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FIRE HAZARD ANALYSIS OF ROCKY FLATS
BUILDING 776/777 DUCT SYSTEMS

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Executive Summary

A Department of Energy (DOE) Technical Safety Appraisal of Building 776/777, resulted in the determination that fire dampers are not installed in ducts which pass through fire barrier walls. These walls divide nuclear weapons production facilities into separate fire areas. The intent is to limit the maximum possible fire loss by containing an uncontrolled fire within the boundaries of the fire walls.

Passive protection provided by fire barrier walls is an element of an overall fire protection plan which includes fire prevention features, automatic suppression and detection systems, and an on-site fire department. Administrative procedures are in place to assure a high degree of reliability for each of these elements. The scope of this study is limited to the evaluation of opening protection in ventilation ductwork passing through fire walls, with the assumption that an ignition will result in an uncontrolled fire.

Since retroactive installation of fire dampers would require extraordinary precautions and installation techniques, alternative protection schemes were initially considered. The objective of this analysis is to determine the response of ventilation ductwork to fire exposures, and evaluate the impact of structural collapse of ductwork which could create through-openings in fire walls where dampers are not installed. Associated with this analysis is the development of analytical methods which, when programmed on a computer, can be used as an engineering tool in determining the effect of fires on ductwork in other areas and buildings.

An approach which combines analytical methods and large scale test data was used. Representative conditions in Building 776/777 were determined during a site survey. The survey resulted in a characterization of ventilation ductwork in terms of size, construction materials, support details, and location with respect to combustible materials. The combustibles were cataloged and subsequently described in terms of representative fuel packages. Using observed fuel packages as input, estimating techniques were used to calculate potential fire exposures to ventilation ductwork. The response of ductwork to these exposures was analyzed in terms of existing fire test data and data from a fire test performed specifically for this investigation.

Before summarizing the results of this study, it is important to have an understanding of two key aspects of the fire hazard analysis:

1. The performance requirements of fire dampers, and
2. The difference between standard fire test methods and characteristics of fires in the "real world."

A clear understanding of these issues is needed to determine if fire dampers are necessary, and if so, what alternatives are available for providing equivalent protection.

If installed, fire dampers in Building 776/777 would be required to have a fire resistance rating of 1.5 hours when tested in accordance with Underwriters Laboratories Standard 555. The rating of a fire damper is determined by exposing the damper and sleeve assembly to a prescribed temperature in a standard fire test furnace. The temperature in the test furnace follows the standard time-temperature curve, which reaches a maximum of 1844°F (1007°C) at the completion of a 1.5 hour exposure. An inherent assumption in the test method is that structural failure and collapse of the connecting ductwork would occur. This is because only the damper and sleeve assembly are tested and exposed to the fire. The criterion for passing the fire test is that the damper remain in the opening throughout the duration of the fire test. Specifically, no flaming of the damper assembly materials and no through opening which would allow flames to penetrate to the unexposed side are permitted. There are no requirements or limitations related to convective or conductive heat transfer or smoke spread through the damper. It follows that, if it can be shown that ducts will remain intact during a fire, flame penetration to the opposite side of the wall will be prevented regardless of the absence of fire dampers. The intact duct may be considered as providing protection equivalent to the situation where a damper assembly protects an opening created when the connecting duct has failed and collapsed away from the opening. This equivalency approach can be extended to the situation where a duct without a damper remains intact near the wall opening but may fail and collapse at some distance from the opening.

The standard time-temperature curve represents one possible fire situation. The report describes the concepts of fire severity, fire resistance and fuel loading in terms of standardized test methods and conditions which actually occur in buildings. While the duration of a fire in Building 776/777 may be substantially shorter than the 1.5 hours used in the standard test method, peak temperatures may exceed the temperatures which damper assemblies are normally exposed to in the standard test method. This is important because duct and duct hanger support materials are thermally "thin," i.e., they heat more rapidly than heavier steel members such as beams and columns. As a result, short duration, high temperature exposure could result in structural degradation

of the duct or hanger. On the other hand, if the result of fire exposure estimates for actual observed fuel packages show that exposure of ducts and hangers to critical temperatures is highly unlikely, then fire dampers are unnecessary. In this situation, administrative controls regarding the arrangement and quantity of combustibles would have to be strictly enforced.

The areas surveyed included Room 134 Advanced Size Reduction, Room 127 Drum Storage, Room 452/475 Special Assembly, and Room 430. The observed fuel loading was light, approximately 1 lb/ft², except in areas which had large plywood crates. Other combustibles observed include Benelex glove boxes, various plastic products, and electronic equipment cabling. Room 127 Drum Storage had a higher distributed fuel load than other areas, but, since most of the combustibles are sealed in steel drums, the fire threat is substantially reduced.

The resulting fire exposure analysis, in which representative fuel packages were defined either in terms of peak heat release rate or equivalent plywood storage crates, indicates that:

1. Flashover conditions (resulting in the upper layer temperatures sufficient to cause rapid heating of duct system elements and ignition of additional fuel) are unlikely to occur in any surveyed area except Room 134 Advanced Size Reduction. Flashover may occur in Room 134 if a fire involves more than 6 plywood crates.
2. Flame impingement of duct systems may result from localized fuel packages, particularly when the fuel is located near walls. Localized flame temperatures on the order of 2000°F (1093°C) could occur.

Based on the survey, an inventory and layout of typical duct systems penetrating fire barrier walls was made. Ventilation ductwork was cataloged in terms of size, hanger type and details, joist construction, and the estimated loading of the hangers. Ducts penetrating the roof/ceiling assembly to filter plenum areas were observed but not specifically evaluated. Two typical duct system designs observed during the survey were round stainless steel ducts with welded joints and rectangular galvanized steel ducts constructed with mechanical joints. The round ducts were usually supported by hangers consisting of a band around the duct, attached to a steel rod. The rod in turn was attached to the ceiling. The rectangular ducts were typically supported by trapeze hangers consisting of angle steel and

two steel rods. Hanger spacing ranged from 5 to 15 feet. Based on visual observation and review of HVAC drawings, it was judged that the ductwork was installed substantially in accordance with the Sheet Metal and Air Conditioning Contractors National Association (SMACNA) standards.

During the survey, it was noted that there were areas where structural columns, beams and girders were unprotected. No fire resistance material was applied to these structural elements. Since hanger rods, straps and trapeze elements of the duct systems are supported to one degree or another by the building structural steel elements, failure of the unprotected elements may cause failure of the duct supporting elements.

Having determined the structural characteristics of representative duct systems, one can evaluate the response of the ducts to a fire insult. This insult can be expressed in terms of both a standard fire exposure and exposure fires expected to occur in Building 776/777 as determined by the fuel loading survey. A review of the technical literature and existing test data identified mechanisms by which ducts may fail and collapse in a fire, with resulting flaming through a wall opening. The data in the literature shows that failure of ducts (without dampers) to resist fire spread through fire barriers can be attributed to three events: failure of the supporting hangers; failure of the joint connecting horizontal duct sections; and, duct material degradation which results in warpage of the duct walls around the penetration opening. However, the applicability of the existing test data to Building 776/777 duct systems is questionable. The primary limitation is the substantially greater size of the ducts in Building 776/777 compared to ducts previously tested, which were generally exposed to a fire of only one hour duration. It was not clear that the duct warpage and joint failure characteristics from previous tests could be reasonably scaled to typical designs in Building 776/777 for a longer or hotter exposure. Therefore, an interim recommendation was made, and subsequently approved, to perform a full scale fire test of representative ducts.

A two hour standard fire test of three ducts was performed by an independent testing laboratory. The set-up of the fire test was designed to derive the maximum amount of data for representative duct systems, within the constraints of the furnace size and single test limitation. Both a rectangular and round duct were tested. An additional rectangular duct was installed in the test furnace. This duct was identical to the other rectangular duct except that measures were taken to provide additional protection in anticipation of increasing the endurance of key structural

elements. The additional protection included insulating hanger rods and attaching steel angles to reinforce the duct near wall openings. At the conclusion of the two hour test fire, during which exposure temperatures reached a maximum of 1850°F (1010°C), all duct systems remained in place. The integrity of each system, where it extended through the fire wall, remained intact. No through-openings developed at wall openings. Longitudinal and transverse duct joints remained tight throughout the test.

While none of the ducts failed per se (i.e., there was no flaming through or around the duct opening), response characteristics of the rectangular duct with the modified features were improved compared to the unmodified rectangular duct. The stiffeners reduced the warpage of duct walls near the fire barrier opening, and the insulation delayed heating of the hanger rod.

The results of the literature review and the full scale duct tests are consistent with the equivalency approach described earlier. If a duct maintains its structural integrity near an opening in a fire barrier wall, it provides protection equivalent to a fire damper.

The primary limitation of the existing test data and the data derived from the full scale fire test is correlating these data to all possible loading, hanger, joint attachment, and material construction conditions. Therefore, a generalized analysis of duct failure modes was performed to consider all possible duct designs. Two construction details are identified as being particularly important to the maintenance of duct integrity: hanger assemblies (steel rods for trapeze type hangers and strap hangers); and, duct reinforcement near fire barrier openings. The integrity and strength of hanger rods and straps is a function of the load on the rod or strap. While the full scale test showed that a representative hanger rod can withstand an 1850°F (1010°C) exposure, the reaction of hanger rods or straps under worst case loading conditions could only be estimated. Critical temperatures as low as 1125°F (607°C) may result with maximum loading conditions as estimated in the analysis. There is also a relatively small yet important difference between the maximum test exposure temperature and maximum temperatures which may result from direct flame impingement from a fire in fuel packages observed in Building 776/777. Additional protection of the hanger rod or strap can be achieved by installing insulation around the rod or strap as was done in the full scale test. This insulation should be installed where the fire hazard is sufficient to create critical temperatures.

The other important construction detail is the

performance (warping) of steel duct walls near fire barrier openings. While no through flaming was observed around the unreinforced rectangular duct in the full scale test, the degree of warpage was reduced when the duct was reinforced with steel angle stiffeners. Given the importance of maintaining the integrity of ducts at the barrier opening, it is recommended that steel angle stiffeners be installed on rectangular ducts where the fire hazard is sufficient to create critical temperatures. Round ducts, because of their inherent structural characteristics, do not require stiffeners.

It only remains to match actual fuel packages (and their possible fire characteristics in terms of rate of heat release, plume characteristics and flame profiles) with duct systems over or near the fuel. While substantial analysis was performed to evaluate all fuel packages and duct system critical temperatures, the net result can be described in relatively simple terms and applied to those areas surveyed as well as other areas with similar conditions:

1. Representative fuel packages can be defined in terms of peak heat release rate and in terms of equivalent plywood storage crates. This data can be used to determine if flames might impinge on ducts or whether flashover can occur.
2. Flashover can occur in a space similar to Advanced Size Reduction if a fire involves more than 6 plywood crates. The implication of this is that flames may impinge on ducts anywhere in the space, should flashover occur. Aside from the impact on ductwork, the possibility of flashover is undesirable from an overall fire safety standpoint. In Advanced Size Reduction, as well as other areas found to have flashover potential, combustible loading should be reduced to limit flashover potential.
3. Localized duct temperatures exceeding estimated critical temperatures or actual exposure temperatures observed in the full scale test may result from direct flame impingement. The possibility of direct flame impingement is a function of the fuel package, and fuel orientation and location of the exposed duct. Flame heights may double if a fuel package is located near a wall. To the maximum extent possible, combustibles should be moved away from walls.
4. Applying the damper equivalency concept, direct flame impingement on ductwork is only an issue when

it occurs near a wall opening. The inherent assumption is that ductwork away from a wall opening is permitted to collapse and fall away.

5. When it is determined that flames may impinge on ducts near wall openings or where flashover may occur, improvements to ducts should be made. The hanger rods or straps for rectangular ducts should be protected with insulation and rectangular ducts should be reinforced with steel angle stiffeners on both sides of the opening, near the barrier wall. The hanger rods or straps closest to the wall should be insulated as well as all those rods or straps within 10 feet of the wall.

Detailed recommendations for the areas surveyed are described, including specific construction details for steel angle stiffener and hanger rod or strap insulation improvements. Two additional issues impact on the analysis and recommendations. The analysis assumes that the building structural steel, from which ducts are ultimately supported, will survive the exposures calculated for the ductwork. Since some areas have unprotected structural steel, this assumption is not necessarily valid; the impact of fire on unprotected structural steel should be determined. An addendum to this report will be prepared which analyzes this situation. The other recommendation addresses administrative and logistical aspects of a ductwork improvement and combustible fuel load monitoring program. In spaces where flashover may occur, the recommendation is to improve all ducts since the fire may not remain localized. A combustible fuel load reduction program is also recommended. Where only localized flame impingement occurs near wall openings, it is, from a technical standpoint, only necessary to improve ducts where the direct flaming may occur, i.e., above the specific fuel package. Inherent in this assumption is the monitoring of all combustibles, both in terms of transient materials, (e.g., wood storage crates) and combustibles associated with building equipment/operations. Although most of the combustible materials observed in Building 776/777 are not inherently "transient", consideration should be given to reinforcing all rectangular ducts and hanger rods and straps as described in the report. This provides an additional level of protection and reduces reliance on administrative programs to monitor fuel load and changes to the building layout.

Finally, the impact of vertical duct openings to the filter plenums and mechanical spaces should be determined. This was outside the scope of the fire barrier wall duct opening analysis. This situation may have already been addressed in previous fire protection audits/analyses.

1.0 BACKGROUND

Rockwell International operates an industrial complex in Rocky Flats, Colorado for the Department of Energy (DOE). Nuclear weapon components are manufactured at this facility. A recent Technical Safety Appraisal (TSA) conducted by DOE noted a lack of fire dampers installed in ventilation ductwork where ducts pass through fire separation walls in Building 776/777. Masonry walls separate this manufacturing facility into fire areas. The intent of this subdivision is to limit the maximum area which can be destroyed by an uncontrolled fire. These maximum fire areas are created based on the value of the enclosed area, so that not only a maximum area is defined, but also a maximum dollar loss associated with the loss of that area. DOE established policy defines these limits and valuations [Dept. of Energy]*. The established fire areas enclosed by separation walls is a passive element of an overall fire protection plan which includes fire prevention (e.g., control of combustible contents and ignition sources), automatic active systems (automatic sprinkler, gaseous total flooding systems, and glove box nitrogen inerting), and manual intervention (on-site fire department). The scope of this analysis is limited to the passive element of the protection matrix, specifically opening protection in ventilation ductwork passing through representative separation walls in Building 776/777.

The accepted practice for protecting openings created by ventilation ducts in separation walls is to install fire dampers where the duct penetrates the wall. This philosophy was developed for standard commercial, industrial and manufacturing facilities where the interruption of the ventilation system is not crucial to the overall facility mission and public safety. At Rocky Flats, interruption of the ventilation system creates a direct conflict with other safety parameters associated with containment of radioactive environments. Installing fire dampers in the ducts would cause significant problems with respect to maintaining pressure differentials between the outside environment, the building, and the glove box systems. Retroactive installation of fire dampers would also require extraordinary precautions and installation techniques because many ducts contain radioactive materials. A suggested alternative was to increase the duct fire resistance with a protective material, e.g., a wrap or coating. The efficiency of retroactive installation of a protective material is uncertain. Should a wrap be installed, an evaluation of the duct suspension systems would have to be performed to determine if the resulting increased loading on the ducts could be sustained by existing supports.

* Names in brackets refer to the References listed in Section 10.

2.0 OBJECTIVE

The objective of this analysis is to determine if ventilation ductwork in Building 776/777 will maintain their structural integrity during expected fire conditions as well as standard design fires typically used to ascertain fire resistance ratings. If the analysis shows that ductwork will not maintain structural integrity, the impact of this failure will be determined and analyzed, and alternative solutions recommended. Associated with this analysis is the development of a computer fire model which can be used as an engineering tool in analyzing the effect of fires on ductwork in other areas and buildings.

3.0 APPROACH

A site survey was conducted in representative areas of Building 776/777. There were two objectives in performing the survey: to determine structural characteristics of ductwork and their locations; and, to catalog fuel loading in the areas. Associated supporting information, including drawings and existing reports related to fire protection at Rocky Flats, were obtained. The Bibliography, Section 11, provides a listing of reports reviewed. Based on the site survey, a fire exposure and fuel load analysis was performed using a simplified estimating technique [Foote, et al] and a computerized zone fire model [Mittler and Emmons]. Concurrent with the fuel load/fire exposure analysis, a thermal and structural analysis was performed for the Rocky Flats ductwork. The intent was to evaluate the response of the existing ductwork to the reduction in yield stress due to heating by a fire. Based on a review of existing duct fire test data and a preliminary analysis of the Rocky Flats ductwork, it was recommended that a full scale fire test be performed. This test was performed at an independent testing laboratory. The results of the test, combined with the fuel loading survey and resultant fire threat analysis, were used to analyze the impact of fire on the Rocky Flats ductwork.

Before discussing specific survey and analytic results, a review of fire resistance requirements is appropriate. This sets the context of the overall analysis. The next section reviews fire resistance requirements.

4.0 FIRE SEVERITY AND PERFORMANCE OF DUCT SYSTEMS

In order to evaluate the Rocky Flats duct systems, it is important to have an understanding of the concept of fire resistance and the test methods used to establish fire resistance ratings. An understanding of the performance requirements of fire dampers is critical in determining the response of ducts with unprotected openings (no dampers) relative to ducts with dampers. This leads to a review of equivalency concepts, i.e., if it is determined that it is appropriate to provide some type of protection, a method of equivalency must be established for alternatives to backfitting fire dampers in existing ductwork.

4.1 Fire Severity and Fire Resistance

Regulations for preventing fire spread in buildings are based on two concepts: (1) control of fire development by intervention from an "active" system, e.g., sprinkler system; or (2) compartmentation of a building using "passive" fire resistant barriers to create fire areas. The size of these fire areas are consistent with an acceptable degree of loss and business interruption. The building areas evaluated at Rocky Flats are protected by automatic sprinklers, but the impact of these systems has been ignored for the purposes of this analysis.

Fire resistive barriers are evaluated in a test furnace by exposure to a fire whose severity follows a time-varying temperature curve known as the standard time-temperature curve [ASTM]. This is shown in Figure 4.1-1. This "standard" fire test was devised to obtain comparative data on the behavior of different structural assemblies when exposed to a standard fire.

A number of full scale tests have been conducted to determine how actual building fires compare with temperatures represented on the curve [Ingberg]. The principal variable considered in these tests was the amount of combustible materials present (fire load). Ventilation (air available to a fire) per se was not reported or specifically investigated. These tests provided quantitative data on the temperature history of fires that were representative of various occupancies and fire loads at that time. From these tests, relationships between fire load and fire severity, expressed in terms of duration of exposure under the time-temperature curve, were developed. Table 4.1-1 show these relationships.

The standard time-temperature curve may not be indicative of actual building fire conditions. The difference between standard fire conditions and fire duration and peak temperatures which may occur is emphasized

Figure 4.1-1 Standard E119 time temperature curve

Table 4.1-1

Estimated Fire Severity as a Function of the Standard
Time-Temperature Curve [Ingberg]

<u>Combustible Content, Lbs. per sq. ft.</u>	<u>Assumed B.T.U. per sq. ft. (wood equivalent)</u>	<u>Equivalent Fire Severity*</u>
5	40,000	30 min.
10	80,000	1 hour
15	120,000	1.5 hour
20	160,000	2 hour
30	240,000	3 hour
40	320,000	4.5 hour
50	380,000	6 hour
60	432,000	7.5 hour

* Approximately equivalent to that of test under standard curve for the following time periods.

in Figures 4.1-2 and 4.1-3. Figure 4.1-2 shows four time-temperature curves obtained by burning a fire load of ten pounds per square foot and varying the natural ventilation (vent area) of the test compartment. Peak temperatures are increased but duration is substantially less with respect to the standard time-temperature curve. Figure 4.1-3 shows the influence of fuel load for a fixed forced ventilation flow. It shows that fire loads of ten, fifteen, and twenty pounds of combustible material per square foot vary little in terms of duration when adequate ventilation is available.

Fire dampers are tested in accordance with the standard time-temperature curve. Both the standard time-temperature curve data and realistic fire exposures must be addressed in this analysis. The fire growth estimating technique and zone fire model used in this analysis result in more realistic fire growth and peak temperature estimates which are consistent with actual fire package and ventilation conditions.

4.2 Fire Damper Integrity

When a duct passes through a wall with a fire resistance rating of 2 hours, a damper with a 1.5 hour rating is required as specified by NFPA 90A [NFPA, 1985]. Dampers are required to meet the fire resistance rating as specified in UL 555, which is the test method for fire dampers [UL]. In

Figure 4.1-2 - Effect of ventilation opening on temperature and duration from AISI

Figure 4.1-3 - Effect of fuel load on temperature and duration from AISI

order to determine the criteria for judging the effectiveness of any method designed to protect openings in a fire barrier used for compartmentation, it is necessary to clearly understand the criteria used to evaluate currently acceptable devices for protecting duct openings in fire barriers.

Fire dampers are tested as an assembly in the ASTM E119 or Underwriters Laboratories, Inc., UL 263, test furnaces which are used to develop fire resistance ratings for walls. The fire damper test procedure is detailed in UL 555. The fire damper assembly consists of a steel sleeve to which the fire damper is attached and the steel sleeve is in turn attached to the wall.

The UL 555 fire test is conducted with no ductwork connected to the fire damper assembly on either side of the wall. The reason for this is that a fire damper is used to protect the opening in the wall made by the duct should the duct fail structurally and fall away from the wall opening. The inherent assumption is that in an actual fire there would be no duct assembly left in place. The criteria for passing is that the damper remain in the opening during the duration of the fire endurance test and subsequent hose stream test. Specifically, no flaming of the damper assembly materials and no through openings which would allow flames to penetrate are permitted. There are some specific exceptions related to flaming of duct materials, warpage and through opening. These have been developed based on test experience of actual damper assemblies. NFPA 90A recognizes the need to provide clearance around ducts for installation purposes. Approved fire stopping material is permitted to fill these openings.

It should be clearly understood that a fire damper assembly when tested in accordance with UL 555 is not required to resist heat transmission through the damper assembly. The fire rated wall or barrier on the other hand must meet a heat transmission limit of 250°F average temperature rise and 325°F single point temperature rise. There are no requirements in the UL standard on the degree of control or limitation of the passage of smoke or products of combustion through the fire damper assembly. The fire damper assembly is only required by the test procedure to prevent flame penetration of the opening it protects.

4.3 Equivalent Protection

The ducts in Rocky Flats Building 776/777 would be deemed acceptable if fire dampers meeting UL 555, i.e., a 1 1/2 hour "standard" time-temperature exposure, were installed at the wall penetrations. The criteria for acceptance in UL 555 is prevention of flame penetration

during the 1.5 hour fire test. It follows that if it can be shown that ducts will remain intact during a fire, flame penetration to the opposite side of the wall will be prevented. By the pass/fail criteria defined in UL 555, the duct may be considered as providing equivalent protection to the situation where a damper assembly protects an opening created when the connecting duct has failed and collapsed away from the opening. This rationale may be extended to the situation where a duct without a damper remains intact near the wall opening but may fail and collapse at some distance from the opening. A damper provides a barrier to direct flame-through to the opposite side. Radiative and convective heat transfer through the damper remains high, given the thermal inertia characteristics of relatively thin steel (and hence the elimination of any heat transmission monitoring or criteria in the UL test method). The maintenance of the duct integrity near the wall opening provides the same thermal barrier as a damper, even with the duct being open to the fire environment (e.g., through collapse of the duct section in the middle of the room). Maintenance of the duct integrity near the unprotected opening in effect provides a flame barrier consistent with the protection provided by a damper. It is reasonable that maintenance of the duct integrity within 10 ft or one hanger length of the wall opening would maintain the flame barrier protection at the opening.

