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7. Abstract

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Fire Modeling for Building 221-T
T Plant Canyon Deck and Railroad Tunnel

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EXECUTIVE SUMMARY

1. Introduction

Fire hazard calculations have been performed for the Building 221-T, T-Plant canyon, and railroad tunnel at the Department of Energy (DOE) Hanford Site to assess the potential consequences of fires in the facility. Concerns have been raised regarding the effects of a fire on Building 221-T during decontamination operations. The modeling described in this report is intended to quantify the potential consequences of fires in identified combustible fire sources in the canyon in Building 221-T. The scope of the model incorporates the building construction, existing building exhaust ventilation system, and combustible material storage in the building as identified by the facility staff. The results are presented in terms of the impact of fire on the building structure, contents, and ventilation systems. Quantification of radioactive releases and their dispersion is not considered.

A site visit was conducted which included a discussion with facility fire protection personnel and review of drawings and site plans.

Different fire scenarios were simulated using a multi-zone computer fire model, CFAST (Consolidated Model of Fire Growth and Smoke Transport), which was developed at the National Institute of Standard and Technology (NIST).

The results of this study are predicated on the assumption that the types and quantities of combustibles identified by the facility staff are representative of the potential fire hazards in the Building 221-T. In keeping with sound engineering practice and in the absence of technical information, conservative worst case assumptions were made.

2. Conclusions

The following conclusions are based on the analysis documented in this report:

- (1) Several of the candidate fire scenarios were quantified to allow assessment of the potential impact on the building, its contents, and exhaust ventilation system;

- (2) The thermal impact of the fire in the canyon and tunnel environment would be minor due to the compartment size and ventilation system;
- (3) In all fire scenarios, the heat release rate is limited below that which could result in significant damage to the structure;
- (4) The potential for the release of hazardous products of radioactive waste exists due to HEPA filter failure. The HEPA filter clogging estimates were based on test data for burning wood, plastic, and liquid hydrocarbons available in the open literature. Burning two stacks of wood pallets or two plywood boxes filled with combustibles, or two 55-gallon drum filled with flammable soaked rags with 20 ft separation distance from other fuel packages are not sufficient to cause HEPA filter failure in T-Plant exhaust ventilation system;
- (5) Sprinkler response time was estimated using the computer model, DETACT, for fires located in the canyon and railroad tunnel. The calculations are based on conventional fixed temperature sprinkler with rated temperature of 71°C (160°F) and spacing of 10 ft. The results of the sprinkler activation calculations show that pallet stack fires are detected in the tunnel and canyon in about 4 and 5 minutes, respectively. Of course, some fires of interest do not grow to this size. While the activation times are longer, these fires can be detected if they exceed the minimum fire sizes of 1220 and 2240 kW. A ceiling mounted sprinkler system will not be effective against all fires which can cause HEPA failure.

3. General Description

Building 221-T is located inside the Hanford Site 200 West Area at the Department of Energy (DOE) facility at Richland, Washington. Building 221-T provides services in radioactive decontamination, reclamation, and decommissioning of process equipment contaminated with fissionable plutonium. The canyon service area (canyon deck) is composed of 37 cells and one railroad tunnel entrance/exit. The canyon deck is used for special decontamination services, repairs, and storage. The railroad tunnel used for transporting equipment into and out of the canyon and is also used for waste drum repackaging operation and for temporary storage area. The tunnel and the canyon areas share a common atmosphere and are considered radiation areas.

There are two separate ventilation systems for Building 221-T: (1) the canyon supply and exhaust system, and (2) the supply and exhaust system for the galleries. The Building 221-T

galleries are maintained at atmospheric pressure while the Building 221-T canyon area is maintained at a negative pressure with respect to atmosphere.

4. Canyon Deck and Railroad Tunnel Inventory

Combustible fuels present in the canyon included piles of wood pallets at locations 3L, 3R, 13L, 14L, and 15L, drums filled with 91 kg (200 lb) of flammable liquid soaked rags at locations 7L and 13L and burial (plywood) boxes at locations 8L, 17L and 18L. The combustible loading in the canyon at location 13L was relatively higher as compared to other locations (for example 3R or 17L). Also, mechanical and electrical equipment are located in the canyon, for example pumps, welders, power tools, jumper cutters, mill machines, and electric polishers. The railroad tunnel is used for the repackaging of 210 L (55 gal) waste drum operation (with associated short term storage) and is used for transporting material.

5. Heat Release Rate Estimates

In this study, the heat release histories were estimated for critical fuel packages. For some fuel packages in canyon deck and railroad inventories, burning rate data were available from laboratory tests. For those cases where test data were not available, the heat release rate histories were conservatively approximated from estimates of initial growth rates, peak energy release rate, and the time to reach the peak heat release rate.

As a means of bounding the thermal effects on the building, we have, in addition to realistic scenarios, considered the maximum heat release rates possible in the building. These energy release rates produce the maximum thermal effects to the structure. Peak heat release rates for the bounding cases were calculated based on the exhaust flow rates. These fire scenarios are structured to illustrate the maximum thermal effects on the canyon and railroad tunnel structure.

Wood pallet fire test data were reviewed for the burning of 1.22 m (4 ft) high standard wood pallet stack based on the experimental work of Krasner (1988). The predication of peak heat release rate for the plywood box filled with ordinary combustibles was correlated with mail bag fire test data of FMRC. The peak heat release rate for the 210 L (55 gallon) drum filled with flammable liquid soaked rags is based on a kerosene pool fire.

Based on the current information and knowledge of burning rates of combustible fuels, estimates of the heat release rate of the potential fuel element appear to conservatively represent the potential hazard.

6. Estimating Potential Fire Exposure

The potential for ignition and fire spread exists in the canyon and railroad inventories due to radiative heating from the burning of wood and other combustibles/fuels. An analysis was performed to determine the extent to which such a fire would likely induce ignition of nearby materials causing an increase in total heat release rates.

