the tests, approximately 500 pounds of an HTA fuel/oxidizer mix similar to that used in Puyallup was prepared. The principal components were aluminum powder and flake, potassium perchlorate ($KClO_4$), sodium chlorate ($NaClO_3$), ammonium nitrate ($NH_4NO_3$), and diesel. Although participants from Puyallup had used ammonium perchlorate for the generation of excess hydrogen (and arguably extra heat output), it was decided that at the Plymouth test, potassium perchlorate would be used to see if the resulting difference in cation choice was obvious. Like the Puyallup mix, the Plymouth HTA was fuel rich.

Once mixed, the fuel was placed in 5-gallon plastic buckets, with each bucket containing approximately 60 pounds. Three such fuel packages were placed in the first floor of the grainery, one near the southwest corner, one adjacent to the wooden support column near the room's center, and one near the northeast corner. Positioned less than two feet above the fuel in the northeast corner was a 4 x 10 inch steel I-beam, approximately six feet long. The fuel packages were ignited with incendiary devices containing aluminum and a perchlorate oxidizer, a combination of magnesium powder and two inorganic peroxides, and hobby fuse.

Prior to igniting the fuel, the door to the grainery was closed. This was done in order to trap as much of the hot combustion gases inside as possible. With the grainery's several "leaks" throughout, it was thought that any substantial pressure increase would be mitigated through those holes. In case of too large a pressure increase however, the door was spring loaded so that it could open if necessary but would then again close.

Though only a limited amount of instrumentation was available, fifteen type-K thermocouples were installed in the grainery, mounted along the interior of the south and west walls and along the south side of the roof. No oxygen sensors, radiometers, or pressure transducers were available.

Thermocouples placed near the fuel buckets confirmed each ignited as expected. From the east side of the building, bright flames were visible through the cracks in the door. Within seconds, light grey smoke began flowing out of the building and swirling away in the slight easterly winds. It soon was obvious that the hot gases were flowing out under somewhat increased pressure. Smoke continued to vigorously pour out of every roof and wall seam for about five minutes and then a decrease in the flow occurred. The only fire visible from the building during this time were modest flames at the edges of fiberglass panels covering the first floor windows.

After about 15 minutes, the smoke flow out of the grainery had diminished to a slight seeping. Since the fire was obviously not spreading, the grainery door was then opened and the spring disconnected. Within seconds, black smoke started pouring out of the door though no flames were visible inside. After about 1 minute and 40 seconds, the smoke burst into reddish-orange flames at the door and the first floor of the grainery appeared to flashover. Second floor windows remained intact during this entire period. After flames began gushing from the door, firefighters broke the west-side second story window. Pressurized smoke then began flowing out that opening also.

During the next 40 minutes, the fire progressed through the building from east to west. At one point, much of the entire eastern wall had burned away or fallen revealing internal fire from floor to roof. At the same time, however, no fire was visible in the western windows, and the smoke flowing from the broken second story window had not yet ignited.

Unlike the dazzling HTA fire observed at Puyallup, the Plymouth fire was, at least visually, much less energetic. Initially it was assumed that the fuels had not burned as intended, resulting in much lower flame temperatures. Prior to the burn, rods made of metals with extremely high melting points were placed above or in two of the fuel packages. The metals included molybdenum, tungsten (98%), and Inconel, a chrome-nickel-iron alloy similar to a stainless steel. The melting points of the metals were: tungsten - approximately 6,100°F (3,371°C); molybdenum - 4,742°F (2,617°C); and Inconel - 2,550°F (1,399°C). It was hoped that any melting of the rods would indicate a temperature range for the HTA flames. Throughout the fire, no water was applied to the building to avoid any sudden quenching of the hot metal which might result in undesired crystalline changes. Once the rods were retrieved, a metallurgical analysis of each was begun. None had undergone melting or bending as had been expected.

The Inconel and molybdenum had badly oxidized but neither had melted or bent. The tungsten also oxidized and experienced what appears to be a previously undetected phenomenon. The tungsten grains compressed into the rod seem to have alloyed with aluminum from the fuel. This curiosity is currently being studied by Alliant metallurgists, scientists intimately familiar with the behavior of tungsten. While the rods provided no obvious indication of the HTA temperature, initial analysis shows that they did not reach 5,000°F. There was certainly no evidence that this fuel was capable of producing 7,000°F temperatures as has been previously estimated.

Temperature data collected from the thermocouples placed in the building was next analyzed. Thermocouples had been mounted near the south wall of the grainery on the first floor at floor level, 4 feet, and 8 feet. Additional sensors were placed on the south wall of the second floor at 12 feet (above the ground floor reference), and along the west wall at the 8 and 12 foot levels and through the frame of the second story window.

As in the China Lake and Puyallup tests, shortly after ignition, sharp temperature in

' were seen at Plymouth, but not to the extent of the other tests. In general, the initial first-floor smoke layer temperature spikes at Plymouth ranged from about 1,000°F (540°C) to 1,300°F (700°C) (**figures 43-46**). These temperatures then gradually diminished and stabilized near 350°F - 400°F (175°C - 200°C) until the time the door was opened. That opening (which led to flashover) is prominently displayed on the graphs by the sudden second rise in temperatures. Comparing the general shape of the Plymouth graphs to those of China Lake and Puyallup, it seems reasonable to conclude that the length of burn of the Plymouth fuel packages was probably between three and four minutes. Such a time would also be comparable with the combustion of the fuel in Puyallup.

A review of the Plymouth fire test begs the question of why the initial temperature of the smoke layer at the Plymouth grainery was not as high as in the other tests. One possibility might be that the HTA fuel used in Plymouth did not burn as hot as that used in Puyallup. Chemically, the two mixes were substantially the same in terms of fuel/oxidizer/diesel stoichiometry. Additionally, the time of combustion of buckets of equal amounts of fuel were quite similar indicating the chemical rates of reaction were likely on the same order. While the actual burning of the fuel in the grainery was not directly observed, a second burn was conducted later that day using fuel from the same batch mixed that morning. The visual effects of that second burn were brilliant white/orange flames similar to those seen in Puyallup. While these comparative results are qualitative at best, they do suggest that the fuel likely functioned as intended, and that flame temperatures were probably close to those expected.

Another theory that might account for the low temperature measurements is the lack of hydrogen produced during the HTA combustion. As mentioned earlier, scientists participating in the Puyallup test speculated that without the additional heat generated from the burning of the surplus hydrogen gas, the building would not have reached flashover. If such a theory is true, then the choice of potassium perchlorate as the principal oxidizer in Plymouth eliminated much of the hydrogen that would have been available had ammonium perchlorate been used. That in turn would have reduced the cumulative heat output.

A third potential explanation for lower temperature readings is associated with the manner in which the Plymouth thermocouples were positioned. There, the sensors were inserted less than two inches into the grainery through exterior walls. That was done so that small ceramic sleeves could cover the exposed thermocouple leads to protect them from destruction by high heat. At China Lake and Puyallup, the thermocouples were located more towards the center of the buildings, often in instrument trees not obstructed or affected by nearby materials. The wooden grainery walls, like the walls of any burning compartment, acted somewhat as heat sinks, absorbing energy from the smoke layer. The resultant cooling of the gaseous boundary layer adjacent to the walls may have been detected by the thermocouples situated there.

Yet another theory exists that might explain the lower temperatures and involves the oxygen content of the rooms during the fires. At Plymouth, the initial air to fuel ratio (for the first floor) was approximately 17.4 $ft^3$ air/lb fuel. That compares with an estimated ratio of 642 $ft^3$ air/lb fuel in Puyallup (based on building measurements provided by test participants), almost a 37 to 1 difference. Visually, the Puyallup HTA fire appeared to consistently grow until an unusually quick flashover occurred. The instrumental data from there indicates a slightly different growth pattern which may offer a possible explanation of the Plymouth mystery.

A review of the Puyallup temperature data reveals initial temperature peaks of 300°C to 700°C (600°F - 1,320°F) (**figures 47-48**) at about 80 seconds into the test followed by 25-30 seconds of temperature decline. Subsequent rises then led to eventual flashover of the building. Also of interest during this time was the oxygen concentration in the building. At about 80 seconds into the test, oxygen levels began rapidly dropping for the next 20 seconds from about 21% to 9% (**figure 49**). They then began rising almost as quickly, reaching 20% in another 30 seconds. The sudden rise in oxygen level corresponds quite closely to the time when the first set of glass double doors was forced open during the test. As quickly at the oxygen levels rose, they then again sharply dropped to less than 4% until about 2 minutes and 20 seconds into the test. At that time, flashover occurred and several large plate glass windows failed. Subsequently, the oxygen levels once again rapidly recovered to 21%.

At Puyallup, despite the HTA continuing to burn at 80 seconds, there was a substantial, albeit not visibly obvious, drop in temperature. This drop followed within seconds of the reduction in oxygen concentration throughout the room. Once the oxygen level hit bottom and began to recover, again, the temperature followed shortly thereafter.

Although the mechanism responsible for these fluctuations has yet to be identified, it suggests a potentially feasible explanation for the lower temperatures at Plymouth. Since its initial air to fuel ratio was so much less than at Puyallup, available oxygen in the grainery was likely depleted much earlier in the HTA burn. Further, with no doors opening or windows breaking during the first few minutes, there was no way to entrain sufficient fresh air into the building to adequately raise the oxygen levels and apparently, the temperature. While there were several cracks and leaks, the HTA's heating of the grainery would have resulted in tremendous gaseous expansion and would have caused gases to flow out of the building, thereby limiting the entraining of outside oxygen through those modest openings.

It is still uncertain what the role of the oxygen is in raising the smoke temperature during the actual HTA burn. It might lie in allowing excess hydrogen (or other HTA by-products) to burn as theorized by participants from the Puyallup test. Or, perhaps similarly, it might enable smoke layer combustion of pyrolyzates of cellulosic or hydrocarbon fuels native to the compartment. Again, gaseous oxygen might play a role in the burning of the HTA although that suggestion seems less likely than the others, especially considering the relatively small reaction zone for the HTA burn as compared to that of the overall smoke layer.

Although the Plymouth grainery was not instrumented with gas sensors, it is obvious that the interior oxygen levels quickly dropped below those capable of sustaining flaming combustion. Despite the radiant heat of the smoke layer undoubtedly causing considerable pyrolyzation of the various combustible contents, the ensuing smoke, though quite fuel rich, could not burn. Once the door was opened and oxygen allowed to replenish the building, the combustion gases, already near their autoignition temperatures, burst into flames. Shortly after those flames first appeared, flashover was evident once the tremendous amount of excess pyrolyzates began burning outside the building.

Although the fire behavior at Plymouth was different than what had been expected, it should be remembered that one of the primary objectives of the test was the possible identification of fuel components from the fire debris. To that end, several evidence samples were collected the day following the test. After a typical suspected arson fire, investigators looking for accelerants might collect debris from the edges of centers of fire damage, or under or behind trim boards. Almost never would they concentrate their collection at the center of the most heavily damaged areas. In this case however, the scientists from Alliant did just that. For the best chance of locating the ionic remnants of the solid fuel and oxidizers, it was necessary to collect the ash directly from the suspected point of origin. Another area where evidence was sought was on the surface of the snow downwind from the fire. The heavy particulates of combustion products would have eventually settled to the ground. As in a standard fire investigation, control samples of upwind snow that were obviously not contaminated were also obtained. A third type of evidence collected from the fire scene was fragments of glass from the windows. From these pieces, it was hoped that aluminum oxide particles would be found adsorbed to the surface.

Typically, forensic analysis of arson debris for liquid accelerants is performed with a gas chromatograph (GC). That instrument performs a separation of the volatile, organic compounds most often associated with arson accelerants. A G.C. can not identify inorganic ionic chemicals. Such an examination requires one of a number of different instruments, such as high performance liquid chromatographs (HPLC), atomic absorption spectrophotometers (AA), and energy dispersive x-ray analyzers (EDX). Alliant's analysis used these very instruments. From the HPLC examination, it was hoped that the negative ions (anions) from the oxidizers could be identified. Whereas most of the oxidizers used involved chlorate $(ClO_3)^-$ and perchlorate $(ClO_4)^-$ anions, the Alliant TechSystems analysis revealed only chloride ions $(Cl)^-$ remaining in the debris. The combustion reaction of the HTA either caused the oxygen from those anions to either oxidize the aluminum, or it was simply released in a thermal degradation of the anion to its elemental parts. If the concentration of an anion such as chloride was unusually high in ash found at the point of origin, it *might* indicate the prior existence of chlorates or perchlorates there, but it might also be a representative by-product of other common fuels such as polyvinylchloride (PVC) or other chlorine containing hydrocarbons.

Alliant was able to identify substantial amounts of aluminum oxide residue adsorbed on glass fragments. While such a finding might not be unusual for a fire scene where aluminum powders or flakes are normally kept, it might be useful in identifying the fuel from a suspected HTA fire. The analysis of the debris collected from the snow has, as of the time of this report, not been completed. It is hoped that if the HTA flames were sufficiently turbulent, some unburned or only partially burned oxidizer may have been carried away in the convective plume and will be isolated and identified.

In addition to collecting evidence for analysis, investigators also conducted a visual inspection of the remains of the grainery and its contents. Fire investigators have since reported that generally, the fire scene did not look any different than might have been expected from a common building fire. Even the steel I-beam positioned directly over one of the three buckets of fuel did not exhibit severe damage. While the beam was not placed under any load prior to the fire which could have resulted in deformation once it was heated, there was no evidence of severe surface damage such as melting of the steel.