Failure mechanisms of steel duct systems at wall penetrations were evaluated. If ducts without dampers structurally fail, collapse, and pull away from the opening, a sufficient gap may be created at the opening to permit through-flaming or the flame barrier protection might be degraded. It also remains to be determined whether the ASTM E119 standard time-temperature curve is representative of situations at Rocky Flats. The results of Section 6 of this report, Fire Exposure Analysis, will be applied to Section 7, Duct Analysis, to determine if the Rocky Flats ducts provide protection equivalent to fire dampers. If it is shown that the ducts may fail near the wall opening, modifications to existing conditions are warranted. If they do not, protection equivalent to fire rated dampers is provided by the existing ducts. However, an additional point to consider is that even if the duct or duct hanger fails near the wall opening and a through opening is created, the impact on the adjacent room will probably be negligible. As it will be shown in later sections of this report, the fuel loading in the surveyed areas was light and no significant combustibles were observed near (less than 4 ft) the duct wall openings. Assuming the conditions on the other side of the wall are the same, what flame or heat is able to pass between the duct and wall would not impinge on any combustible materials. Most likely it would just dissipate into the room.

5.0 SURVEY RESULTS

5.1 Compartment Description and Fuel Loading

A survey was conducted of Rocky Flats Building 776/777 by a fire protection engineering team from Hughes Associates, Inc., from May 23 to 27, 1988. The purpose of the survey was to determine the fuel available for a fire, and the size, design and quantity of ductwork. The specific areas surveyed included Room 134 Advanced Size Reduction (ASR), Room 127 Drum Storage, Room 452/475 Special Assembly, and Room 430. Sufficient time was available to thoroughly examine Rooms 134 and 127, but security restrictions reduced the time to survey Rooms 452/475 and 420 to approximately 30 minutes each. Security restrictions completely prevented access to Rooms 134A, 452, 475, and 445 which had been initially identified as areas of concern. Assuming that the non-surveyed areas do not differ significantly from those areas which were surveyed, the results of this analysis should apply to all areas.

A summary of the survey results is shown below for each of the rooms. Appendix A gives the complete results including lists of the major fuel packages, floor areas, and the calculation procedure for determining wood equivalent fuel load. Because both cellulosic and polymeric combustibles were observed in Building 776/777, the wood equivalent fuel load was calculated. This calculation accounts for the difference in combustion properties between these two combustibles by doubling the mass of any polymer material. The mass doubling results from the heat of combustion of polymeric materials, which is generally double that of wood. The wood equivalent fuel load is the total mass of combustibles divided by the floor area of concern. Appendix A also describes localized fuel loading conditions within a room.

5.1.1 Room 134 Advanced Size Reduction

Room 134 had a floor area of approximately 9106 ft² (157 ft x 58 ft) with a floor to ceiling height of 18 ft. The primary activity in this room is the reduction of the size of worn or unrepairable radioactive material machining equipment into small pieces. This facilitates handling and long term storage. Approximately 25% of this floor area (2061 ft²) was occupied by an enclosed machine break down canyon where the majority of the size reduction takes place. This area was separated from the main room by stainless steel and lead walls and leaded glass windows. This separation is not considered to have a fire resistance rating because of the numerous openings for gloves, utilities, etc. There were

few combustibles in this canyon with the exception of a large pile of debris and trash near the east wall.

Another major area (576 ft²) in Room 134 was a holding/storage area for large plywood crates and steel drums used for storing contaminated machinery. Other combustibles were observed along the north, south, and west walls. These included plywood crates, rolls of paper and polyethylene, plastic sheets, and various electronic equipment and cables. In the middle of the room there was a small glove box (6 ft x 5 ft x 6 ft high), number J-177. This glove box was constructed of stainless steel, lead, PMMA (plexiglass), leaded glass, and neoprene gloves.

As shown in Appendix A, the total wood equivalent mass of combustibles in this room was 16,190 lbs which gives an equivalent wood fuel loading of 1.8 lb/ft². This corresponds to a "standard" post flashover fire duration of 11 min. using the estimated fire severity shown in Table 4.1-1.

5.1.2 Room 127 Drum Storage

Room 127 had a floor area of approximately 9107 ft² and a floor to ceiling height of 18 ft. This room was used principally for the long term storage of approximately 2000 steel drums. They contained approximately 90% radioactive salts and 10% miscellaneous combustibles. These drums were stored upright, no more than two high. There was also a small process area on the north side of the room which included several fiberglass tanks and plastic pipe. No other combustible materials were observed. The total equivalent wood mass as calculated in Appendix A was 77,666 lbs which gives an equivalent wood fuel loading of 8.5 lb/ft². However, 74,314 lbs of the total equivalent wood mass was in the steel drums which would be very difficult to ignite. This effect is accounted for by derating the fuel mass in the steel drums and using 10% of the combustible mass in the fuel load calculation [NFPA 1986]. This gives an equivalent wood fuel loading of 1.2 lb/ft², which corresponds to a "standard" fire duration of 8 min.

5.1.3 Room 452/475 Special Assembly

Room 452/475 had a floor area of approximately 4194 ft² and a floor to ceiling height of 18 ft. In this room were stand alone glove boxes in which material machining takes place. Combustibles observed included several glove boxes constructed of Benelex, neoprene and PMMA, polymer insulation on control equipment wires, and cables and small amounts of miscellaneous ordinary combustibles such as plastic sheets and a wood desk. The total equivalent wood mass as calculated in Appendix A is 5063 lbs, resulting in an

equivalent wood fuel loading of 1.2 lb/ft². This corresponds to a "standard" fire duration of 8 min.

5.1.4 Room 430

Room 430 had a floor area of approximately 15,800 ft² and a floor to ceiling height of 18 ft. This room was similar to Room 452/475 except that it was larger and contained a greater number of glove boxes and approximately 200 steel storage drums were stored in this room. Several glove boxes were constructed of Benelex and PMMA shielding material. In addition, there was a plywood crate similar to those observed in Room 134. Security requirements prevented a more thorough survey but it is believed that the major fuel packages in the room were identified. The total equivalent wood mass as calculated in Appendix A is 16,413 lbs, which results in an equivalent wood fuel loading of 1.1 lb/ft². This corresponds to a "standard" fire duration of 7 min.

5.2 Ventilation and Air Filtering Ductwork

An inventory and layout of typical ductwork which was observed to penetrate fire barrier walls in the surveyed areas is given in Appendix B. Ducts penetrating the roof/ceiling assembly to filter plenum areas were observed but not specifically evaluated. Information concerning the ductwork was also obtained from HVAC drawings of Building 776/777 provided by DOE/Rockwell International. The ductwork consisted of stainless steel round ducts which were used for glove box ventilation and galvanized steel rectangular ducts which were used for room ventilation. The stainless steel ducts had welded joints and the rectangular galvanized ducts were joined by a mechanical "s" joint. The round ducts were supported by hangers consisting of a band around the duct attached to a steel rod. The rod in turn was attached to the ceiling. The rectangular ducts were supported by trapeze type hangers consisting of angle steel and two steel rods. Hanger spacing ranged from 5 to 15 ft. Based on visual observation and review of the drawings, it was judged that the ductwork was installed substantially in accordance with sheet metal contractors HVAC duct standards [SMACNA]. Fire stopping around duct openings through walls was observed to be rigid-type fill material. Overall fire resistance integrity of the separation walls were not evaluated.

From a discussion with the building engineer it was learned that the building is ventilated at a rate of 15 air changes per hour and the glove boxes at 30 air changes per hour with 80% being recirculated. In the event of a fire all systems are put on 100% exhaust.

5.3 Exposed Structural Steel

During the survey, it was noted that there were areas where structural columns, beams and girders were unprotected. No fire resistance material was applied to these structural elements. Exposed steel elements were observed in Rooms 137, 452 and 430. While the evaluation of exposed steel elements is outside the scope of this analysis, this observation is important to the overall duct system analysis. Hanger rods, straps and trapeze elements are supported to one degree or another by the building steel structural elements. Failure of the unprotected elements will cause failure of the duct supporting elements. This failure mode is not considered in this report, however.

6.0 FIRE EXPOSURE ANALYSIS

The standard method for evaluating the severity of fires in buildings is by associating an equivalent fire severity, given in time, to a standard time-temperature curve. The standard curve shown in Figure 4.1-1, is a baseline exposure against which the fire resistance of structural assemblies can be compared. It assumes post-flashover, natural ventilation controlled fires, and cellulosic fuels. The standard time-temperature curve does not represent the fire environment in real buildings.

The fire exposure analysis has been performed using the best available methods. It includes four parts, as follows:

1. equivalent "standard" fire exposure based only on the fuel load of the room;
2. estimation of time dependent intensity of fire source terms, i.e., the energy release rate of fuel packages as a function of time;
3. prediction of local temperature environment at duct penetrations for a range of expected fire source terms; and,
4. prediction of mean hot layer temperature exposure throughout the compartment of interest.

The critical temperature of the steel hangers and ducts is dependent on the loading of that steel. This is discussed in detail in Section 7.3, but generally a critical temperature of 500°C was used here as a conservative estimate.

6.1 Equivalent Fire Severity

The equivalent fire severity is derived from early work by Ingberg and is the basis of requirements for 2 hour fire resistive barriers. It relates time or duration of a standard ASTM E119 time-temperature curve as a function of the average wood equivalent fire load in an entire compartment. They are given here for comparison purposes only, and as a reference point for the beginning of the analysis.

<u>Room</u>	<u>Average fuel load (over entire fuel area)</u>	<u>Equivalent fire duration (min)</u>
134, ASR	1.8 lbs/ft ²	11
127, Drum Storage		
Total	8.5 lbs/ft ²	48
Derated for Steel		
Drum Storage	1.2 lbs/ft ²	8
475, Special Assembly	1.2 lbs/ft ²	8
430	1.1 lbs/ft ²	7
Ordinary Combustibles	15 lbs/ft ²	90
Ordinary Combustibles	20 lbs/ft ²	120

The assumptions and calculation of the fuel loading are given in Appendix A.

6.2 Fire Source Term Definition

The primary fire growth rate description of interest is the time dependent heat release rate of a fire. Figure 6.2-1 illustrates a range of typical energy release rate versus time curves for common materials.

Full scale burning rate test data on the fuel packages and materials at Rocky Flats was not available, hence these source terms had to be estimated. This was done using standard fire growth estimation procedures.

The calculation of these burning rates are shown in Appendix C and were estimated as follows:

1. calculate total surface area of fuel package;
2. obtain heat release rate per unit area at high incident flux, estimated at 250 kW/m² for plywood;
3. fit growth curve to power law, fast t² fire, or ultra fast t² fire;
4. fix peak burning rate by available surface area; and,
5. fix burnout time by mass consumption rate and total fuel package mass.

Figure 6.2–1 Typical energy release rates for common materials

The shape of the resulting curve is given by $\dot{Q} = \alpha t^2$, where $\dot{Q}$ = heat release rate, t = time in seconds and α is a constant defining the relative rate of early growth of a fire. The analysis was performed using fast and ultra fast fire assumptions;

Fast Fires $\dot{Q} = .0465 t^2$, $\dot{Q}$ in kW, t in sec

Ultra Fast Fires $\dot{Q} = .1876 t^2$

The exact early stage time dependence is not critical since the concern is for the behavior of the ductwork at peak temperature conditions.

The analysis was performed using several representative fuel packages. These are described below:

<u>Fuel Package</u>	<u>Peak Heat Release Rate (kW)</u>
1 plywood shipping crate	2156 kW
2 plywood shipping crates	4312 kW
4 plywood shipping crates	8624 kW
6 plywood shipping crates	12,936 kW
representative fire: 500 kW	500 kW
representative fire: 1000 kW	1000 kW
representative fire: 2000 kW	2000 kW

The representative fires are used to simulate the impact of incidental combustibles or for fuel packages where the burning rate data is not available. They correspond approximately to actual fuel packages as follows:

1. Representative fire, 500 kW
 - 1 trash cart in the ASR facility,
 - 1 roll of PE film (ASR),
 - 2 rolls of paper film (ASR),
 - 1 m² electrical cable insulation (PE/PVC),
 - 1 m² PMMA glove box windows, or
 - 5 open steel drums filled with combustibles
2. Representative fire, 1000 kW
 - 2 trash carts in ASR facility,
 - 2 rolls of PE film (ASR),
 - 4 rolls of paper film (ASR),
 - 2 m² electrical cable insulation (PE/PVC),
 - 2 m² PMMA glove box windows,
 - 4 m² Benelex, or
 - 10 open steel drums filled with combustibles

3. Representative fire, 2000 kW
- 4 trash carts in ASR facility,
 - 4 rolls of PE film (ASR),
 - 8 rolls of paper film (ASR),
 - 4 m² electrical cable insulation (PE/PVC),
 - 4 m² PMMA glove box windows,
 - 1 Benelex glove box, 8 m² Benelex, or
 - 20 open steel drums filled with combustibles

For Room 134 some of the calculations used greater than 6 crates to reflect the observed conditions.

These representative fires are also used due to the transient nature of some of the combustibles, yielding conservative estimates of fire size for a variety of fuel packages.

In the case of the steel drums, the worst case was considered by having a number of these open and filled with combustibles. This was done because of the difficulty in igniting the contents of a closed drum and the limited oxygen available for combustion in a closed drum. However, the probability of having these drums open is very low considering that their contents would pose an immediate radiological health hazard and this would quickly be detected and acted on by personnel.

Since a single plywood crate was estimated to have a heat release rate of approximately 2150 kW, fuel packages above a heat release rate of 2000 kW can be equated to a number of plywood crates. Based on the fuel load survey, a worst case peak heat release rate of 2150 kW can be assumed for all areas except the ASR which may contain many plywood shipping crates or rooms with Benelex glove boxes.

This simplified representation of the peak burning rates of fuel packages is now used to estimate the fire environment to which the steel ductwork will be exposed.

6.3 Compartment Fire Temperatures

At this point in the analysis, the average hot gas temperature in a forced ventilation compartment is estimated assuming the peak heat release rates described in Section 6.2. The calculation is performed in two ways. First, correlations of gas temperature as a function of room size, wall materials, heat release rate and ventilation are used [Foote, et al]. Second, a compartment fire model, FIRST, is used to calculate the upper layer temperature [Mitler and Emmons]. If the average upper layer temperature exceeds the critical temperature for steel, the ducts may fail. If the

average layer temperature is below the critical temperature, there is no risk of all of the ducts failing in a single compartment. However, the risk of localized failure exists. This localized failure is discussed in section 6.4.

6.3.1 Upper Layer Gas Temperature Correlation

The correlation developed by Foote et al is as follows:

$$\Delta T = 0.63 T_{\infty} \left[\frac{\dot{Q}}{\dot{m} C_p T_{\infty}} \right]^{0.72} \left[\frac{h_K A_T}{\dot{m} C_p} \right]^{-0.36}$$

where:

ΔT = temperature rise, °C or K
 T_{∞} = ambient temperature, K
 $\dot{Q}$ = heat release rate, kW
 $\dot{m}$ = mass flow rate of ventilation, kg/sec
 C_p = specific heat of air, KJ/kg-K
 A_T = area of bounding wall surface, m²
 h_K = heat loss coefficient, kW/m²K
 $h_K = k/\delta$

where:

k = thermal conductivity of wall, KW/m-K
 δ = wall thickness, m.

The estimated upper layer gas temperature for each room for a range of fire sizes is given below.

Fire Size (kW)	Room 134 (°C)	Room 127 (°C)	Room 475 (°C)	Room 430 (°C)
500	60	60	86	48
1000	84	84	129	66
2000	125	125	200	96
1 crate	136	136	210	100
2 crates	211	211	332	152
4 crates	334			
6 crates	441			
8 crates	670			
12 crates	900			

A 12 in. thick cinder block wall was the assumed wall lining material, and the ventilation rate was 15 air changes/hour.

Note that the only case where the average upper layer temperature estimate exceeded 500°C (assumed critical temperature of steel) is in Room 134 where greater than 6 crates are burning. Where temperatures are below 500°C,

flashover throughout a room is not expected to occur given the fuel packages available. Except for the situation where more than 6 crates are available to burn in Room 134, the problem remaining to be evaluated is one of localized exposure to the steel ductwork immediately above a fire source.

These results also demonstrate that the overall combustible loading is generally small compared to the 2 hour requirement. The problem is really one of localized fuel packages and localized (vs. compartment wide) temperatures.

6.3.2 Peak Upper Layer Gas Temperatures, FIRST Compartment Fire Model

FIRST, a mathematical fire model developed by the National Bureau of Standards, Center for Fire Research was also used to evaluate peak upper layer temperatures. The fire sizes were varied as specified in section 6.2, and the details of the input data are attached as Appendix D.

The fire growth curves used in the analysis are summarized in Figure 6.3.2-1 for ultra fast fires and 6.3.2-2 for fast fires.

The results of the analysis are presented as curves of average upper layer temperature versus time and layer depth versus time for each room at selected fire sizes and are given in the figures listed below.

Room 134:	Figures 6.3.2.-3 to 6.3.2.-6
Room 127:	Figures 6.3.2.-7 to 6.3.2.-10
Room 430:	Figures 6.3.2.-11 to 6.3.2.-14
Room 475:	Figures 6.3.2.-15 to 6.3.2.-18

The peak temperatures for each room for the worst case fire growth rate (ultra fast) at 15 air changes per hour are given below.

Fire Size (kW)	ASR			
	Room 134 (°C)	Room 127 (°C)	Room 475 (°C)	Room 430 (°C)
1000	---	57	58	45
1 Crate	52	52	89	55
2 Crates	77			
4 Crates	152			
6 Crates	217			
12 Crates	377

Figure 6.3.2-1 Heat release rate vs. time, ultra fast fire

Figure 6.3.2-2 Heat release rate vs. time, fast fire

Figure 6.3.2-3 Layer temperature vs. time, ultra fast fire, room 134

Figure 6.3.2-4 Layer depth vs. time, ultra fast fire, room 134

Figure 6.3.2-5 Layer temperature vs. time, fast fire, room 134

Figure 6.3.2-6 Layer depth vs. time, fast fire, room 134

Figure 6.3.2-7 Layer temperature vs. time, ultra fast fire, room 127

Figure 6.3.2-8 Layer depth vs. time, ultra fast fire, room 127

Figure 6.3.2-9 Layer temperature vs. time, fast fire, room 127

Figure 6.3.2-10 Layer depth vs. time, fast fire, room 127

Figure 6.3.2-11 Layer temperature, ultra fast fire, room 430

Figure 6.3.2-12 Layer depth vs. time, ultra fast fire, room 430

Figure 6.3.2-13 Layer temperature vs. time, fast fire, room 430

Figure 6.3.2-14 Layer depth vs. time, fast fire, room 430

Figure 6.3.2-15 Layer temperature vs. time, ultra fast fire, room 475

Figure 6.3.2-16 Layer depth vs. time, ultra fast fire, room 475

Figure 6.3.2-17 Layer temperature vs. time, fast fire, room 475

Figure 6.3.2-18 Layer depth vs. time, fast fire, room 475

These temperatures are uniformly much lower than the previous correlation results. The correlation results are based on worst case heat transfer conditions, while the FIRST model includes greater heat transfer losses to the wall and does not include any combustion in the upper layer. This substantially lowers the upper layer temperatures. Further, since the rooms are so large relative to the fire size, the assumption of an average hot upper layer gas temperature may not be valid. In either case, the calculations demonstrate that the compartment wide fire severity is quite low, except in the case of greater than 6 crates in Room 134, and as expected we are dealing with a localized fire source.

6.4 Localized Fire Exposure Calculations

The calculations presented in section 6.3 indicate that, except in Room 134 where there are more than 6 crates involved, the average compartment upper layer temperature is not high enough to cause generalized steel failure or flashover. Hence the baseline assumption of a required 2 hour fire resistance barrier as per a post flashover E119 curve, are invalid.

The problem remaining is the local effects of these fire sources on the steel ductwork. A duct located directly above a fuel package will see a much higher temperature than one located some distance away.

This section evaluates the temperature of hot gases in a fire plume or flame flowing past objects located at various heights above the floor. A schematic of this problem is given in Figure 6.4-1.

Directly above the fuel package is a flame zone with height, H_f and an assumed average uniform temperature of 1125°C . Flame temperature is variable depending on the fuel and stoichiometry, and typically it ranges from 1200° to 1400°K [Mudan]. Determining the magnitude of the flame temperature here is not needed recognizing that direct contact with flame will result in a large temperature gradient and rapid heat exchange, causing a rapid rise in the temperature of the object to nearly that of the flame. The exception to this rapid heating is when the object is of significant size and mass and it can be considered thermally thick. Exposing a thermally thick object to the heat exchange discussed above will result in a temperature gradient. Eventually the object will reach steady state and a uniform temperature. An object is considered thermally thick when the ratio of the internal resistance to heat conduction to the external resistance to heat conduction is greater than 0.1. This ratio is called the Biot Number and

Figure 6.4-1 - Plume and flame regions of a fire

is the ratio of the convective heat transfer coefficient, h , and object thickness, l , to the thermal conductivity, k , of the object, hl/k .

If an object is thermally thin, then a temperature gradient will not exist and it will heat uniformly. A steel rod or steel duct wall would be considered thermally thin whereas a steel beam or column would be thermally thick. Exposing a duct or hanger rod to direct flame contact will increase the temperature of it to nearly that of the flame in a short time.

Above the flame zone, a buoyant plume is formed. The temperature of the plume is a function of height above the fuel source, Z . In addition, a temperature gradient will exist within the plume with it hottest at the centerline. Plume temperatures will always be less than the flame temperature because combustion does not take place in the plume. In addition, the plume entrains cool, ambient air as it rises to the ceiling. However, the convective nature of a plume can result in significant heat transfer. For the most part the plume is not affected by compartment boundaries unless the fuel is located near a wall or in a corner.

These calculations assume that there is no enclosing room. They are designed to evaluate the fire condition and height above the floor where fire damage may occur to the ductwork, i.e., the assumed steel critical temperature of 500°C is reached. Whether or not failure of the duct actually occurs is the subject of the ductwork analysis described in Sections 7.0 and 8.0 of this report.

The calculations are based on well developed correlations of flame height, heat release rate and fire diameter shown below [Heskestad]:

Flame Height:

$$H_f = -1.02 D + 0.23 \dot{Q}^{2/5}$$

where:

H_f = flame height, m
 D = base diameter of fire, m
 $\dot{Q}$ = heat release rate, kW

Plume Temperature, T_p , as a function of height, Z :

$$T_p(Z) = T_\infty + 9.1 \left[\frac{T_\infty}{g C_p^2 \rho_\infty^2} \right]^{1/3} \dot{Q}^{2/3} (Z - Z_0)^{-5/3}$$

where:

T_∞ = ambient temperature, K
 g = gravitational constant, 9.8 m/sec²
 C_p = specific heat of air, KJ/kg-K
 ρ_∞ = density of air, kg/m³
 Z = height above fire, m
 Z_0 = virtual source correction, m

The results of these calculations are shown in Table 6.4-1, Table 6.4-2, and Figure 6.4-2. The base diameters of the fires were obtained using the plywood crate base area, and for the representative fires a fire strength of 500 kW/m².

Table 6.4-1 Flame Height for Fuel Away From Walls

<u>Heat Release Rate (kW)</u>	<u>Flame Height (m)</u>	<u>Flame Jet Radius (m)</u>
500	1.9	0
1000	2.5	0
2000	3.7	0
2156 (1 Crate)	4.2	0
4312 (2 Crates)	5.8*	0.28
8624 (4 Crates)	7.0*	1.52
12,936 (6 Crates)	8.5*	3.02

* Flame impingement on ceiling (floor-ceiling height = 5.48 m, fuel height = 1.22)

Table 6.4-2 Flame Height for Fuel Near a Wall

<u>Heat Release Rate (kW)</u>	<u>Flame Height (m)</u>	<u>Flame Jet Radius (m)</u>
500	3.8	0
1000	5.0	0
2000	7.3*	1.86
2156 (1 Crate)	7.2*	1.68
4312 (2 Crates)	10.3*	4.82
8624 (4 Crates)	12.8*	7.32
12,936 (6 Crates)	15.9*	10.42

* Flame impingement on ceiling

As shown in Table 6.4-1, if the base of the fire is located at the top of a plywood crate which is located in the center of the room, and 2 crates are burning, the calculated flame height is greater than the floor to ceiling height. If greater than 2 crates are burning, or another fuel source is burning with a heat release rate greater than 2156 kW, the flames will not only impinge on the ceiling above the crate but will also spread radially along the ceiling as a flame jet. Research has shown that the radial distance that flame will spread beyond the center line is not less than the difference between the flame height and floor to ceiling height [Drysdale]. In the case of 2 plywood crates burning with a heat release rate of 4312 kW, the flame jet will extend approximately 0.28 m (0.9 ft) from the flame center line. Depending on the ceiling material and construction, the flame jet length may be 150% of the difference between the flame height and the ceiling height.