The potential for ignition of nearby material from fires was evaluated. For a continuous heat flux on a solid, the ignition is based on the concept of a critical or minimum surface temperature. Most common combustible materials have a range of ignition temperatures of approximately 300 to 400°C (572 to 752°F). This corresponds to a minimum or critical radiant heat flux for ignition of approximately 10 to 30 kW/m² (0.88 to 2.65 Btu/ft²sec). Below these heat fluxes, an object will not ignite, and above these heat fluxes, the time to ignite will decrease with increasing heat flux. In T-Plant inventory burning, three stacks of wood pallets with a separation distance of 25 ft will not ignite other fuel packages, but if this distance is reduced to 20 ft, this will cause the ignition of other fuel packages. Burning one, two, three, or four plywood boxes with a separation distance of 20 ft will not ignite other fuel packages in a single location in T-Plant inventory. Finally, burning one, two, three, or four drums with a separation distance of 20 ft will not ignite other fuel packages in single location in T-Plant inventory.

7. Method of Compartment Fire Analysis

A multi-zone computer model "CFAST" is utilized for fire simulation. Input data included enclosure dimensions, construction materials, physical properties, vents openings, ventilation system, compartment fire origin, and fire growth rate. Output results included the smoke layer temperatures and interface position, gas species concentration (O₂, CO, CO₂), differential pressure, and mass flow.

8. Results and Discussion on Fire Modeling

CFAST simulations were performed using the maximum heat release rate supported by the existing exhaust ventilation systems. This analysis shows that a flashover condition cannot be achieved in the canyon due to the ventilation rate and wall heat loss characteristics.

The worst case fire expected at location 13L was found to yield 15 MW (14,226 Btu/sec) heat release. The calculated compartment fire environment in the canyon includes a hot smoke layer temperature of 112°C (234°F) with a hot smoke layer interface at 3.0 m (10 ft) above the compartment floor when both exhaust systems are operating.

The worst case fire expected at location 3R was found to yield an 8.7 MW (8,251 Btu/sec). The maximum smoke layer temperature determined from CFAST simulation of this scenario is 87°C (189°F), with a hot smoke layer interface of 4.60 m (15 ft) above the floor when both exhaust systems are fully operation. The impact from this size of fire is less significant than the fire at location 13L.

Similar evaluations for fires involving a plywood box in the tunnel (1,200 kW (1138 Btu/sec) heat release rate) yield a hot smoke layer temperature rise of about 39°C (102°F) in the canyon and 67°C (153°F) in the tunnel. The smoke interface positions in the canyon and tunnel are 11 m (36 ft) and 5.70 m (19 ft), respectively.

A fire involving 210 L (55 gal) drums filled with flammable liquid soaked rags in the tunnel yield a peak heat release rate of 3,520 kW (3,338 Btu/sec). This gives hot layer temperatures of 52°C (126°F) in the canyon, and 118°C (224.5°F) in the tunnel. The smoke layer interface for this fire is 9.80 m (32 ft) above the floor in the canyon and is 5.50 m (18 ft) above the floor in the tunnel.

9. HEPA Filter Performance

HEPA filters can withstand short periods of high temperature exposure 400°C (725°F) and long term exposure to lower temperatures 120°C (248°F) (DOE, 1993). Determination of the effects of fire on the exhaust ventilation system is based on the failure of the HEPA filters or breach of the system. Breaching of the system can be caused by high temperature exposure to the HEPA filters, i.e., 135°C (257°F). According to one manufacturer of the HEPA filters,

(Flanders Filters (003-8-04-00-NU-GG-F)), HEPA's are fire resistant to spot temperature up to 648°C (1198°F).

9.1 HEPA Filter Clogging

HEPA filters are provided in the exhaust system to filter contaminants. Clogging of HEPA filters due to soot from fires will reduce exhaust and, therefore, eliminate the negative pressure required in radiologically contaminated areas.

A complete analysis of filter clogging requires very detailed ventilation system data which in many cases, as for this facility, are not available. As such, simpler methods are required to evaluate the effect of fire on HEPA filters. A review of the literature and the development of simple methods of analysis are included in Appendix A.

Based on the review of HEPA filter loading included in Appendix A, the amount of fuel burned which will cause filter clogging can be estimated. This is done on the basis of the number of HEPA filters available in parallel. No credit is taken for multiple stages since it is assumed that the important aspect of filter clogging is the increase in resistance and the accompanying reduction in flow which can cause loss of containment.

Table ES1 summarizes the mass of fuel burned which causes HEPA filter failure in the T-Plant based on the existing filter area identified by the T-Plant facility management (WHC, September 1994). The estimations for mass of fuel burned are based on the correlations developed in Appendix A. These results show that two stacks of wood pallets, two plywood boxes filled with combustibles, or two 55 gallon drums filled with flammable liquid soaked rags at separation distance of 20 ft are allowed in single areas of the T-Plant inventory to prevent clogging of HEPA's in exhaust ventilation system during a fire.

Table ES1. Mass of fuel burned to cause HEPA filter failure
in T-Plant exhaust ventilation system

Fuel	Mass fuel burned M_b	Recommended number of fuel packages allowed with separation distance
Wood	970 (kg/floor filter) 2138 (lb/floor filter)	Two stacks of wood pallets or two plywood boxes filled with combustibles at 20 ft separation distance (Eqi. mass for two pallets or boxes= 750 kg)
	1534 (kg/roof filter) 3382 (lb/roof filter)	Three stacks of wood pallets at 25 ft separation distance (Eqi. mass for three pallets=1050 kg) Three plywood filled with combustibles at 20 ft separation distance (Eqi. mass for three boxes=1050 kg)
70/30 n-Dodecane/TBP (Flammable & Combustible Liquid)	184 (kg/floor filter) 406 (lb/floor filter)	Two 55 gallon drums filled with flammable liquid soaked rags at 20 ft separation distance (Eqi. mass for two drums = 180 kg)
	300 (kg/roof filter) 661 (lb/roof filter)	Three 55 gallon drums filled with flammable liquid soaked rags at 20 ft separation distance (Eqi. mass for three drums = 270 kg)

9.2 Thermal Effects HEPA Filter Limits

Based on the results of the CFAST modeling, the thermal hazards to HEPA filters are negligibly small. Predicted compartment temperatures are less than HEPA filter temperature limits, and heat losses in the exhaust ducts are significant.