The only damage investigators could find which they considered abnormal was to concrete pads placed under the HTA buckets. The pads had suffered severe weakening and could be easily crumbled by one's hands. Although there was no melting or blue-green discoloration, the apparent destruction of the cement paste was similar to damage seen at other suspected HTA fires. Such damage is indicative of dehydration of cement exposed to 900°C (1,652°F) for prolonged periods.

With the exception of this finding, each of the investigators perusing the scene agreed that all other indicators, including what would have likely been lay witness accounts of the fire, would not necessarily prompt an investigator to believe the grainery fire was due to anything other than ignition of available combustibles. Had the fire been suppressed early, the investigators further theorize, the chances of recognizing the unusual patterns of damage indicative of high temperature might have been greater.

In the second Plymouth HTA test, approximately 300 pounds of the same fuel used in the grainery was used to destroy a 1900 vintage farm house being cleared for a new development. The test was intended to be a visual observation only and no instrumentation was involved. The building was a three story structure with a full basement. Not counting the basement, it had approximately 4,500 feet of living space. It was built of balloon construction. The Plymouth, Minnesota fire department had previously conducted fire suppression training at the house. Most if not all of the windows had been broken out, allowing for free ventilation throughout the structure. Additionally, due to the relatively cool temperatures in Minnesota in February and March, there was still a substantial amount of fire fighting water inside the house that had frozen after earlier training sessions.

Nine buckets of HTA fuel were placed in the basement and fitted with igniters like those used in the grainery. Because limited ventilation slowed fire progression in the first test, the decision was made not to obstruct the exterior openings into the basement, but to allow them to remain open for air entrainment.

Once the fuel was ignited in the basement, a brilliant display of white violent flames erupted from the buckets. The basement quickly filled with white aluminum-oxide smoke. The smoke also travelled upstairs into the main body of the house as well as out through all openings. This excessive production of white smoke has become a standard occurrence seen at each of the HTA tests.

Unlike the test at the grainery, this fire had sufficient oxygen to promote fire extension throughout the building. Even so, it appeared that the combination of excess ventilation in the upper section of the house coupled with the standing water and ice, inhibited the rapid ignition of the structure. The stairwell leading out of the basement to the first floor as well as some of the basement's wooden ceiling and structural members did ignite. After the initial surge of white smoke diminished, only small flamelets were visible. Fire hidden in the wall spaces eventually rose to the top floor and attic and the house was eventually destroyed by the fire, but only after more than an hour had passed since the HTA ignition.

## **Chemistry of Metal Combustion**

As fire investigators began researching HTA fires, many scientists and engineers with whom they consulted speculated that the fires probably involved some type of metal combustion. Though high temperature fire behavior was not commonly understood in the fire community, the science of such combustion had been studied for decades. In fact, the study of pyrotechnics and metal/oxidizer combustion began as early as the 1780's. The advancements in this field received wide attention during the world wars. Metal combustion was at the center of the production of munitions such as illumination flares and incendiary weapons (9). By the 1980's, the scientific community had a full understanding of such chemical processes. Today, pyrotechnic studies probably offer the best in-depth look at HTA behavior.

It is commonly known that fire is simply a chemical reaction between a fuel and oxidizer. It is no different with high temperature fires, except that different fuels and oxidizers are thought to be involved and the reaction rates and mechanisms are distinctive. Though the fuels thought to have been used in the suspected HTA fires have been described by media sources as "exotic" (10), similar mixtures are common in applications such as pyrotechnics, propellants, and the preparation of relatively pure metals or alloys. The advantage of using metal (and some inorganic non-metal) fuels in these processes lies chiefly in their comparably high *heats of combustion*, $H_c$. It is this high heat output that is of primary interest to pyrotechnic chemists and rocket propellant engineers seeking increased thrust for their rockets. (11,12).

"Ordinary" fires are the result of an organic fuel (solid, liquid or gaseous) consisting mainly of carbon and hydrogen, reacting with oxygen from the air to produce carbon oxides (CO and $CO_2$), and water, $H_2O$. The flames in such reactions usually reach between 800°C (1,472°F) and 1,100°C (2,012°F). Conversely, solid, inorganic fuels and oxidizers believed to constitute HTAs can produce temperatures exceeding 2,000°C (3,632°F) (3).

High temperature fuels are typically metallic although some are not. Examples include lithium, beryllium, sodium, magnesium, potassium, aluminum, titanium, zinc, zirconium, boron, silicon, phosphorus, strontium, sulfur, manganese, tungsten, nickel, vanadium, iron and even in certain instances, carbon. Frequently encountered oxidizers include perchlorates, chlorates, nitrates, nitrites, chromates, sulfates, oxalates, manganates, oxides, peroxides, and chlorine- or fluorine-based oxidizers. This review will focus on aluminum combustion although comparable studies of most of the other potential metal fuels would yield similar information.

One common misconception in the fire service is the definition of "oxidation." It has too often been simply defined as the combining of a fuel with oxygen. In fact, this is only one example of a class of reactions more correctly known as *oxidation-reduction* or *redox* reactions. The definition of an oxidation-reduction reaction is a transfer of one or more electrons between atoms. The atom undergoing electron loss is said to be oxidized while that acquiring electrons is reduced. Redox reactions form the core of such disciplines as electrochemistry, pyrotechnics and explosives among others.

While equations for several electrochemical and pyrotechnic reaction appear similar, the distinction between the reactions is in the rate at which they occur. Examples of these types of reactions (6) are:

$$Zn + Ag_2O \rightarrow ZnO + 2\,Ag \quad \text{(electrochemical reaction)}$$

$$2\,Al + Fe_2O_3 \rightarrow Al_2O_3 + 2\,Fe \quad \text{(pyrotechnic reaction)}$$

Each of these reactions proceeds with drastically different speeds and consequences. The first is a relatively slow, zinc-silver battery mechanism while the second is the typically violent thermite reaction.

Whether any chemical reaction occurs naturally is dependant upon the thermodynamic state of the system. To determine if a reaction will be spontaneous, the chemical system must be examined to determine if energy is released. Reactions in which heat is liberated are said to be *exothermic*. Even though a reaction is determined to be energetically spontaneous, there is no assurance that it will automatically occur. For instance, consider the complete combustion of cellulose in oxygen, represented by:

$$C_6H_{10}O_5 \ + \ O_2 \ \rightarrow \ 6\ CO_2 \ + \ 5\ H_2O$$

Thermodynamically, this reaction is spontaneous. Fortunately though, at room temperature, wood does not burst into flames upon contact with oxygen. It must be raised from its standard energy state to an excited state at which point it will ignite.

The energy required to achieve this ignition is known as the *activation energy*, $E_a$. The lower the $E_a$, the easier a reaction is to initiate. The speed, or rate of the reaction, is also dependent upon the value of $E_a$ as well as the temperature. In general, among similar chemical compounds (i.e. alkanes, alkenes, aromatic rings, etc.) in similar physical states, the lower the $E_a$, the faster the reaction will progress. The higher the ignition temperatures (and thus high energies of activation) of fuels, the slower the burning rates of the materials will be (6,13). It must be emphasized that this relationship is not a major factor when comparing different types of chemicals such as metals with hydrocarbons, or alkanes with aromatic compounds.

Another influence on the rate of metal combustion is the degree of subdivision, or size of the fuel. As with most chemical reactions involving solid reactants, the smaller the particles, the greater the surface area and the number of exposed atoms where the reaction can occur. As an example, consider a 140 micron aluminum particle (approximately 0.0055 inches diameter). Even in a particle this small, 99.998% of all aluminum atoms are inner ones, and not vulnerable to surface combustion (9). While bulk metals have been made to burn in controlled tests, such behavior typically requires very high pressures (14-17).

Earlier mention was made that the value of metal fuels lies in their heat output. An important factor in determining the energy potential of incendiaries is their heat output or *heat of combustion*. Some heats of combustion values are published in pyrotechnics references for various incendiary mixtures (6,18). For mixtures not listed, values can be calculated using heat of formation figures for the various incendiary reactants and products (6,9,11,13,18-23). The heats of combustion of several fuels are listed in Table 3 (19).

Note how the values for gasoline, asphalt and charcoal are higher per gram than those of aluminum and magnesium. One explanation of this apparent anomaly is offered by a Sandia National Lab scientist participating in the HTA research. He argues that it is not only the high heat of combustion that makes metal fuels attractive, but rather what he refers to as "energy density" (25). This property can be determined by multiplying the heat of combustion and the fuel's density. For instance, gasoline has a density of approximately 0.7 grams/$cm^3$ while that of aluminum

**TABLE 3**

*Heat of Combustion of Various Materials* (19,24)

| Materials | Kcal/gram |
|---|---|
| Hydrogen (to $H_2O$) | 28.7 |
| Beryllium | 16.2 |
| Boron | 14.0 |
| Carbon (to $CO_2$) | 7.8 |
| Aluminum | 7.4 |

| | |
|---|---|
| Silicon | 7.3 |
| Magnesium | 5.9 |
| Phosphorus (white) | 5.8 |
| Phosphorus (red) | 5.7 |
| Titanium | 4.6 |
| Zirconium | 2.8 |
| Sulfur (to $SO_2$) | 2.2 |
| Iron (to $Fe_2O_3$) | 1.8 |
| Zinc | 1.3 |
| | |
| Gasoline | 10.4 |
| Asphalt | 9.5 |
| Wood Charcoal | 8.1 |
| Douglas Fir Wood | 5.0 |
| Nitrocellulose (combustion) | 2.2-2.6 |
| Nitrocellulose (explosion) | 1.0 |

is about 2.7 grams/cm$^3$. Their respective energy densities are found by multiplying these values by the heats of combustion.

Gasoline 0.7 g/cc * 10.4 Kcal/g = 7.3 Kcal/cc

Aluminum 2.7 g/cc * 7.4 Kcal/g = 20 Kcal/cc.

Through this comparison, it is easy to see why aluminum would be far more attractive as a fuel than gasoline in terms of heat per volume.

Although a fuel may be calculated to have a relatively high heat output, the relationship between the flame temperatures and heat output is tenuous (19). Other factors such as the speed of the reaction, the state of the reaction products, and the chemical structure of the fuel have a more direct effect on flame temperature.

In chemical terms, temperature is simply a measurement of molecular activity. The higher a molecule's kinetic energy (a measure of its velocity and mass), the higher the temperature. For instance, if equal amounts of energy are applied to a cubic centimeter of water and a cubic meter of water, the temperature in the cubic centimeter will be higher. In this instance, there are fewer molecules in the smaller volume over which the energy could be dispersed.

In examining the flame temperature of charcoal combustion,

$$C \text{ (solid)} + O_2 \text{ (gas)} \rightarrow CO_2 \text{ (gas)}$$

one can see all of the product is in a gaseous state. The heat needed to vaporize the carbon dioxide emanates from the heat output of the reaction. Once vaporized, the gas carries much of this heat away from the flame zone.

One important aspect of metal combustion unlike that of organic fuels, is the common presence of condensed-phase products (26). For instance, when aluminum is burned in the following reaction,

$$4\ Al\ (s) + 3O_2\ (g) \rightarrow 2\ Al_2O_3\ (liq/gas)$$

much of the aluminum oxide that might be anticipated to be gaseous, actually condenses into tiny liquid droplets near the flame. As it does, the energy it absorbed in vaporization is released back into the system, contributing to a rise in the flame temperature.

Conversely, even if aluminum combustion products were completely gaseous, such a reaction would still produces less than one-quarter of the gas than would an equal weight of burning carbon. The heat in aluminum combustion therefore remains more concentrated on the products and in the flame zone resulting in a higher temperature (27).

Recall that in normal flaming combustion, liquid or solid fuels must first be heated to the gaseous state before they are oxidized. Accordingly, the flame temperatures of organic fuels, unlike metals, are limited by the heat needed to decompose and vaporize them. If the fuel is comprised of long-chain molecules or polymers, several chemical bonds may be broken prior to vaporization. The remainder will be likely be severed during the combustion. These processes remove energy from the reaction. Unlike organics, metal combustion typically occurs at an atomic level where molecular bonds do not need to break to vaporize the fuel. For these reasons, the presence of even small quantities of organic material such as hydrocarbons in an incendiary mixture will markedly reduce flame temperatures.

An example of this effect is clear with a magnesium-solid oxidizer flame. The flame temperatures for such reactions are near 3,550°C (6,422°F) for a variety of oxidizers. When 10% shellac is added however, the temperatures fall approximately 26% to about 2,550°C (4,622°F) (6).

Several calculated temperatures for adiabatic flames (no heat transferring to or from the system) have been published for various fuels. They are listed in Table 4 (28,29). Measured flame temperatures typically fall below these values. The reduction depends upon the extent of phase changes occurring in the reaction (i.e. solids to liquids, liquids to gases), chemical dissociations (breaking of bonds), and unanticipated high-temperature chemistry (6). Each of these events consumes energy. Studies of aluminum and magnesium flames (not inhibited by organic additives) showed actual flame temperatures of 3,260°C (5,900°F) and 2,620°C (4,748°F) respectively (26), approximately 10% below calculated values.