If the fuel package is located next to a wall rather than in the middle of the room, the resulting flame height may be approximately doubled [Alpert and Ward]. This is caused by the reduction in the area available for entraining air into the flame zone. Table 6.4-2 shows the calculated flame heights when the fuel is located near a wall. In this case a single plywood crate located next to a wall will result in flame impingement and a flame jet which extends approximately 1.68 m (5.5 ft) beyond the flame center line.

Figure 6.4-2 shows the temperature in a plume as a function of the height above the floor. A solid line at 1150°C denotes regions in the flame zone. The dashed line represents the critical temperature of steel of 500°C. For a fire strength of 500 kW, any object below 2.2 m will see a peak plume temperature of 500°C. For a fire strength of one

Figure 6.4-2 Plume temperature above design fires

crate, any object below approximately 3.5 m will see temperatures greater than 500°C. For fire strengths equivalent to 2 crates or larger, any object within the plume will be in an environment above 500°C.

These results indicate that for rooms, other than Room 134 (ASR), where the fuel is located away from walls and the fire strength is less than 2100 kW, steel ducts or hangers located near the ceiling will not fail using a generalized steel failure temperature of 500°C. Problems occur when a duct or hanger which is located above the plywood crates in Room 134 ASR or other spaces, is located less than 10 feet from the floor. If a fire source of 2100 kW or greater (e.g., one crate equivalent) is located near a wall, flames will reach the ceiling and impinge on any duct or hanger above the fuel. Larger fires will result in direct flame impingement on the steel above the fuel and at a distance away from the fuel as a result of a ceiling flame jet.

None of these results indicates that steel failure will actually occur, they merely indicate that significant heat transfer may take place, and that the failure of the ductwork is possible. Section 7 addresses in detail duct failure modes.

6.5 Duration of Fires

A fire in a relatively large compartment will usually have three distinct phases: growth, free burning, and decay. The growth phase begins after ignition takes place. The duration of the growth phase will be dependent on the type of fuel, its configuration, and the conditions within the room. Eventually an object which is burning will reach a maximum heat release rate and at this point is said to be in the fully involved or free burning stage. In this stage, the flame height and plume temperature will be at their maximums. This will produce the greatest amount of radiant heat output which may cause other nearby combustibles to ignite. The burning will continue in this phase until the mass of the fuel is reduced to the point where the heat release rate begins to decrease. During this decay phase, the heat release rate will continue to decrease until all of the fuel has burned out.

In the case of the plywood crates, the mass of one crate was estimated at 160 kg (348 lbs) and the maximum heat release rate at 2156 kW. Assuming that 90% of the mass must be consumed before the heat release rate begins to decrease and using a heat of combustion for plywood of 16 MJ/kg [Drysdale], the time to burnout is approximately 17 min. Multiple crates igniting simultaneously will have approximately the same burnout time as the single crate. If

the crates ignite in series, the fire duration will be considerably longer but the peak total heat release rate will be less than if the crates ignited and burned simultaneously.

Table 6.5-1 shows the estimated fire duration and peak heat release rate for the representative fuel packages. These were calculated in the same manner as the plywood crate discussed above.

Table 6.5-1
Estimated Fire Durations and Peak Heat Release Rate

1 Paper roll	14 min	260 kW
1 Trash cart	16 min	430 kW
1 Plywood crate	17 min	2150 kW
1 Open Drum	30 min	100 kW
1 m ² cable	35 min	400 kW
1 m ² PMMA	46 min	740 kW
1 Polyethylene roll	65 min	360 kW
2 m ² Benelex	100 min	500 kW
1 Typical Benelex glove box	150 min	2740 kW

6.6 Summary

The calculations and analysis presented in this section have demonstrated the following:

1. no areas have localized, incidental fuel packages which will exceed 2000 kW, or the equivalent of 1 plywood crate with the exception of Benelex glove boxes;
2. flashover is not expected to occur in any of the compartments evaluated, except in Room 134 when the fuel packages exceed 6 crates or its equivalent;
3. the average upper layer gas temperature during a fire will not exceed the critical temperature of steel; unless the fire strength is sufficient to cause flashover;
4. the fire endurance requirement of 2 hours is excessive given the fuel loading, except in the case of a Benelex glove box; and,

5. the conservative critical temperature of steel in the duct system of 500°C^1 is exceeded:
- a. in Room 134 ASR where the ductwork is located above the plywood crates;
 - b. in other compartments where the ductwork is below 10 ft above the floor and directly over a combustible fuel package; or,
 - c. when a fuel package of 1500 kW or greater is located next to a wall and under ductwork in Room 134 ASR, or other cases which result in direct flame impingement on the ductwork.

¹ This conservative steel failure temperature is further evaluated in Section 7.0

7.0 ANALYSIS OF BUILDING 776/777 DUCTS

7.1 Existing Test Data

Existing test data on steel ducts exposed to the ASTM E119 fire exposure test have demonstrated that the method of duct support and type of joint connection are important factors in the integrity of a steel duct system. Fire tests of various steel duct arrangements have been conducted at Southwest Research Institute (SwRI), Underwriters Laboratories, Inc. (UL), and the National Bureau of Standards (NBS) for the American Iron and Steel Institute and the Thermal Insulation Manufacturers Association. In these fire tests of ducts penetrating a fire barrier, the arrangement was limited due to the testing equipment. Generally, the ASTM E119 vertical furnace was used. This limited the duct size and the span between duct hangers within the furnace. Most of the ducts were tested without fire dampers.

In the 1 hour, ASTM E119 SwRI test [Bauerschlag], 12 inch by 12 inch, 26 gage, rectangular steel ducts demonstrated some warpage of the duct walls at the wall penetration. This test did not include dampers and all ducts were connected to an operating warm air residential furnace during the fire test. Temperature at the exhaust end of the steel ducts, which were exterior to the furnace wall, did not exceed 500°F when the temperature in the furnace was approximately 1600°F. The warpage of the steel duct indicated that duct dimensions and construction details may be critical in preventing warpage and subsequent through-openings around the outside of the duct. However, the steel duct did remain intact and prevented flame and superheated gases from passing through the opening. These tests did not examine the issue of support failure and no conclusions could be made regarding this.

Underwriters Laboratories, Inc. [Plens, et. al.] conducted tests in 1985 which were similar to those conducted by SwRI. This test used an ASTM E119 vertical furnace to heat three duct assemblies. Two of the ducts were 10 inch x 10 inch, constructed of 24 gage galvanized steel. One duct was covered with glass fiber duct insulation. The third duct was 10 inches x 10 inches, constructed of 1 inch thick rigid fiberglass. Each duct was suspended by trapeze hangers which used 1/4 inch steel rods and 1 in. x 1 in. x 1/8 in. steel angles, spaced 24 inches apart. Since only single 8 foot sections of the steel duct were tested, there were no transverse joints. The ducts were connected to a steel sleeve attached to the wall. No fire dampers were installed and all ducts were open to the furnace atmosphere during the 1 hour test duration. After 19 minutes the fiberglass duct failed and collapsed. The steel ducts in the furnace

remained in place and suffered slight warpage which was especially noticeable on the insulated duct, probably due to the increased weight from the insulation. The temperatures within the steel ducts, 3 in. from the unexposed side of the wall assembly, were approximately 1400°F for the insulated duct and 1300°F for the uninsulated ducts. Maximum temperature within the ducts, 6 ft. from the unexposed side of the wall assembly, were approximately 1100°F and 1250°F for the insulated and uninsulated ducts, respectively. On the outside surface of the ducts, 3 in. from the wall assembly, the temperature did not exceed 175°F and 500°F for the insulated and uninsulated ducts, respectively. Because of the short sections of duct which were tested, lack of mechanical joints, and the light loading on the hangers, the conclusions from these tests are not readily applicable to the thermal resistance of complete duct systems.

In the tests conducted by NBS [Issen], five ducts constructed of galvanized sheet steel were subjected to a fire which also followed the ASTM E119 standard time-temperature curve for 2 hours. The objective of these tests was to study the effects of hanger size, hanger spacing, duct wall thickness (gage), and joint technique on the structural behavior of steel ducts exposed to a fire. Duct penetration of a fire barrier or fire damper effectiveness was not studied.

In the NBS test, the hangers were of the trapeze type utilizing 1/4 inch rods. The ducts were 20 inch by 20 inch and constructed of 20 and 24 gage steel. As the temperature of the ducts rose during the tests, the steel softened and the ducts sagged at midspan and over the trapeze supports. Eventually four of the five ducts collapsed by increased buckling and joint failure. The joints were made with pop rivets rather than slip joints which allowed the metal on each side of the joint to separate. The time of failure ranged from 26 to 66 minutes. In every case of failure, the duct ultimately failed at the joints. Thus the joint connection is an important factor governing the performance of the duct. In the one case where the duct did not fail it had the shortest span between supports. The conclusion made by NBS from this work was that with reduced hanger spacing and adequate joints, a sheet steel duct can probably be designed to withstand a fire exposure of up to 2 hours without failure.

It should be noted that, based largely on the one hour fire test data, NFPA 90A does not require the installation of fire dampers in steel ducts penetrating one hour fire rated partitions [NFPA 90A]. The absence of similar recognition for steel ducts penetrating 2 hour fire barriers results from a lack of 2 hour fire test data.

The data in the literature shows that failure of ducts without dampers to resist fire spread through fire barriers can be attributed to three events: (1) failure of the supporting hangers; (2) failure of the method used to join horizontal sections of duct; and (3) duct material degradation which results in warpage of the duct walls which allows openings between the duct and the wall, allowing flame passage.

1. Failure of supports are a function of the:
 - o Type of hanger (e.g., diameter or gage of steel rods, strap or trapeze),
 - o Method of attachment (e.g., screw attachment, under-duct support or location of duct on trapeze), and
 - o Load on supports.
2. Failure of the duct joints is a function of the type of transverse and longitudinal joints.
3. Failure due to duct material degradation which could result in through-openings between the duct and wall is a function of the:
 - o Gage of the steel as a function of duct size and shape,
 - o Duct span between supports, and
 - o Location of joints between supports.

A review of the duct survey results and existing fire test data indicated that it would be difficult to apply existing data to analyze the Building 776/777 duct systems. A two hour fire exposure was specified for analysis while existing data is nearly all for one hour exposures. The duct dimensions observed in Building 776/777 were, in some instances, substantially greater than those previously tested, as described in the literature. It was not clear that duct warpage and joint failure characteristics could reasonably be scaled. Given these factors, a recommendation was made to perform a full scale fire test on ducts representative of those found in Building 776/777.

7.2 Test of Building 776/777 Duct System

7.2.1 Test Set-Up

In order to measure the three modes of duct system failure, a fire test was designed to evaluate hanger supports, duct rigidity at wall penetrations, and duct construction details representative of those ducts surveyed in Building 776/777. Testing was limited to a single 2 hour standard furnace test. This limitation required that the set-up be designed to obtain the maximum amount of data which could be applied in analyzing the Building 776/777 ducts observed and for future evaluation of other areas. The maximum test furnace area of 12 ft (3.66 m) by 16 ft (4.88 m) also restricted the number, size and design of the ducts to be tested. Based on the evaluation of existing test data, it was judged important to test both a rectangular and round duct. Assuming that the rectangular duct was most likely to fail over the 2 hour fire test duration, an additional rectangular duct was included in the test scheme. This duct was identical to the other rectangular duct except that measures were taken to provide additional protection in anticipation of increasing the endurance of key elements of the duct system.

The testing equipment at Southwest Research Institute (SWRI), San Antonio, Texas, was used for this test. This equipment is normally used for conducting standard ASTM E119 floor tests. For these tests, the furnace was modified by raising the four walls enclosing the furnace by approximately 5 feet to permit the horizontal installation of three ducts. The fire exposure and duration was that used for a standard ASTM E119 two hour fire test used to rate floors and walls. The furnace pressure was adjusted to a slight positive pressure with respect to the ducts and the outside of the furnace.

Three horizontal ducts, two rectangular 36 x 30 inch 22 gage galvanized steel and one 36 inch diameter, 20 gage stainless steel round duct, were tested. The first rectangular duct, designated Duct No. 1, was representative of the most prevalent dimensional range observed in Building 776/777. The longitudinal seams were of the button punch snap-lock type. Transverse joints were of the standing-S type. The duct section was supported by a trapeze comprised of 3/8 in. steel rods (the smallest as observed in the survey) and a 1- 1/4 in. x 1/4 in. steel angle. For the test, the trapeze hanger was located at the midpoint of the span to create a maximum load condition and bending moment within the constraints of the furnace set-up. Loading was calculated in accordance with SMACNA standards and the resulting load on the hanger assembly was calculated to be

14% of the total allowable load. The transverse joints were also located with respect to the hanger to create maximum stress on the joints. The other rectangular duct, designated Duct No. 3, was identical to Duct No. 1 except that:

- o The duct was reinforced with 1-1/2 in. x 1-1/2 in. x 10 gage steel angles tack welded approximately 2 in. from both the inside and outside of the furnace wall. This was installed in anticipation of maintaining duct rigidity at the wall opening to prevent through-openings;
- o Hanger rods were protected with 1/2 in. dia. x 1 in. thick, 14 lb/ft³ Manville Thermo-12 calcium silicate pipe insulation rated for prolonged exposure of 1200°F (649°C). The insulation was cut to fit on-site and secured in-place with 16 ga. steel bands, 12 in. on center. This protection was provided to increase the fire endurance of the rods in anticipation of possible failure of the unprotected rods used in the Duct No. 1 support; and,
- o The installation of an additional trapeze support to provide increased overall support of the duct system. Again, this was in anticipation of possible failure of the single support installed on Duct No. 1.

The circular duct was selected to be representative of circular ducts installed in Building 776/777. The lightest gage of steel, 20 ga. was selected. A single 3 in. wide x 20 ga. stainless steel band wrapped around the duct, attached to a clevis-type hanger suspended from a 1/2 in. dia. hanger rod, supported the duct at mid-span. This resulted in a loading of 9% of the total allowable load as calculated in accordance with SMACNA standards. Transverse joints were of the continuous weld-type. The arrangement of the ducts in the test furnace is shown in Figure 7.2.1-1.

The duct construction conformed to the SMACNA HVAC Duct Construction Standards, First Edition, 1985. Gaps between the ducts and the masonry block wall of the furnace were fire stopped with flexible ceramic fiber blanket insulation, as permitted by NFPA 90A.

Fifty-two thermocouples were used to instrument the duct systems in order to record, for later evaluation, the thermal effects on the materials and construction details.

Figure 7.2.1-1 - Furnace modification and steel duct layout with thermocouple locations

A detailed description of the test arrangement including location of thermocouples, duct construction, temperature data, and observations during and after the two hour test are contained in the October 1988 final report by Southwest Research Institute (SwRI), Project No. 01-2427-001, "Ad Hoc Fire Endurance Test of Unprotected Steel Duct Systems," (Appendix E) and in observation notes (Appendix F).

7.2.2 Results

None of the duct sections collapsed into the furnace. The integrity of each system, where it extended through the fire wall, remained intact. No through-opening developed between a fire stop and a duct at any wall penetration. The longitudinal and transverse duct joints remained tight throughout the test, preventing flames from entering and using the duct as a conduit for fire spread.

It was observed after the test that, where the sides of Duct No. 3 which had stiffeners, passed through the masonry wall, there was a maximum warpage of 1/2 in. at the tops and sides. The fire stopping material prevented any through opening between the duct and wall, thereby maintaining the fire stop required to prevent flame passage. The tops and sides of Duct No. 1, which had no stiffeners attached to the duct walls, warped a maximum of 2 inches at the wall penetrations. During the fire test the furnace fire was visible between the vertical duct wall and the furnace wall. However, the ceramic fiber fire stopping continued to fill the fire stopped opening, owing to the flexibility and compressibility characteristics of the material. There was no detectable distortion of Duct No. 2 or its hanger.

Figure 7.2-1 shows duct temperatures inside the furnace, measured inside the duct. Figure 7.2-2 shows representative hanger temperatures for the three ducts. Except for the protected hanger (Duct No. 3), these data show that there was virtually no thermal lag, between the furnace temperature and the steel rod or duct temperatures. This is as expected for relatively thin steel members. The insulation on the hanger rod of Duct No. 3 increases the time for the hanger to reach 1000°F (538°C) by about 30 minutes. Figure 7.2-3 shows temperatures 3 in. away from the furnace wall, measured on the outside of the duct. The temperature range at 60 min. was 500-1000°F (260-538°C), and 800-1200°F (427-649°C) at 120 minutes.

Figure 7.2—1 ASTM E119 Furnace test on steel ductwork
Duct temperature inside furnace

Figure 7.2-2 ASTM E119 Furnace test on steel ductwork
Hanger temperatures inside furnace

Figure 7.2-3 ASTM E119 Furnace test on steel ductwork
Duct temperature 3 in. outside furnace

7.3 Analysis

The key results of the SwRI fire test are that none of the duct sections failed and the integrity of each system where it extended through the fire wall remained intact. The longitudinal and transverse duct joints remained tight throughout the two hour test, preventing flames from entering the duct. Using UL 555 criteria for fire dampers as a basis for comparison, the three tested duct systems would be deemed to have met the criteria; in fact, they exceed the criteria because they were exposed an additional 1/2 hour over that required by UL 555. Not only is the duration longer, but the fire exposure temperature is higher because it continues to increase over that time period. The ducts in the SwRI test survived a peak temperature 1850°F (1010°C). Additionally, the furnace was run at a slight positive pressure instead of a neutral or slightly negative pressure normally used in the UL 555 test procedure. The SwRI fire test had the net effect of increasing the possibility of through flaming at any wall opening since the hot fire gases would tend to flow toward any opening to the outside of the furnace. Some scorching of the fire stopping on Duct No. 1 was observed after the test.

7.3.1 Supports

The primary limitation of the SwRI test data is the difficulty of correlating the results from a single fire test to all possible loading conditions. A method exists whereby critical temperatures can be estimated as a function of loading [Jeanes]. This method was developed for evaluating steel structural elements. This approach is based on the fact that the mechanical properties of the structural material are reduced as the temperature is raised, ultimately failing at some critical temperature. The critical temperature is generally defined as the temperature at which the yield strength of the material is reduced until it nearly equals the design strength, and the factor of safety approaches unity. This approach offers a reasonably simple solution to an otherwise complex problem.

Figure 7.3.1-1 shows steel strength vs. temperature. Failure is assumed to occur when the average steel temperature exceeds the temperature on the yield strength curve for a given loading condition or when a single point steel temperature exceeds the temperature on the ultimate strength curve. For this analysis, average temperatures will be used. Figure 7.3.1-1 shows an example of a steel element heated to 1000°F (538°C) which reduces its strength to 60% of its normal strength. This is the basis for the ASTM E119 failure criteria being an average steel temperature of 1000°F (538°C) for a steel column tested without a load, i.e., 60% of the maximum yield strength is normally used as the design

working stress. If, in actual conditions, the steel is stressed to only 35% of normal strength, then the average critical temperature is estimated to be 1225°F (663°C).

This estimating technique is applied to the conditions observed in Building 776/777. Table 7.3.1 was prepared to estimate critical temperatures of all of the surveyed ducts. Hanger loading was calculated in accordance with SMACNA Standards based on duct weight and hanger weight and spacing. Average critical temperatures for the hangers were then estimated using Figure 7.3.1-1. For the ducts surveyed, estimated critical temperatures range from 1125°F (607°C) for a hanger supporting a rectangular duct which loads the hanger to 43% of its recommended maximum allowable load; to 1660°F (904°C) for a round duct which loads the hanger to only 3% of its recommended maximum allowable load.

The SwRI test results show that this estimating technique is conservative in estimating critical temperatures. The critical temperatures for the rectangular duct (duct no. 1) loaded to 14% of its recommended maximum allowable load and the circular duct (duct no. 2) loaded to 9% of its recommended maximum allowable load are 1425°F (774°C) and 1500°F (815°C) respectively using the estimating technique. The average furnace temperature at the end of the test was 1850°F (1010°C). The rods following the initial fire exposure are assumed to be at the same temperature as the furnace atmospheres. Hanger rod temperatures of Duct No. 1 at 120 min. ranged from 1749°F (954°C) to 1805°F (985°C), and the supporting angle temperatures ranged from 1776°F (969°C) to 1874°F (1023°C). The reasons for these conservative results are the safety factor inherent in the estimating technique (e.g., no interaction between elements are considered), and the high safety factor inherent in the maximum loads for the hanger rods allowed by SMACNA. A further indication of this safety factor is the integrity of the duct systems at the conclusion of the test, i.e., the supports still had not failed. The actual critical temperature for these hanger rods are unknown, but for the tested loading conditions it is greater than a 1850°F (1010°C) exposure temperature and 1775°F (968°C) material temperature.

Laboratory fire tests of floor or roof and ceiling constructions sometimes incorporate HVAC systems. These HVAC systems are generally supported by wire or strap hangers, screw attached to the underside of the duct where the strap or wire hangers lap the corner of the duct. Even when ceiling protective systems fail in two hour fire tests the duct systems remain intact at fire exposures sufficient to raise the temperature of steel beams to 1100-1300°F (593-704°C).

Table 7.3.1
Estimation of Hanger Rod Critical Temperatures

<u>Size inches</u>	<u>Hanger Rod, dia.</u>	<u>Actual Load, lbs</u>	<u>Allowable Load, lbs*</u>	<u>% of Total Allow.</u>	<u>Estimated Average Critical Temp. °F (°C)+</u>
<u>Rectangular Ducts - 22 gage</u>					
80x36	1/2"	217	1250	17	1375 (746)
50x20	1/2"	90	1250	07	1600 (871)
44x24	1/2"	127	1250	10	1600 (816)
36x30	1/2"	93	1250	07	1600 (871)
36x24	steel strap (22 ga)	84	260	32	1230 (656)
30x30	steel strap (22 ga)	112	260	43	1125 (607)
30x24	1/2"	84	1250	07	1600 (871)
	3/8"	84	680	13	1450 (788)
	steel strap (22 ga)	84	260	32	1230 (656)
24x24	3/8"	56	680	08	1510 (821)
	steel strap (22 ga)	56	260	20	1350 (732)
24x12	3/8"	68	680	10	1500 (816)
18x12	steel strap (22 ga)	42	260	16	1400 (760)
16x10	3/8"	30	680	04	1650 (899)
<u>Round Ducts</u>					
36 ss (18 ga)	1/2"	158	1250	12	1450 (788)
	3/8"	158	680	23	1310 (710)
36 ss (22 ga)	1/2"	119	1250	09	1525 (830)
30	None (10" span)	112	----	--	
14	3/8"	53	680	08	1510 (821)
14	3/8"	43	680	06	1610 (877)
12	3/8"	46	680	07	1600 (871)
12	3/8"	37	680	05	1630 (888)
6	3/8"	24	680	04	1650 (899)
6	3/8"	19	680	03	1660 (904)
<u>SwRI Tested Duct System</u>					
36x30	3/8"	93	680	14	1425 (774)
36 ss	1/2"	119	1250	09	1525 (830)

* Table 4-1, SMACNA HVAC Duct Construction Standards, First Edition 1985.

+ Based on Figure 7.3.1-1

ss stainless steel

Also, post-fire investigations of major high rise building fires (such as those in the Westvaco Building, and One New York Plaza in New York City and the Occidental Building in Los Angeles) demonstrated the structural stability of duct systems using strap supports. These systems remained intact during a complete burnout of fire compartments in which fire temperatures reached 2000°F (1093°C).

The load on the hanger is a combination of duct size and hanger spacing. The hangers observed in the survey appear to comply with the SMACNA recommendations in the HVAC Construction Standards. Those ducts systems involved in fire tests, have shown satisfactory performance at real fire temperatures based on studies of building fires.

The angle iron trapeze duct supports observed in the survey are not considered a critical factor in the stability of the duct system under fire exposure conditions which may be more severe, over a short duration, than the E119 test. The allowable loads for trapeze angles decreases when the hanger rod is greater than 4 inches from the duct side. The observed distance was 4 inches or less. The SMACNA recommended loads are based on the steel having a minimum yield strength of 25,000 psi. Most construction steels are A36 steel with a minimum yield strength of 36,000 psi. However, if no grade of steel was specified, the steel could be "merchant steel" in which case the steel properties are uncertain.