10. Hazard Assessment

Based on this analysis, the most serious hazard associated with the identified fire scenarios is the clogging of HEPA filters. This clogging is expected to lead to loss of containment of airborne particulate. Smoke will leak from the building giving rise to a low buoyancy release of smoke.

11. Sprinkler Response Time in the Canyon and Railroad Tunnel

An analysis was performed to determine the activation time of a sprinkler head in the canyon and railroad tunnel using DETACT-QS as included in FPETool (Nelson, 1990). The calculations are based on fixed temperature, conventional type sprinkler with rated temperature of 71°C (160°F). The response conditions for a sprinkler are as follows:

Canyon	"Fast" fire (wood pallet or plywood box) Sprinkler actuation time, 289 seconds (5 minutes); fire size 3865 kW (2666 Btu/sec); smoke layer temperature, 91°C (196°F)
Tunnel	"Fast" fire (wood pallet or plywood box) Sprinkler actuation time, 239 seconds (4 minutes); fire size 2662 kW (2525 Btu/sec); smoke layer temperature, 102°C (216°F)

Also, an estimate was performed for minimum heat release rate of a fire required needed to raise the temperature of the gas to 71°C (160°F). This represents the minimum fire size that can activate the sprinkler system. The minimum fire size is 2.2 MW (2,124 Btu/sec) in the canyon and 1.2 MW (1,138 Btu/sec) in the tunnel. Fires which are less than this heat release rate but which can cause filter failure are possible. This indicates that ceiling mounted sprinklers will not be effective in preventing loss of containment for all cases.

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1.0 BACKGROUND

1.1 Problem Description

Building 221-T (see Figure 1) provides services in radioactive decontamination, reclamation, and decommissioning of process equipment contaminated with fissionable plutonium (WAC, 1993). Building 221-T is the original Bio₄ Separation Plant built in 1944. The building was shut down in 1956 and converted to a decontamination facility in 1957. A cutaway view of Building 221-T is shown in Figure 2. The layouts of each building level are shown in Figure 3a, 3b, 3c, and 3d.

Concern has been raised regarding the effects of a fire on Building 221-T during decontamination operations. The modeling described in this report is intended to quantify the potential consequences of fires in identified combustibles fire sources on the canyon in Building 221-T.

1.2 Scope and Objectives

Fire hazard (FH) modeling is used to assess the potential consequences of fires in the T-Plant canyon and railroad tunnel. The model incorporates the building construction, existing building exhaust ventilation system, and combustible material storage in the building as identified by the facility staff. The results are presented in terms of the impact of fire on the building, structure contents, and ventilation systems. Quantification of radioactive releases and their dispersion are not considered.

1.3 Approach

The approach includes several tasks. A site visit was conducted which included a discussion with facility fire protection personnel and review of drawings and site plans.

Figure 1 T-Plant complex layout (WHC report, 1993)

Figure 2 Building 221-T, cutaway view (WHC report, 1993)

Figure 3a Building 221-T, basement layout (WHC report, 1993)

Figure 3b Building 221-T, first floor layout (WHC report, 1993)

Figure 3c Building 221-T, second floor layout (WHC report, 1993)

Figure 3d Building 221-T, third floor layout (WHC report, 1993)

An analysis is then performed to evaluate the damage potential associated with specified fires. This analysis involves modeling and analytical analysis in order to quantify the potential impact of fire scenarios on the building, its contents, and the ventilation system. Particular attention is directed at the potential for loss of negative pressure due to clogging of filtration system.

Different fire scenarios were simulated using a zone fire model, CFAST (Consolidated Model of Fire Growth and Smoke Transport). The model predicts the effects of a fire in a compartment and the subsequent transport of the smoke and toxic gases (Peacock et al., 1993).

1.4 Assumptions and Limitations

The results of this study are predicated on the assumption that the types and quantities of combustibles indicated by facility staff are representative of the potential fire hazards in Building 221-T. In the event that significantly greater quantities of combustibles are allowed in the building, the basis for determining the potential impact presented in this study may no longer be valid. It is further assumed that the information provided in drawings and plans are accurate. In keeping with sound engineering practice in the absence of technical information, conservative worst case assumption were made.

2.0 FACILITY DESCRIPTION

2.1 General Description

Building 221-T is located inside the Hanford Site 200 West Area at the Department of Energy (DOE) facility at Richland, Washington. Building 221-T provides services in radioactive decontamination, reclamation, and decommissioning of process equipment contaminated with fissionable plutonium. The building consists of the canyon, three galleries, one craneway, and a headend facility (Figures 2, and 3) (WAC, 1993).

The canyon service area (canyon deck) is composed of 37 cells and one railroad tunnel entrance/exit. The cells are grouped into 12 m (40 ft) sections arranged in a single row running

the length of the building. The canyon deck (Figure 4) is about 12 m (40 ft) below a 0.9 to 1.22 m (3 to 4 ft) thick concrete roof. The headend is isolated from the building 221-T canyon by a metal wall located at the beginning of section 2, Table 1. The canyon deck is used for special decontamination services, repairs, and storage. An example of a typical layout of stored equipment that requires decontamination for repairs, storage, or burial is shown in Table 1 (WAC, 1993). The amount and type of equipment stored on the canyon deck varies with decontamination support requirements.

The railroad tunnel is used for transporting equipment into and out of the canyon. Also, a 5 m by 6.8 m (16 ft by 22 ft) high floor/ceiling opening covered by a motor driven rolling steel door provides railroad canyon access.

Shielding walls made of 2.7 m (9 ft) thick reinforced concrete separate the cells from the electrical and pipe galleries. The operating gallery is separated from the canyon deck by a 1.5 m (5 ft) thick concrete wall that extends part way, 2.75 m (9 ft), to the ceiling. Most of the cells are covered by four 1.80 m (6 ft) thick reinforced concrete blocks (WAC, 1993).