Calculated flame-temperatures are generally based upon the fuel burning in atmospheric oxygen. If solid oxidizers are used, experiments show that the temperatures for the same fuel can vary significantly, depending upon the oxidizer (27). For instance, when shellac is burned in potassium perchlorate and ammonium perchlorate, the maximum temperatures are 2,250°C (4,082°F) and

**TABLE 4**

***Calculated*** *Flame Temperatures at 1 atm* (28)

| Fuel | T °C | T °F |
|---|---|---|
| Aluminum | 3635 | 6575 |
| Boron | 3513 | 6355 |
| Beryllium | 3937 | 7118 |
| Lithium | 2573 | 4663 |
| Magnesium | 2956 | 5353 |
| $MgAl_2$ alloy | 3534 | 6393 |
| *(at Lower Limit Fuel/Air Mixtures)* (19,29) | | |
| Methane | 1173 | 2143 |
| Ethane | 1229 | 2244 |
| Propane | 1281 | 2338 |

| | | |
|---|---|---|
| n-Butane | 1339 | 2442 |
| n-Octane | 1359 | 2478 |
| Acetylene | 3410 | 6170 |

2,200°C (3,962°F), respectively. If, however, potassium nitrate is used, the maximum temperature reaches only 1,700°C (3,092°F), a substantial drop of more than 22%.

## Thermite Reactions

While the HTA reactions discussed so far involved the general combustion of metals and solid oxidizers, there is another commonly encountered HTA that undergoes a specific type of metal combustion. This is known as the "Goldschmidt process," or its better recognized name ***thermite*** (19). The reaction is an oxidation-reduction mechanism, usually involving aluminum and iron oxide. It is represented by the following equations:

$$2\ Al + Fe_2O_3 \rightarrow Al_2O_3 + 2\ Fe \quad (H_c = 0.93\ Kcal/g)$$

(red iron oxide)

$$8\ Al + 3\ Fe_3O_4 \rightarrow 4\ Al_2O_3 + 9\ Fe \quad (H_c = 0.85\ Kcal/g) \quad (6)$$

(black iron oxide)

These classic thermite mixtures were originally used for welding and as a means of manufacturing "pure" iron. Subsequently they have been used as destructive incendiary compositions.

The reason these reactions occur is because aluminum-oxygen bonds are more stable than those between iron and oxygen. Once the energy of activation ($E_a$) is absorbed and the reaction starts, oxygen transfers rapidly to the aluminum, "oxidizing" it. The resulting energy loss takes the forms of light and heat. The heat is great enough to melt the iron. The thermite reactants shown here, iron oxide and aluminum, constitute the classic thermite mixture. Numerous other combinations also react similarly. For instance, active metals such as calcium, magnesium, titanium or zirconium can be substituted for the aluminum, keeping iron oxide as the oxidizer. Likewise, when aluminum is used as the fuel, other oxidizers including chromium (III) oxide, silicon dioxide, cupric oxide, and manganese dioxide can be swapped for the iron oxide. Generally, if the energy of the metal-oxide bond is higher than the potential bond between the fuel and oxygen, the reaction is energetically feasible.

Temperatures for thermite reactions have been reported between 2,000°C (3,632°F) and 2,800°C (5,072°F) (13,30). Even though the heat of combustion of an Al-Fe thermite reaction is only about 12% of that for general aluminum combustion, the peak temperatures are about 75% as high. One reason thermites create such high temperatures is because of the minimal amount of gas produced. This enables heat to concentrate in the solid and liquid products rather than being carried away in a gas cloud (6). One distinction between these reactions and standard combustion of metals, is that in a thermite reaction, a clearly detectable slag remains. This is of utmost importance to fire investigators who suspect thermites may have been used.

## Radiant Heat Transfer in HTA Fires

A commonly reported characteristic of HTA fires is bright white flames. Light intensity, like that of heat radiation, is determined to a great extent by the temperature of the emitter. It follows the *Stefan-Boltzmann* law that says radiation from a "black body" is proportional to the fourth power of its absolute temperature (degrees Kelvin).

In pyrotechnics, white light emission is usually produced using magnesium or aluminum powder. Both burn at high temperatures, and their oxides, $Al_2O_3$ and MgO, are good light emitters (6). Consider the relative radiation emitted for an aluminum flame and a propane flame (assuming both are good emitters). The absolute temperature of an adiabatic aluminum flame is 3,908°K (3,635°C) while that for propane is 1,554°K (1,281°C). The radiation of each type flame can be estimated by raising these temperatures to their fourth powers. Doing so, one finds the radiation (or heat flux) from an aluminum flame should be almost 40 times as great as that of the propane.

Abnormally high heat fluxes provide the best explanation of the incredible fire growth rates experienced in HTA fires. Thermal radiation is widely recognized as the dominant mode of heat transfer where flame lengths exceed 0.2 meters (8 inches), while convection is more significant in smaller flames (31).

The primary radiant emitter in a fire is soot particles found in the smoke layer. For aluminum fires, the reaction products do not contain "classic" carbon soot, but as noted earlier, consist primarily of aluminum oxide found predominantly as small liquid particles. Its white color and high luminosity makes it a great radiant emitter (11). Though not providing as great a radiant contribution as aluminum oxide, the water vapor and carbon dioxide produced as the principal gases in the high energy test reactions, are also strong emitters (6,11).

Accurately calculating the radiant emission from gas-soot mixtures require tremendous amounts of information such as soot volume fraction, the absorption coefficient of the soot, temperature of the particles, geometric flame length, etc. Since precise data such as these rarely exist in a fire situation, estimations are necessary. Currently, efforts are planned to use the data from the Puyallup and China Lake tests to develop reasonable estimates of the contribution of radiant heat transfer to HTA fire growth.

In addition to being a good white-light source, aluminum can also produce brilliant sparks. As relatively large aluminum particles are heated, they are sometimes ejected from burning surfaces by gas pressures formed during the combustion. If sufficiently hot, they can continue radiating outside the combustion zone as sparks. The size of the metal particles is critical in determining the quality and size of sparks. While small particles can be easily ejected into the fire plume, they often burn out too early. Conversely, too large a particle may have trouble igniting or being ejected from a burning surface. An excess of metal in the mixture usually increases the light intensity and also lengthens the life of ejected sparks.

Other common white spark producers include titanium and "magnalium" alloy (a combination of magnesium and aluminum). Magnesium does not tend to be a good spark producer. Its low boiling point usually results in it being consumed prior to ejection from the flame zone (6).

The high radiant heat fluxes generated within seconds during the various HTA tests are not typically experienced in carbon fires. One reason is that the smoke layer temperatures in carbon fires rarely exceed 1,200°F (650°C), even at the point of flashover. The smoke temperatures in the HTA tests commonly reached 800°C (1,472°F) and frequently higher. These higher temperatures in HTA fires (all other factors equal), result in a near doubling of the radiation experienced in carbon fires. This extra radiation in turn causes added pyrolyzation of available fuels, structural or otherwise, which, once burned, lead to a more rapid flashover than seen in typical fires.

The violent flashover observed in the Puyallup test was predominantly due to a rapid application of high heat fluxes. Though fuel gases were being pyrolyzed from the building early on in the test, this was not evident until the first door opened allowing oxygen to flow into the building. Once it did, additional combustion appears visible in the smoke layer moving from the area of the door to the west. The resulting additional heat release produced even higher radiant heat fluxes which advanced the progression towards flashover even faster. (While some of the extra fuel gas may have arguably been hydrogen from the HTA combustion instead of pyrolyzates, the effect of the added radiant heat is similar). The extra heat contributed by such burning gases is dependant upon sufficient gaseous oxygen.

One of the first publicized indications of HTA fires was large infernos occurring in buildings with little or no fuel load. As stated, this is inaccurate. While the particular buildings might have been void of contents such as furniture, cardboard storage, or any other ***live fuel-load***, most were of wood frame or heavy timber construction and had tremendous structural fuel loads. While it is true that in normal fires such structures are not easily ignited, in conditions of extreme radiant heat fluxes, the timbers and wood floors may quickly pyrolyze, charging the space with hot, flammable fuel gases. The only remaining necessary part of the fire triangle at that point is oxygen.

This effect was obvious at the Plymouth test fire. Although participants were initially disappointed at the apparently lackluster test, the results clearly demonstrated how HTA fires can produce rapid flashovers. Even though the test fuel had extinguished more than 10 minutes before oxygen was allowed to flow into the building, there was still enough hot, fuel-rich gases remaining that the first floor flashed over in less than two minutes. Had the door remained open during the actual HTA burn, it is likely that the fire would have more closely resembled that seen in Puyallup.

While HTA combustion certainly supports rapid fire extension, the metal fuel is not the principal heat source in that spread. Rather, most of the heat in the violent flashovers seen in these fires originates from the fuel in the structural members. An HTA might well be considered something like an enormous match, able to liberate its energy quickly. The sudden heat release causes rapid pyrolyzation and gasification of fuel gases from the structure. But it is the subsequent ignition of large quantities of this fuel which provides the greatest contribution to fire spread.

HTAs' high rate of heat release is the key to the puzzle of their ability to cause rapid fire involvement. Scientists who analyzed the Puyallup test fire reported that the heat release rate for the test fuel was probably between 3.5 MW and 7.0 MW. Though high, these rates could certainly be reproduced by igniting sufficient amounts of common combustibles simultaneously. On a volumetric basis, however, HTAs are far more energetic than common fuels, thereby providing a bigger "punch" from a smaller package. Further, and probably more important, the higher temperatures of the combustion gases generate higher heat fluxes which accelerate liberation of fuel gases.

## ANALYSIS OF SUSPECTED HTA FIRES

### NORTHWEST PRODUCE WAREHOUSE, Yakima, Washington 1/27/81

(No complete cause and origin reports were found for this fire. The following information was found in earlier published HTA reports containing accounts of the fire scene(2)).

The **NORTHWEST PRODUCE WAREHOUSE** was constructed of concrete floors and walls, topped by a wooden laminated beam roof. According to reports, the warehouse was empty at the time of the fire. Upon the arrival of firefighters, the building had at least partially collapsed. Investigators reported that heat damage to the structure was greater than they would have expected considering the lack of fuel load. The aggregate had apparently been sheared and had a polished appearance. A 21 foot, irregularly shaped crater was found in the concrete with the deepest portion measuring 11 inches deep. There was also reportedly a bluish discoloration of the concrete.

In May 1991, investigators received reliable information that the fire at the **NORTHWEST PRODUCE WAREHOUSE** had not been an HTA fire. Statements by a person intimately familiar with the start of the fire indicated that only common combustible fuels were used to initiate it. Accordingly, this fire should not be considered HTA related.

## TRI-STATE DISTRIBUTORS, Spokane, Washington 9/11/82

This four alarm fire in a large commercial building resulted in the death of a Spokane firefighter. The investigation into the cause and origin of the fire was conducted by investigators of the Spokane fire and police departments as well as ATF's National Response Team (Western Team). Reports were issued by ATF (assisted by a Los Angeles City Fire Investigator assigned to the NRT) and by the Spokane Fire Department.

The approximately 50,000 square foot, single story brick warehouse was built in 1932 as a truck terminal. It was fitted with 21 wooden garage doors. The wooden arched roof was supported by wood beams and steel trusses. The area of origin of the fire contained mostly televisions and stereo components.

The fire was reported by a citizen who saw flames inside the building through a window. Upon arrival, first-in firefighters noticed very light smoke but no flames or glow. When they turned into a south side alley, they could see flames extending through several windows. Looking inside, they described the fire as a large column of fire near the center of the warehouse. Approximately eleven minutes after the fire department's arrival, two firefighters preparing to re-enter the building, felt "a blast of heat simultaneous with a large flash" (32) from inside. Both were blown 12 to 15 feet into the street. Shortly after, they heard the roof collapse, resulting in the death of a fireman who was on the roof venting the fire.

The fire investigation discovered three five gallon cans located in areas near severe concrete spalling. Two of the cans had small puncture holes near the bottom edges from either nails or a can opener type device. One of the cans bore a label "Ban-Ice", a Chevron de-icer for gasoline. Also found near these cans were combustible materials such as cardboard and cloth that appeared to be positioned to best propagate the fire. Fire damage in these areas was considered extreme.

One conclusion by fire investigators was that the fire was accelerated by a flammable/combustible liquid, possibly one that was water soluble. Recently, Chevron officials advised ATF that

Ban-Ice contained 100% methyl alcohol, completely soluble in water.

Since the fire occurred three years before Seattle Fire began its investigation into HTA fires, no such descriptive phrase had yet been coined. Accordingly, original fire reports did not suggest this was an HTA fire, but described a rapid fire spread and commented on an unusually quick roof collapse.

According to witness reports, the exact time this fire started is unknown. First in firefighters did not even notice flames when they arrived although fire was already extending through windows on the rear side of the building. Though firemen determined the roof was sound when then climbed onto it, its eventual failure appears due not only to possible weakening by fire damage, but also to the apparent explosion that preceded it. Besides rapid fire spread, the only other signs suggesting an HTA-like fire was severe concrete spalling. It must be remembered however, that all investigators on scene noted the spalling was worst near the five gallon cans and attributed it to concentrated heat from the flammable liquids.

No evidence has been found to suggest the initial determination the fire was caused by flammable liquids was incorrect. Skillfully placed containers of slowly flowing accelerant along with combustibles arranged as trailers likely caused the rapid spread of this tragic fire. Although an HTA might have created an equally fast or perhaps even faster fire, there is no available evidence that would suggest it as the actual cause or that the original conclusions were deficient.