7.3.2 Joints

The longitudinal joints on the rectangular ducts are the button-punch snap-lock type and the transverse joints are "Standing-S." These joints, as well as welded joints on the circular ducts, were fire tested. The results show that, during a two hour ASTM E119 fire exposure, the joints remained tight and withstood considerable sagging and movement of the duct under temperature conditions of 1850°F (1010°C). This same performance of these joints has been demonstrated in the building fires mentioned previously where fire temperatures reached 2000°F (1093°C) during a compartment burnout. Generally, transverse joints are located near the duct supports. However, in the fire test at SwRI, Duct No. 1 had duct joints located approximately midway between the duct supports and remained tight with no openings throughout the two hour fire exposure.

7.3.3 Material Degradation

The duct gage is selected based on the size of the duct. The primary concern is not performance under fire exposure but rather under normal use conditions. The gage is selected to avoid noise from the "oil can" action that takes place from expansion and contraction of the duct under heating or cooling cycles. In some cases, this can be overcome by reinforcing the duct walls, but generally the sheet steel thickness is increased to provide rigidity. In previous fire testing cited in Section 7.1, most ducts tested were small and of light gage (24-26 gage). In the SwRI fire tests, the ducts were 22 gage galvanized and 20 gage stainless steel. These ducts were 36 x 30 inches and 36 inches in diameter and represented all of the duct types observed in Building 776/777 which penetrated fire barriers. In the case of Duct No. 3, 10 gage sheet steel angles were tack welded to the outside duct walls inside and outside the furnace wall penetration. This reinforcing of the duct walls prevent the warping and movement of the duct walls during the fire test which occurred in the unreinforced duct (Duct No. 1). Thereby, the ducts performance in preventing the passage of flames between the duct and the fire stopped wall opening was improved. While Duct No. 1 did not permit through flaming, there was considerably more warping (2 in. maximum) of the duct at the wall opening than for the reinforced duct, Duct No. 3 (0.5 in. maximum warpage). The steel reinforcing substantially improves the integrity of the duct at the opening and the ability to prevent through flaming. The flexible fire stopping at the opening continued to fill the gap between the wall opening and duct. A gap may be created where fill material is rigid; rigid fill material was observed in the Building 776/777 survey. It is advisable to reinforce all rectangular ducts which may be exposed to high temperatures in order to maintain the steel duct position against the fire stopping in the wall opening.

The round duct, because of its shape, does not require reinforcing. In the SwRI fire test, there was little if any movement of the duct throughout the two hour fire exposure. It appeared that the single hanger was unnecessary in that the round shape of the duct provided a superior "beam" which was required only to support its own weight. Several round ducts in the survey spanned a clear distance (12-15 ft) between a wall penetration and a floor/ceiling penetration without an intermediate support. Based on the SwRI fire tests, these ducts should perform equally as well.

7.4 Summary

A review of the technical literature and existing test data identified mechanisms by which ducts may fail and

collapse in a fire, with resulting flaming through a wall opening. A fire test was designed and conducted to evaluate representative duct designs from Building 776/777.

The results of the literature review and the duct test are consistent with the equivalency approach developed in Section 4.0: if the duct maintains its structural integrity near an opening in a fire barrier wall, it provides protection equivalent to a fire damper. A generalized analysis of duct failure modes was performed to consider all possible duct designs. This is based on previous test results, the fire test performed, observations from floor/ceiling tests, and actual fires involving complete burnout. Two construction details have been identified as being particularly important to the maintenance of duct integrity: steel strap hangers, rods for trapeze type hangers and duct reinforcement near fire barrier openings. The integrity and strength of hanger rods or straps are a function of the load on the rod or strap. While the test conducted showed that a representative hanger rod can withstand an 1850°F (1010°C) exposure, the reaction of hanger rods under worst case loading conditions could only be estimated. Additional protection of the hanger can be achieved by installing pipe insulation around the rod or strap. Reinforcement of rectangular ducts near fire barrier openings improves the ability of the duct to prevent through flaming at the wall opening. The next section of this report will use the results of the fire exposure analysis (Section 6) as they apply to the duct failure mode analysis. The "expected" fires will be applied to Building 776/777 ducts to draw the final conclusions and recommendations.

8.0 DISCUSSION AND CONCLUSIONS

8.1 Fire Hazard

The analysis in Section 6 developed anticipated fire intensities and durations for the fuel packages observed. It must be realized that there are limitations to estimating fire growth and heat release rate curves for fuel packages; existing test data from similar packages or materials must be used where specific test data is not available. When estimating the characteristics of these fuel packages, practical effects have been considered so that the predicted characteristics are realistic. Where judgments are made, the tendency was to err on the conservative side, e.g., assume a faster growth rate or larger involved surface area. The basic assumption that the fuel package "sees" a sufficient ignition source capable of igniting the target and sustaining combustion is in itself a conservative assumption. It neglects the impact of ignition control measures and active suppression systems.

Sections 4, 6, and 7 show the inherent weaknesses in correlating ASTM E119 time-temperature data with real building fires. The standard time-temperature curve exposure duration of 1.5 hours for dampers is excessive under most situations evaluated, both in terms of standard time-temperature estimating techniques, and in terms of fire duration using fire growth calculation techniques. It was shown that peak temperatures (and associated peak heat release rates) are not necessarily achieved with relatively longer duration fires (Figure 4.1-3 and Table 6.5-1).

Based on the observed fuels, design fires of 500, 1000, and 2000 kW were selected for the analysis. In addition 1, 2, 4, and 6 plywood crates were used as design fires because they were the most significant fuel package in any of the surveyed rooms. Except for the areas which had plywood crates, the fuel loading was light and for this reason an upper layer with a significantly elevated temperature is not expected. In other words, flashover is not expected to occur. The high ventilation rate, 15 air changes per hour, also helps to prevent high upper layer temperatures or flashover. Where the plywood crates were found, however, the fuel loading is greater and the potential for flashover is significant. This is principally the case for Room 134, Advanced Size Reduction. Analysis has shown that flashover conditions may be reached, if greater than 6 plywood crates are simultaneously burning in Room 134. Flashover will produce high temperatures in the room which may exceed the critical temperature of the steel hangers. From an overall fire protection view, avoidance of flashover conditions or the possibility of flashover conditions is highly desirable.

Fuel packages located close to walls is another area of concern. In this case, the wall causes the flame height from the burning package to roughly double. Where a fuel could not generate flame which would reach the ceiling when it was away from a wall, the flames may reach the ceiling when it is next to a wall. These flames may impinge on the ceiling and then spread radially outward, or they could impinge directly on a duct and its hanger. Flame temperatures may be 2000°F (1093°C) or higher.

In the cases where the flame height does not reach the ceiling or duct, the plume above the flame will be hot, although not as hot as the flame. The plume temperature will decrease with the height above the flame, so only a portion of the plume will be hot enough to be of concern. This poses a threat to the ductwork where the fuel is elevated above the floor or the ductwork is well below the ceiling.

One consideration in reducing fuel load is the use of fire retardants. The most significant fuel packages observed in Building 776/777, were the plywood crates. The use of a retardant coating or treatment increases the amount of energy needed to achieve ignition of a cellulosic material and they may reduce the flame spread rate. Therefore, a fire retardant can prevent or delay ignition and also slow the fire growth rate. The latter will reduce the severity of the fire and increase the time to flashover.

The drawbacks of fire retardants are that they do not reduce the overall fuel load per se and they require extensive administrative controls (in terms of fire retardant integrity and control of non-treated materials). Since ignition of combustibles has been assumed, the effect of fire retardants becomes one of rate of fire growth and peak heat release rate. Within the constraints of this study, fire retardants are not considered a viable alternative to reducing overall fire hazard. Storage of materials in noncombustible containers, e.g., steel storage crates, could be a method of reducing the overall fuel load.

8.2 Duct Analysis

It was shown in Section 6 that peak temperatures resulting from flame impingement (2000°F+) may exceed the maximum exposure temperature of the ASTM E119 furnace at 2 hours (1850°F). Because the steel ductwork system has a high thermal inertia, i.e., thin elements are heated quickly, this maximum temperature condition cannot be ignored. Because there is little thermal lag between the exposure temperature and the steel temperature, any fire with a flame height large enough to cause direct impingement of any

significant duration, must be addressed. For this analysis, any fire which causes flame impingement with a duration of greater than 5 min. is considered significant. All Building 776/777 observed fuel packages, which create flame impingement conditions, are expected to have a duration of at least 5 min as shown in Table 6.5-1.

Section 7 included an analysis of duct failure modes. It was shown that all elements of the duct system, when constructed in accordance with SMACNA Standards, could withstand the E119 time-temperature exposure. The tested ducts could be considered as providing protection equivalent to 1.5 hour fire dampers. Supporting rods of trapeze hangers or hanger straps supporting rectangular ducts and angle reinforcement of ducts near wall openings were identified as key construction details. The limitation of these data are the possible lower critical temperature of supporting hanger rods under maximum loading conditions, and exposure temperatures higher than the E119 furnace at the end of the 2 hour test.

Tables 8.2-1, 8.2-2, 8.2-3, and 8.2-4 were developed to evaluate the observed fuel fire exposure on the ducts surveyed. It provides the framework for evaluating other ducts in areas not surveyed. The location of ducts was matched with observed fuel packages as shown in Figures 8.2-1, 8.2-2, 8.2-3, and 8.2-4.

Fuel packages of concern are only those that may cause high temperatures near the wall (recalling that duct failure at a distance away from the wall is acceptable in the damper equivalency approach). Where the loading of a duct exceeds the loading of the SwRI test duct (14%), the estimated critical temperature from Table 7.3.1 is listed. Otherwise, the actual test exposure temperature of 1850°F (1010°C) is listed. Next, the equivalent design fire based on observed conditions is identified. The resulting maximum predicted exposure temperature, derived from upper layer, plume and flame impingement scenarios are listed. If the estimated critical or actual test exposure temperature is exceeded by any of the three predicted maximum exposure temperatures, then an upgrade of the duct near the wall is recommended, consistent with the findings in Section 7. It was assumed here that the plywood crate fuel loading in Room 134 would be limited to no more than six. If there are more than six plywood crates, the modeling showed that layer temperatures in excess of 500°C could be expected which could cause the rapid, simultaneous ignition of all combustibles in the room. This is commonly called flashover. If this situation cannot be prevented then all of the ducts in this room should be upgraded.

Table 8.2-1
Room 134
Advanced Size Reduction

<u>Duct Designation*</u>	<u>Estimated Critical or Actual Exposure Temperature, °F</u>	<u>Design Fire</u>	<u>Maximum Predicted Exposure Temperature, °F</u>			<u>Upgrade of Duct Near Wall Opening Recommended</u>
			<u>Upper Layer</u>	<u>Plume</u>	<u>Flame</u>	
1	1850	2 Crates	480	1740	2000***	Yes
2	1850	2 Crates	480	1740	2000***	Yes
3	1850	2 Crates	480	1740	2000***	Yes
4	1375	2000 kW	330	840	2000***	No#
5	1850	1000 kW	230	554	NFI***	No

- * See Appendix B for description
- ** flame impingement on duct due to fuel being close to wall
- *** No flame impingement
- # Fire source is not located near the wall penetration, ductwork will not fail near wall opening

Table 8.2-2
Room 127
Drum Storage

<u>Duct Designation**</u>	<u>Estimated Critical or Actual Exposure Temperature, °F</u>	<u>Design Fire</u>	<u>Maximum Predicted Exposure Temperature, °F</u>			<u>Upgrade of Duct Near Wall Opening Recommended</u>
			<u>Upper Layer</u>	<u>Plume</u>	<u>Flame</u>	
1	1850	1000 kW	230	554	NFI*	No
2	1850	500 kW	170	375	NFI	No
3	(See Note 1)					
4	1850	500 kW	170	375	NFI	No
5	1850	500 kW	170	375	NFI	No
6	1850	500 kW	170	375	NFI	No
7	1500	500 kW	170	375	NFI	No
8	1510	500 kW	170	375	NFI	No

* No flame impingement

** See Appendix B for description

Note 1. This duct did not have any hangers because only a short section was exposed where it entered the room and then turned and went up through the ceiling.

Table 8.2-3
Room 452/475
Special Assembly

Duct Designation**	Estimated Critical or Actual Exposure Temperature, °F	Design Fire	Maximum Predicted Exposure Temperature, °F			Upgrade of Duct Near Wall Opening Recommended
			Upper Layer	Plume	Flame	
1	1850	1000 kW	326	554	NFI	No
2	1230	1000 kW	326	554	2000+*	Yes
3	1350	1000 kW	326	554	2000+*	Yes
4	1125	1000 kW	326	842	2000+*	Yes
5	1510	500 kW	230	320	NFI***	No
6	1450	1000 kW	326	482	NFI	No
7	1230	500 kW	230	320	NFI	No
8	1400	500 kW	230	320	NFI	No
9	1230	500 kW	230	302	NFI	No
10	1230	500 kW	230	320	NFI	No
11	1400	1000 kW	326	590	2000+*	Yes
12	1850	500 kW	230	401	2000+*	Yes
13a	1510	500 kW	230	572	NFI	No
13b	1850	500 kW	230	572	NFI	No
13c	1850	500 kW	230	842	NFI	No
13d	1510	500 kW	230	451	NFI	No

* Flame impingement on duct due to fuel being close to wall.

** See Appendix B for description

*** No flame impingement

Table 8.2-4
Room 430

<u>Duct Designation*</u>	<u>Estimated Critical or Actual Exposure Temperature,*F</u>	<u>Design Fire</u>	<u>Maximum Predicted Exposure Temperature, °F</u>			<u>Upgrade of Duct Near Wall Opening Recommended</u>
			<u>Upper Layer</u>	<u>Plume</u>	<u>Flame</u>	
1	1500	1000 kW	185	554	NFI**	No

* See Appendix B for description

** No flame impingement

HVAC and Glovebox Ventilation Ductwork
Building 776/777 Room 134
DOE-Rocky Flats, Golden CO

Hughes Associates, Inc.
Wheaton, MD 20902
10/12/88 KJB

Figure 8.2-1 - Ductwork and fuel packages in room 134

HVAC and Glovebox Ventilation Ductwork
Building 776/777 Room 127
DOE-Rocky Flats, Golden CO

Hughes Associates, Inc.
Wheaton, MD 20902
10/12/88 KJB

Figure 8.2-2 - Ductwork and fuel packages in room 127

HVAC and Glovebox Ventilation Ductwork
 Building 776/777 Room 452
 DOE-Rocky Flats, Golden CO

Hughes Associates, Inc.
 Wheaton, MD 20902
 10/12/88 KJB

Figure 8.2-3 - Ductwork and fuel packages in room 452/475

Figure 8.2-4 - Ductwork and fuel packages in room 430

It becomes readily apparent that the significant issue is fuel located near walls. Because of flame height enhancement due to proximity to a wall, flames are likely to impinge on ducts and critical temperatures may be exceeded for sufficient time to cause failure of duct elements. The installation of insulation around hanger rods should provide up to 30 minutes additional protection (Section 7). This should be sufficient protection considering the duration and character of the impinging fires. The extent of this protection is dependent on the magnitude of radial flame spread (in the form of a flame jet) from the wall anticipated for a given fuel package. This is dependent on the geometry of the fuel package and the height of the base of the flame above the floor. Rough estimates of flame jet radii range from 5 to 15 feet. It is reasonable to protect all hangers supporting a duct which may have flame impingement, within a distance of 10 feet from the wall. As a minimum, the rods of the nearest supporting hanger should be protected, even if it is greater than 10 feet from the wall.

Angle reinforcement of the duct wall was identified in Section 7 as a key element to maintaining fire stopping integrity. While no through flaming was observed in the SWRI test duct with no reinforcing (Duct No. 1), there was warping and scorching of the fire stopping material. The solid fill observed between the ducts and wall openings in Building 776/777 may not fill gaps created by warpage as observed with the flexible firestop material in the SWRI test. Given that this reinforcement is a key construction detail in preventing through flaming, rectangular ducts exposed to direct flame impingement should be reinforced with angle stiffeners, tack welded to the duct walls approximately 2 in. from the wall openings.

Based on the analysis in Section 7, circular ducts require no upgrading.

The findings in Section 7 presume that the structural steel supporting the duct hanger elements resists the fire exposures identified in this study. Bare steel structural elements were noted in the survey. The impact of fire on these elements must be identified, otherwise the findings here for ducts are incomplete.

If greater than 6 plywood crates become involved in fire in Room 134, it was predicted that flashover conditions could be achieved. Given that flashover occurs, all of the ducts and hangers within the room and particularly those above fuel packages, would be exposed to extreme heat and may reach critical temperatures. Only Room 134 was observed to have this potential. This potential for flashover is considered

sufficient justification to recommend improvement of all rectangular ducts near wall openings in Room 134.

8.3 Conclusions

Summarizing the findings, analysis, and conclusions of this report:

1. The rationale for installing dampers in HVAC system ductwork and the performance criteria for dampers has been described:
 - Performance criteria for dampers assumes collapse of surrounding ductwork;
 - Fire dampers must prevent through-flaming to adjacent areas. There is no heat or smoke transmission criteria; and,
 - Protection equivalent to dampers is provided if ducts stay in place near wall openings, and the seal around the penetration is maintained so that there is no through flaming.
2. The fuel survey and resulting modeling of anticipated fire exposures indicated that:
 - Flashover conditions are unlikely to occur in any space other than in Room 134, Advanced Size Reduction. Flashover may occur in Advanced Size Reduction if a fire involves more than 6 plywood crates;
 - Flame impingement of duct systems may result from localized fuel packages, particularly when the fuel is located near walls;
 - Representative fuel packages have been defined in terms of peak heat release rate (500, 1000, 2000 kW) and in terms of equivalent plywood storage crates; and,
 - Fire in a Benelex glove box may result in a long duration fire, greater than 2 hours.
3. Evaluation of existing duct fire test data and the results of the SwRI fire test of representative ducts in Building 776/777 indicate that:

- Ducts can be designed to maintain their structural integrity near the wall opening and prevent through flaming so that fire protection equivalent to dampers is provided;
 - Ducts representative of Building 776/777 ducts, designed and constructed in accordance with SMACNA Standards, can meet the performance criteria for 1 1/2 hour fire dampers (no through flaming) when exposed to a standard time-temperature exposure of 2 hours;
 - The most important aspects in maintaining duct structural integrity near the wall are:
 - Preventing gaps between the barrier wall opening and duct; and,
 - Maintaining the integrity of hanger rods so that ducts are supported near the wall; and,
 - Temperature failure criteria for straps or rods of trapeze hangers supporting rectangular ducts can be estimated for all conditions. These estimates are inherently conservative when compared to actual test data.
4. Localized temperatures exceeding estimated critical temperature and actual exposure temperatures observed in the E119 test may result from flames impinging on ducts.
- When flames impinge on ducts near wall openings, the hanger rods and straps for rectangular ducts should be protected with pipe insulation and ducts should be reinforced with angle stiffeners on both sides of the opening near the barrier wall;
 - Although most of the combustible materials observed are not inherently "transient," it is advisable to reinforce all ducts and protect all hanger rods and straps near wall openings. This eliminates the need for administrative controls for transient materials and future modifications to building layout. This also provides an additional level of protection for all building areas.
 - To the maximum extent possible, combustibles should be removed where they are adjacent to walls.

5. Duct integrity is dependent on the integrity of structural elements from which ducts are supported. Assuring duct integrity is of little value if hanger supporting elements (beams, girders, columns) fail. Unprotected structural steel elements were observed in Building 776/777 areas. The impact of fire on these elements should be analyzed.
6. The impact of vertical duct openings (through the ceiling or roof) to filter plenums above manufacturing areas was not considered. The effect of fire on these openings and the need to provide fire barrier protection should be addressed.

9.0 RECOMMENDATIONS

1. Install angle stiffeners and pipe insulation on hanger straps and rods on rectangular duct systems where they penetrate wall openings in the following locations:
 - a. At all horizontal ducts passing through fire barrier walls in Room 134, Advanced Size Reduction;
 - b. In all other locations, at ducts penetrating fire barrier walls where flame impingement will occur near wall openings as identified in Tables 8.2-2, 8.2-3, and 8.2-4; and,
 - c. At ducts penetrating fire barrier walls in other locations not surveyed, where it is determined that flame impingement may occur within 10 feet of the wall opening. If it is determined that flashover may occur, all ducts should be upgraded near wall openings. The methodology developed in this report should be used to analyze other areas.

The upgrade of these specific ducts should consist of the following:

- a. 1.5 in. x 1.5 in. steel angle reinforcement, minimum of 10 gage, tack welded around the perimeter of rectangular ducts on both sides of wall openings. The angle should be located on the duct approximately 2 inches away from where the duct penetrates the fire barrier; and,
- b. Insulation of trapeze hanger rods with 1/2 in. diameter x 1 in. thick x 14 lbs/ft³ Manville Thermo - 12 calcium silicate pipe insulation (or equal). The hanger rods of the support closest to the wall should be insulated as well as all those rods within 10 feet of the wall, or
- c. Insulation of hanger straps with 1 in. diameter x 2 in. thick x 14 lbs/ft³ Manville Thermo - 12 calcium silicate pipe insulation (or equal). The hanger strap need only be protected from the top of the duct to the ceiling connection. The hanger straps of the support closest to the wall should be insulated as well as those straps within 10 feet of the wall, and

- d. All hanger insulation should be secured in place by steel straps spaced no more than 12 inches.
2. Consider protecting all rectangular ducts as described above, even where the flame impingement or flashover conditions are not predicted. This provides an additional level of protection and reduces reliance of future administrative programs to monitor fuel load and changes to building layout.
3. Reduce the storage in Room 134, Advanced Size Reduction, to a maximum of 6 wood crates within the designated storage area. In future analyses, if room flashover is predicted by the fire model, institute a fuel reduction program in the area to limit flashover potential.
4. To the maximum extent possible, combustibles should be removed where they are adjacent to walls and where resulting fire may impinge on ducts.
5. To the maximum extent possible remove Benelex glove boxes.
6. The impact of fire on bare structural steel should be determined.
7. The impact of vertical duct openings to the filter plenums and mechanical spaces should be determined.

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APPENDICES

APPENDIX A
Survey Findings (Fuel Loading)

The results of the survey conducted of Rocky Flats Building 776/777 which included rooms 134, 127, 452/475, and 430 are presented here. The primary information collected during this survey was quantification and description of combustible materials and the design and location of the ductwork in these rooms. Secondary information included identification of the active and passive fire protection systems. The duct system survey results are given in Appendix B.