The canyon services areas, cell sections 4 through 10, are used as staging and storage areas for contaminated and decontaminated equipment. The major staging and storage areas for pumps and agitators are located in cell section 4 and 6 (WAC, 1993). All decontamination work is performed in cell section 11 through 15. A description of decontamination and service equipment used within this area is given in Table 2 (WAC, 1993).

Several entry and exit doors are located throughout the canyon area. The main canyon entry is located in cell section 20. The rear canyon "R" doors are normally used for emergency exit only, except for R-19, which is used for access to the laundry storage area and a canyon viewing room at cell section 13 (WAC, 1993).

Section	Cell	On deck	In cell
1		Headend CSTP occupancy	—
2	2L 2R	Railroad tunnel	— PWR spent fuel storage pool, 72 elements
3	3L 3R	PWR equipment Miscellaneous equipment	Miscellaneous equipment Pumps from PUREX and S Plants
4	4L 4R	— 1 wooden box (16- by 8- by 6-ft) 1 Pelican deck pan for miscellaneous 4-to-1 pump and Partex hoses (burial) 1 portable chemical pump stir hose 1 waste tanker unloading flex assembly and quick-disconnect in cell 1 waste tanker decontamination siphon tank	1 LACK 1 PUREX 22-1 pump 1 S Plant 22-1 pump 1 PUREX 3-21 pump 1 PUREX 67-13 pump 1 PUREX (no ID) pump 1 PUREX (no ID) pump 1 PUREX 22-2 pump 2 PUREX F-13 pumps without meters 1 PUREX 304173 pump 1 PCS2 pump 2 tank farm siphon assemblies 1 miscellaneous jumper assembly 1 Pelican 2 contaminated filter assemblies

Section	Cell	On deck	In cell
5	5L 5R	2 sections of erected scaffold 1 working scaffold (9- by 9-ft) 1 pump and agitator miscellaneous fuel handling tools 1 jumper assembly (44400) 1 drum of pool filters 1 section of single-shell pipe from pool (12-ft) 1 Pool storage rack (burial)	2 tanks in use: +5-6 (4,800-gal) +5-9 (4,600-gal) Original equipment tank 5-7 (10,000-gal)
6	6L 6R	17 non-TM drums for burial (15-gal) —	Tank 6-1 1 agitator 18-1 1 pump 25-1 1 agitator 26-31-1 1 pump P25-F13 1 pump 6-22-1 1 agitator A25-1 1 agitator (shilly gears agitator) 1 pump P6-22-1 1 pump 65P-F13 1 pump P25-1 1 agitator A11-1-1 1 pump P17-2 1 pump P-12-1 2 high-speed S Plant agitators 1 (no ID) PUREX pump
7	7L 7R	2 S Plant jumper 2 S Plant pulser 1 power transformer on stand 1 skid (jumper, motor, hoses) 1 001 AR agitator	2 PUREX Ti-tube bunnies 1 PUREX tower vent line pulser stand 2 pulser 001 AR agitator 2 jumpers

Section	Cell	On deck	In cell
8	8L 8R	Pieces of PUREX dissolver 14-2 tank process jump 1 PUREX process pump 1 tank farm jumper 1 S Plant pulser in pulser run-in rack 1 L-shaped centrifuge (shielded) 1 10-ton power crane hook	Original equipment tanks and jumpers Original equipment jumpers and centrifuges
9	9L 9R	1 PWR unloading tool (move to PWR area) 1 PWR swimming pool monorail and hoist assembly 8 slush buckets (lead bricks in buckets) 3 portable working shields 1 pallet (lead shielding 2,000- lb) 1 scaffolding storage rack 1 storage rack (N-2-44978) 1 miscellaneous sheet (6-ft by 4-ft by 3-in.-thick lead) 1 HFS storage box 8 miscellaneous yolk (equipment-handling yolk)	Original equipment tank, jumpers, etc. Original equipment tanks, jumpers, centrifuges
10	10L 10R	1 modified 100-H cask lid top for centrifuge shielding rack 1 SS work hood 1 002 CR pump 2 miscellaneous motors 1 obsolete lamp from crane 1 miscellaneous storage stand (3- by 3-ft) 1 pallet miscellaneous connector heads (12-24) 1 miscellaneous piece of water hose (waste)	Miscellaneous T Plant jumpers, drums of connector heads Open top decontamination tank (16- by 16- by 10-ft)

Section	Cell	On deck	In cell
11	11L	1 extension ladder 2 hose (18- by 30-in.) 1 HFS fuel storage stand 1 HFS fuel-handling stand 1 L-shaped pipe 2 S Plant agitators 1 SS decontamination pad thimble 1 lid for thimble 1 2 portable decontamination tanks 3 drum pallets PWR dummy fuel 1 drum-handling ship 1 tanker-eluting pump 1 designated salt well 1 jumper station	Open top decontamination tank (16- by 16- by 10-ft; 14,000-gal) Open-top Waste tank (14- by 16- by 10-ft; 14,000-gal)
12	12L 12R	Decontamination cell (empty) Decontamination cell (empty)	Decontamination cell (empty) Decontamination cell (empty)
13	13L 13R	1 Plant pulser yolk 1 miscellaneous 15-ton lift yolk (possible bent leg) 1 S Plant pulser 1 decontamination cell 1 SS flat cover block	PUREX offgas silver reactor Jumpers and connector heads
14	14L 14R	1 portable chemical mixing tank (3- by 4-ft) 1 power panel for electro-polisher 3 pipes (6-in.-diameter) 1 bucket and drum lid (5-gal) 1 4-to-1 pump stand 1 4-to-1 pump portable cart 1 heat coil 1 drum (SS29) 1 electrorefiner	12 centrifuges Centrifuge block Original equipment