**ARTIFICIAL ICE, Yakima, Washington 9/16/83**

(No reports from the investigators on scene were available for use in examining this fire. A synopsis of this fire as reported by other investigators who have reviewed the reports (2) follows)

This fire was first reported as a slight amount of smoke showing from a closed warehouse door. There was reportedly no contents in the building at the time with the exception of an ice making machine with a stainless steel exterior. The roof was about 40 feet above ground and constructed of 2 x 6 inch tongue and groove boards.

Minutes after firefighters arrived, the roof collapsed. The fire investigation revealed severe cratering of the concrete along with aqua blue discoloration. Part of the stainless steel exterior to the ice machine melted.

Relying only on the above information, no conclusions can be drawn. While there are indications of high temperature damage, there is apparently no reliable evidence of the time the fire actually started. Although there was metal and concrete damage, several factors would have to be considered in analyzing this fire to insure normal fire conditions could not have caused similar results. A review of the reports of the **NORTHWEST PRODUCE WAREHOUSE** fire (also in Yakima two years previous) apparently describes similar, and possibly more severe damage. That fire has been reportedly determined not to have involved HTAs. No conclusive evidence was found indicating HTA fuels were not used in this fire. However, any conclusion that this fire was caused by high temperature fuels based solely upon similar claims of damage, must be approached carefully.

**CLASEN FRUIT WAREHOUSE, Yakima, Washington 9/16/83**

This approximately $3,000,000 fire was investigated by a fire investigator from the Washington State Fire Marshal's office and a report was issued as to the cause and origin of this fire. It should be noted that this fire occurred on the same day as that at the **ARTIFICIAL ICE** warehouse also in Yakima. Investigators from the Yakima Fire Department involved in determining the cause of the **ARTIFICIAL ICE** fire were not available for this case.

According to the fire report, a night watchman working at the warehouse near the packing room had parked a lift truck in that space. He later reported hearing a swishing sound and saw that another propane powered lift truck was on fire. Though the watchman stated he saw lift truck #1 on fire, the subsequent fire investigation indicated that the fire origin appeared to be in lift truck #6. That was the truck the watchman had parked earlier adjacent to truck #1. Despite the inconsistency, the fire marshal investigator declared the cause of the fire was accidental.

The investigators at the **ARTIFICIAL ICE** fire believe it was caused by an HTA. Despite the fire marshal's conclusion that the **CLASEN FRUIT** fire was accidental, other investigators have declared it suspicious because of the close proximity in time to that at **ARTIFICIAL ICE**, and because of possible connections between the owners of the two companies. Despite these conceivable links, no evidence could be found to support any allegation that the **CLASEN FRUIT WAREHOUSE** fire was accelerated by a high temperature fuel.

**CARPET EXCHANGE, Seattle, Washington 1/17/84**

The Carpet Exchange fire investigation was conducted jointly between the Seattle Fire Department and ATF's National Response Team (NRT) (Western team) and a joint report was issued as to the cause and origin of the fire. The nearly 50 year old structure measured approximately 145 feet by 200 feet. It had a flat wood roof supported by steel trusses, concrete or brick walls and a concrete foundation. The building was fitted with six skylights and large delivery doors on three sides. Several personnel doors were also located on all sides. Much of the building consisted of warehouse storage, although there was an office, display area and boiler room. The primary contents were rolls of carpet.

The fire was discovered by employees at an adjacent business sometime between 10:35 and 10:40 p.m. They heard an explosion and saw a small amount of flames and tremendous amounts of thick, black smoke along the interior of the building's west side, in the warehouse. Firefighters reported the main body of smoke in the west center section of the warehouse at floor level. Later, glass was found blown into a street over which one employee had driven prior to reporting to work at 10:28 p.m. He had noticed no smoke or glass in the street at that time.

About 15 minutes after the arrival of the first-in firefighters and a Seattle Detective, fire was noted as blowing through the roof. After another few minutes, the warehouse roof over the fire collapsed. Unfortunately the exact time was not found in any reports. At about the same time of the collapse, however, a separate explosion and ignition occurred at the north warehouse door. It included a pyrotechnic-like display of white light and large sparks flying well above the roof line. The center of this separate fire burned for some time and was described as similar to a phosphorus/magnesium type chemical reaction.

An injury suffered by a firefighter suggests an interesting aspect to this fire. Approximately 15 minutes before the pyrotechnic-like ignition in the north end of the building, he and others advanced a hose line into the same area. There was smoke present but no fire. They later reported they thought they were walking on broken glass. After kicking something, a firefighter felt a burning pain in his right foot. At the time, he was standing on dry concrete, no water having yet been applied. The injury to his foot involved third degree molten metal-like burns to the outside of his right foot below the ankle although there were reportedly no visible burns to his shoe.

The firefighter's shoe and debris from elsewhere in the fire scene were collected and sent to the ATF laboratory in San Francisco. Forensic scientists detected traces of aluminum, magnesium, titanium, manganese, copper, zinc, calcium and silicon as well as traces of methanol and naphthalene in the samples. They also discovered that within a few days, the cans in which some of the evidence was packaged had so severely corroded that they had lost their integrity. Though this indicated a very caustic environment, the specific corrosive agent was not identified.

At the origin of the secondary fire and pyrotechnic display, investigators found slag and welding to a steel corner beam, extreme spalling and residues which they submitted to the laboratory. Discovered elsewhere in the building was an area of spalling in an aisleway between carpet rolls, and severe damage to steel roof trusses. This included "bluing of the steel, formation of an *inordinate* (emphasis added) amount of slag, melted steel bolts and extreme metal distortion."(33)

Although there have been several claims throughout the HTA investigations that no slag has ever been found at any of the scenes, the Carpet Exchange fire report indicates otherwise. Slag was found not only at the north end of the building near where the pyrotechnic explosion occurred, but also near the failed steel trusses. The idea that no slag has ever been encountered may have inaccurately bolstered the speculation that a thermite mixture has never been used in the suspected HTA fires. Even though slag was collected from the Carpet Exchange and submitted for lab analysis, a complete identification of its constituents could not be found. Accordingly it cannot be determined if the slag was simply melted steel from materials native to the scene, a byproduct of a fuel, or something else. Several photographs and written descriptions of the slag indicate it was "silver" in color. Such a description does not suggest melted steel. It seems likely that considering the various trace metals found at the scene (including in and near the injured firefighter's shoe), the slag may, at least in part, have originated with a fuel.

Based on available witness reports (including television footage), scene investigation reports, and forensic analysis, it seems very likely that a high temperature metallic fuel was present and burned during the Carpet Exchange fire. Despite this, no conclusive proof has been found to identify the type of accelerant used. Because of the various factors described above, it seems probable that some type of thermite reaction may have been involved in the fire, although perhaps not as the principal accelerant. To suggest otherwise seems inconsistent with information discovered at the scene.

**FIRST CHRISTIAN CHURCH (LANDMARK BLDG), Bellingham, Washington 3/25/84**

This fire scene was examined by investigators from the Bellingham Fire Department and the Washington State Fire Marshal's office. The sixty year old, three story, brick building enclosed approximately 40,000 square feet of space not counting the basement. Vacant for twelve years preceding this fire, it had at least two previous fires in it attributed to transients that had never extended beyond the rooms of origin. In total, the building had suffered five previous fires, each of which burned out undetected.

The building had floors supported by mill-style construction and interior walls covered with lath and plaster. There was no glass in the windows, all having been boarded over with plywood sheets, several with holes in them. The only exposed combustible materials besides the window coverings was the 1 x 4 inch tongue and groove decking of the floors. A building inspector in the church within six months of the fire reported the floors had been swept clean of debris.

As with many of the other suspected HTA fires, the time of ignition of this blaze is not accurately known. A police officer reported the fire before dawn upon seeing smoke escaping all the windows. Firefighters reported the top floor and roof completely involved within four minutes. Fire suppression efforts were aimed at protecting exposures and no water was applied to this fire which burned intensely for about an hour. During the fire suppression, bright flashes were seen inside the building although electrical service had been disconnected.

Because of the complete burn, no point of origin could be determined. There was only one window through which fire had extended and impinged on the exterior brick. During the scene examination, investigators reported encountering strong odors of sulfur or methane (presumably odorized) from the debris. As to unusual damage, two of fifty-two cast iron radiators suffered severe fire damage, melting the metal and resulting in a magnetic slag.

The history of fires in the building offers a sharp contrast in behavior compared to this fire. Previous, apparently non-accelerated fires caused limited damage. No indication was seen in the reports as to whether evidence samples were collected, and no mention was made of what type of accelerant might have been used. One indication suggesting the presence of a high temperature accelerant at this fire was the melting of cast iron radiators. References have been made in various HTA reports that the melting point of cast iron is 2,850°F, and that such a temperature is higher than expected in a non-HTA fire. A review of the literature shows that this figure has apparently been inaccurately cited. The Handbook of Chemistry and Physics reports typical melting points of cast iron between 2,100°F and 2,200°F (23). The 2,850°F figure is more representative of the melting point of ingot iron, iron not contaminated with components like carbon, manganese and silicon as is usually the situation with cast-iron.

Since no lab analysis is available of the chemical nature of the cast iron or the slag, only assumptions can now be made as to the reason for the damage. It is possible that a metal/oxidizer mix (such as an HTA) burning in the vicinity of the radiators caused the melting. It is also possible that that mix was thermite and that some of the slag is due to iron slag caused by the thermite. However, since no water was applied to the fire, and since the damage is localized, it is also feasible that the damage may have been "normal". A protected area of smoldering combustibles fed by oxygen from a vent or draft is certainly capable of generating temperatures in excess of 2,000°F. Such an exposure over an extended period of time may have caused melting such as that observed. There are numerous examples of this type behavior in non-arson fire scenarios. One need only consider scenarios like blacksmithing and older steel mills, both fed with only carbon-based fuels and oxygen, to conjure up images of molten iron and steel.

Investigators surmised that this fire burned too intensely and rapid for the available fire load. However, since no further evidence of a high temperature fuel was discovered, this report cannot conclusively determine this fire involved an HTA. While some indications exist to support such theories, other non-exotic explanations may also account for the damage suffered in the fire.

## HANSEN FRUIT COMPANY, Yakima, Washington 5/2/84

The **HANSEN FRUIT COMPANY** fire was investigated by the same Washington State Fire Marshal investigator as was the **CLASEN FRUIT WAREHOUSE** fire. His reports were available for this review. This estimated $1,000,000 fire occurred in the cold storage portion of the warehouse which measured approximately 240 feet by 90 feet. The bowstring roof over the space reportedly consisted of plywood sheeting covered with mopped tar and paper, and a reflective aluminum coating. It was supported by wooden beams arranged in a truss. A hatch in the roof was open at the time of the fire. The walls were reinforced, hollow core, concrete walls. A more detailed description of the premises was unavailable.

The fire was reported at 3:59 a.m. by a security guard at an auto dealership, a deputy sheriff, and a city policeman. When firefighters arrived, the building was fully involved and the roof apparently failing.

The area of origin was found to be near the cherry packing line. According to the investigator, large areas of concrete spalling were visible at each of six sorting tables and a conveyer. Structural portions in this section of the building were found to be consumed and the roof totally destroyed. Large amounts of concrete broke away from the walls exposing steel rebar. A determination was made that the fire had apparently been caused when thermite was introduced and ignited along with a flammable liquid. No further description of slag or other reasons to suspect thermite were given. Several photographs were taken including specific pictures of what was called thermite, however, none of those pictures were available during this review.

With several references given to finding thermite at the fire scene, it is possible the investigator was alluding to locating slag. Without further descriptions, photographs, or laboratory analyses, a thorough review of the fire cause at this late date is difficult. It can be assumed that this fire was in fact started by thermite spread along the cherry packing equipment and ignited. It might also be assumed that another metal/oxidizer mix may have been used and caused severe metal damage to the equipment. Unfortunately, no conclusions as to the accuracy of either scenario can be drawn. For a more specific examination of this fire, scene photographs must be collected and examined along with more detailed statements of investigators and firefighting personnel.

**CAL-WOOD SUPPLY, Woodland, California 5/23/85**

This fire was investigated by members of the Yolo County Arson Investigation Unit and the Woodland Fire Department. A report was issued detailing their findings. The fire was reported at about 9:40 p.m. in a vacant, 30 year old warehouse covering approximately 42,000 square feet. Two police officers in the area 35 minutes before noted nothing unusual. First arriving firefighters found fire venting through the roof. Several hand lines and large appliances were used to fight the fire.

The building was constructed of reinforced, masonry block walls, concrete floor, and a plywood roof. The roof was supported by laminated wood beams, and covered with tar and gravel. Several roll-up and sliding doors were fitted on the north and east sides of the building, and were open at the time of the fire. Combustibles in the warehouse were limited to small piles of debris, a storage room in the northwest corner, and doors piled along the west wall.

When the fire was reported, flames were visible but the extent of the fire seemed minor. Within seven minutes of the initial alarm, the structure was reported fully involved. Flames were through the northwest corner of the roof, and loading dock doors in the north wall. Thick smoke was visible through the eastern doors. The fire involved the east half of the structure in about thirty minutes.

Spalling in some sections of the building was as deep as 4 inches. No distinct pattern to the spalling was observed. It could not even be correlated with the extent of building damage.