SUMMARY OF RESULTS

I. Advanced Size Reduction (Room 134)

A. General Description

1. Gross floor area = 9106 ft²
2. Floor to ceiling height = 18 ft.
3. Separation: concrete block wall provides complete separation from all other rooms.
4. Gross fuel loading = 1.8 lb/ft²

B. Storage/holding area

1. Floor area = 576 ft²
2. Separation: area is surrounded by a chain link fence, no fire separation provided.
3. Observed fuels: 11 plywood crates
3 wood planks
22 storage drums
5 refuse carts (just outside fence)
4. Fuel loading = 20.0 lb/ft² (maximum anticipated)

C. Machine break down canyon

1. Floor area = 2061 ft²
2. Separation: canyon area is separated from main room by lead, stainless steel, and leaded glass shielding. Combustible gloves are also located in this wall.
3. Observed fuels: 1 large pile of combustible refuse on east side interior
4 20% H₂/80% Ar cylinders (exterior south-west wall)
1 plywood crate (exterior north wall)
4 storage drums (exterior north wall)
electrical wires and cabling
4. Fuel loading = 1.67 lb/ft² (includes only interior fuel)

- D. Along North wall
 - 1. Observed fuels: 4 plywood crates against wall
 - 2. Fuel loading = 12.4 lb/ft^2
- E. Along West wall
 - 1. Observed fuels: 8 paper rolls, 6 in cardboard boxes
4 polyethylene rolls, 3 in cardboard boxes
 - 2. Fuel loading = 39.5 lb/ft^2
- F. Storage Cabinet along South wall, east end
 - 1. Observed fuels: 1 cabinet with electronic equipment, tools and 300 ft (estimate) of cabling
 - 2. Fuel loading = 8.8 lb/ft^2
- G. Small storage area on south wall
 - 1. Floor area = 48 ft^2
 - 2. Floor to ceiling height = 8 ft
 - 3. Separation: chain link fence on the north side, concrete block on the other three sides
 - 4. Observed fuels: 20 folded plastic sheets on shelves
 - 5. Fuel loading = 4.2 lb/ft^2
- H. Glove box J-177 (small stand alone)
 - 1. Floor area = 120 ft^2
 - 2. Height = 8 ft.
 - 3. Observed fuels: 45 pairs PbO/neoprene hypalon gloves
24 ft^2 , 3 in thick plexiglass (PMMA)
 - 4. Fuel loading = 8.7 lb/ft^2

II. Drum Storage (Room 127)

- A. General Description
 - 1. Gross floor area = 9107 ft^2
 - 2. Floor to ceiling height = 18 ft
 - 3. Separation: concrete block wall provides complete separation from all other rooms.
 - 4. Gross wood equivalent fuel loading = 8.5 lb/ft^2
- B. Drum storage area
 - 1. Floor area = 4568 ft^2
 - 2. Separation: area is surrounded by chain link fence or lead shielding, no fire separation provided
 - 3. Observed fuels: 1987 sealed 55 gal steel drums
 - 4. Wood equivalent area fuel loading = 16.3 lb/ft^2
- C. Process area
 - 1. Floor area = 506 ft^2
 - 2. Separation: area is not separated

3. Observed fuels: 4 fiberglass liquid holding tanks
150 ft of 1-2 in polybutylene pipe
4. Wood equivalent area fuel loading = 6.6 lb/ft^2

III. Special Assembly (Room 475)

A. General Description

1. Gross floor area = 4194 ft^2
2. Floor to ceiling height = 18 ft
3. Separation: concrete block wall provides complete separation from all other rooms.
4. Observed fuels: 1 large benelex glove box
electronic cabinets
various ordinary combustibles and plastics
5. Wood equivalent fuel loading = 1.20 lb/ft^2

B. Benelex glove box

1. Floor area = 64 ft^2
2. Wood equivalent mass per box = 5022 lb
3. Wood equivalent area fuel load = 78.5 lb/ft^2

C. Electronic Cabinet

1. Floor area = 6 ft^2
2. Wood equivalent mass = 40.9 lb
3. Wood equivalent area fuel load = 6.8 lb/ft^2

IV. Room 430

A. General Description

1. Gross floor area = $15,799 \text{ ft}^2$
2. Floor to ceiling height = 18 ft
3. Separation: concrete block wall provides complete separation from all other rooms.
4. Observed fuels: 3 benelex glove boxes
1 wood crate
206 contaminated storage drums
5. Wood equivalent fuel loading = 1.04 lb/ft^2

B. Benelex glove box and 1 wood crate

1. Floor area glove box = 64 ft^2
2. Wood equivalent mass glove box = 3776 lb
3. Floor area wood crate = 28 ft^2
4. Mass wood crate = 348 lb
5. Total area = 92 ft^2
6. Total mass = 4124 lb
7. Wood equivalent area fuel load = 44.8 lb/ft^2

FUEL PACKAGE CALCULATIONS

I. Plywood Crates

A. Dimensions

1. Length = 7 ft
2. Width = 7 ft (large), 4 ft (regular)
3. Height = 4 ft
4. Thickness = 0.75 in (nominal)
5. Trim 1"x4" (actual) used on ends
6. Bottom blocks 3"x3.5"x4' (actual) 4 under each crate

B. Material Volume

1. Large Crate = $[4(4 \times 7) + 2(7 \times 7)] 3/4"$
= 13.125 ft³ (excludes trim and bottom blocks)
Trim = 28 ft (0.0278 ft²) = 0.778 ft³
Bottom blocks = 4(0.29 ft³) = 1.16 ft³
Total = 15.0 ft³
2. Regular Crate $[2(4 \times 4) + 4(7 \times 4)] 3/4" = 9.0$ ft³
(excludes trim and bottom blocks)
Trim = 22 ft (0.0278 ft²) = 0.612 ft³
Bottom blocks = 4(0.29 ft³) = 1.16 ft³
Total = 10.7 ft³

C. Package Occupied Floor Area

1. Large Crate = 49 ft²
2. Regular Crate = 28 ft²

D. Density of Plywood (specific gravity)

1. Douglas Fir (principal component) = 0.51
[Mantel, pg. 29-11]
2. Plywood = 0.54 [King, pp.12]

E. Density of Trim

1. White Fir = 0.40 [Mantel]

F. Package Mass

1. Large Crate
Mass = $[13.125 \text{ ft}^3 (0.54) + 1.94 (0.4)] 62.43$
lb/ft³
= 491 lb
2. Regular Crate
Mass = $[9.0 \text{ ft}^3 (0.54) + 1.77 (0.4)] 62.43$ lb/ft³
= 348 lb

II. Refuse Containers/Carts

A. Dimensions

1. Length = 3 ft
2. Width = 2 ft
3. Height empty = 3 ft
Height Full = 4 ft
4. Wall thickness = 0.003 in (1/16th in.
approximate)
5. Weight = 100 lb (estimated by lifting)
6. Volume Full = 24 ft³
7. Occupied Floor Area = 6 ft²
8. Note: 5 containers were observed to be full of refuse such as paper, respirator filters, miscellaneous plastics and combustibles, all of which was in polyethylene bags.

B. Various Specific Gravities [Weast]

1. Paper 0.7 - 1.15
2. Polyethylene 0.926 - 0.941
3. Polypropylene 0.90
4. Polystyrene 1.04 - 1.08
5. Polyvinyl Chloride 1.35
6. Note: Difficult to estimate actual density of refuse in the containers.

C. Groups of 5 Containers

1. Total mass = 500 lb
2. Equivalent wood mass = 1000 lb

III. Rolled Paper and polyethylene

A. Dimensions

1. Diameter = 9 in. (0.75 ft)
2. Roll length = 3 ft paper, 3.3 ft polyethylene
3. Thickness: paper was 5 mils (0.005 in.)
4. Paper sheet length = 100 ft
5. Note: Some (8) of this stock was horizontal and vertical on the floor in cardboard boxes, some (2) was installed on the walls in a horizontal orientation, and some (3) were horizontal on the floor without boxes.
6. Note: Each roll had a 1 1/2 inch diameter opening in the ends which ran through the roll for the purpose of putting the roll on a rack for use.

B. Material Volume

1. Paper volume =
$$[\pi/4(0.75 \text{ ft})^2 - \pi/4(0.125 \text{ ft})^2](3 \text{ ft})$$
$$= 1.29 \text{ ft}^3$$

2. PE volume =
$$[\pi/4(0.75 \text{ ft})^2 - \pi/4(0.125 \text{ ft})^2](3.3 \text{ ft})$$
$$= 1.42 \text{ ft}^3$$
- C. Specific Gravity
 1. Paper = 0.7 - 1.15
 2. PE (low density) = 0.91 - 0.925
- D. Mass (The low value for the specific gravity was used to account for air within the roll)
 1. Paper: $1.29 \text{ ft}^3(0.7)62.43 \text{ lb/ft}^3 = 56.4 \text{ lb ea}$
 2. PE: $1.42 \text{ ft}^3(0.91)62.43 \text{ lb/ft}^3 = 80.7 \text{ lb ea}$
 3. PE equivalent wood mass = 161.4 lb ea
- E. Occupied Floor Area
 1. Vertical = 0.44 ft^2
 2. Horizontal Paper = 2.25 ft^2
 3. Horizontal PE = 2.47 ft^2
 4. Total = $8(2.25)+4(2.47)$
 $= 27.8 \text{ ft}^2$

IV. Sealed Contaminated Storage Drums

- A. Dimensions and mass
 1. Diameter = 20 in. (1.67 ft)
 2. Height = 3.35 ft
 3. Volume = 7.35 ft^3 (55 gal)
 4. Occupied floor area = 2.19 ft^2
 5. Mass of drum empty = 30 lb (estimate)
 6. Mass of drum full = 92 kg (marked on typical drum)
= 202 lb
 7. Mass of materials in drum = 172 lb
- B. Contents
 1. The majority of the drum contents are metal machine parts. Communication with the on-site fire protection engineer (B. Campbell) indicated that approximately 10% of the net drum mass could be considered combustible. In addition some of the drums contain a polypropylene/polystyrene liner.
 2. Combustible mass per drum excluding liner
= 17.2 lb
 3. Liner thickness = 1/16 in (estimate)
 4. Material volume of liner =
$$[\pi(1.67 \text{ ft})(3.35 \text{ ft})+2.18 \text{ ft}^2]0.005 \text{ ft}$$
$$= 0.099 \text{ ft}^3$$
 5. Mass of liner = $0.099 \text{ ft}^3(0.9)62.43 \text{ lb/ft}^3$
= 5.6 lb
 6. Combustible mass per drum including liner
= 23 lb

V. Hydrogen Cylinders (20% H₂ by volume)

A. Dimensions [Air Products]

1. Diameter = 9.25 in. (0.77 ft)
2. Height = 55 in. (4.58 ft)
3. Cylinder Volume = 2.133 ft³
4. Normal Fill Pressure = 2600 psi

B. Contents

1. Volume of gas at STP = 262 ft³
2. Cylinder marked 20% by volume H₂,
80% by volume Ar
3. Volume of hydrogen = 52.4 ft³
4. Mass of hydrogen = 0.271 lb

C. Combustion Properties and Equivalent Weight

1. Heat of Combustion = 68,317 cal/mol [Smith and vanNess]
$$= 122,970.6 \text{ BTU/lbmol}$$
$$= 61,485.3 \text{ BTU/lb}$$
2. Heat of Combustion of wood = 7103 BTU/lb
3. Wood equivalent of 1 lb H₂ =
$$\frac{61,485.3 \text{ BTU/lb H}_2}{7103 \text{ BTU/lb wood}}$$
$$= 8.65 \text{ lb wood/lb H}_2$$
4. Wood equivalent weight of 1 cylinder 20/80
$$= 8.65(0.271 \text{ lb})$$
$$= 2.34 \text{ lb}$$

VI. Loose Cable in Cabinet

A. Dimensions

1. Cable diameter = 3/4 in. (approximate)
2. Cabinet length = 6 ft
3. Cabinet width = 2 ft
4. Cabinet height = 7 ft
5. Cabinet floor area = 12 ft²
6. Cabinet had 5 shelves including bottom. The bottom 3 shelves had cabling on them. The top 2 had various electronic equipment and tools.

B. Cable Characteristic [Hasegawa]

1. Neoprene (3/4")
Total weight = 1.29 kg/m (0.868 lb/ft)
Jacket wt.% = 23.5
Conductor wt.% = 76.5
2. PVC (1")
Total weight = 1.12 kg/m (0.754 lb/ft)
Jacket wt.% PVC = 18.9
Insulation wt.% PE = 32.9
Conductor wt.% = 49

VII. Glove Boxes

A. Glove box dimensions

1. Length = 6 ft
2. Width = 5 ft
3. Height = 6 ft
4. Description: These boxes were stand alone and were constructed of stainless steel, lead, glass and in some cases benelex and PMMA.

B. Gloves (Siebe North Model S2P2)

1. Mass of each glove = 2.408 lb [Siebe North Inc.]
2. Diameter of glove = 8 in.
3. Length of glove = 24-30 in.
4. Composition
52 % wt. neoprene and hypalon
48 % wt. lead
5. Quantity per box = 30 (approximate)
6. Mass combustibles per glove = 1.25 lb
7. Mass combustibles per box = 37.56 lb
8. Wood equivalent mass per box = 75.13 lb

C. PMMA Windows

1. Thickness = 3 or 4 in (measured)
2. Typical widths = 2.3 ft (small), 4 ft (large)
3. Typical heights = 1.8 ft, 3 ft
4. Specific gravity = 1.18 - 1.20
5. Typical Areas = 4.14 ft², 12 ft²
6. Typical Volumes = 1.03 ft³, 4 ft³
7. Mass of material =
1.18 (62.43) 1.03 = 75.8 lb ea. (small)
1.18 (62.43) 4 = 294.6 lb ea. (large)
8. Note: PMMA windows were found on only a few of the observed glove boxes and the majority of these were the small, thin size. The majority of the glove boxes used leaded glass for shielding of an observation window. Two of the large (4 ft x 3 ft 4 in) PMMA windows were used for shielding on the front of one of the Benelex glove boxes. The smaller (2.3 ft x 1.8 ft x 3 in) PMMA panels were on the front and sides of a glove box for observation.
9. Quantity per box = 10 (approximate for those observed)
10. Mass PMMA per box = 10 (75.8 lb) 758 lb
= 758 lb
11. Wood equivalent mass per box = 1516 lb

C. Benelex (when used on a glove box)

1. Thickness = 3 in [B. Campbell, Rockwell]
2. Height = 3 ft (front), 6 ft (sides)
3. Length = 5 ft (front) 6 ft (sides)

4. Volume (front and back) = 3.75 ft^3
Volume (sides) = 9 ft^3
5. Specific gravity = 1.37 [Masonite Corp.]
6. Mass (front and back) = 320.7 lb
Mass (sides) = 769.7 lb
7. Total mass per box = 2180.8 lb
8. Note: Only 3 boxes with benelex were observed in room 430 and 1 box with benelex was observed in room 475.

VIII. Fiberglass Storage Tanks And Plastic Piping

A. Fiberglass tanks

1. Height = 6 ft (measured)
2. Diameter = 6 ft (measured)
3. Wall thickness = $1/4$ in (estimated)
4. Volume of fiberglass per tank = 3.53 ft^3
5. Specific gravity of fiberglass = 1.8 [Perry and Chilton]
6. Mass per tank = 397.2 lb
7. Wood equivalent mass per tank = 794.4 lb

B. Plastic pipe

1. Length = 150 ft (estimate)
2. Diameter = 1-2 in (estimate)
3. Mass per length polyvinyl chloride pipe = 0.584 lb/ft
4. Mass of pipe = 87.6 lb
5. Wood equivalent mass = 175.2 lb

FUEL LOADING CALCULATIONS

I. Advanced Size Reduction

A. Storage/holding area- fuel principally wood crates

1. Area = 576 ft^2
2. Quantity and Mass
 - a) Mass regular size crate = 348 lb
Mass large size crate = 491 lb
 - b) Observed: 9 regular = 3,132 lb
2 large = 982 lb
 - c) Estimate Area 75% Full
Number Regular Crates = $576 \text{ ft}^2 / 28 (0.75)$
= 15
Pile 2 High = 30
Mass = 10,440 lb
3. Area Fuel Load
 - a) Observed = $4114 \text{ lb} / 576 \text{ ft}^2$
= $7.1 \text{ lb} / \text{ft}^2$

$$\begin{aligned} \text{b) } 75\% \text{ Full Estimate} &= 10,440 \text{ lb}/576 \text{ ft}^2 \\ &= 18.1 \text{ lb}/\text{ft}^2 \end{aligned}$$

B. Storage/holding area- fuel: wood crates, storage drums and refuse carts

1. Mass of crates (75% full assumption) = 10440 lb
2. Mass of refuse carts = 100 lb
3. Number of refuse carts = 5
Total mass = 500 lb
Equivalent wood mass = 1000 lb
4. Number of storage drums = 22
Mass combustibles per drum = 23 lb
Total combustible mass = 506 lb
5. Occupied floor area = $5(6 \text{ ft}^2) + 576 \text{ ft}^2$
= 596 ft^2
6. Area fuel load = $11946 \text{ lb}/596 \text{ ft}^2$
= $20.0 \text{ lb}/\text{ft}^2$

C. Rolled paper and polyethylene (west wall)

1. Paper roll mass = 56.4 lb
Polyethylene roll mass = 80.7 lb
2. Occupied area, group of 12 horizontal rolls (8 paper, 4 polyethylene) = $8(2.25 \text{ ft}^2) + 4(2.47 \text{ ft}^2)$
= 27.8 ft^2
3. Area equivalent wood fuel loading =
 $8(56.4 \text{ lb}) + 8(80.7 \text{ lb})/27.8 \text{ ft}^2$
= $1098 \text{ lb}/27.8 \text{ ft}^2$
= $39.5 \text{ lb}/\text{ft}^2$

D. Refuse storage in east end of machine breakdown canyon

1. East canyon floor area = 360 ft^2
2. Mass of refuse = 300 lb (estimate)
Equivalent wood mass = 600 lb
3. Area fuel load = $1.67 \text{ lb}/\text{ft}^2$

E. Wire in storage cabinet (south wall)

1. Mass of cable = 75 lb/shelf (estimated)
3 shelves observed with cable
Total = 225 lb
2. Cabinet occupied floor area = 12 ft^2
3. Mass of Combustible Neoprene = $.23(225 \text{ lb})$
= 52.8 lb
4. Fuel Loading in cabinet = $52.8 \text{ lb}/12 \text{ ft}^2$
= $4.4 \text{ lb}/\text{ft}^2$
5. Equivalent wood fuel loading = $105.6 \text{ lb}/12 \text{ ft}^2$
= $8.8 \text{ lb}/\text{ft}^2$

F. Wood crates along north wall

1. Total observed = 4 regular size
2. Total mass = $4(348 \text{ lb})$
= 1392 lb

G. Glove box J-177

1. Number of gloves = 45
2. Combustible mass per glove = 1.66 lb
Total combustible mass = 74.7 lb
3. Total wood equivalent combustible mass = 149.4 lb
4. Area of PMMA windows = 24 ft²
Thickress of PMMA = 3 in
5. Volume of PMMA = 6 ft³
6. Specific gravity of PMMA = 1.2
7. Mass of PMMA = 449.5 lb
8. Wood equivalent mass of PMMA = 899 lb
9. Total wood equivalent mass = 1048.4 lb
10. Wood equivalent fuel load = 1048.4 lb/120 ft²
= 8.7 lb/ft²

H. Total combustible wood equivalent mass in room =
16,190 lb

I. Gross wood equivalent fuel loading = 16,190 lb/9106 ft²
= 1.78 lb/ft²

II. Drum Storage Room

A. Drum Fuel Loading (assume that 10% by weight of the drums are combustible [B. Campbell, Rockwell Int.])

1. Mass of combustibles = 0.1 (172 lb) + liner mass
2. Assume ordinary combustibles
Combustible mass = (17.2 lb + 2(5.8 lb))
= 28.8 lb
3. Assume polymer combustibles
Combustible mass = 2(17.2 lb + 5.8 lb)
= 46 lb
4. Number of drums = 1987
5. Total combustible mass assuming 50% ordinary,
50% polymer contents =
993.5(28.8 lb) + 993.5(46 lb)
= 74,314 lb
6. Derating of fuel mass due to total enclosure in
steel drum = 0.1 (enclosed fuel mass)
= 7,431 lb
7. Occupied floor area = 4568 ft²
8. Equivalent wood area fuel loading (w/o derating)
= 16.3 lb/ft²
9. Equivalent wood area fuel loading (w/ derating)
= 1.6 lb/ft²

- B. Process area: fiberglass acid storage tanks and plastic pipe
1. Number of tanks = 4
 2. Mass of tank = 397.2 lb
Total mass = 1588.7 lb
 3. Mass of plastic pipes = 87.6 lb
 4. Occupied floor area = 506 ft²
 5. Total mass = 1676 lb
Area fuel loading = 3.3 lb/ft²
 6. Wood equivalent mass = 3352 lb
Wood equivalent area fuel loading = 6.6 lb/ft²
- C. Total wood equivalent fuel mass in room (w/o derating)
= 77,666 lb
- D. Total wood equivalent fuel mass in room (w/ derating)
= 10,783 lb
- E. Gross floor area = 9107 ft²
- F. Wood equivalent fuel loading = 8.5 lb/ft² (w/o derating)
= 1.2 lb/ft² (w/ derating)

III. Special Assembly

- A. Electronic controller: combustibles consist principally of wires and cables within the electronic cabinet
1. Estimated length of wire/cable = 100 ft
 2. Weight per length of wire/cable = 0.87 lb/ft
for 3/4 in
 3. Weight fraction combustible = 0.235
 4. Mass combustibles = 20.4 lb
 5. Equivalent wood mass = 40.9
- B. Benelex Glove box
1. Number of gloves = 40
Mass combustibles per glove = 1.25 lb
Total mass neoprene and hypalon = 50 lb
Wood equivalent mass = 100 lb
 2. Total area of PMMA = 7.33 ft²
Thickness of PMMA = 4 in
Volume of PMMA = 2.44 ft³
Mass of PMMA = 180 lb
Wood equivalent mass = 360 lb
 3. Total area of benelex = 160 ft²
Thickness of benelex = 4 in
Volume of benelex = 53.3 ft³
Mass of benelex = 4562 lb
- C. Total equivalent wood mass in room = 5063 lb

- D. Gross floor area = 4194 ft²
- E. Wood equivalent fuel loading = 1.20 lb/ft²

IV. Room 430

- A. Benelex Glove boxes
 - 1. Number of boxes = 3
 - 2. Mass of benelex per box = 2180.8 lb
Total mass of benelex = 6542.4 lb
 - 3. Mass of neoprene/hypalon in each glove = 1.25 lb
Number of gloves per box = 30
Number of gloves = 90
Total mass of neoprene/hypalon = 112.9 lb
Equivalent wood mass of neoprene/hypalon
= 225.0 lb
 - 4. Mass of PMMA per window = 76 lb
Number of windows per box = 10
Total number of windows = 30
Total mass of PMMA = 2280 lb
Equivalent wood mass of PMMA = 4560 lb
 - 5. Total mass of combustibles = 8935.3 lb
 - 6. Total equivalent wood mass = 11,327.4 lb
- B. Regular wood crate
 - 1. Number of crates = 1
 - 2. Mass of crate = 348 lb
- C. Contaminated storage drums
 - 1. Number of drums = 206
 - 2. Mass combustibles per drum = 23 lb
 - 3. Total combustible mass = 4738 lb
- D. Gross floor area = 15,799 ft²
- E. Total wood equivalent mass = 16,413 lb
- F. Wood equivalent fuel loading = 1.04 lb/ft²

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APPENDIX B
Survey Findings (Ductwork)

The results of the ductwork survey conducted of Rocky Flats Building 776/777 which included rooms 134, 127, 452/475, and 430 are presented here. The information collected in this survey consisted of duct dimensions, material, joint type, hanger type, dimension and spacing, and the height of the ducts above the floor. The ducts of principal concern were those that passed through the fire rated walls. Tables B-1, B-2, B-3, and B-4 list all of the data collected. Tables B-5 and B-6 give the approximate weight of duct between hangers for round and rectangular ducts, respectively.