Section	Cell	On deck	In cell
15	15L 15R	2 small impact wrench motors 1 tanker tube assembly (8-ft-long) 1 drum (15-gal; solidified 4818) 1 pad drum Valves from waste tanker (tube assembly)	Waste tanks 15-6 and 15-9 (not in use) Waste tank 15-1 (14,000-gal)
16	16L 16R	1 waste tanker piping assembly 1 SS plate (6-ft by 10-ft 5/8-in.) 1 work platform PWR 2 wooden pallets 1 1/2-hp motor 1 used crane cab filter 2 empty cans (5-gal) 1 bag Charisma 4 SS pipes (10-ft-long; tank farms) 3 tank farm sludge sampler stands 1 S Plant tank 16-2 1 miscellaneous repair stand 1 S Plant jumper P6-2 pump run-in piping 1 tank farm jumper 46401 1 tank farm jumper	Original equipment, tanks, and jumpers Original equipment, tank centrifuges, and jumpers
17	17L 17R	1 centrifuge run-in stand 2 jumpers 1 hydraulic press 1 metal waste skip 1 suction jig 1 242-S resin column (4374-2412-E) 1 motor stand (miscellaneous wood) 1 P6-2 pump and flowmeter stand	Original equipment, tanks, and jumpers Original equipment tank, centrifuges, and jumpers

Section	Cell	On deck	In cell
18	18L 18R	1 suction jig 1 well from car 29 1 portable welder 3 suction jigs 1 coiled blower 1 unidentified cylinder	Original equipment and tank jumpers Original equipment, centrifuge, tanks, and jumpers
19	19L 19R	1 power hose-damped (10-ton) 1 sheeting lathe 1 elevated block for sheeting lathe 1 portable pipe cutter 3 welding bottle rigs 1 contaminated paint pot 1 centrifuge motors 1 base plate for (no ID) pump 2 empty drums (55-gal) 1 pump run-in station and repair 1 repaired pump (35P-F13)	Original equipment tanks Pump run-in recirculation tank
20	20L 20R	2 centrifuge motors 2 drums (unidentified PUREX pump parts) 2 10-ft wooden skips 5 miscellaneous motors 3 and bell centrifuge motors	Original equipment 20-1 tank Not for storage Contains miscellaneous centrifuge parts

*Containment Systems Test Facility.⁽¹⁾
 *Identification.
 *Stainless steel.

Table 1 Typical layout of Building 221-T canyon cell and storage equipment (WHC 1993)

Equipment	Section	Description	Function
Decontamination thimbles 1	11R	68-in.-deep by 50-in.-diameter, SS, 2,128-gal-capacity.	Immersion tank for chemical decontamination purposes. Piping includes air, steam, caustic, acid, and water.
2	15R	48-in.-deep by 30-in.-diameter, SS, 350-gal-capacity.	
3	15R	48-in.-deep by 36-in.-diameter, SS, 332-gal-capacity.	
Electrochemical decontamination equipment	14R	4- by 4- by 6-ft, SS, 700-gal-capacity. Rectified-input power requirement of 25 A for three-phase 440 V ac; produces 1,000 A at 0 to 12 V.	Alpha and beta-gamma decontamination using reverse electroplating processes in phosphoric chromic acid bath.
Partek liquid blaster headers from Partek pumps	12 through 15 (headers) 13 (pump located in operating gallery)	Main header--16-gauge; SS; welded pipe construction.	Beta-gamma decontamination using water or sand and water mixture with a 10,000 lb/in ² output pressure.
4-to-1 and 5-to-1 portable chemical spray pumps	Where needed (i.e., 11R, 13R, 15R)	SS pump section. Outlet discharge pressure is four or five times greater than inlet supply pressure.	Beta-gamma decontamination using chemicals or water. Pressure at nozzle four times greater than air pressure applied.

Table 2 Equipment available for decontamination and run in support (WHC 1993)

2.2 Ventilation Systems

There are two separate ventilation system areas for Building 221-T: (1) the canyon and (2) the galleries. The Building 221-T galleries are maintained at atmospheric pressure while the Building 221-T canyon area is maintained at a negative pressure with respect to atmosphere. The Building 221-T ventilation system is shown in Figure 5.

2.3 Existing Canyon HVAC System

The canyon ventilation system has been revised since original construction. The original stairwell supply units have been sealed and replaced with the 221-TA supply system. This system discharges $19 \text{ m}^3/\text{sec}$ (40,000 cfm) directly into the canyon.

The exhaust system has also been revised. Three different filtration systems have been installed. The first was a underground sand filter which eventually plugged and caused high differential pressures. This system was subsequently replaced with a High Efficiency Particulate Air (HEPA) filter system. It was installed as a temporary emergency measure. In 1991, permanent above ground HEPA filter system was installed adjacent to the 291-T exhaust fans.

The 291-T exhaust fans have also been modified since original construction. During the earlier sand filter installation, the two original fans used for normal operation were rearranged from parallel to series arrangement to increase the differential pressure capability. This is the current exhaust fan arrangement. An additional exhaust fan was also installed to the system. Exhaust fan 296-T-13 was installed on the building roof during the 221-TA supply system addition. The 291-T exhaust system includes a HEPA filtration system and exhaust fan with exhaust capacity of $14 \text{ m}^3/\text{sec}$ (30,000 cfm). The 221-T-13 exhaust system uses a $20 \text{ m}^3/\text{sec}$ (42,000 cfm) fan which exhausts air from the ceiling of the canyon (WAC, 1992).

Figure 5 Building 221-T ventilation system (WHC report, 1993)

One additional change to the exhaust ventilation system concerns the emergency backup fan. The steam powered fan has been removed from operation entirely (see Figure 6 schematic of existing ventilation system) (WAC, 1992). The ventilation control system for the canyon has also changed since original installation. The current supply and exhaust fans are electrically interlocked and alarmed to prevent over pressurization of the canyon. This is achieved by a simple on/off operation of the appropriate fan at preset pressure limits.

A 3.20 m (10.5 ft) square concrete exhaust air tunnel runs parallel to the canyon and provides exhaust for canyon cells. The tunnel exits Building 221-T at cell sections 3 and 22 below the deck level where it narrows to a 1.22 m by 2.15 m (4 ft by 7 ft) duct. The duct then runs approximately 61 m (200 ft) underground to the HEPA filter system which discharges to the 291-T stack exhaust system. Further data concerning the ventilation systems including fan curves and HEPA filter detail were not available. As such, detailed ventilation calculations are not possible. The HEPA evaluation section reflect this lack of data.