Combustible structural components in the western half of the building were almost completely consumed. The northwest storeroom was identifiable only from stains on the floor. Unusual damage suggested as indicative of high temperatures included copper wiring melting and flowing from conduit, and a brown glazing of the concrete blocks in the northwest corner. There was no indication of an electrical malfunction at the main power panel near the northwest corner. A large transformer mounted above the panel showed severe interior damage although no electrical malfunction could be identified to explain the damage.

Finding no accidental sources of ignition (including spontaneous combustion), investigators concluded this fire was incendiary. Because of the apparent high heat experienced and the rapid fire spread to the east, it was suspected that this fire was HTA related.

An analysis of the glazing on the blocks was conducted by the ATF laboratory in San Francisco. The reddish brown coloration was found to contain high concentrations of iron and silicon. The silicon was thought to have originated in the concrete and, once exposed to high heats, melted and flowed. The iron may have then contaminated the melted "glass".

As with many of the other suspected HTA fires, a conclusion cannot be drawn confirming or eliminating this fire as an HTA event. The northwest corner of the building was apparently subjected to high concentrations of heat. The source of this heat is unknown. Though melting of copper is frequently encountered in non-HTA fires, perhaps the amount of the damage described in the investigation reports can substantiate higher than normal temperatures.

The high concentrations of iron may be indicative of a fuel or then again, may have been native to the building. Considering the near total destruction of all wooden structural members, deep spalling is not necessarily an uncommon finding. According to leading petrographers at Construction Technology Laboratory in Skokie, Illinois, spalling is more often a function of the concrete composition than not. If the concrete in the warehouse floor was not homogeneous, uniform damage might not be expected under the same thermal conditions.

**ADVANCED ELECTROPLATING, Tacoma, Washington 11/20/85**

This $400,000 fire was examined by investigators with the King County, Washington, Department of Public Safety. The fire in the 180 foot by 98 foot building was reported at 6:44 p.m. by an employee of the company who was in the building at the time. He said the fire appeared to have started in the area of a chrome dip tank which was not operating.

The building housed a relatively new chrome plating operation. It was constructed of steel beams supporting steel walls and had an exposed concrete floor throughout. A wooden catwalk, four feet above the floor was constructed to the west of a north-south line of plating tanks.

The fire origin was determined to be below the catwalk in the general area of the chrome dip tank. Large copper buss bars were extensively heat damaged. Some of the copper melted and ran, pooling on the floor. According to the fire report, another investigator determined that the electrical system had not been responsible for the fire. Damage to wooden blocks supporting the dip tanks was most severe near the chrome tank. Further, spalling to the concrete was greatest near the most extensive wood damage. The spalling was on the top side of the sloped concrete floor below the tanks, indicating to the investigators that flammable liquids were not involved.

As with many of the suspected HTA fires, no record of forensic analyses could be found. The apparent reasoning for the HTA claim is the extensive damage to the buss bars. While the report claimed the electrical buss bars were determined to have not been involved in the fire, factors leading up to that conclusion were not found in the report reviewed for this analysis. Two of the power legs for a large transformer station at the southwest corner of the building tripped during the fire. It is not known if there was power to the buss bars during the fire or if the electrical system could have contributed to the damage at the bars. Occasionally, damage to "live" electrical components in a fire environment can sometimes emulate that caused by an initial failure in that electrical system. It is not known if this type of effect might have encourage the melting and flowing of copper observed at this fire scene. Again, no photographs of the scene were available for this examination. The narrative descriptions reviewed were insufficient to form a conclusion as to the cause of this fire.

**VICTORY BUMPERS, Seattle, Washington 11/30/85**

This $400,000 fire was reported at about 10:02 p.m., ten days after the fire at **ADVANCED ELECTROPLATING** in Tacoma, Washington. It was examined by investigators of the Seattle Fire Department. The building was constructed of concrete blocks and heavy timber beams. The flat roof was covered with a combination of hot tar and a fiberglass component. The building was split into two near equal parts by a north-south concrete block wall. The eastern part was a one-story section while the west section contained two stories. Damage was most severe in the center of the western section near the dividing wall. The primary contents of the western section of the building were non combustible metal auto-bumpers.

Witness reports indicated that in the early stages of the fire, smoke production from the building was considerable and that escaping smoke appeared to be significantly pressurized. Video footage of this event shows the smoke situation to be comparable with known HTA fires such as in the Puyallup and China Lake tests.

Damage included an 8 inch, concrete-filled steel column which melted and collapsed onto itself. Additionally, the concrete floor in the general center east section of the shop suffered severe spalling including fractured aggregate. One such area was under a steel table while another was under the welder. Because of the protection afforded the floor by these objects, the spalling was not believed to be due to radiant heat or falling debris. No mention was made in the reports whether the concrete had suffered melting or glassification of the cement as has been identified in HTA tests.

Liquid samples collected from these areas of origin had petroleum-like sheens on them and molten metal was found adhered to the underside of the welder. A forensic examination yielded no indications of flammable liquids in any of the samples except in a damp cloth that contained a "complex mixture of vaporizeable components" which could not be identified (36). The molten metal was determined to be primarily aluminum with appreciable amounts of zinc and lesser amounts of nickel, copper, iron and calcium. White deposits consisted primarily of oxides and carbonate.

Much of the information reported about the **VICTORY BUMPERS** fire seems consistent with combustible metal fires. The localized severe concrete damage in areas typically protected from fall-down and radiant heat coupled with molten metals and oxides adhering to the bottom of the welder are compatible with metal combustion. While these indications as well as the smoke production are fitting with aluminum/solid oxidizer combustion, as in other cases, this fire cannot be conclusively determined to have been caused by an HTA though such a theory seems in part supported.

**COMFORT INN MOTEL, Perry Township, Indiana 7/29/86**

Available information about this fire is very limited. The fire investigation was conducted by the Perry Township Fire Department. Though specific accounts of damage were not available, this fire was initially reported to be a flammable liquid fire. Later, it was apparently implied that that determination was incorrect and that perhaps a high temperature accelerant had been used instead. This change was eventually reported to investigators at the Seattle Fire Department. Eventually, officials changed their reported cause of the fire back to flammable liquids after persons involved in setting the fire admitted how it was set.

**CROWN PRODUCTS, INC., West Chicago, Illinois 4/7/87**

This fire which caused an estimated $3,000,000 loss, occurred in a very large building measuring approximately 420 feet by 300 feet. An investigation was conducted by the Illinois State Fire Marshal's office as well as ATF. The Fire Marshal issued a report as to the origin and cause of the fire. The fire was reported at 7:30 p.m. by an aircraft controller at a nearby airport who first noticed it upon seeing flames extending through the roof and thinking an airplane had crashed on the building.

The building was a one story building consisting of brick walls and a wooden roof. The bow-string truss roof was supported by large wooden chords and members. The floor was predominantly concrete, but in some places was covered with other materials such as tile. The building had previously served as an airplane manufacturing facility, and a scrap plastic business. At the time of the fire, it was shut down for remodeling.

The warehouse was destroyed by the fire. Huge wooden roof members between 12 and 15 inches thick were totally consumed as were all other combustible items. Little to no firefighting water was applied to the building and the fire was allowed to mostly burn itself out over more than 12 hours.

Firefighters stationed across the street from the warehouse received the fire call. About four to six minutes after being notified, a fireman took photographs of the warehouse. At the time, fire appeared to be on or near the floor below where a hoist truck was parked.

During the afternoon of the fire, maintenance personnel were inside, cutting pipe near the top of the open warehouse. The pipes had previously served to transport plastic particles throughout the building. Roofers had also been involved in cutting metal flashing from the roof that day, some near where flames were first seen venting through the roof. The hoist truck near the area of origin had been left under where personnel were doing the hot work. During the week before this fire, a few small fires had been caused by the welders and roofers. The afternoon of the fire, overhead exhaust fans had to be used because the building filled with smoke. The last person known inside the building left at about 4:30 p.m.

Most of the damage in the building consisted of consumed wood, melted aluminum, bubbled tile, and large expanses of spalled concrete. A review of the Fire Marshal's cause and origin report indicates that the fire cause was determined to be arson caused by someone pouring flammable/combustible liquids throughout the warehouse. ATF agents disagreed, theorizing that because the area of origin of the fire was directly under where a hoist truck was used to raise workers doing metal cutting to the roof, the fire had likely started as a result of that work and had burned for a long period of time before being noticed. Because the last workers stopped their cutting approximately four hours before flames were first seen through the roof, the State Fire Marshal concluded that work could not have led to the fire.

Although there was no suggestion in any reports that this was suspected of being an HTA fire, some conclusions have since been reached that that was indeed the most likely cause. Two reasons for such a conclusion were the apparent rapid fire spread and wide-ranging concrete spalling.

These two factors do not offer adequate justification that this fire was HTA related. First, since the fire was reported only after a large amount of flames showed through the roof, there is no indication that the fire began only moments before that time. Considering the large size of the building, a fire may have been burning for some time before venting through the roof. Further, a plausible explanation for the fire has been offered relating to the hot work occurring that afternoon. While no flames were noticed when the last employee left the building, smoldering at the roof could have taken place. With the known smoky environment inside the building that day, such a fire might not have been discovered. Even if this were not the fire cause, however, no justification was found to support a conclusion that the fire started just shortly before it was reported.

Second, as to the concrete spalling, sufficient evidence exists to show that such damage is in no way indicative of HTA fires. In the HTA test fires, concrete damage was often limited to only areas near the fuel location. That being the case, widespread spalling would then indicate a vast amount of the fuel would have been scattered about. Considering this fire burned unimpeded for several hours consuming all of the combustible material, a tremendous amount of heat was released. That long-term heat exposure is most likely responsible for the observed concrete damage. For these reasons, the probability that this fire was caused by HTA fuels is doubtful.

**BUCK CREEK LUMBER, Perry Township, Indiana 5/12/87**

The **BUCK CREEK LUMBER** fire was reported at 2:36 a.m. and occurred in two metal-sided storage buildings, approximately 120 feet by 30 feet, with a metal roof and concrete floor. One wall in each building was open. The investigation of the approximately $1,000,000 fire was conducted by the Indiana State Fire Marshal's office and the Perry Township Fire Department.

Most severe damage occurred in the two open buildings which were separated by a 250 foot by 40 foot office structure. In one of the burned buildings, the concrete floor was spalled to depths of four inches and resembled flammable liquid pour patterns. In the areas thought to be pours, the cement had a bluish-green tint. The other building also showed evidence of a flammable liquid type pattern. Witness statements described the fire within each of the buildings as having a white or blue flame.

Forensic analyses showed that evidence taken from one of the warehouses had the presence of an organic nitrite compound (37). Also found were melted aluminum and small brittle pieces of iron. A trace of a heavy petroleum distillate was present in some charred debris, but no other confirmation of flammable or combustible liquids were found.

Because of the limited information available in the reports, no conclusions can be drawn about this fire. While the bluish-green tinted concrete may indicate extremely high temperatures, the nature of available fuels in a lumber yard coupled with a fire that was obviously non-ventilation limited, would likely provide an ideal scenario for fire progression. The damaged steel or iron and aluminum may indicate metal combustion, but they may as likely represent materials native to the scene. As for the description of organic nitrites, such a compound might be indicative of an explosive oxidizer. Without a more definite identification, however, this can only be assumed.

One record of the fire that impressed investigators was a photograph showing flames extending horizontally several yards out of one of the buildings. A review of this photograph in the absence of any other relevant information proves only that a surplus of combustible gases was present in the fire and that once flashover occurred in that structure, the gases rolled out of the building before ignition. This type of situation is common in instances where an excess of fuel exists. While an HTA may have started such a fire, such behavior can not be considered definite proof of metal fuel combustion.

**GOLDEN OZ RESTAURANT, Kitsap County, Washington 1/28/88**

This fire occurred at 9:27 p.m. in a 1,350 square foot, single story, log cabin style restaurant. Investigators from the Kitsap County Fire Marshal's office and a private investigator examined the scene. The heaviest fire damage was to the owner's offic

(%1073(ially enclosed space with pressboard walls and wood framing. The localized severe damage in the office included melting of part of a metal desk, a portion of a metal serving table, and the legs of an overturned metal framed chair. Small "blobs" of melted metal were found in the fire debris under the melted metal furniture. A burn pattern covered with "brown blotches" was present on the concrete, but no spalling was noted. Elsewhere, firefighters found far lesser amounts of fire damage. Interestingly, papers stacked close to the work table were only slightly charred on the edges.

A brown liquid was collected from the fire scene and later determined by forensic analysis to be similar to a petroleum distillate serving as a solvent for wood stain pigment. The pigment was thought to contain a high concentration of iron, likely in the form of iron oxide.

Because of the damage to the metals, one investigator concluded that the flame temperatures in the fire were on the order of 4,000°F to 5,000°F. This was based upon an assumption that some of the damaged metal included sheet steel which had been 18 to 24 inches from the point of origin. Stainless and carbon steels typically melt in the range of 2,600°F to 2,800°F.

The conclusion of the private investigator on the scene was that a thermite mixture was ignited in the office near the melted metal objects. Though slag samples were apparently collected for analysis, the available forensic reports do not describe the exact nature of the metal debris found.