Table B-1

HVAC AND EXHAUST DUCT SYSTEMS
PENETRATION OF FIRE BARRIERS

Room 134

Duct No.	Duct Dimensions inches	Duct Material	Joints	Hanger Type	Hanger Spacing Ft.	Clearance To Floor, Ft.
1.	36 Dia.x20 ga.	Stainless steel	Welded	3 in.x 20 ga. band; 1/2 in. dia. rod	8	14
2.	24x24x22 ga.	Galv.	Mechanical	Trapeze angle 2x2x1/4; 3/8 in. dia. rods	5	14
3.	30x24x22 ga.	Galv.	Welded	Trapeze angle 2x2x1/4; 1/2 in. dia. rods	12	14
4.	80x36x22 ga.	Galv.	Mechanical	Trapeze angle 2x4x1/4; 1/2 in. dia. rods	8	14
5.	16x10x22 ga.	Galv.	Mechanical	Trapeze angle 2x2x1/4; 3/8 in. dia. rods	8	14

Table B-2

HVAC AND EXHAUST DUCT SYSTEMS
PENETRATION OF FIRE BARRIERS

Room 127

Duct No.	Duct Dimensions inches	Duct Material	Joints	Hanger Type	Hanger Spacing Ft.	Clearance To Floor, Ft.
1.	36x30x22 ga.*	Galv.	Mechanical	Trapeze angle 2x2x1/4; 1/2 in. dia. rods	6	12
2.	36x30x22 ga.	Galv.	Mechanical	Trapeze angle 2x2x1/4; 1/2 in. dia. rods	6	6
3.	30 Dia.x22 ga.*	Galv.	Welded	none	10	10
4.	30x24x22 ga.*	Galv.	Mechanical	Trapeze angle 2x2x1/4; 1/2 dia. rods	8	14
5.	50x20x22 ga.*	Galv.	Mechanical	"	6	14
6.	50x20x22 ga.*	Galv.	Mechanical	"	6	14
7.	24x12x22 ga.	Galv.	Mechanical	Trapeze angle 2x2x1/4; 3/8 in. dia. rods	8	14
8.	24x24x22 ga.	Galv.	Mechanical	Trapeze angle 2x2x1/4; 3/8 in. dia. rods	8	14**

* Floor penetration

** Duct shielded by steel deck located 10 feet above floor.

Table B-3

HVAC AND EXHAUST DUCT SYSTEMS
PENETRATION OF FIRE BARRIERS

ROOM 430^a

Duct No.	Duct Dimensions Inches	Duct Material	Joints	Hanger Type	Hanger Spacing, Ft.	Clearance to Floor, Ft.
1.	24x44x22 ga.	Galv.	Mechanical	Trapeze angle 2x4x1/4; 1/2 in. dia. rods	8	14

^aMovement restricted, resulting in limited visual inspection of ductwork

Table B-4

Rooms 452 and 475

1.	36 dia.x18 ga.	Stainless steel	Welded	a. straps b. 3 in.x18 ga. steel band - 1/2 in. dia. rod	8 6	10
2.	36x24x22 ga.	Galv.	Mechanical	Wire tie and sheet steel strap	8	12
3.	24x24x22 ga.	Galv.	Mechanical	Wire tie and sheet steel strap	8	12
4.	30x30x24 ga.	Galv.	Mechanical	Wire tie and sheet steel strap	8	10
5.	24x24x22 ga.	Galv.	Mechanical	Trapeze angle 2x2x1/4; 3/8 in. dia. rod.	6	15
6.	30x24x22 ga.	Galv.	Mechanical	Trapeze angle 2x2x1/4; 3/8 in. dia. rod.	4 and 8	15

Table B-4 (Continued)

Rooms 452 and 475

Duct No.	Duct Dimensions Inches	Duct Material	Joints	Hanger Type	Hanger Spacing Ft.	Clearance to Floor - Ft.
7.	30x24x22 ga.	Galv.	Mechanical	Sheet steel strap screwed to duct wall. Trapeze angle 2x2x1/4	6	15
8.	18x12x22 ga.	Galv.	Mechanical	Sheet steel strap screwed to duct.	6	15
9.	30x24x22 ga.	Galv.	Mechanical	Sheet steel strap screwed to duct.	6	16
10.	30x24x22	Galv.	Mechanical	Sheet steel strap screwed to duct.	6	15
11.	36 Dia.x18 ga.	Stainless steel	Welded	3 in.x18 ga. steel band - 3/8 in. dia. rod	8	12
12.	18x12x22 ga.	Galv.	Mechanical	Sheet steel strap screwed to duct	15	12
13.	a) 14 Dia.x22 ga.	Galv.	Mechanical	Steel trapeze	8	10
	b) 6 Dia.x22 ga.	"	"	"	"	10
	c) 12 Dia.x22 ga.	"	"	"	"	8
	d) 14 Dia.x22 ga.	"	Mechanical	Steel trapeze	8	11

Table B-5

Approximate Weight - Round Ducts

Duct Dia., Inches (Circum., Ft.)	Stainless Steel Weight per L.F.			Galvanized Steel Weight per L.F. 22 ga.	Span Between Hangers, Ft.	Total Weight lbs.
	22 ga.	20 ga.*	18 ga.*			
36 (9.425)	14.85	19.80			8 (18 ga.) 8 (20 ga.)	158.4 118.8
30 (7.854)				11.22	10	112.2
14 (3.665)				5.33	10 8	53.3 42.64
12 (3.142)				4.60	10 8	46.0 36.8
6 (1.571)				2.39	10 8	23.9 19.12

*18 ga. stainless steel weight, 2.1 lbs. per s.f.

20 ga. stainless steel weight, 1.575 lbs. per s.f.

Table B-6

Approximate Weight - Rectangular Ducts

Duct Dimensions Inches	Galvanized Steel	Span Between Hangars Ft.	Total Weight lbs.
	Weight per L.F. 22 ga.* 20 ga. 18 ga.		
80x36	27.18	8	217.44
50x20	15.0	6	90.0
44x24	15.93	8	127.44
36x30	15.47	6	92.82
36x24	14.06	6	84.36
30x30	14.06	8	112.48
30x24	12.65	12	151.8
24x24	11.25	5	56.24
24x12	8.44	8	67.52
18x12	7.03	6	42.18
16x10	6.09	5	30.45

*galv. sheet, 22 ga. = 1.406 lbs./s.f.

APPENDIX C
Hand Calculations

I. Estimating Heat Release Rate (HRR) and Fire Growth Rate of Plywood Crate

A. Peak HRR

The peak HRRs per unit area as reported by 3 different sources for various plywood samples are shown in Table C-1. For 3/4 in. plywood, a value of 250 kW/m² was used.

B. Flame Spread Rate

The following correlation of flame spread rate as a function of incident flux given in the literature [Drysdale 1985] was used:

$$V^{-\frac{1}{2}} = C (\dot{q}_i'' - \dot{q}_E'') \quad (1)$$

where: V = flame spread rate
 C = correlation constant
 $\dot{q}_i''$ = minimum flux for ignition
 $\dot{q}_E''$ = incident flux

$$\text{HRR} = 250\pi (Vt)^2 \quad (2)$$

C. Surface Area of Plywood Crate

$$\begin{aligned} A_s &= (7 \text{ ft} \times 4 \text{ ft}) + 2(4 \text{ ft} \times 4 \text{ ft}) + 2(7 \text{ ft} \times 4 \text{ ft}) \\ &= 116 \text{ ft}^2 \\ &= 10.78 \text{ m}^2 \end{aligned}$$

Table C-1. Peak HRR kW/m² for Wood

Source	19/32 DF Plywood	3/4 in. DF Plywood	19/32 DF Plywood Treated	1/2 in. DF Plywood Treated	5/8 in. Particleboard	Hardboard	Hardboard Treated
NBS Calorimeter [1]	251	211	182 NBS-1R	107 NBS1-R	250	NA	NA
Chamberlain - NBS [2]			55 NBS 11	85 NBS 11			
ISO-O ₂ Consumpt. [3]		180		40	NA	325	50 @ 3 w/cm ²
Janssens [4]							150 @ 6 w/cm ²
Furnace Calorimeter Substitution Burner [5]	NA	116.5	25	NA	177	219	NA
Brenden FPL [6]		133.4					

DF = Douglas Fir

D. Maximum HRR

$$\begin{aligned} \text{HRR}_{\text{max}} &= A_s \text{HRR}_{\text{max}}'' \\ &= 10.78 \text{ m}^2 (250 \text{ kW/m}^2) \\ &= 2695 \text{ kW (2554 BTU/s)} \end{aligned}$$

II. Estimating Flame Height

A. Alpert and Ward

$$H_f = 0.6 \dot{Q}^{2/5} \quad (3)$$

where:

$\dot{Q}$ = heat release rate, BTU/s

H_f = flame height, ft

B. Heskestad (virtual source correction)

$$H_f = -1.02D + 0.23 \dot{Q}^{2/5} \quad (4)$$

where:

D = base diameter of flame (m) = $(4A/\pi)^{1/2}$

D = 6 ft (1.83 m)

$\dot{Q}$ = 2695 kW

$$\begin{aligned} H_f &= -1.02(1.83) + 0.23(2695)^{2/5} \\ &= 3.55 \text{ m (11.6 ft)} \end{aligned}$$

III. Maximum Plume Temperature

Equation 5 as presented by Heskestad was used to calculate the maximum centerline plume temperature above the flame.

$$T_o = 9.1 [T_a/gC_p^2 a^2]^{1/3} \dot{Q}^{1/3} (Z - Z_o)^{-5/3} \quad (5)$$

$$Z_o = D(-1.02 + 0.083 \dot{Q}^{2/5}/D) \quad (6)$$

where:

T_o = temperature difference between ambient and centerline plume

T_a = ambient temperature (K)

$$g = 9.81 \text{ m/s}^2$$

C_p = heat capacity of air = 1.04 KJ/kg

ρ = density of air = 1.1 kg/m³

IV. Radiant Heat Flux

Equation 7 was used to estimate the radiant flux at various distances from the fire. Equation 7 is a point source approximation and therefore is not very good close to the flame.

$$\dot{q}''_R = \frac{X_R \dot{q}''}{4\pi R^2} \quad (7)$$

where:

$\dot{q}''$ = radiant flux

X_R = fraction of energy release, $\dot{q}''$, which is given off as radiation (assumed to be 0.3)

R = distance from radiation source

V. Hot Layer Temperature in a Compartment with Forced Ventilation

A correlation presented by Foote, Pagni and Alvares in the literature as shown by equations 8, 9, and 10 was used to estimate upper layer temperature as a function of heat release and mass ventilation rates. This was done for Room 134, Advanced Size Reduction with an air change rate of 7 and 15 per hour, and the results are shown in Figure A-4.

$$T = 0.63 T_{\infty} \left[\frac{\dot{Q}}{\dot{m} C_p T_{\infty}} \right]^{0.72} \left[\frac{h_K A}{\dot{m} C_p} \right]^{-0.36}$$

where:

$$h = k/\delta$$

k = thermal conductivity of room wall material
(kW/mK) (concrete $k = 1.6 \times 10^{-3}$ kW/mK)

δ = thickness of wall (m) = 8 in.

A = wall surface area = 2410.8 m²

$\dot{m}$ = mass ventilation rate (kg/g)

C_p = heat capacity of air = 1.04 KJ/kg K

T = difference between upper layer temperature and ambient temperature (K)

$\dot{Q}$ = heat release rate (kW)

T_∞ = ambient temperature (K)

The calculation of the mass ventilation rate, $\dot{m}$, from the number of air changes per hour is shown below.

Volume of room 134 = 4,640.6 m³

Density of air = 1.29 kg/m³

$$\begin{aligned}\dot{m} &= (1.29 \text{ kg/m}^3) (15/\text{hour}) (1 \text{ hr}/3600 \text{ s}) (4640.6 \text{ m}^3) \\ &= 24.9 \text{ kg/s}\end{aligned}$$

VI. Fire Load for Flashover

A correlation presented by Thomas determines the wood fuel mass required under natural ventilation conditions to cause flashover in a compartment. The correlation is given by Equations 11, 12 and 13.

$$\theta_f = 6000 \left(\frac{1 - e^{-0.13}}{1/2} \right) (1 - e^{-0.05\tau}) + T_o \quad (11)$$

where:

θ_f = upper limit air temperature at flashover
= 500°C

T_o = ambient temperature

$$= A_T / A_w \sqrt{h} \quad (12)$$

$$\tau = L / \sqrt{AwA_T} \quad (13)$$

where:

A_T = total enclosure area (m^2)

A_w = area of vent opening (m^2)

h = height of opening (m)

L = wood fuel mass (kg)

For Room 134 Advanced Size Reduction,

$A_T = 1564.89 \text{ m}^2$

$A_w = 1.947 \text{ m}^2$

$h = 2.13 \text{ m}$

Table C-2 shows the results obtained by having a different number of doors open.

Table C-2. Wood Mass to Reach Flashover

<u>Number of Doors</u>	<u>Wood Mass, kg</u>	<u>Number of Plywood Crates</u>
1/2	1129.7	7.0
1	1317.7	8.2
2	1507.0	9.4
3	1615.2	10.0
4	1689.6	10.6
5	1745.5	10.9

APPENDIX C REFERENCES

- 1) Walton, W.D., and Twilley, W.H., "Heat Release and Mass Loss Rate Measurements for Selected Materials," NBSIR 84-2960, National Bureau of Standards, Washington, DC (1984).
- 2) Chamberlain, D.L., "Heat Release Rate Properties of Wood-Based Materials," NBSIR 82-2597, National Bureau of Standards, Washington, DC (1982).
- 3) Babrauskas, V., "Development of the Cone Calorimeter - A Bench Scale Heat Release Rate Apparatus Based on Oxygen Consumption," NBSIR 82-2611, National Bureau of Standards, Washington, DC (1982).
- 4) Janssens, "Rate of Heat Release - A Review," Benjamin, Clarke Associates, Kensington, MD (1983).
- 5) Brenden, J.J., "An Apparatus Developed to Measure Rate of Heat Release from Building Materials," Forest Products Laboratory, USDA, FPL 217 (1973).
- 6) Brenden, J.J., "Rate of Heat Release From Wood-Base Building Materials Exposed to Fire," Forest Products Laboratory, USDA, FPL 230 (1974).

APPENDIX D

FIRST INPUT DATA FILE LISTING

2 CRATES

2 PHYS. SUBR. "TMPO"
2 PHYS. SUBR. "ABSRB"
1 PHYS. SUBR. "PLUM"

1 NUMBER OF ROOMS

ROOM GEOMETRY FOR ROOM #1

0.2900E+02 LENGTH IN X DIRECTION
0.2900E+02 LENGTH IN Y DIRECTION
0.5486E+01 LENGTH IN Z DIRECTION
2 NO OF OBJECTS IN ROOM
0.3000E+03 INITIAL ROOM TEMP.
0.0000E+00 PHOTOEL. SMOKE DET.
0.3300E-01 DET. ABSORB. COEF. TH
0.2000E-01 POS. OF DETECTOR
2 KNOSKR
0 KNOS(KR)
2 KNOKR

OBJECT GEOMETRIC PROPERTIES FOR OBJECT #1

0.1450E+02 X COORDINATE IN ROOM
0.1450E+02 Y COORDINATE IN ROOM
0.0000E+00 Z COORDINATE IN ROOM
0.0000E+00 ANGLE WITH HORIZONTAL
0.0000E+00 ANGLE WITH VERTICAL
0.1905E-01 THICKNESS
0.1312E+01 INITIAL BURN. RADIUS
0.1204E+01 OBJECT RADIUS
0.1312E+01 MAX. BURNING RADIUS
F LOGICAL-> CIRCLE

OBJECT PHYSICAL PROPERTIES FOR OBJECT #1

5 3 VARIABLES USED FOR
3 TYPE OF FIRE
0 RELATION TO WALLS
0.4000E-01 THERMAL CONDUCTIVITY
0.1700E+04 SPECIFIC HEAT
0.4700E+02 DENSITY
0.9800E+00 EMIS./ABS. OF SURF.
0.9850E+01 AIR/FUEL MASS RATIO
0.9850E+01 STOCH. MASS RAT.
0.1000E+01 FRAC. OF HEAT OF COMB
0.4645E+08 HEAT OF COMBUSTION
0.2580E+07 HEAT OF VAPORIZATION

0.6852E+01	INITIAL FUEL MASS
0.7700E+03	TEMP. OF IGNITION
0.6000E+03	TEMP. OF ONSET PYRO.
0.1510E+01	CO2 MA. EVOL./FUEL MA
0.1300E-01	CO MA. EVOL./FUEL MA.
0.2400E+00	SMOKE MA. EV./FUEL M.
0.7140E+00	H2O MA. EVOL/ FUEL MA
0.2000E-02	HC MASS EVOL./FUEL MA
0.3000E+02	SEMIAPEX ANG. OF FLAM
0.1372E-01	FIRE SPREAD PARAMETER
0.2000E+02	BURNOUT PARAMETER
0.1280E+01	FLAME EXTINCTION COEF

9 # SEG.IN VAR. BRNR FI

0.0000	0.000000	TIME AND RATE POINT
20.0000	0.001615	TIME AND RATE POINT
40.0000	0.006462	TIME AND RATE POINT
60.0000	0.014540	TIME AND RATE POINT
80.0000	0.025848	TIME AND RATE POINT
100.0000	0.040387	TIME AND RATE POINT
120.0000	0.058158	TIME AND RATE POINT
140.0000	0.079159	TIME AND RATE POINT
160.0000	0.092831	TIME AND RATE POINT
600.0000	0.092831	TIME AND RATE POINT

0 # SEG.IN VAR. HETR RT

0.0000	0.000000	TIME AND RATE POINT
--------	----------	---------------------

1 KRO(KO)
0.9980E-02 BETA(KO)
0.5006E-06 ZGOZZ(KO)

OBJECT GEOMETRIC PROPERTIES FOR OBJECT #2

0.2060E+02	X COORDINATE IN ROOM
0.1460E+02	Y COORDINATE IN ROOM
0.5182E+01	Z COORDINATE IN ROOM
0.0000E+00	ANGLE WITH HORIZONTAL
0.0000E+00	ANGLE WITH VERTICAL
0.1000E+00	THICKNESS
0.3700E-01	INITIAL BURN. RADIUS
0.3439E+00	OBJECT RADIUS
0.4657E+00	MAX. BURNING RADIUS

F LOGICAL-> CIRCLE

OBJECT PHYSICAL PROPERTIES FOR OBJECT #2

2 3 VARIABLES USED FOR
7 TYPE OF FIRE
0 RELATION TO WALLS
0.4000E-01 THERMAL CONDUCTIVITY
0.1700E+04 SPECIFIC HEAT

0.4700E+02 DENSITY
 0.9800E+00 EMIS./ABS. OF SURF.
 0.9850E+01 AIR/FUEL MASS RATIO
 0.9850E+01 STOCH. MASS RAT.
 0.6500E+00 FRAC. OF HEAT OF COMB
 0.2870E+08 HEAT OF COMBUSTION
 0.2580E+07 HEAT OF VAPORIZATION
 0.1096E+01 INITIAL FUEL MASS
 0.9000E+04 TEMP. OF IGNITION
 0.9000E+04 TEMP. OF ONSET PYRO.
 0.1510E+01 CO2 MA. EVOL./FUEL MA
 0.1300E-01 CO MA. EVOL./FUEL MA.
 0.2400E+00 SMOKE MA. EV./FUEL M.
 0.7140E+00 H2O MA. EVOL/ FUEL MA
 0.2000E-02 HC MASS EVOL./FUEL MA
 0.3000E+02 SEMIAPEX ANG. OF FLAM
 0.1372E-01 FIRE SPREAD PARAMETER
 0.2000E+02 BURNOUT PARAMETER
 0.1280E+01 FLAME EXTINCTION COEF

1 # SEG.IN VAR. BRNR FI

0.0000 0.010000 TIME AND RATE POINT
 40.0000 0.010000 TIME AND RATE POINT

0 # SEG.IN VAR. HETR RT

0.0000 0.000000 TIME AND RATE POINT

1 KRO(KO)
 0.9980E-02 BETA(KO)
 0.5006E-06 ZGOZZ(KO)

F F F F F TOUCH ARRAY VALUES
 F F F F F TOUCH ARRAY VALUES
 F F F F F TOUCH ARRAY VALUES
 F F F F F TOUCH ARRAY VALUES
 F F F F F TOUCH ARRAY VALUES

2 NUMBER OF VENTS

VENT PROPERTIES FOR VENT #1

0.7620E+00 VENT WIDTH
 0.9144E+00 VENT HEIGHT
 0.3048E+00 TRANSOM DEPTH

1 SIDE 1
 0 SIDE 2

0 OPENING CODE
 0.3000E+03 OPENING CONDITION
 T FORCED VENTILATION

2 # SEG. IN VENT FLOW R

0.0000	0.000000	TIME AND RATE POINT
20.0000	38.675000	TIME AND RATE POINT
600.0000	38.675000	TIME AND RATE POINT

VENT PROPERTIES FOR VENT #2

0.7620E+00	VENT WIDTH	
0.9144E+00	VENT HEIGHT	
0.4572E+01	TRANSOM DEPTH	
1	SIDE 1	
0	SIDE 2	
0	OPENING CODE	
0.3000E+03	OPENING CONDITION	
F,	FORCED VENTILATION	
1	# SEG. IN VENT FLOW R	
0.0000	0.000000	TIME AND RATE POINT
0.0000	0.000000	TIME AND RATE POINT
1	NUMBER OF WALLS	

WALL PROPERTIES FOR WALL #1

0.1016E+00	THICKNESS
0.1100E+01	THERMAL CONDUCTIVITY
0.8800E+03	SPECIFIC HEAT
0.2100E+04	DENSITY
0.5952E-06	TH. DIF. OF WALL

NON-INDEXED VARIABLES

0.1004E+04	SPECIFIC HEAT OF AIR
0.3000E+03	AMB. TEMP. OUTSIDE
0.5000E+02	MAX HEAT TRANS COEFF.
0.5000E+01	MIN HEAT TRANS COEFF.
0.1000E+02	HEAT TRANSFER COEFF.
0.1000E+00	PLUME ENTRAIN. COEFF.
0.6800E+00	VENT FLOW COEFFICIENT

IOUT(I)-> ARRAY CONTAINING INDEXES OF
VARIABLES TO BE DISPLAYED IN OUTPUT

0	
0	
0	
0	
0	
0	
0	
0	
0	
F	FLSO

0		SHRT-LONG FORM OUTPUT
0		SUPPRES HNORM & FNORM
	20.0000	TERM. OUTPUT INTERVAL
	10.0000	DISK OUTPUT INTERVAL
	1200.0000	RUN LENGTH OF SIM.
	2.0000	BASIC TIME INCREMENT
	0.1000E-03	TOLERANCE VALUE
100		ITERATION LIMIT

APPENDIX E

SwRI Report

"Ad-Hoc Fire Endurance Test of Unprotected Steel Duct Systems"

SOUTHWEST RESEARCH INSTITUTE

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DEPARTMENT OF FIRE TECHNOLOGY

AD-HOC FIRE ENDURANCE TEST OF UNPROTECTED STEEL DUCT SYSTEMS

FINAL REPORT

SwRI PROJECT NO. 01-2427-001

OCTOBER 1988

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SAN ANTONIO, TEXAS

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I. OBJECTIVE

The objective of this program was to demonstrate whether an unprotected steel duct that does not contain a fire damper at the fire barrier opening, will remain in place throughout a 120-minute fire exposure and effectively maintain the integrity of the fire barrier at that opening, consistent with the criteria for fire dampers. The results obtained from this test program will be used to determine whether fire dampers are needed in existing steel duct systems at 2-hour fire barriers or what modifications to the duct system would be required to protect the fire barrier opening.

II. INTRODUCTION

The test exposes the test specimens to a standard fire exposure (ASTM E119-83, Standard Methods of Fire Tests of Building Construction and Materials) controlled to achieve specified temperatures throughout a specified time period, as shown below:

<u>TIME</u>	<u>TEMPERATURE</u>
0 minutes	Ambient
5 minutes	1000°F (538°C)
10 minutes	1300°F (704°C)
30 minutes	1550°F (843°C)
45 minutes	1638°F (892°C)
60 minutes	1700°F (927°C)
2 hours	1850°F (1010°C)
4 hours	2000°F (1093°C)

This report describes the analysis of three distinct assemblies, and includes descriptions of the test procedure followed, the assemblies tested, and all results obtained. The results presented in this report apply only to the material tested, in the manner tested, and not to any identical or similar materials or material combinations. All test data are on file and are available for review by authorized persons.

III. TEST PROCEDURE

SwRI's large horizontal exposure furnace is capable of exposing a maximum test specimen of 12 ft long and 16 ft wide. The 80-in. deep furnace is equipped with 14 premixed air/natural gas burners located across the walls, 18 in. up from the bottom and controlled by a variable air/gas ratio regulator. Capable of a maximum heat output of 14 million Btu/hour, these burners are arranged well below the exposed face of the specimen to ensure an even temperature at the face of the specimen. Windows are located on all sides of the furnace to allow observation of the surface exposed to flame.

The conduct of the fire test is controlled according to the standard time/temperature curve, as indicated by the average temperature obtained from the readings of ten thermocouples symmetrically located across the face of the specimen, 12 in. away. The thermocouples are enclosed in protection tubes of such material and dimensions that the time constant of the thermocouple assembly lies between 5.0 and 7.2 minutes, as required by the standard. The furnace temperature during a test is controlled such that the area under the time/temperature curve is within 10 percent of the corresponding area under the standard time/temperature curve for 1 hour or less tests, 7.5 percent for those less than 2 hours, and 5 percent for those tests of 2 hours or more duration.

Temperatures of both the unexposed and exposed surfaces are measured with No. 20 B&S gauge, type K (Chromel-Alumel) welded thermocouples.

The furnace pressure was controlled at the Client's request to be approximately +0.03 in. of water pressure, measured 0.78 in. (20 mm) below the insulated cover slabs.