2.4 Existing Railroad Tunnel

The railroad tunnel used for transporting equipment into and out of the canyon and is also used for waste drum repackaging operation and for temporary storage area. The tunnel and the canyon areas share a common atmosphere and are considered radiation areas. High air infiltration from the outside into the canyon occurs each time the main entrance door is opened (WAC, 1992). Also, when door is closed, 4.60 m³/sec (9700 cfm) of air move into the canyon through the door air gap. The air gap is approximately 0.1 m by 20 m (4 in. by 66 ft) long and was caused by the removal of door seal since original installation (WAC, 1992).

Figure 6 Schematic of the existing ventilation system (WHC report, 1993)

2.5 Building 221-T Air Balance System

An air balance for Building 221-T is shown in Figure 7a, 7b, 7c, and 7d. Normal canyon pressure ranges from -0.25 to -0.5 in of water. The Building 221-TA supply fan, the roof fan, and both Building 291-T exhaust fans can be operated together to ensure that negative pressure is maintained in the canyon with maximum air flow. An interlock system is provided between the 221-TA supply fan and the roof exhaust to prevent operation of a supply fan unless the roof exhaust is running. Also, the Building 221-T air balance system is equipped with a pressure control system. All supply and exhaust systems are individually connected with pressure switches. The switches energize or de-energize the fan in use as needed. The control diagram for these pressure switches is given in Figure 8 (WAC, 1993).

3.0 CANYON DECK AND RAILROAD TUNNEL INVENTORY

3.1 Canyon Deck Inventory

The amount and type of material and equipment stored in canyon deck service area is shown in Figure 9. Combustible fuels present in sections included piles of wood pallet at locations 3L, 3R, 13L 14L, and 15L, drums filled with 91 kg (200 lb) of flammable liquid soaked rags at locations 7L and 13L and burial (plywood) boxes at locations 8L, 17L, and 18L. The combustible loading in the canyon at location 13L was relatively higher as compared to other locations (e.g., 3R or 17L). Also, mechanical and electrical equipment is located in the canyon (e.g., pumps, welders, power tools, jumper cutters, mill machines, and electric polishers).

Combustible materials observed in Figure 9 consist of various quantities of Class A combustibles. The most significant of these are the wood pallets and drums filled with 91 kg (200 lb) of flammable liquid soaked rags.

Figure 7a Building 221-T basement airflow diagram (WHC report, 1992)

Figure 7b Building 221-T first floor airflow diagram (WHC report, 1993)

Figure 7c Building 221-T second floor airflow diagram (WHC report, 1993)

Figure 7d Building 221-T third floor airflow diagram (WHC report, 1993)

Figure 8 Building 221-T ventilation control diagram (WHC report, 1993)

Figure 9 Canyon deck inventory layout (WHC report, 1993)

3.2 Railroad Tunnel Inventory

The railroad tunnel is used for the repackaging of 210 L (55 gal) waste drum operation (with associated short term storage) and is used for transporting material. An example of a typical layout of stored 210 L (55 gal) drums is shown in Figure 10. Also, a series of empty drums is shown in the layout. A empty 1.22 m x 1.22 m x 2.44 m (4 ft x 4 ft x 8 ft) reusable plywood box is shown, which can be used for transporting repackaged low level waste (LLW).

3.3 Significant Fire Sources in the Canyon and Railroad Tunnel Inventory

Three areas within the canyon deck and railroad tunnel inventory have being identified by the facility plant personnel as potentially posing serious fire hazards. Location 13L in the canyon deck inventory is one of the areas under consideration. Potential fires include in 1.22 (4 ft) high piles of pallet as illustrated in Figure 9. A second area under consideration in the railroad inventory is a fire initiated in oil soaked rags exposing wood burial (plywood) boxes and 210 L (55 gal) drums, both open and closed. The final location under consideration for this analysis is location 3R in the canyon deck inventory; this fire size is based on the burning of stack of wood pallets with a height of 4 ft (Figure 9).

4.0 HEAT RELEASE RATE ESTIMATES

4.1 General

An essential component of the fire modeling in this study was the determination of the energy release rate characteristics of the critical fuel packages discussed in Section 3. Critical fuel packages identified by the T-Plant facility are shown in Figures 9 and 10.

For many types of analyses, gross simplification of burning rates are acceptable. For instance, post flashover structure analyses are often based on the fire duration or severity associated with an aggregate fuel loading (i.e., combustible load per unit floor area). However,

Figure 10 Railroad tunnel inventory layout (WHC report, 1993)

if it is essential to estimate specific fire effects within an enclosure, a more accurate determination of burning rate characteristics (i.e., heat release rate) is necessary. Specific characteristics of interest in this study included initial fire growth rate, peak burning rate, and duration of burning.

Heat release rate is not a fundamental property of a fuel and, therefore, cannot be calculated from basic material properties. It depends on the fire environment, the manner in which the fuel is volatilized, and combustion efficiency. Often, burning rate data are obtained for specific fuels by laboratory testing. Work has lead to specific burning rate curves for selected fuels, e.g., wood cribs, wood pallets, and flammable liquid pools (Lee, 1985 and Babrauskas, 1988). In the absence of such information, one must construct or estimate the heat release rate history for particular fuel. While not as accurate as laboratory testing, information exists in the literature that permits estimates of initial fire growth, peak burning rates, and duration for fuels and fuel geometries.

4.2 Initial Fire Growth

Evaluation of data collected on burning rates for a wide range of fuel packages indicates that the initial period of rapid fire growth can be reasonably approximated by the following geometric expression, reported in the NFPA Standard 92B "T-Squared Fires", (NFPA, 1993).

$$\dot{Q} = \alpha t^2 \quad 1$$

where $\dot{Q}$ = heat release rate (kW),
 t = time (sec), and
 α = coefficient governing the fire growth (kW/sec²).