Despite the lack of a conclusive identification of the metal slag, this scenario fits well with the type of damage that might be expected from a thermite fire. The short duration of such burns would explain the relatively minimal damage to nearby cellulosic materials, while the high heats would be capable of melting adjacent metal parts. While such a determination is not wholly substantiated, it seems to offer the most feasible exp

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**MARITIME SHIPPING BUILDING, Seattle, Washington 2/17/89**

This approximately $2,500,000 fire was investigated by personnel from the Seattle Fire Department who issued a report as to the origin and cause of the fire. The fire was reported at 8:22 p.m. in the heavy timber building which measured approximately 300 feet by 200 feet with a general interior ceiling height of 50 feet. The roof consisted of wooden trusses supported by wooden columns. The trusses employed 10 x 24 inch wooden stringers supporting 10 x 10 inch wooden members. The support columns consisted of three connected wooden 10 x 10 and/or 12 x 12 inch posts, mounted on concrete bases. Walls were constructed of 2 x 6 inch tongue and groove boards. The floor was concrete and in some cases was covered by wooden decking and other materials. The building was fitted with substantial amounts of glass and several roll-up and personnel doors.

Several witnesses described the early stages of the fire. Each confirmed that the fire originated at floor level near the center of the building. Those with the best views stated the main part of the fire early on was near vertical columns with little to no nearby combustible material. The first known reports stated that several bright flashes similar to arc welding occurred near the center of the building. Within about ten minutes, flames vented through the roof directly above where the flashes had been. The eastern wall began to collapse at about 8:50 p.m.

Roof support columns in the area of origin were found to have been completely destroyed by flame. The concrete bases supporting those columns were badly heat damaged and had turned a bluish-green color. The concrete was crumbling and was easily broken by investigators' hands. Concrete flooring was also damaged and spalled to depths of three inches. Other damage included sections of cast iron pipe that had melted and steel plates with very localized damage.

Another interesting aspect of the **MARITIME SHIPPING BUILDING** fire was that at several times during suppression efforts when water was applied to fire, the flames seemed to have intensified. This phenomenon was reportedly clearly visible in a videotape (which was not examined during this review).

Reports indicate that early during the suppression efforts, fire hydrants near the fire did not function. The resulting need to lay long supply lines resulted in delays in the start of fire suppression. One truck company was without any water for about twenty minutes.

The witness reports of white arc-welding like flashes, and the apparent high temperature damage to building materials seems consistent with known factors corresponding with combustible metal fires. Considering the tremendous amount of wood fuel in the building, resulting concrete spalling would be expected, especially since fire suppression efforts appear to have been somewhat delayed. The high temperature damage to the concrete footings at the area of origin however is not as easily explainable by wood combustion alone. As was earlier discussed, petrographers report that the temperatures necessary to melt concrete (which is the apparent explanation for blue-green discoloration), are near 2,500°F (1,350°C). Such high temperatures are not necessarily required to greatly diminish concrete's integrity. Prolonged exposure to near 1,650°F (900°C) can result in such damage.

Elaborate methods of forensic analysis were employed to analyze debris from this fire. Early results from these tests indicated that traces of zirconium were found at the fire scene. Since zirconium is a well known combustible metal commonly used in military applications, investigators initially thought part of the accelerant had been identified. Unfortunately, those results were later found to be aberrations and the end result was that again, no traces of the accelerant were found.

Because of the above considerations, it seems likely that the fuel used to initiate the fire at the **MARITIME SHIPPING BUILDING** was some type of a high temperature accelerant. Because no mention was made of finding thermite-like slag, and because of the early witness descriptions, it is plausible that the fuel employed was similar to that used in the HTA tests at Puyallup, China Lake and Plymouth.

## BLACKSTOCK LUMBER COMPANY, Seattle, Washington 9/9/89

The **BLACKSTOCK LUMBER COMPANY** fire was the most tragic of the suspected HTA fires in Seattle, resulting in the death of a Seattle Fire Lieutenant. The fire was investigated by the Seattle Fire Department, Seattle Police Department, the Washington State Fire Marshal's Office and ATF. The Seattle Fire Department and State Fire Marshal's office prepared reports as to the cause and origin of the fire. In addition to the written reports, a videotape of most of the fire was available for review. During the period of this review, investigators in Seattle have uncovered several previously unknown facts. Though not in the initial reports, these details will be mentioned herein.

The approximately 300 foot by 150 foot building had been vacant for nearly two years prior to the fire. Utilities had been disconnected before the fire, but there was live electrical service to at least the main breaker panel on the eastern wall. While one quarter of the building consisted of two stories used for office spaces, the remaining three quarters had a ceiling height of about 30 feet and was used for dry lumber storage. The interior was separated into four distinct areas by fire walls and doors.

The building was constructed at about the turn of the century using heavy timbers. Exterior walls were 2 x 6 inch planks covered by plywood and shiplap siding. Interior walls were wood frame. Some had been covered with gypsum board in the office spaces. Firewalls were two layers of 2 x 6 inch tongue and groove boards sandwiching a half inch layer of sheetrock between them. Floors were 2 x 12 inch wood planks and in some areas were covered by plywood and 1 inch hardwood. The floor was supported by post and beam construction and was about five feet above grade. The roof was wood sheeting covered with tar and tar paper. At the exterior of the southwest corner of the building was a semi-enclosed, wooden storage shed.

Initial reports stated the owners claimed there was no fire load in the building with the exception of the structure itself.

Recent interviews with principals in the investigation bring into question this previously accepted account. Newly obtained information suggests that when the building was vacated, a significant amount of wood framing and platforms were present including large wooden storage racks and other combustible materials. Though it can not be confirmed the materials were still there during the fire, the owners claim no one should have had access or reason to remove them beforehand.

Early on, only a few witnesses were thought to have observed the fire starting in the storage shed on the southwest corner of the building. Investigators now know several people saw the fire to have originated outside the building in a trash can. Because of a lack of windows, it could not be seen if the fire was also burning inside.

There are also inconsistencies as to reports of explosions occurring during the fire. One firefighter along the south exterior wall reported an explosion-like sound before the collapse of much of that wall. Other people have claimed there were no explosions.

First-in firefighters noted that upon their arrival, flames were showing from under the southwest corner of the building. Shortly thereafter, the raging fire involved much of the west side of the structure and was venting through the southwest corner of the roof. Clearly visible in a videotape is what some investigators have referred to as pyrotechnic-like displays from the top of flame plumes where burning embers sprayed upwards. During this time, railroad ties several yards west of the west wall of the building appeared to have creosote bubbling from them.

Eventually the main fire progressed to the north and destroyed most of the warehouse, primarily in the western sections. Final damage included severe burn-through of much of the wood floor, collapse of walls and roof, and melting of some metal items.

A second shed about 100 feet south of the main structure was thought to have experienced a separate fire although no mention was found in the reports of witnesses seeing a second fire there before or during the main blaze. That fire reportedly self extinguished. Under an irregularly shaped hole burned through some plywood, a white, powdery ash was found which reportedly had a different appearance than the wood ash. No lab reports were found identifying components of the ash. In 1994, witnesses were identified who state that the remains of large fireworks containers such as Roman Candles were frequently found in the area of this shed. Other witnesses have also stated that in the week before the fire, fireworks had been used in that vicinity.

One unusual and unexplained event during the fire was what appeared to be an electrical circuit arcing and spraying sparks from the north end of the building. Experienced fire investigators and firefighters who have reviewed a videotape of this event claim it appears identical to other electrical failures they have observed. Even so, the power company in Seattle reportedly insists there was no power to the building at the time. Further, investigators did not report finding any transformer or high voltage equipment in that area. This reported absence of power and of electrical distribution equipment was a major part of what led investigators to believe that an HTA may have ignited there during the fire.

Recent interviews, conducted nearly five years after the fire, have revealed that an electrical panel serviced with 440 volts was located near where the sparking occurred. Though it had been disconnected from circuits servicing the rest of the building, it was believed to have still been connected to the city's high voltage lines. This information is clearly inconsistent with early beliefs that there were no electrical circuits in the area of the sparking.

Examination of the videotape shows the source of the sparks was at least a few feet above the ground along the north wall. If these sparks were caused by an HTA, it would seem likely that other visible displays whould have been observed at floor level throughout the building where burns were reportedly caused by an HTA. As the fire progressed, a substantial number of openings into the building occurred which would have allowed firefighters a view to the interior. Despite this, no other such sparking was reported. Although the local power company insists the power was deactivated at the time, numerous fire personnel who have viewed the tape report what appears to be an electrical failures in the vicinty of an electrical panel. Accordingly, the conclusion that the sparking must have been due to an HTA igniting seems tenuous.

Much of the information leading to the conclusion that this fire was caused by a high temperature accelerant lies in descriptions of incredible heats experienced during this fire, pyrotechnic effects and the locating of melted pieces of metal. Additionally, investigators have pointed to the lack of any flammable liquid traces found in the fire debris.

Although the fire has been described as spreading unusually fast, a review of available videotapes along with consideration of the type and age of structural members leaves the author doubting such a conclusion. Once the old wood ignited, it would have provided a substantial amount of energy into the various sections of the building. HTA test data showed the significance of heat generated by structural components in spreading a fire. It seems feasible that as the heat built up in the "compartments" forcing each towards flashover, it would spread through open fire doors into adjacent areas and begin heating those sections. Once oxygen became available, the hot fuel gases would burn, releasing even more heat into the compartment. The tremendous build-up of combustible gases in this fire is evidenced by the enormous flames extending through the roof once it vented over the various building sections separated by firewalls.

As for the metals, it was again suggested after **BLACKSTOCK** that iron and iron alloys do not melt in temperatures less than 2,800°F. As previously discussed, this is not true except for ingot iron. Various cast irons actually melt at temperatures closer to 2,100°F. As for the various metal items in the building, no evidence was shown that the metals were not alloys which have lower melting points than their pure constituents. While it is true that in general, the temperatures in wood or flammable liquid fires do not typically exceed much above 1,800°F, this is not a hard-fast rule. Numerous instances have shown that wood based fires can reach temperatures adequate to melt steels. Although this is not the "typical" situation, it certainly is possible, particularly when there is sufficient ventilation.

Since **BLACKSTOCK's** floor was 5 feet above grade with winds from the south, it is feasible that oxygen could have entered the building from below the floor. The resulting ventilation might very well have resulted in higher than normal temperatures. One finding at the scene was that fire apparently spread underneath the raised floor to other parts of the building. In the northeast section, charring was severe to the posts and floor joists.

Another conclusion by on scene investigators about the **BLACKSTOCK** fire raises questions. It was claimed that equal amounts of damage to both sides of a fire wall meant there were separate fires on each side. If a compartment on one side of the wall burned for some time and then the roof significantly vented, much of the heat in that room would then flow out of the compartment causing charring to slow. If at the same time, wood in an adjacent room was ignited by hot gases or trailers from the first fire and continued to burn until the roof opened over its space, it is conceivable that the amount of char on both sides of the wall could be similar. Videotape of this fire shows that the entire roof along the west wall did not collapse at one time, but failed one section at a time towards the north.

Investigators uncovered floor damage during their investigation that resembled that from a flammable liquid fire. During the scene investigation, an accelerant detection dog from the State Fire Marshal's office examined most of the building. The dog alerted in several areas including along the edges of burned out sections of floor. More than 100 samples of debris were collected from the building for analysis. While none of the samples contained any trace of flammable liquids, several included terpenes. Because of the extremely large area encompassed by the burn patterns and the lack of any laboratory confirmation of flammable liquids, investigators concluded that liquids were not likely used as the primary accelerants.

According to the fire reports, most of the debris samples were collected from the floor. Although there were several mentions that the dog alerted near holes in the floor, there was no indication that samples were collected from the soil beneath the holes. In long-burning fires, it is not uncommon for flammable liquids to be consumed from exposed areas. It is also common for flammables poured on a raised wooden floor to flow or drip between the boards and onto the soil below. Flammable liquid-like burn patterns coupled with the canine's alerts near holes in the floor, certainly suggests a potential for finding traces of liquid accelerants in the ground. It is also possible that flammable liquids were present inside the building, but that the dog alerted to an accelerant at levels below the detection capabilities of the laboratories. In either case, investigators' conclusions regarding flammable liquids not being used as the primary accelerant seem unproven. Perhaps more correctly it should be stated that no flammable liquids were found.

If the floor burns were due to an HTA spread throughout the building as suggested, the resulting damage seems extraordinary considering the damage seen in HTA tests where wooden members were exposed to the fuels. In those cases, the burning duration of the HTAs were quite short, usually less than three minutes, even when confined. If the fuels had been dispersed over a large area the size of the **BLACKSTOCK** burn patterns, it is quite likely that they would have burned out even faster as was the situation with uncased vs. cased fuels at the China Lake tests. It also seems likely that someone would have observed the symptomatic white flame and sparking displays seen at HTA test fires. It was suggested that it would have been difficult for an arsonist to cover the floor with enough liquid to cause the resulting burn patterns. In review, it seems even more unlikely that someone could have substituted solid fuels to cover the same area than it does to assume a liquid accelerant was used.

With regards to the displays in the flame plumes, the only visual record of the fire was a videotape which tended to show most of the fire as white. While some hot particles were easily observed escaping the tops of the flames, identifying them as metal particles versus wood brands by their color was impossible.

In review, while there is substantial information regarding the **BLACKSTOCK** fire, several questions still loom as to its cause. Early indications that this fire was consistent with other suspected HTA fires now appear in question. It appears to the author that many facets of this fire are explainable by normal fire behavior. In any case, this fire could easily be the subject of a lengthy report detailing its various aspects. Instead, it has been addressed here only briefly with the awareness that the actual fire cause is still in question. In essence, while it cannot be concluded that the fire did not involve an HTA, significant doubts still exist about this being anything other than a normal fire.