IV. TEST ASSEMBLY

A. Duct No. 1

A rectangular steel duct, constructed of 36 x 30-in. x 22-ft long 22-gauge galvanized steel sheet, was comprised of three 5-ft sections and two 3.5-ft sections. The duct construction conformed to the Sheet Metal and Air Conditioning Contractors National Association, Incorporated (SMACNA), HVAC Duct Construction Standards, Metal and Flexible, First Edition, 1985. The longitudinal seams were of the

button punch snap-lock type, identified as L-2 in the SMACNA standards. The transverse (girth) joints were of the Standing S type, identified as T-11 in the SMACNA standards to give a minimum rigidity of Class D. The duct section was supported by a trapeze comprising 0.375-in. diameter steel hanger rods and 2.5 x 0.25-in. steel angle, located at the midpoint of the span (6 ft from the furnace walls). Both of the hanger rods were positioned 2 in. away from the sides of the duct. The trapeze was adjusted so the top surface of the duct was located approximately 30 in. below the underside of the insulated cover slabs.

B. Duct No. 2

A circular duct, constructed of 36-in. diameter x 22-ft long 20-gauge stainless steel sheet, was comprised of four 4-ft sections and two 3-ft sections. All joints between the duct sections were continuously welded together. The duct construction conformed to SMACNA, HVAC Duct Construction Standards, Metal and Flexible, First Edition, 1985. It was supported at the mid-point (6 ft from the furnace walls) by a 3-in. wide x 20-gauge stainless steel band wrapped around the duct which was attached to an adjustable clevis type hanger suspended from a 0.5-in. diameter steel hanger rod. The hanger assembly was adjusted so that the top surface of the duct was located approximately 24 in. below the underside of the insulated cover slabs.

C. Duct No. 3

A rectangular steel duct, constructed of 36 x 30-in. x 22-ft long 22-gauge galvanized steel sheet, was comprised of three 5-ft sections and two 3.5-ft sections. The duct construction conformed to SMACNA, HVAC Duct Construction Standards, Metal and Flexible, First Edition, 1985. The longitudinal seams were of the button punch snap-lock type, identified as L-2 in the SMACNA standards. The transverse (girth) joints were of the Standing S type, identified as T-11 in the SMACNA standards to give a minimum rigidity of Class D. The duct was reinforced with 1.5 x 1.5-in. x 10-gauge (0.138-in.) steel angle tack welded to the duct (see SMACNA, HVAC Construction Standards, Metal and Flexible, First Edition, 1985). The angle reinforcement was located a minimum of 2 in. away from both the inside and outside of the furnace wall. The duct was supported by a pair of trapezes located 4 ft on center, comprising 0.375-in. diameter steel rods and 2.5 x 0.25-in. thick steel angle. The hanger rods were adjusted so that the

top surface of the duct was located approximately 30 in. below the underside of the cover slabs. They were insulated with 0.5-in. diameter x 1-in. thick x 14-lb/ft³ Manville Thermo-12 calcium silicate pipe insulation. The insulation was cut to fit on-site and the longitudinal joints were tightly butted together and wired in place with 16-gauge stainless steel wire, 12 in. on center.

The two ducts with mechanical joints (Duct Nos. 1 and 3) were assembled at SwRI and all three were laid across the 12-ft dimension of SwRI's large horizontal furnace. They were spaced 1.5 ft from the inside furnace walls and 2 ft apart (Figure 1). The height of the furnace walls were then increased by an additional 69 in., using masonry blocks, to ensure that the ducts were exposed on all four sides. A minimum 1-in. clearance was maintained around the perimeter of all three ducts (except for the base of each which was in contact with the masonry). The ducts extended a minimum of 5 ft beyond the furnace on either side. The furnace was then covered with concrete cover slabs insulated with ceramic fiber. The hanger rods for all three ducts extended through the cover slabs and were secured on the unexposed surface. The gaps between the ducts and the masonry block wall were then fire stopped with ceramic fiber blanket.

V. INSTRUMENTATION

The temperatures of the outside (exposed and unexposed) surfaces of the steel ducts were measured with No. 20 B&S gauge, type K (Chromel-Alumel) welded thermocouples. Temperature readings were taken on the duct walls, at the duct joints, the hanger rods and the steel angle-section supports. The locations of all thermocouples are shown in Appendix A, Construction Drawings. The radiant heat flux from the unexposed face of Duct No. 3 was measured using a heat flux transducer (radiometer) with a view restrictor attachment producing a 30° angle of view. The radiometer was positioned so that its field of view was entirely filled with the steel duct section and nothing else.

VI. RESULTS

On September 9, 1988, at 4:25 P.M., the thermocouple connections were verified and the furnace ignited with the following people in attendance: Mr. Richard G. Gewain and Mr. Joseph Scheffy representing the Client; Mr Bruce G. Campbell representing Rockwell International; and Mr. Andrew Pryor representing the Department of Energy.

The furnace was controlled according to the requirements of ASTM E119-83, Standard Method of Fire Tests of Building Construction and Materials, Section 4, Furnace Temperatures. The furnace pressure was controlled as per the Client's request to be approximately +0.03 in. of water pressure, measured 0.78 in. below the concrete cover slabs.

There were no significant observations recorded throughout the 120-minute fire exposure. None of the duct sections collapsed or fell into the furnace and the integrity of each system, where it extended through the fire wall, remained intact. No through-opening developed between a fire stop and a duct at any wall penetration.

VII. POST-TEST OBSERVATIONS

After the furnace had been allowed to cool down for several days, a thorough investigation was conducted to confirm the condition of the exposed portion of each duct system (see Appendix B, Photographic Documentation).

A. Duct No. 1

The duct had warped such that the top of the duct had buckled downward by a maximum of 11 in. in the center. The sides of the duct had warped and buckled inward by a maximum of 5.5 in. at the center of the 12-ft span. Where the duct extended through the masonry wall, there was a maximum warpage of 2 in. at the top and sides. The hanger assembly was intact and still in place.

B. Duct No. 2

There was minimal, if any, visible distortion of this duct or the hanger.

C. Duct No. 3

The duct had warped such that the top of the duct had buckled downward by a maximum of 8.75 in. in the center. The sides of the duct had warped and buckled inward by a maximum of 3.5 in. at the center of the 12-ft span. Where the duct

extended through the masonry wall, there was a maximum warpage of 0.5 in. at the top and sides. Two of the spot welds between the angle reinforcement and the duct had been broken inside the furnace. The hanger assembly was intact and still in place.

A complete listing, with graphical presentation of data from the radiometer and all thermocouples monitored, is presented in Appendix C.

VIII. CONCLUSIONS

All conclusions relating to this project will have to be drawn by the Client. All necessary temperature data and observations are contained in the appropriate appendices.

APPENDIX A
CONSTRUCTION DRAWINGS

DEPARTMENT OF FIRE TECHNOLOGY

APPENDIX B
PHOTOGRAPHIC DOCUMENTATION

DEPARTMENT OF FIRE TECHNOLOGY

1. Construction Of Masonry Block Wall Before Test
Left To Right: Duct Nos. 1 Through 3

DEPARTMENT OF FIRE TECHNOLOGY

2. Plan View After 60 Minutes

3. Plan View At End Of 120-Minute Fire Exposure

4. Plan View After Ducts Have Cooled Down

5. Duct No. 1 After Test: View From Outside Furnace Through Duct

6. Exposed Portion Of Underside Of Duct No. 1 After Test

7. Exposed Portion Of Top Surface Of Duct No. 1 After Test

8. Exposed Portion Of Duct No. 1 After Test As It Extends Through
The Fire Wall

9. Duct No. 2 After Test: View From Outside Furnace Through Duct

10. Exposed Portion Of Underside Of Duct No. 2 After Test

12. Exposed Portion Of Duct No. 2 After Test As It Extends Through
The Fire Wall

DEPARTMENT OF FIRE TECHNOLOGY

11. Exposed Portion Of Duct No. 2 After Test As It Extends Through
The Fire Wall

14. Exposed Portion Of Top Of Duct No. 2 After Test As It
Extends Through The Fire Wall

13. Duct No. 3 After Test: View From Outside Furnace Through Duct

15. Duct No. 3 After Test With Fire Stopping Removed

16. Hanger Rods—Duct No. 3 After Test

17. Exposed Portion Of Top Of Duct No. 3 After Test

DEPARTMENT OF FIRE TECHNOLOGY

APPENDIX C
TEMPERATURE DATA

HUGHES ASSOCIATES INC.
DUCT 1

HUGHES ASSOCIATES INC.

DUCT 1

HUGHES ASSOCIATES INC.
DUCT 3

HUGHES ASSOCIATES INC.

DUCT 3

□ TC 50

○ TC 51

△ TC 52

HUGHES ASSOCIATES INC.

FURNACE PROBES

TEMPERATURE (DEGREES FAHRENHEIT)

DATE: 9 SEPTEMBER 1988
 FILE: 253HUGHES.DAT

SWRI PROJECT NO.: 01-2427-001
 TEST TYPE: ASTM E119

MIN SEC	TC 53	TC 54	TC 55	TC 56	TC 57	TC 58	TC 59	TC 60	TC 61	FURN AVG
0: 0	180	180	166	169	165	163	164	162	150	167
5: 0	667	734	766	684	631	641	758	746	612	693
10: 0	1131	1196	1310	1246	1149	1160	1235	1291	1202	1213
15: 0	1279	1341	1464	1408	1316	1322	1400	1457	1361	1372
20: 0	1396	1444	1556	1505	1431	1434	1502	1546	1457	1475
25: 0	1450	1477	1568	1519	1483	1481	1520	1554	1496	1505
30: 0	1466	1489	1579	1532	1495	1494	1533	1572	1510	1519
35: 0	1497	1517	1608	1559	1514	1517	1562	1598	1535	1545
40: 0	1543	1564	1665	1612	1560	1563	1610	1655	1591	1596
45: 0	1607	1631	1729	1676	1628	1631	1678	1717	1661	1662
50: 0	1606	1629	1717	1663	1616	1620	1668	1711	1654	1654
55: 0	1632	1656	1738	1686	1647	1651	1693	1735	1682	1680
60: 0	1656	1681	1760	1710	1665	1668	1713	1756	1708	1702
65: 0	1689	1716	1789	1739	1701	1704	1745	1790	1742	1735
70: 0	1701	1722	1790	1744	1709	1711	1751	1791	1748	1741
75: 0	1714	1735	1807	1762	1723	1726	1763	1804	1765	1755
80: 0	1729	1750	1818	1774	1737	1741	1779	1824	1784	1770
85: 0	1748	1768	1836	1792	1756	1760	1795	1840	1802	1789
90: 0	1751	1767	1834	1791	1760	1764	1798	1841	1805	1790
95: 0	1770	1783	1850	1808	1779	1783	1817	1857	1817	1807
100: 0	1772	1784	1855	1812	1781	1785	1819	1860	1818	1809
105: 0	1788	1800	1866	1827	1798	1802	1835	1873	1837	1825
110: 0	1798	1811	1877	1837	1807	1811	1842	1883	1845	1834

HUGHES ASSOCIATES INC.
FURNACE PROBES

TEMPERATURE (DEGREES FAHRENHEIT)

DATE: 9 SEPTEMBER 1988
FILE: 253HUGHES.DAT

SWRI PROJECT NO.: 01-2427-001
TEST TYPE: ASTM E119

MIN SEC	TC 53	TC 54	TC 55	TC 56	TC 57	TC 58	TC 59	TC 60	TC 61	FURN AVG
115: 0	1810	1821	1886	1847	1818	1821	1853	1893	1856	1845
120: 0	1816	1825	1889	1853	1823	1826	1860	1897	1861	1850

PAGE NO. 1

HUGHES ASSOCIATES INC.
RADIOMETER
W/CM2

DATE: 9 SEPTEMBER 1988
FILE: 253HUGHES.DAT

SWRI PROJECT NO.: 01-2427-001
TEST TYPE: ASTM E119

MIN SEC		W/CM2

0:	0	0.01
5:	0	0.02
10:	0	0.02
15:	0	-0.01
20:	0	0.04
25:	0	0.02
30:	0	0.03
35:	0	0.00
40:	0	0.02
45:	0	0.01
50:	0	-0.01
55:	0	0.01
60:	0	0.02
65:	0	0.00
70:	0	0.02
75:	0	0.03
80:	0	-0.03
85:	0	0.04
90:	0	0.05
95:	0	0.04
100:	0	0.02
105:	0	0.03
110:	0	0.04

PAGE NO. 2

HUGHES ASSOCIATES INC.
RADIOMETER
W/CM2

DATE: 9 SEPTEMBER 1988
FILE: 253HUGHES.DAT

SWRI PROJECT NO.: 01-2427-001
TEST TYPE: ASTM E119

NIN	SEC	W/CM2
115:	0	0.05
120:	0	0.06

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HUGHES ASSOCIATES INC.
DUCT 1
TEMPERATURE (DEGREES FAHRENHEIT)

DATE: 9 SEPTEMBER 1988
FILE: 253HUGHES.DAT

SWRI PROJECT NO.: 01-2427-001
TEST TYPE: ASTM E119

MIN SEC	TC 01	TC 02	TC 03	TC 41
0: 0	97	102	97	101
5: 0	118	172	126	186
10: 0	199	292	244	436
15: 0	263	375	279	465
20: 0	338	436	337	540
25: 0	412	473	397	597
30: 0	430	497	386	609
35: 0	523	503	401	688
40: 0	721	522	485	709
45: 0	779	670	583	810
50: 0	837	897	624	887
55: 0	900	965	632	1030
60: 0	958	1071	788	1099
65: 0	1023	1148	900	1153
70: 0	1019	1169	914	1163
75: 0	1025	1188	919	1169
80: 0	1229	1227	917	1179
85: 0	1283	1260	941	1193
90: 0	1309	1259	953	1193
95: 0	1303	1243	906	1192
100: 0	1343	1256	926	1201
105: 0	1347	1268	955	1216
110: 0	1337	1275	959	1224

PAGE NO. 2

HUGHES ASSOCIATES INC.
DUCT 1
TEMPERATURE (DEGREES FAHRENHEIT)

DATE: 9 SEPTEMBER 1988
FILE: 253HUGHES.DAT

SWRI PROJECT NO.: 01-2427-001
TEST TYPE: ASTM E119

MIN SEC	TC 01	TC 02	TC 03	TC 41
115: 0	1347	1277	986	1235
120: 0	1342	1279	1003	1240

PAGE NO. 1

HUGHES ASSOCIATES INC.
DUCT 1
TEMPERATURE (DEGREES FAHRENHEIT)

DATE: 9 SEPTEMBER 1988
FILE: 253HUGHES.DAT

SWRI PROJECT NO.: 01-2427-001
TEST TYPE: ASTM E119

MIN SEC	TC 10	TC 11	TC 12	TC 30	TC 31	TC 32
0: 0	151	145	157	159	150	158
5: 0	649	624	678	693	590	597
10: 0	1035	1085	1093	1079	1073	1075
15: 0	1186	1230	1257	1227	1230	1245
20: 0	1313	1342	1364	1341	1346	1358
25: 0	1367	1383	1398	1383	1386	1394
30: 0	1384	1401	1416	1405	1403	1409
35: 0	1403	1424	1439	1426	1426	1429
40: 0	1453	1475	1489	1482	1477	1481
45: 0	1517	1531	1546	1539	1535	1539
50: 0	1512	1525	1539	1533	1524	1533
55: 0	1541	1551	1564	1560	1542	1562
60: 0	1567	1574	1586	1583	1565	1583
65: 0	1605	1605	1617	1614	1591	1613
70: 0	1611	1608	1622	1617	1593	1618
75: 0	1633	1624	1639	1633	1606	1630
80: 0	1644	1632	1647	1641	1614	1632
85: 0	1670	1650	1667	1662	1629	1646
90: 0	1674	1652	1666	1663	1631	1655
95: 0	1686	1664	1681	1677	1643	1670
100: 0	1696	1671	1688	1683	1647	1674
105: 0	1708	1681	1696	1695	1655	1686
110: 0	1720	1693	1709	1707	1664	1696

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HUGHES ASSOCIATES INC.

DUCT 1

TEMPERATURE (DEGREES FAHRENHEIT)

DATE: 9 SEPTEMBER 1988 SWRI PROJECT NO.: 01-2427-001
FILE: 253HUGHES.DAT TEST TYPE: ASTM E119

MIN SEC	TC 10	TC 11	TC 12	TC 30	TC 31	TC 32
115: 0	1729	1701	1714	1714	1670	1703
120: 0	1736	1705	1719	1720	1676	1709

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HUGHES ASSOCIATES INC.
DUCT 1
TEMPERATURE (DEGREES FAHRENHEIT)

DATE: 9 SEPTEMBER 1988
FILE: 253HUGHES.DAT

SWRI PROJECT NO.: 01-2427-001
TEST TYPE: ASTM E119

MIN SEC	TC 42	TC 43	TC 44
0: 0	93	101	93
5: 0	101	165	108
10: 0	137	293	160
15: 0	192	339	215
20: 0	218	393	238
25: 0	239	424	258
30: 0	255	418	273
35: 0	267	427	285
40: 0	277	444	283
45: 0	287	468	293
50: 0	284	469	304
55: 0	279	489	294
60: 0	285	493	291
65: 0	294	512	300
70: 0	297	518	294
75: 0	300	525	293
80: 0	285	503	280
85: 0	286	519	289
90: 0	284	516	288
95: 0	287	524	292
100: 0	286	516	287
105: 0	289	522	289
110: 0	297	536	296

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HUGHES ASSOCIATES INC.
DUCT 1
TEMPERATURE (DEGREES FAHRENHEIT)

DATE: 9 SEPTEMBER 1988
FILE: 253HUGHES.DAT

SWRI PROJECT NO.: 01-2427-001
TEST TYPE: ASTM E119

MIN	SEC	TC 42	TC 43	TC 44
115:	0	301	534	294
120:	0	302	535	295

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HUGHES ASSOCIATES INC.
DUCT 1
TEMPERATURE (DEGREES FAHRENHEIT)

DATE: 9 SEPTEMBER 1988
FILE: 253HUGHES.DAT

SWRI PROJECT NO.: 01-2427-001
TEST TYPE: ASTM E119

MIN SEC	TC 23	TC 24	TC 25	TC 26	TC 27	TC 28	TC 29
0: 0	192	182	170	149	167	185	193
5: 0	753	626	663	565	769	798	842
10: 0	1160	1049	1101	1158	1230	1233	1243
15: 0	1282	1198	1256	1540	1371	1382	1380
20: 0	1384	1314	1365	1592	1500	1483	1477
25: 0	1440	1393	1425	1521	1520	1500	1487
30: 0	1458	1424	1448	1584	1531	1515	1505
35: 0	1472	1440	1468	1625	1551	1530	1523
40: 0	1520	1483	1518	1656	1604	1577	1572
45: 0	1577	1539	1580	1702	1667	1633	1626
50: 0	1572	1539	1574	1709	1652	1628	1624
55: 0	1597	1567	1600	1708	1675	1647	1641
60: 0	1615	1584	1619	1743	1696	1670	1665
65: 0	1649	1618	1652	1758	1727	1703	1694
70: 0	1652	1626	1656	1776	1729	1703	1694
75: 0	1671	1643	1673	1799	1745	1721	1710
80: 0	1681	1655	1686	1817	1755	1731	1721
85: 0	1704	1680	1709	1822	1777	1752	1744
90: 0	1704	1684	1712	1816	1773	1751	1742
95: 0	1718	1701	1729	1826	1791	1766	1755
100: 0	1729	1712	1738	1847	1797	1775	1764
105: 0	1737	1721	1748	1849	1806	1782	1772
110: 0	1750	1737	1763	1858	1821	1798	1785

PAGE NO. 2

HUGHES ASSOCIATES INC.
DUCT 1
TEMPERATURE (DEGREES FAHRENHEIT)

DATE: 9 SEPTEMBER 1988
FILE: 253HUGHES.DAT

SWRI PROJECT NO.: 01-2427-001
TEST TYPE: ASTM E119

MIN SEC	TC 23	TC 24	TC 25	TC 26	TC 27	TC 28	TC 29
115: 0	1756	1741	1768	1869	1825	1801	1791
120: 0	1763	1749	1776	1874	1830	1805	1796

PAGE NO. 1

HUGHES ASSOCIATES INC.
DUCT 2
TEMPERATURE (DEGREES FAHRENHEIT)

DATE: 9 SEPTEMBER 1988
FILE: 253HUGHES.DAT

SWRI PROJECT NO.: 01-2427-001
TEST TYPE: ASTM E119

MIN SEC		TC 04	TC 05	TC 06	TC 45
0:	0	96	103	95	102
5:	0	156	199	155	244
10:	0	304	377	299	393
15:	0	369	451	367	481
20:	0	456	533	465	531
25:	0	545	604	545	619
30:	0	572	613	566	652
35:	0	589	630	573	672
40:	0	620	671	615	687
45:	0	663	709	660	736
50:	0	661	707	659	761
55:	0	687	728	680	769
60:	0	706	740	690	814
65:	0	740	765	716	839
70:	0	743	778	720	849
75:	0	763	781	732	853
80:	0	757	795	741	829
85:	0	780	805	765	877
90:	0	773	813	751	857
95:	0	794	815	778	887
100:	0	795	823	773	868
105:	0	814	837	791	894
110:	0	827	837	798	918

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HUGHES ASSOCIATES INC.
DUCT 2
TEMPERATURE (DEGREES FAHRENHEIT)

DATE: 9 SEPTEMBER 1988
FILE: 253HUGHES.DAT

SWRI PROJECT NO.: 01-2427-001
TEST TYPE: ASTM E119

NIN SEC	TC 04	TC 05	TC 06	TC 45
115: 0	834	840	808	923
120: 0	838	846	814	926

AIM

Association for Information and Image Management

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301/587-8202

Centimeter

Inches

MANUFACTURED TO AIM STANDARDS
BY APPLIED IMAGE, INC.

3 of 3

PAGE NO. 1

HUGHES ASSOCIATES INC.
DUCT 2
TEMPERATURE (DEGREES FAHRENHEIT)

DATE: 9 SEPTEMBER 1988
FILE: 253HUGHES.DAT

SWRI PROJECT NO.: 01-2427-001
TEST TYPE: ASTM E119

MIN SEC	TC 38	TC 39	TC 40
0: 0	162	165	164
5: 0	705	769	671
10: 0	1132	1124	1035
15: 0	1292	1270	1175
20: 0	1387	1358	1276
25: 0	1357	1351	1304
30: 0	1397	1385	1336
35: 0	1441	1422	1388
40: 0	1493	1471	1437
45: 0	1539	1519	1496
50: 0	1547	1523	1498
55: 0	1556	1539	1523
60: 0	1590	1568	1546
65: 0	1610	1590	1584
70: 0	1613	1599	1593
75: 0	1633	1613	1602
80: 0	1643	1625	1621
85: 0	1661	1642	1641
90: 0	1662	1643	1638
95: 0	1677	1659	1662
100: 0	1684	1661	1661
105: 0	1695	1674	1678
110: 0	1703	1687	1689

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HUGHES ASSOCIATES INC.
DUCT 2
TEMPERATURE (DEGREES FAHRENHEIT)

DATE: 9 SEPTEMBER 1988
FILE: 253HUGHES.DAT

SWRI PROJECT NO.: 01-2427-001
TEST TYPE: ASTM E119

MIN	SEC	TC 38	TC 39	TC 40
115	0	1713	1696	1700
120	0	1722	1703	1703

PAGE NO. 1

HUGHES ASSOCIATES INC.
DUCT 2
TEMPERATURE (DEGREES FAHRENHEIT)

DATE: 9 SEPTEMBER 1988
FILE: 253HUGHES.DAT

SWRI PROJECT NO.: 01-2427-001
TEST TYPE: ASTM E119

NIN SEC	TC 46	TC 47	TC 48
0: 0	93	98	94
5: 0	115	162	123
10: 0	188	293	192
15: 0	248	383	254
20: 0	284	400	283
25: 0	351	475	335
30: 0	390	515	372
35: 0	411	532	404
40: 0	430	536	401
45: 0	456	557	431
50: 0	456	552	424
55: 0	478	564	439
60: 0	484	570	443
65: 0	501	593	466
70: 0	514	587	468
75: 0	529	604	480
80: 0	506	560	452
85: 0	533	603	479
90: 0	533	587	477
95: 0	552	622	497
100: 0	547	613	498
105: 0	555	621	501
110: 0	573	636	514

PAGE NO. 2

HUGHES ASSOCIATES INC.
DUCT 2
TEMPERATURE (DEGREES FAHRENHEIT)

DATE: 9 SEPTEMBER 1988
FILE: 253HUGHES.DAT

SWRI PROJECT NO.: 01-2427-001
TEST TYPE: ASTM E119

MIN SEC	TC 46	TC 47	TC 48
115: 0	576	642	518
120: 0	578	640	523

PAGE NO. 2

HUGHES ASSOCIATES INC.
DUCT 2
TEMPERATURE (DEGREES FAHRENHEIT)

DATE: 9 SEPTEMBER 1988
FILE: 253HUGHES.DAT

SWRI PROJECT NO.: 01-2427-001
TEST TYPE: ASTM E119

MIN	SEC	TC 46	TC 47	TC 48
115:	0	576	642	518
120:	0	578	640	523

PAGE NO. 2

HUGHES ASSOCIATES INC.