A t-squared fire is one where the burning rate varies proportionally to the square of time. Figure 11a illustrates four commonly accepted forms of this expression used for estimating

Figure 11a Characteristic t-Squared initial fire growth, $Q = \alpha t^2$ (NFPA 92B)

Figure 11b Relation of t-Squared fires to some fire test (NFPA 92B)

initial, pre-flashover burning rates. Selection of a particular growth rate curve to approximate the initial burning rate of a particular fuel package is dependent on the quantity and arrangement of the fuel, and its flammability characteristics.

Researchers have measured and cataloged the appropriate characteristics fire growth rate for a range of material types and configurations. Figure 11b relates the classes of t-squared fire growth curve to a selection of actual fires. The fires are classified by speed of growth: ultra fast, fast, medium, and slow.

4.3 Procedure

In this study, the heat release histories were estimated based on the fast fire growth rate approximation for critical fuel packages. For some fuel packages in canyon deck and railroad inventory, burning rate data were available from laboratory tests. For those cases where test data were not available, the heat release rate histories were conservatively approximated from estimates of initial growth rates, peak energy release rate, and the time to reach the peak heat release rate. The assumption associated with the heat release estimates included the following:

- (1) the initial growth rate corresponded to $Q = \alpha t^2$, fast fire growth rate,
- (2) 75 percent of the total available external surface area was burning, and
- (3) the mass available for consumption during the period of peak energy release rate was 80 percent of the total available combustible mass, therefore attributing 20 percent of the mass loss to the initial growth period and the decay period.

This approach lead to estimates of release rate which were higher than would be expected because (1) it assumes complete combustion, (2) it assumes a high surface area of flame involvement, and (3) it assumes a fuel controlled burning regime.

4.3.1 Steady State Heat Release Rate Based on Exhaust Flow Rates

As a means of bounding the thermal effects on the building, one can consider the maximum heat release rates possible in the building based on the available ventilation. Table 3 shows the resulting heat release rates calculated from the exhaust flow from the canyon deck. These energy release rates produce the maximum thermal effects to the structure. Three scenarios were evaluated based on the exhaust ventilation conditions. In case of fire alarm, HVAC supply systems in building shut down automatically. Therefore, in our analysis, supply air fan are considered to be off in all cases (WAC, 1993). Table 3 is based on the use of all available oxygen supplied to the building using

$$\dot{Q} = \dot{V} \rho_{air} \Delta H_{r,air} \quad 2$$

where $\dot{Q}$ = heat release rate (kW),
 $\dot{V}$ = volume flow rate (m³/sec),
 ρ_{air} = density of air (kg/m³), and
 $\Delta H_{r,air}$ = heat of reaction for air (kJ/kg).

The maximum heat release rate is achieved when both exhaust fans are in operation.

Flow Conditions	Exhaust Flow Rate, $\dot{V}$	Density of Air, ρ_{air} (kg/m ³)	Mass Flow Rate (kg/sec)	Heat of Reaction for Air (kJ/kg)	Heat Release Rate (MW)
Floor exhaust on only (291-T exhaust system)	30,000 cfm (14 m ³ /sec)	1.17	16.38	3 x 10 ³	49
Roof exhaust on only (291-T-13 exhaust system)	42,000 cfm (20 m ³ /sec)	1.17	23.40	3 x 10 ³	70
Both exhaust on (291-T and 221-T-13)	72,00 cfm (34 m ³ /sec)	1.17	39.78	3 x 10 ³	120

Table 3 Steady state heat release rate results based on exhaust rates

4.3.2 Heat Release Rate from Burning Wood Pallet

Based on site information, wood pallets are currently stored in the canyon deck inventory at location 13L (see Figure 9). Test results of the burning rate of stack wood pallet have been reported in Babrauskas (1988) based on the work of Krasner (1988). Different conditions have been reported, and the heat release rate is based on the height of the stack. A heat release rate curve of a fire involving 1.22 m (4 ft) tall stack of 1.22 m by 1.22 m by 0.14 m (4 ft by 4 ft by 5.5 in) pallets is shown in Figure 12. Also, Figure 13 provides heat release rate of wide range of pallet heights and shows dependence of pallet burning rate on stack height. Table 4 summarizes the results of the estimated burning rate of one 1.22 m (4 ft) high stack based on test data. The time to reach the peak heat release rates calculated based on the fast growth rate approximation and is shown in Figure 11b.

Pallet Size (m)	Stack Height (m)	Surface Area (m ²)	Density (kg/m ³)	Heat of Comb. (kJ/kg)	Mass Loss Rate (kg/sec)	Peak Rate of Heat Release (kW)	Time to Peak Heat Release (sec)
1.22 x 1.22 x 0.14	1.22	1.48	329	12x10 ³	0.31	3,750	300

Table 4 Heat release rate results for 1.22 m (4 ft) high wood pallet stack

4.3.3 Heat Release Rate from Burning Plywood Box Filled with 227 kg (500 lb) Ordinary Combustibles

A review of the literature was made of experiments concerned with fire growth from plywood box filled with ordinary combustibles. It appears that there are no direct data available on the burning of these fuel packages at full or intermediate scale. However, there are full scale test results available for trash bag fires. Some typical trash bag fires are shown in Figure 14 (Lee, 1985). Also, Lee (1985) has correlated the peak heat release rate values according to the

Figure 12 Heat release rate of 1.22 m (4 ft) high wood pallet stack (Krasner 1968)

Figure 13 Dependence of pallet burning rate on stack height (Babrauskas 1988)

Figure 14 Heat release rate for trash bags (Lee 1985)

effective diameter and packing density. Figure 15a shows the total burning rate (kW) increases with the effective base diameter, but decreases with the higher packing density. Figure 15b, conversely, illustrates that the increase in heat release with diameter is not sufficient to be proportional to base area; thus, when per unit base area results (kW/m²) are expressed, a downward trend is seen. This correlation according to packing density should only be considered as guidelines. Application of this method to the plywood crates is an extrapolation of the available data and should be viewed in this light.