**PATIO DEL RAY CAFE, Del Ray Beach, Florida 10/29/89**

The **PATIO DEL RAY CAFE** was the first suspected HTA fire reported in Florida. It was investigated by the Florida State Fire Marshal's Office. The abandoned restaurant measured about 120 feet by 80 feet by 25 feet high. It had been vacant since 1985. Walls were constructed of masonry block over a concrete floor. The roof was predominantly glass and aluminum. There was no utility service at the time of the $750,000 fire.

The fire was reported at 6:19 a.m. and reportedly spread rapidly throughout the building despite having vented itself. An aluminum support beam (type 6063-T6 aluminum, reported melting point of 1,200$^{o}$F) with an acrylic thermosetting coating melted during the fire. Investigators smelled what they thought was a lighter fluid in the vicinity of concrete spalling. Once water was applied, a rainbow sheen appeared. Additionally, forensic tests found evidence of "unidentified flammable liquids" on the shoes of one of two runaway boys that had been staying in the building at the time of the fire. Though the cause of the fire seemed apparent during the investigation, investigators questioned why the aluminum beam melted in the manner it did. Since the failure was so localized, the thought existed that other than hydrocarbon fuels may have been responsible.

No additional evidence was found in the review of investigation reports to suggest any involvement of HTA. Though the damage may have been confined and unusual, without further indications of HTA-like fuels, such a conclusion seems unlikely.

**KIRBY TERRACE APARTMENTS, Winnipeg, Manitoba 1/10/90**

This eight story, 75 unit apartment complex was reported on fire at 5:07 a.m. on January 10, 1990. Fire investigations were conducted by the Winnipeg City Fire and Police Departments, as well as private investigators and engineers working for the Manitoba Public Insurance Corporation, all of whom prepared reports of their findings.

A review of the investigation records shows that the fire originated in the vicinity of an open-air parking garage on the ground floor and extended vertically on the exterior of the building. Fire damage included heavily spalled concrete columns and ignition of upwards of 25 automobiles. Although fire spread was very rapid, the cause of the fire has apparently been identified according to the reports.

According to the various investigators, the fire probably originated in the ceiling space above the garage because of a defective electrical heater. Wood sections around the heater showed evidence of extensive heating resulting in pyrophoric carbon.

The rapid spread of the fire was apparently not surprising to the investigators. They explained the fast growth at least in part because of the ignition of a combustible Exterior Insulation and Finish System (EFIS). The system was an exterior wall cladding system of insulation boards fastened to the structure and covered with a protective outer coating, usually made up of a synthetic resin and Portland cement.

Investigators claim that by minimizing heat loss from the garage to the ceiling, the insulation allowed the flames to remain hotter and extend farther than normal. It additionally provided extra fuel to the fire on the ceiling. Further, the resulting molten plastic which dripped down acted as an ignition source for the cars below.

There is no indication in the Canadian's reports of why this fire was ever considered to be an HTA fire with the possible exception of rapid flame spread and concrete pillar damage. After review of the official records, it seems to be an excellent candidate for exclusion from such suspicion.

**E & H BOAT WORKS, Lake Park, Florida 3/21/90**

This nearly $700,000 fire was investigated by the Florida State Fire Marshal's office, the Palm Beach County Fire Rescue Department, the Palm Beach County Sheriff's Department and ATF. Reports were prepared by the Fire Marshal's office and the Sheriff's Department. The fire is though to have started between 1:30 a.m. and 2:00 a.m. It was not reported to the fire department, however, until 2:23 a.m. by a neighbor who first heard someone knocking on her door and then later observed white flashes and orange flames and heard popping noises emanating from the boat works. When firefighters arrived, the building was fully involved in flames. A videotape of part of the fire was taken by persons living on the opposite side of the Intercoastal Waterway, along which **E & H BOAT WORKS** was located. That videotape showed white flashes coming from inside the building early in the fire.

The building was a two story concrete block building approximately 80 feet by 30 feet with a pre-poured concrete roof covered with gravel. The area of origin was determined to be inside the north half of the building near the entrance. Flammable accelerants were believed to have been poured on the concrete, counter tops and in the showroom. Several containers of mineral spirits and paint were stored in the showroom. After the investigation into the cause and origin of the fire was conducted, a witness was located who was reportedly at the building the night of the fire. He reported seeing an orange glow in the building adjacent to the north entrance prior to a vehicle speeding away. This witness was later identified as a suspect in the fire but committed suicide before the investigation could be completed.

The primary indication found suggesting this fire might be HTA related was the white flashes recorded on the videotape as well as the statements of the reporting party. A review of the damage as reported by the scene investigators reveals no mention of specific high temperature damage. One investigator accounts for the white flashes as being caused by electrical service inside of the building during the fire. Adjacent to the north entrance, evidence of electrical shorting was found that was determined to have been caused by the fire rather than causing it.

According to the available reports, there was no specific information correlating this fire with high temperature fires. While there was mention of white flashes, they seem to have been explained by electrical power failures. In the absence of other information, this fire seems an unlikely candidate for inclusion in a list of HTA fires.

**CENTRAL FLORIDA MACK TRUCK BUILDING, Orlando, Florida 3/1/91**

This $60,000 fire was investigated by members of the Florida State Fire Marshal's Office and the Orange County, Florida Fire Department. A brief report by the Fire Marshal's Office along with a newspaper account were used in reviewing this fire. At the time of the fire, this building was owned by Chevron Chemical Corporation. Chevron had previously manufactured chemicals on the site but later sold or leased it to **CENTRAL FLORIDA MACK TRUCK.** That firm moved out of the building more than two years earlier and Chevron Chemical regained possession. It was a wood frame warehouse covered with a metal skin and measured approximately 300 feet by 80 feet, with an addition of 120 feet by 45 feet.

According to reports, the building was fully involved in fire and was collapsing at the arrival of the first-in units. No information has been found to identify when and how the fire was discovered. One witness report did indicate that near the center of the warehouse early in the fire, there was a bright column of fire.

Available reports describing the damage caused by this fire were extremely limited. One account did indicate that steel pipes were melted and that concrete was spalled. Another fire description indicated that although flames would subside when water was applied, they would reappear as is common with burning liquids. A list of contents was not confirmed. One mention was made of a group of unmarked and unburned 55 gallon drums as well as the presence of a large amount of wood piled at one end of the building.

One newspaper account suggests the combination of rapid fire spread in a mostly empty building coupled with the steel and concrete damage indicate this was an HTA fire. On record, however, the investigators being interviewed refused to classify the fire as such, although they did agree the tell-tale HTA indications were present. In the absence of more complete information, no opinions can be offered in this review supporting or refuting such a possibility.

**13410-8th STREET, Sumner, Washington 4/19/91**

There were no available reports to use in examining information about this fire.

**GALAXY CHEESE, Sharon, Pennsylvania 6/29/91**

This $6,000,000 fire was investigated by the Pennsylvania State Police along with a private investigator. The State Police report along with statements of the private investigator were reviewed in examining this fire. The **GALAXY CHEESE** factory was a 55,000 square foot concrete block structure with a wooden roof assembly and concrete floors. Most of the building contained a single story with 15 foot high roofs with the exception of an office area which had two stories.

The fire was discovered by a security guard on duty who reported seeing separate fires in one of the warehouses. Though he tried to get a fire extinguisher to put out the fire, he was unable to do so. The fire quickly spread and caused near total destruction of the building.

The State Police concluded that this fire was incendiary because of the rapid spread of the fire coupled with severe concrete spalling in the room of origin. Additionally, positive readings from a flammable gas sensor were obtained throughout the building.

The reports reviewed in this analysis did not contain a detailed description of the damage encountered in the post-fire investigation. Even so, it appears that much of the reasoning behind the suggestion that this fire was HTA related lies in the rate of fire development. Within three minutes of noticing the fire, thick black smoke was flowing out of the building. In another four minutes flames were visible through the end of the warehouse roof and in fifteen to eighteen minutes, much of the factory was fully involved.

One important factor in the development of this fire was the amount of combustible materials in the room of origin. It was estimated that about half of the warehouse contained palletized cardboard boxes. Additionally, there were additional packaging materials and plastic cups in the same room. Provided there was adequate ventilation, the resulting fire could have naturally propagated throughout the structure. As mentioned several times earlier, the presence of large amounts of combustible materials can lead to concrete spalling in the absence of any accelerant.

During the investigation, it was discovered that a man working nearby reported hearing a whoosh or poof-like explosion prior to seeing substantial amounts of smoke. This possibility of a fuel-air ignition might have been supported when a fireman reported that prior to entering one of the warehouses, he smelled a definite odor of kerosene (despite no later laboratory confirmation).

After completing the review of the available information surrounding this fire, there does not appear to be any evidence which supports a conclusion this was an HTA fire.

**ADAMS VEGETABLE OIL PLANT, Woodland, California 7/16/91**

This $2,000,000 fire was investigated by the Woodland Fire Department who also participated in the **CAL-WOOD** fire investigation six years earlier. A report prepared by that department was used in this review. **ADAMS VEGETABLE OIL PLANT** was an approximately 31,000 square foot building originally constructed in 1905 and completed in 1951. It was built with a wood frame wall and roof truss structure, and was covered with corrugated metal sheeting. It had a concrete floor and concrete stem walls. The building had been converted in the year prior to the fire from bulk grain storage to vegetable oil production. It was fitted with an auger assembly mounted through the roof.

Building contents included large amounts of raw materials including almonds, almond cake, canola, rice hulls, and prune cake. Additionally, there were about 17,800 gallons of various vegetable oils stored within the structure in tanks.

At 11:55 p.m. on 7/15/91, a woman drove past the building and noticed nothing unusual. At 12:47 a.m., the fire was reported as fully involved. At about 12:30 to 12:45 a.m., a man and his wife had been sleeping in their tractor/trailer in the parking lot of the plant when they smelled burning rubber. Upon looking outside, they observed flames extending above the roof of the building. Within minutes, the building was fully involved before fire engines arrived on scene. Upon their arrival, first-in firefighters reported that while the walls and most of the roof remained intact, fire could be seen throughout the building in what they described as a white glow.

The fire investigation revealed that all wood supporting members were consumed in the fire. Additionally, about 15,600 gallons of vegetable oil either burned or were lost during fire suppression operations.

Other damage found at the scene was a substantial amount of concrete spalling and discoloration ranging from "fire clay" brown to blue and jade green. Also, molten samples of iron were found in the vicinity of the spalls. A further examination of the collapsed auger assembly inside the warehouse showed that copper wire in conduit leading to the assembly melted.

Because of this damage and the apparent rapid spread of the fire, fire investigators determined this fire was incendiary and that an unknown high temperature accelerant was used. While these factors might be used to suggest that an HTA was used to set this fire, such a conclusion can not be confirmed.

The discovery of molten iron around the spalls certainly indicates the possibility that a thermite mixture was used. At the same time, depending upon the amounts located, it might simply represent damaged metals native to the scene. Large areas of damaged and discolored concrete might also imply that a high temperature accelerant was used. Previous tests have shown that when such fuels were employed, such discoloration was generally quite localized. Similar spalling damage and minor discolorations have also been produced using common fuels.

A review of the investigation reports shows the fuel load in the warehouse was substantial. Additionally, it was determined that a large warehouse door was open during the fire. While it has been suggested that the fire progressed quickly, in actuality, the fire could have started as much as 35 - 45 minutes before it was reported. If a conventional accelerant had been used to start the available fuels in the building, the outcome might have been the same.

In essence, while there are indications of fire behavior here consistent with that at other suspected HTA fires, there is no evidence decisively eliminating the possibility that common fuels were not used to start it. Accordingly, no conclusions can be made, nor are any offered.

**PUREWAL BLUEBERRY FARMS, Pitt Meadows, British Columbia 8/8/91**

This $800,000 fire was investigated by personnel with the Canadian Royal Mounted Police and local fire investigators as well as an investigator from the Seattle Fire Department. Fire reports prepared by Canadian fire investigators were available for review. The fire was discovered in a barn at a blueberry farm by a mechanic at 5:00 a.m. He had been working until 4:15 a.m. when he went to sleep. At 5:00 a.m. he was awakened and saw the fire through the roof of the barn. When the fire department arrived, fire had involved the south side of the structure from the ground through the roof.

The building was a single story, wood frame structure measuring approximately 120 feet by 80 feet with a 24 foot high roof. The walls and roof were clad in metal sheeting and the floor and foundation stem walls were made of concrete. Contents of the building included about 350 tons of blueberries on pallets, palletized packing boxes and plastic lids and bound cardboard boxes.

The fire burned the berries nearly to ashes and caused near complete destruction of the wood framed members. It also resulted in severe concrete spalling throughout the building. An aluminum automatic transmission outside the barn partially melted.

Fire investigators concluded that the intense heat build up and severe damage to building materials indicated the use of an HTA. They further speculated that cardboard boxes of an HTA, possibly aluminum powder and ammonium nitrate, were ignited possibly with an electric squib or a chemical incendiary device.

In 1994, police officials arrested the person responsible for this arson fire. His later confession describes his method of burning the building. He said that by using commonly available anarchist-like recipes, he formulated a version of napalm or jellied gasoline by mixing gasoline with styrofoam. He then placed this mixture in a container along with a pipe bomb and delivered it to the barn. The eventual explosion scattered the jellied accelerant and ignited it. As a result, a sudden release of heat ignited a large portion of the building.