DUCT 2

TEMPERATURE (DEGREES FAHRENHEIT)

DATE: 9 SEPTEMBER 1988 SWRI PROJECT NO.: 01-2427-001
FILE: 253HUGHES.DAT TEST TYPE: ASTM E119

MIN SEC	TC 33	TC 34	TC 35	TC 36	TC 37
115: 0	1766	1752	1765	1882	1783
120: 0	1781	1759	1774	1877	1788

PAGE NO. 1

HUGHES ASSOCIATES INC.
DUCT 3
TEMPERATURE (DEGREES FAHRENHEIT)

DATE: 9 SEPTEMBER 1988
FILE: 253HUGHES.DAT

SWRI PROJECT NO.: 01-2427-001
TEST TYPE: ASTM E119

MIN	SEC	TC 07	TC 08	TC 09	TC 49
0:	0	95	98	95	95
5:	0	119	145	115	145
10:	0	215	273	179	283
15:	0	258	339	223	377
20:	0	333	418	277	430
25:	0	397	471	321	550
30:	0	415	494	342	596
35:	0	413	546	359	620
40:	0	446	548	394	640
45:	0	483	590	557	674
50:	0	496	608	619	682
55:	0	519	632	629	704
60:	0	541	658	790	765
65:	0	572	739	882	849
70:	0	614	895	898	878
75:	0	637	965	902	891
80:	0	653	968	919	871
85:	0	683	986	929	902
90:	0	708	991	928	902
95:	0	802	1002	917	908
100:	0	867	1002	930	895
105:	0	925	1023	958	914
110:	0	936	1031	949	917

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HUGHES ASSOCIATES INC.

DUCT 3

TEMPERATURE (DEGREES FAHRENHEIT)

DATE: 9 SEPTEMBER 1988
FILE: 253HUGHES.DAT

SWRI PROJECT NO.: 01-2427-001
TEST TYPE: ASTM E119

MIN	SEC	TC 07	TC 08	TC 09	TC 49
115	0	942	1038	957	925
120	0	951	1047	967	920

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HUGHES ASSOCIATES INC.
DUCT 3
TEMPERATURE (DEGREES FAHRENHEIT)

DATE: 9 SEPTEMBER 1988
FILE: 253HUGHES.DAT

SWRI PROJECT NO.: 01-2427-001
TEST TYPE: ASTM E119

MIN	SEC	TC 20	TC 21	TC 22
0:	0	147	140	143
5:	0	558	538	472
10:	0	1079	1024	842
15:	0	1262	1186	1088
20:	0	1362	1305	1232
25:	0	1394	1364	1304
30:	0	1414	1384	1334
35:	0	1441	1405	1365
40:	0	1490	1454	1414
45:	0	1549	1514	1474
50:	0	1547	1512	1478
55:	0	1571	1539	1503
60:	0	1597	1559	1525
65:	0	1632	1590	1558
70:	0	1636	1592	1563
75:	0	1650	1602	1577
80:	0	1661	1612	1584
85:	0	1679	1632	1602
90:	0	1680	1636	1606
95:	0	1693	1651	1618
100:	0	1692	1656	1618
105:	0	1708	1671	1632
110:	0	1723	1683	1641

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HUGHES ASSOCIATES INC.

DUCT 3

TEMPERATURE (DEGREES FAHRENHEIT)

DATE: 9 SEPTEMBER 1988 SWRI PROJECT NO.: 01-2427-001
FILE: 253HUGHES.DAT TEST TYPE: ASTM E119

MIN SEC	TC 20	TC 21	TC 22
115: 0	1736	1693	1653
120: 0	1740	1697	1658

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HUGHES ASSOCIATES INC.
DUCT 3
TEMPERATURE (DEGREES FAHRENHEIT)

DATE: 9 SEPTEMBER 1988
FILE: 253HUGHES.DAT

SWRI PROJECT NO.: 01-2427-001
TEST TYPE: ASTM E119

MIN	SEC	TC 50	TC 51	TC 52
0:	0	91	94	92
5:	0	108	158	108
10:	0	145	279	154
15:	0	159	341	180
20:	0	173	347	204
25:	0	194	414	236
30:	0	203	426	257
35:	0	219	430	286
40:	0	227	451	277
45:	0	231	470	287
50:	0	235	479	306
55:	0	240	479	295
60:	0	242	490	300
65:	0	248	499	326
70:	0	250	500	307
75:	0	253	501	319
80:	0	242	404	281
85:	0	253	476	302
90:	0	257	482	307
95:	0	259	485	303
100:	0	257	446	287
105:	0	255	467	290
110:	0	267	487	299

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HUGHES ASSOCIATES INC.
DUCT 3
TEMPERATURE (DEGREES FAHRENHEIT)

DATE: 9 SEPTEMBER 1988
FILE: 253HUGHES.DAT

SWRI PROJECT NO.: 01-2427-001
TEST TYPE: ASTM E119

MIN SEC	TC 50	TC 51	TC 52
115: 0	268	487	305
120: 0	266	473	304

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HUGHES ASSOCIATES INC.
DUCT 3
TEMPERATURE (DEGREES FAHRENHEIT)

DATE: 9 SEPTEMBER 1988
FILE: 253HUGHES.DAT

SWRI PROJECT NO.: 01-2427-001
TEST TYPE: ASTM E119

MIN SEC	TC 13	TC 14	TC 15	TC 16	TC 17	TC 18	TC 19
0: 0	96	96	142	140	127	92	96
5: 0	156	161	568	446	287	153	155
10: 0	187	188	1081	1016	649	178	218
15: 0	293	256	1271	1193	877	186	338
20: 0	497	419	1405	1318	1054	274	517
25: 0	767	709	1491	1379	1195	469	771
30: 0	1020	1013	1523	1431	1295	715	999
35: 0	1185	1232	1544	1485	1374	910	1146
40: 0	1299	1542	1586	1501	1452	1089	1234
45: 0	1641	1661	1657	1555	1531	1204	1585
50: 0	1646	1668	1645	1541	1567	1295	1604
55: 0	1666	1679	1673	1568	1609	1377	1623
60: 0	1693	1707	1697	1597	1633	1530	1652
65: 0	1727	1737	1732	1637	1666	1598	1678
70: 0	1731	1744	1741	1651	1677	1599	1679
75: 0	1747	1763	1754	1676	1692	1611	1697
80: 0	1765	1779	1771	1712	1706	1623	1706
85: 0	1781	1791	1791	1733	1725	1640	1711
90: 0	1782	1799	1793	1735	1733	1648	1715
95: 0	1799	1805	1804	1750	1743	1660	1721
100: 0	1817	1819	1808	1752	1748	1667	1726
105: 0	1822	1821	1824	1767	1763	1676	1734
110: 0	1832	1831	1832	1770	1772	1687	1732

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HUGHES ASSOCIATES INC.

DUCT 3

TEMPERATURE (DEGREES FAHRENHEIT)

DATE: 9 SEPTEMBER 1988
FILE: 253HUGHES.DAT

SWRI PROJECT NO.: 01-2427-001
TEST TYPE: ASTM E119

MIN SEC	TC 13	TC 14	TC 15	TC 16	TC 17	TC 18	TC 19
115: 0	1851	1844	1845	1779	1784	1700	1743
120: 0	1844	1844	1848	1783	1789	1705	1739

APPENDIX F
Observations: Fire Test of Steel Duct Systems
September 9, 1988
Southwest Research Institute
San Antonio, Texas

Hughes Associates, Inc. tested two duct systems representative of ducts surveyed at Rocky Flats, CO. One duct system (duct No.3) a modification of duct No.1, was intended to improve the structural integrity by reinforcing the sides of the duct at the wall openings and shortening the span between hangers.

Start of Test Average Initial Temperature 89°F (Hours: Minutes: Seconds), Temperatures in °F.

0:05:00

No noticeable sign of any change in the duct or joints and the steel is not red at this point. We had a false start and now the burners in the furnace have been reignited at 4:35 P.M.

Restart of Test

0:02:00

Duct No.1, some minor candle-like flames licking at the joint in the ductwork which is the first joint on the far side of the furnace. Duct No.2 and duct No.3 appear to be in sound shape. Some blue flaming was seen at the two joints in furnace in duct No.1, just faintly at both joints, however, duct appears to be staying intact and there is no apparent deflection. (Flames may be from lubricant).

0:05:00

All ducts appear to be performing satisfactorily, no visual deflection - there is no noticeable movement of the walls of the ducts. Some small blue and green flames (zinc) flickering at the joints of duct No.1 in the furnace, especially the north joint.

0:07:00

Duct No.1, the hanger temperatures at thermocouples 23, 24, 29 and 28 are 999°F, 838°F, 1144°F and 1168°F, respectively. There is a positive pressure in the furnace of 0.26 inches of water.

0:10:00

Duct No.1 is performing very well. No buckling of the walls, and the joints are intact. Duct No.2, the stainless steel duct is in good shape, all the joints are intact, no flaming visible inside the duct. Duct No.3 is also performing well - no warpage or defection. Duct No.3, small flaming in the back in the lower right hand corner which is

now extinguished. The No. 10 gage steel reinforcing angle welded to duct No.3 on the outside of the furnace, is 2½ inches from the furnace wall.

0:16:00

The ducts are starting to get red, mostly on the bottom part of the duct, but also on the sides and top.

Joints on all ducts are structurally intact with no openings. The walls of the ducts have maintained their vertical and horizontal positions without any buckling or deflection. So far there is no deflection of the duct work. No further flaming visible.

0:20:00

Duct No.1, joint thermocouples 10, 11, 12 are 1303°F, 1333°F, 1356°F. Joint thermocouples 30, 31, 21 are 1341°F, 1346°F, 1358°F, duct No. 1 hanger thermocouples 23, 24, 28, 29 are 1398°F, 1327°F, 1507°F, 1496°F.

0:23:00

Ducts are red hot. The bottom of duct No.1 is sagging somewhat at the south joint. Top of duct in good shape. The sides seem to be vertical.

Duct No.2 is in very good shape - getting red. Duct No.3 appears to be in good shape, no buckling, joints closed, no openings, steel cherry red.

0:25:40

Duct No.1 is starting to show some localized deflection of the top and of the bottom of the duct between supports. The vertical walls of the duct showing very little warping, no joints have opened up. No flaming is visible in any duct.

0:30:30

Duct No.1 is deforming slightly on the bottom and top but the vertical walls are showing no signs of collapse even though they are cherry red. None of the joints in all of the ducts have opened up.

0:31:00

Duct No.2 is intact, cherry red, with all the joints holding. There are no open joints. Duct No.3 is in good shape. All the joints are intact. The bottom of the duct has not sagged. The vertical sides on the duct are showing some localized distortion but are still generally in a vertical condition with no collapse of the duct.

0:33:45

Duct No.1 at joint thermocouples 10, 11, 12 are 1408°F, 1419°F, 1432°F.

0:34:45

Duct No.2, the hanger thermocouples 33, 34, 36 are 1487°F, 1455°F and 1593°F. Joint thermocouples 38, 39 and 40 are 1433°F, 1414°F, 1379°F.

0:35:15

Duct No.3, the joint thermocouples 20, 21, 22 are 1441°F, 1405°F, 1365°F. The furnace pressure is positive .01 inches H₂O.

0:37:00

Duct No.3, the top of the duct is starting to belly down between the two hangers on top. The joints appear to be closed and providing some rigidity, therefore there is some deflection down between the joints of the duct - joints are 5 feet apart. Bottom looks good between hangers. All joints are holding. The vertical sides of the duct are staying vertical. The steel is red hot but there are no openings in any of the joints allowing the fire to enter the duct.

0:39:00

Duct No.1 joints are still intact. There is some sag in the bottom of the duct even at the joints. The duct is red hot. The side walls are still in a vertical position. The bottom appears to be sagging a little bit on each side of the hanger which is located at the center of the duct 6 feet from the walls.

0:45:00

Duct No.1 is still in good shape, all the joints are intact, vertical wall of duct still vertical. Slight bowing down in the bottom of the duct, slight bowing downward of the top. Duct No.2 stainless steel, no change, perfectly round, no joints open, no welds broken.

Duct No.3 is in good shape, the bottom of the duct is still level, the top is sagging somewhat between the two supports, but the sides are vertical, all joints are tight, no flaming inside the duct.

0:50:30

Duct No.1, all joints holding, no flaming inside duct or at duct penetrations of furnace walls. South joint thermocouples 30, 31, 32 are 1541°F, 1531°F, 1543°F. North joint thermocouples 10, 11, and 12 are 1524°F, 1539°F, 1553°F.

0:55:00

Duct No.1 is still intact even though the duct joints have deflected downward. The steel between the duct edges on top is bellying downward, about 4 inches, maybe 5 inches (see photos). The vertical sides of the duct, however, are vertical, very little distortion. The duct is cherry red. Duct No.2 continues in good shape, no welded joints have opened up, no noticeable deformation from out of round.

0:56:35

At duct No.3, which has the hanger spacing reduced, all the joints appear to be tight, not very much deflection longitudinally across the 12 foot dimension of the furnace. A 3 to 4 inch deflection of the top of the duct across the 36 inch dimension was observed. The duct has maintained its rectangular shape and the sides are vertical; the bottom has retained its rectangular shape.

1:01:25

Duct No.1 is still intact, all the joints are still tight, the duct vertical walls are straight, the duct steel spanning across the 36 inch dimension of the duct, top and bottom, are bellying down towards the fire, however, no openings in any of the joints. The total deflection along the longitudinal dimension of the ducts (12 feet) is minimal.

Duct No.2, stainless steel duct is maintaining its shape, cherry red. Hanger performing well, no deflection.

1:02:00

Duct No.3 is in excellent shape, all joints tight, no flaming inside the duct or around the edges at the wall where they penetrate.

1:03:30

Duct No.1, joint thermocouples 30, 31, 32 are 1610°F, 1590°F, 1609°F. The North joint thermocouples 20, 11 and 12 are 1597°F, 1599°F, 1613°F. Hanger thermocouples 23, 24 are 1645°F, 1613°F and hanger thermocouples 29 and 28 are 1702°F, 1692°F.

1:04:30

Duct No.2, hanger thermocouples 33, 34, and 36 are 1669°F, 1642°F, 1777°F. Duct No.2 joint thermocouples 38, 39, 40 are 1614°F, 1594°F, 1580°F. Thermocouple temperatures in the furnace at 1:04:45 are 1688°F, 1716°F, 1789°F, 1739°F, 1701°F, 1704°F, 1745°F, 1790°F, 1742°F. Furnace pressure is +.05 inches H₂O.

1:09:00

There is some flickering of flames coming through the bottom joint of the duct which appears to be galvanizing. Everything else is in good shape, no joints are opened up, no flaming through the joints or at the wall penetration.

1:25:00

Duct No.1 is still continuing to perform without any openings in it, the joints are intact - no openings. The top of the duct spanning across the 36 inch dimension is sagged down maybe 12 inches, but the vertical walls are still holding it up, sloping in slightly, approximately 5 to 10 degrees from vertical. The steel across the bottom of the duct is sagging down, no joints have opened up at this point. The duct is maintaining its integrity at the wall and through the furnace.

The stainless steel duct No.2 continues to perform well, there is no change in its shape, welds have held, with no deflection.

1:26:30

Duct No.3 showing no distortion at the wall penetration. The angles of 10 gage steel welded around the duct, approximately two inches from the wall, are helping to maintain the pretest vertical and the horizontal shape of the duct at the wall penetration. No openings have developed between the wall and the duct. The duct is in good shape, all joints are holding. The steel is getting hot and sagging. The top of the duct has sagged about 12 inches down between supports, however, the joints have maintained their structural integrity, on the sides, bottom and top.

1:30:00

All ducts are still intact, no fire inside ducts. Duct No.1, all joints are tight, top of the duct has sagged down between edges about 12 inches and the bottom 12 inches, the hanger rods are continuing to support the duct. The vertical joints are intact and are sloping in about 5 to 10 degrees from vertical. There is no collapse of the duct. The stainless steel duct (No.2) is still maintaining its shape, there is no noticeable deflection.

1:32:00

Duct No.3 is in good shape even though the top of the duct, across the 36 inch dimension, has sagged down between the vertical sides about 6 to 12 inches and the bottom between supports has sagged down into the furnace about 6 to 12 inches. All joints are intact and holding. There is no flame showing in the duct through the joints. All edges of the duct at each wall penetration are tight against the

firestopping, maintaining the duct integrity at the wall and the duct.

1:34:15

Duct No.1, joint thermocouples 30, 31, 32 are 1675°F, 1641°F, 1668°F, joints 10, 11, 12 are 1685°F, 1661°F, 1678°F. Hanger thermocouples 23, 24, 29 and 28 are 1717°F, 1699°F, 1754°F, 1767°F.

Duct No.2, hanger thermocouples 33, 34, 36 are 1736°F, 1712°F, 1728°F. The joint thermocouples 38, 39, 40 are 1671°F, 1656°F, 1659°F.

1:35:00

Duct No.3, joint thermocouples 20, 21, 22 are 1693°F, 1651°F, 1618°F. Furnace Pressure is +.1 inches H₂O.

1:57:30

Duct No.1, joint thermocouples 30, 31, 32, are 1716°F, 1671°F, 1705°F. Joint thermocouples 10, 11, 12 are 1735°F, 1703°F, 1718°F.

1:58:15

The Hanger thermocouples 23, 24, 28, 29 are 1760°F, 1747°F, 1807°F, 1795°F.

1:58:30

Duct No.2, hanger thermocouples 33, 34, 36 are 1772°F, 1757°F, 1883°F. The duct joint thermocouples 38, 39, 40 are 1716°F, 1701°F, 1703°F.

1:59:15

Duct No.3, joint thermocouples 20, 21, 22 are 1737°F, 1695°F, 1654°F. Furnace pressure is +.03 inches H₂O.

2:00:00

All ducts are intact, joints are tight, hangers still performing well, no failure of duct at furnace walls or flame penetration from furnace. Control of furnace throughout test requires no correction.

FIRE OFF

GENERAL OBSERVATIONS AFTER TEST

Duct No.1 is in good shape although steel sagging on the top and bottom of the duct across the 36 inch dimension. The vertical walls of the duct are deformed but are generally in a vertical position. The hangers are unaffected. The angle iron looks as though it could be reused. The hanger support (3/8 in. dia. threaded rod) is in excellent shape. Movement of the duct vertical walls, bowing in at the furnace walls, are minimal and generally less than an inch, however, the top of the duct is bowed down about 3 3/4 inches on the north end and slightly less than that on the south end.

Duct No.2, the round stainless steel duct, appears to be totally unaffected by the two hour fire exposure with the exception that it has a reddish brown color where exposed to the fire. It is tight against the wall, as it was at the beginning of the fire test.

Duct No.3 is intact, all hangers performed satisfactorily, all joints held, no openings in the duct walls. The duct at the furnace wall penetration is tight against the fire stopping at the walls and did not move throughout the two hour exposure. The 10 gage angle reinforcing, tack welded to the duct about 2 inches from the wall, maintained the duct shape.

SEPTEMBER 10, 1988, DUCT INSPECTION INSIDE TEST FURNACE

Inspection inside the furnace clearly indicated that in the case of Duct No.2, the 3-inch wide band of 20 gage stainless steel and the hanger construction, 1/2 inch diameter threaded steel rod and connection at the top of the duct provided the necessary duct stability during the two hour ASTM E119 fire. The stainless steel duct performed excellent and did not move at the wall penetrations or have any noticeable deflection.

Duct No.3, reinforced with 10 gage angles tack welded to the duct walls two inches from the wall penetration, stiffened the duct walls at the penetration so there was no movement of the duct away from the wall. The 10 gage stiffeners were intact inside and outside of the furnace, although some tack welds were broken. The stiffeners remained in place and kept the duct walls straight and tight against the firestopping at the wall penetrations. The sheet steel duct deflected between the hangers. There was no break in the mechanical joints and the two hangers were in place. These hangers were the 3/8 inch diameter threaded hanger rods protected with a 1200°F insulating material used for pipes. The insulation was totally disintegrated before

the end of the test and the steel bands that held it in place were at the bottom of the hanger resting on the angle iron support. The measured distance between the radiometer and the side of the steel duct was 19 inches. The radiometer was located 16 inches from the outside furnace wall to measure radiation from the side wall of the steel duct.

All ducts outside of the furnace area were supported by angles of 10 gage sheet steel. The angles rested on the furnace catwalk, which was three feet wide.

The furnace had been modified by adding seven courses of 8 inch concrete block with 4 inch solid block on top supporting the furnace enclosure and a 4 inch solid concrete block sill which supported the steel ducts at the furnace penetrations. The total height of the furnace wall concrete block addition was 69 inches.

Duct No. 1, For all ducts, a line was stretched 12 inches below the duct opening at the wall penetrations to measure the distance from the line to the bottom of the duct. For Duct No.1, the distance was $9 \frac{3}{8}$ inches midway between the first north joint and the hanger; at the hanger, 6 inches in from the wall, the distance was $1 \frac{1}{2}$ inches; midpoint between the hanger and the south joint, it was $9 \frac{1}{4}$ inches; at the south joint, it was $8 \frac{1}{2}$ inches and at midpoint between the south joint and the wall, it was $9 \frac{5}{8}$ inches.

For duct No.2, north joint, the distance was 12 inches; at the steel band hanger, (midpoint of span), it was 12 inches; and at the south joint it was 12 inches. The stainless steel duct did not move. At all measuring points it was 12 inches.

For duct No.3, midpoint between the north furnace wall and the first joint, the distance was $10 \frac{1}{4}$ inches; at the hanger, (which is essentially the first joint), the distance was between $10 \frac{1}{2}$ and $11 \frac{1}{4}$ inches; midpoint between the two hangers (4 feet on centers), the distance was $9 \frac{5}{8}$ inches; at the south hanger which is very close to the last joint, it was 11 to $11 \frac{3}{4}$ inches; and midpoint between the south wall and the joint, it was 10 inches.

In measuring the joints in duct No.3, the center section of the duct was 60 inches long. The galvanized ducts within the furnace appeared to be brown. The zinc had bubbled and burned. The stainless steel duct looked more like a piece of weathering steel with a reddish brown appearance.

Angle iron supports for the rectangular ductwork appeared to be in good condition with no deflections across the angle iron. All the galvanized steel hangers were grey

in appearance with the surface of the steel having a burned and blistered appearance.

A close inspection of all the joints in the duct sections indicated that they are all intact.

The stiffeners were placed on the sheet steel duct No. 3, not closer than 2 inches to the furnace wall inside and out. Some of the welds on the stiffeners around duct No. 3 inside the furnace wall, were broken. However, the 10 gage angle reinforcement provided the necessary stiffness for the duct walls to remain tight against the furnace wall opening during the two hour fire test.

The welds on the joint of the stainless steel duct revealed no failure or broken welds.

A small bead formed in the fabricating of the stainless steel duct was 6 inches from the ends of each section of the stainless steel duct. The joint in the stainless steel duct which was at center of the furnace (6 feet from the walls), was placed at the 3 inch wide hanger band. At the thermocouple location, a 1/2 inch wide steel band, approximately 28 or 30 gage steel, was placed around the duct to secure the thermocouples for the stainless steel duct at the locations required on the construction drawings.

The duct walls of duct No. 1 at the inside of the furnace wall appeared to have moved approximately 1½ inches in from its vertical position on both sides, approximately 12 inches up from the bottom of the duct. The longitudinal joints along the edges of duct Nos. 1 and 3 were in excellent condition with no openings. The longitudinal joints were located on both the bottom and top of the ducts. The center section of each rectangular duct was a 5 foot section. The stainless steel ductwork was made up of 4 foot sections with a joint located at the center of the furnace.

DATE

FILMED

10/31/94

END