Because of the confession by the arsonist responsible for this fire, it should not be classified as involving a high temperature accelerant.

**CROWN INDUSTRIES, Hebron, Illinois 8/17/91**

The investigation into this fire was conducted by investigators from the Illinois State Fire Marshal's office and ATF's National Response Team (Midwest Team). Separate reports were issued as to the cause and origin of the fire. Neither report makes any mention of an HTA being suspect, however, according to recent verbal reports from an investigator at the scene, he now believes this fire to have involved such fuels. The fire marshal investigator's report concluded the fire was *suspicious* after finding burn patterns consistent with a flammable/combustible liquid, heavy oxidation of metal computer frames, and smelling an odor similar to toluene when removing debris and carpet. He further interpreted burn patterns in and around the computer room to be indicative of a flammable/combustible liquid burning.

According to ATF investigators, the cause of the fire could not be determined. Additionally, while they never pinpointed an origin, ATF agents believed the fire started in the warehouse. Reports from firefighters that passed through the computer room well before it ignited led ATF to conclude that the computer room was not an area of origin.

The metal clad, one-story building measured approximately 356 feet by 120 feet. Crown Industries manufactured several types of spray paint. To that end, various chemicals were kept at the factory including several volatile and flammable hydrocarbons, zinc dust, aluminum powder and molybdenum powder. It was reported that approximately 3 million cans of paint were at the factory at the time of the fire as well as numerous 55 gallon drums of chemicals and paints.

Soon after the fire was dispatched, a Hebron Police officer in the vicinity of the building observed flames through the roof in the center of the factory. As he drove to the scene, he saw aerosol cans falling onto the highway. First-in fire units also reported seeing the cans dropping.

Because of a lack documentation explaining why this fire is suspected as an HTA fire, it is impossible to thoroughly analyze it in such terms. The only plausible intimation of such a fire was a reference in reports to severely damaged metal racks in the warehouse. According to the ATF fire investigators, these racks held cans of spray paint, many of which contained zinc dust and/or aluminum powder as a component. Since these powdered metals may have combusted during the fire, high temperature damage would not be unexpected.

Reports mentioned "heavy spalling" of the concrete floor and witness reports of bright orange flames. Though the bright flames might signify burning metals, concrete spalling is in no way unique to HTA fires and in fact, as noted by the fire investigator commenting on its appearance, "would be natural with the fuel load that was in this factory." (34)

Recognizing the above factors, a determination that this fire was due to an HTA seems dubious. Not only was there no reference to such a cause in initial reports, most of the investigators at the scene continue to doubt such a conclusion. Further, high temperature fuels indigenous to the building may be responsible for the only reported damage consistent with high temperature fires.

## CONCLUSIONS

After conducting the above analyses of the various fires suspected of involving high temperature accelerants, it is obvious that several of the fires involved some type of burning metals or other high temperature fuels. At the same time, it also seems apparent that HTA mixtures were not used in others. For many of these fires, determining which accelerant(s) was used may never be accomplished without confessions of those involved. Table 5 shows the authors conclusions or lack thereof of the potential that the above fires were HTA related. The column labeled **HTA?** indicates whether, after reviewing the available reports and scene documentation, enough evidence exists to support the suspicion that the fire is HTA related. The categories used to denote the results of the analyses are: **Non-HTA**, **Unlikely**, **Undetermined**, or **Potential-HTA**.

A classification of **Non-HTA** indicates that significant evidence exists nullifying any theory that an HTA was involved in the fire. The evidence was typically confessions or other such facts that clearly established the fire cause. **Unlikely** should be considered a conclusion that there existed sufficient indications in the available reports to rationally explain the fire behavior in terms of normal fuels. **Undetermined** indicates that insufficient information was found to allow for a conclusion as to whether or not a HTA was involved. **Potential-HTA** was chosen to indicate that the available reports describe evidence or fire conditions that would allow a reader to rationally conclude that a combustible metal fuel of some type may have been present and burned during the fire. In those situations where this categorization was used, no conclusion should be drawn as to specific fuel/oxidizer combinations that burned or whether the mixtures were the same as those used in any of the test fires.

Table 5

| **Date** | **Name** | **HTA?** |
|---|---|---|
| 1/27/81 | Northwest Produce Warehouse | Non-HTA |
| 9/11/82 | Tri-State Distributors | Non-HTA |
| 9/16/83 | Artificial Ice Company | Undetermined |
| 9/16/83 | Clasen Fruit Company | Non-HTA |
| 1/17/84 | Carpet Exchange | Potential HTA |
| 3/25/84 | Bellingham 1st Christian Church | Undetermined |
| 5/2/84 | Hansen Fruit Warehouse | Undetermined |
| 5/23/85 | Cal-Wood Supply Company | Undetermined |
| 11/20/85 | Advanced Electroplating | Undetermined |
| 11/30/85 | Victory Bumpers | Potential HTA |
| 7/29/86 | Comfort Inn Motel | Non-HTA |

| Date | Name | HTA? |
|---|---|---|
| 4/7/87 | Crown Products, Inc. | Non-HTA |
| 5/12/87 | Buckcreek Lumber Company | Undetermined |
| 1/28/88 | Golden Oz Restaurant | Potential HTA |
| 2/17/89 | Maritime Shipping Building | Potential HTA |
| 9/9/89 | Blackstock Lumber Company | Undetermined |
| 10/29/89 | Patio Del Ray Restaurant | Unlikely |
| 1/10/90 | Kirby Terrace Apartments | Non-HTA |
| 3/21/90 | E & H Boat Works | Unlikely |
| 3/1/91 | Central Florida Mack Truck | Undetermined |
| 4/19/91 | 13410-8th Street East, Sumner, Washington | Not-examined |
| 6/29/91 | Galaxy Cheese Company | Unlikely |
| 7/16/91 | Adams Vegetable Oil Plant | Undetermined |
| 8/8/91 | Purewal Blueberry Farm | Non-HTA |
| 8/22/91 | Crown Industrial Products | Non-arson HTA |

What should also be apparent by this table is that the behavior of high temperature accelerants is not completely understood in the fire investigation community. As previously discussed, rapidly developing fires (even those in large buildings) are not conclusive proof of high temperature accelerants. Several of the analyzed fires were rapidly developing but were started with common flammable or combustible fuels. One such fire, the **NORTHWEST PRODUCE WAREHOUSE** exhibited substantial damage including 11 inch deep craters in the concrete floor, but did not involve an HTA. Investigators examining such scenes must understand the difference between a high **temperature** fuel, and fuel packages with high **heat release rates**. While high temperature fuels may exhibit high rates of heat release, the converse is not necessarily true.

A commonly occurring obstacle facing many of the investigators of the above fires was not knowing exactly how long a fire had burned before it was reported. Just because a fire goes unnoticed until it vents through a roof or window does not mean it has not burned for some time. Making such a hasty conclusion is reckless and will likely lead to erroneous conclusions about other factors relating to that fire's development. HTA fires can and do, under the right circumstances, promote incredibly rapid fire spread. But investigators MUST NOT attribute such behavior solely to these accelerants.

What should also be evident from the above review is that witness statements are absolutely **crucial** in assisting an investigator in determining whether or not high temperature accelerants have been used in a fire. Because these fuels burn out so quickly, in most cases firefighters will probably not observe their effects except perhaps in the case of delayed ignitions. As a result, investigators must seek out the statements of bystanders and eyewitnesses in addition to first-in firefighters. Knowing the appearance of initial flames and if early smoke was white or black could provide vital indications to guide the scene processing. The more of these witnesses located, the better the chance of obtaining an accurate estimate of a fire's ignition time.

There are several myths within the fire service of how high temperature accelerants behave. Many of these are caused by over-simplifying complex processes. One such falsehood involves finding identifiable evidence of the fuels. It has been too often reported that HTA fuels leave no trace once they burn away. Some such conclusions have undoubtedly been made by investigators labelling carbon based fires as caused by an HTA. In those situations, there is no wonder why evidence of an HTA was not found. It was not there! In instances of probable HTA fires, differing labs have not been able to identify the remains of the fuel. In some of those cases, it is possible that the debris collected from the scene was taken from a less than ideal location.

In order to establish conclusively that some type of HTA fuel was used in a fire, investigators will have to obtain some evidence of that fuel (or get the arsonist to confess). While it will probably not be necessary to always identify a specific fuel to obtain a conviction (if arson is confirmed), in other cases such identification may be crucial. It will also be necessary to be able to identify and understand when an accidental fire shows indications of HTA-like damage as when combustible metals are naturally present at a scene.

Currently, efforts are underway to improve evidence collection and identification procedures for fires believed to involve combustible metal fuels. In a recent case, scientists from Alliant TechSystems in Hopkins, Minnesota were able to isolate and identify the metal fuel and solid oxidizer used in an actual HTA arson fire. That lab along with agents and scientists from ATF are striving to refine such procedures to offer the best chance of reproducible results. While it is true that HTA fires by their very nature consume most of the reactants leaving few traces, collection of some evidence is possible providing the investigator understands the differences between these fires and normal accelerated fires. Once scientists complete their investigation into HTA evidence collection, those methods offering the best likelihood of success will be disseminated to fire investigators.

One aim of this review was to identify similarities in the suspected HTA fires that might suggest investigative leads to pursue. Unfortunately, despite several previous assertions from investigators and media sources alike, no distinguishable physical characteristics of these fires have been identified that would support a conclusion they involve the same *modus operandi*. While some fires such as those at **CARPET EXCHANGE**, **MARITIME SHIPPING BUILDING**, and the **GOLDEN OZ RESTAURANT** seem to have involved HTAs, each had peculiarities not seen at the others. Attempting to link these fires in some conspiracy simply because each exhibited signs of high temperatures would be unjustified. As with any criminal case, investigators must rely on firm evidence rather than mere supposition before claiming the existence of grand conspiracies, particularly in the media arena.

One obvious reason limiting the likelihood of a national HTA conspiracy is the ease with which high temperature accelerants can be prepared. Although several reports have seemed to extol the HTA mixes as being *exotic* and bordering on the realm of science fiction, in reality, many such formulations are commercially available in ready-to-use packages. Other more clandestine formulas like the dozens published in underground handbooks require commonly encountered chemicals that can be obtained from outlets as common as paint or agricultural supply stores. Though the association has not often been discussed, the mixtures are often no different than those found in homemade pyrotechnics.

## SUGGESTED FUTURE EFFORTS

Fire investigators attempting to establish the cause of a fire as being HTA-related face an uphill battle. Those willing to quickly suggest HTA as the cause of unusual fire scenarios may be placing their reputations at risk. Though HTA behavior is relatively new to the fire community, there are numerous scientists from industrial, governmental and educational sources that thoroughly appreciate the thermodynamic performance of highly energetic fuels. These same scientists are available as expert witnesses in criminal and civil court proceedings to expose unsound arguments.

To fully appreciate the complexities of these fires, investigators will not be able to rely solely on conventional wisdom of fire behavior, but must gain a full understanding of scientific principles intrinsic to combustion. A reliance on experience gained only at regular fires may not provide the rational basis upon which an HTA fire cause must be established. Investigators must be able to appreciate concepts such as HTA-like damage being natural to accidental fires, rapid fire growth being inherent to certain scenarios, and melted metals indicating nothing more than a substantial draft.

Assisting investigators in reaching a higher level of proficiency in HTA fire determination will require additional training. Such training needs to emphasize the physical aspects of fire development rather than simply recognizing types of fire damage. Further, a comprehensive program should be developed to optimize evidence collection for accelerants other than flammable liquids. A tremendous amount of information may be present at a fire scene that standard methods of evidence collection and analysis would never identify. The fire investigator needs to start thinking like a forensic scientist, looking for a myriad of possibilities rather than just a few.

Reaching such goals as these will be time consuming and take a substantial effort. It would nevertheless be worth the time of those at the forefront of fire investigation training to incorporate these ambitions into their educational programs. Too many classes taken by senior fire investigators spend too much time on repetitive training. Incorporating new concepts such as these would undoubtedly be welcomed by fire investigators everywhere.

In addition to scene training, the use of mathematical analysis and computer fire modeling in examining HTA fire scenarios may prove promising. While some attempts have already been made at modeling HTA fires, the efforts were short-lived and the reliability of the results now seems in question. In general terms, models are nothing more than a series of mathematical calculations run numerous times for particular scenarios to examine how a fire might have reacted. In a few instances, models incapable of accurately portraying combustible metal fires were used to examine HTA fires. After examining the data collected in the HTA tests, it is now thought that two of the models used previously were incapable of reliably calculating the physical behavior of metal combustion. They were instead, designed for use in carbon-based fires.

Future studies of modeling HTA fires should be attempted with models in which elements such as flame temperature, mass transfer variables, radiation fractions, emissivity, effects of oxygen depletion and the like can be varied by the user. These endeavors may require the use of extremely advanced models not readily available to fire investigators. While input data for many models can be altered so as to insure the expected temperature output, the changes and assumptions necessary to achieve such results make the effort ineffective. This now appears to be the situation encountered in earlier HTA modeling runs.

HTA, the new marvel of fire investigation will undoubtedly present a challenge to the fire community for some time. Probes of such fires, if undertaken thoughtfully, will represent a worthwhile challenge for most participants and should prove rewarding to their general approach to fire investigation.

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