Table 5 shows some data for some stored commodities tested at the Factory Mutual Research Corporation (FMRC) based on the work of Delichatsios (1983), and Alpert and Ward (1984). For example, filled mail bags, stored 1.5 m (5 ft) high had a peak heat release rate per unit floor area of 400 kW/m² (35 Btu/ft²sec). The fire growth time is given as 190 seconds to reach 1 MW (948 Btu/sec). This corresponds to is in the fast growth rate category according to NFPA 92B. In Table 5, it should be noted that the spread in peak heat release rate values shown refers to the same test in each case, but utilizes a different method of estimating the peak heat release rate on the basis of recorded load cell values.

Mail bags heat release data from Table 5 seem to be the most appropriate to predict heat release for a plywood box filled with ordinary combustibles. Table 6 shows the estimation for heat release rate of a plywood box filled with ordinary combustible based on the mail bags and trash heat release data.

Plywood box filled with ordinary combustibles	Floor area (m ²)	Volume (m ³)	Mass of combustibles (kg)	Mass filling density of combustibles (kg/m ³)	Heat release rate (kW) (based on mail bags data)	Heat release rate (kW) (based on trash data)
1.22m x 1.22m x 2.43m	2.97	3.63	227	62	1200	600

Table 6 Estimates of heat release rate for plywood box filled with ordinary combustible

Figure 15a Summary of trash heat release rates - result for a total heat release rate (Lee 1985)

Figure 15b Summary of trash heat release rates - result for heat release rate per unit base area (Lee 1985)

Commodity	Peak heat release rate per unit floor area* (kW/m ²)	Growth time to reach 1 MW (s)
mail bags, filled, stored 1.5 m high	400 -	190
cartons, compartmented, stacked 4.6 m high	1700 - 4200	60
cartons, tri-wall cardboard, metal lined, stacked 4.9 m high	- 2800	
polyethylene bottles, packed in cartons as above	6200 - 7800	85
polystyrene jars, packed in cartons as above	14000 - 20900	55
PVC bottles, packed in cartons as above	3400 - 7000	95
polypropylene food tubs, packed in cartons as above	4400 - 9600	100
polyethylene letter trays, stacked 1.5 m high on cart	8500 -	180
polyethylene trash barrels in cartons, stacked 4.6 m high	2000 -	55
polyethylene bottles, random size, in cartons, stacked 4.6 m high	2000 - 4200	75
polyethylene bottles, large, in cartons, stacked 4.67 m high	- 7300	
polyethylene/fiberglass shower stalls in cartons, stacked 4.6 m high	1400 -	85
polyurethane rigid foam insulation board, stacked 4.6 m high	1900 - 3200	8
polystyrene rigid foam insulation board, stacked 4.3 m high	3300 -	8
polystyrene food tubs, with covers, nested in cartons, stacked 4.3 m high	5400 - 8200	120
polystyrene meat trays, wrapped in plastic sheet	- 12900	
polystyrene meat trays, wrapped in paper	- 13300	
polystyrene toy parts in cartons, stacked 4.6 m high	2000 - 6500	125
polyethylene and polypropylene film in rolls, stacked 4.3 m high	6200 -	40

Table 5 Data for stored commodities tested at Factory Mutual Research Corporation
(Delichatsios, 1983 and Alpert and Ward, 1982)

Mail bags and trash fire data were reviewed, and the peak heat release rates for these fires were used to estimate the plywood box heat release rate. In Table 6, the heat release for a plywood box filled with ordinary combustibles based on mail bags fire is twice the heat release estimated on the basis of a trash bag fire. The 1,200 kW (1138 Btu/sec) predicted heat release rate for a mail bag seems appropriate and a best approximation for a plywood box fire. Therefore, based on the peak unit area rate of heat release, the mail bag representation of the burning rate is the more conservative and is selected for use in this analysis.

4.3.4 Heat Release Rate From Burning 55 Gallon Drum Filled With Maximum 91 kg (200 lb) Flammable Liquid Soaked Rags

There are no experimental burning rate data available for cotton rags soaked with flammable liquid stored in 210 L (55 gal) drum. Without experimental data on the characteristics of oil soaked rags burning, the prediction of heat release rate is difficult.

Therefore, due to lack of data, we assume that the burning rate is dominated by the flammable liquid. It is further assumed that the flammable liquid soaked rags have burning rates similar to kerosene and a fast growth rate. Babrauskas (1983) has correlated burning rate for large flammable liquid pool fires from experimental data. Babrauskas (1983) provides values for burning rate for a wide range of fuels. The results are listed in the Table 7 with the values of relevant thermochemical properties.

In order to estimate the heat release of the rags, it is assumed that only the top surface of the 210 L (55 gal) drum is involved in the fire. The peak energy release rate for the vaporizing liquid is given by

$$\dot{Q}_{pool} = \Delta h_c \dot{m}'' A_{pool} \quad 3$$

where A = pool area (surface area of top of 55 gal drum) (m²),
 Δh_c = heat of combustion of kerosene (kJ/kg), and
 $\dot{m}$ = burning rate of kerosene (kg/m² sec).

Material	Density (kg/m ³)	Δh_c (kJ/kg)	Δh_v (MJ/kg)	$\dot{m}_{\infty}^*$ (kg/m ² -s)	$h\delta$ (m ² /s)	k (m ² /s)	T_f (K)	References
Cryogenics								
Liquid H ₂	700	442	120.0	0.169 (± 0.006)	6.1 (± 0.4)	—	1600	4.5
LNG (mostly CH ₄)	415	619	50.0	0.078 (± 0.018)	1.1 (± 0.8)	0.5	1500	1,4,30
LPG (mostly C ₃ H ₈)	585	428	46.0	0.099 (± 0.009)	1.4 (± 0.5)	0.4	—	20,35
Alcohols								
Methanol (CH ₃ OH)	796	1230	20.0	0.017 (± 0.001)	—	—	1300	5,22,37
Ethanol (C ₂ H ₅ OH)	794	1000	28.8	0.015 (± 0.001)	—	0.4	1490	7,9,24,31
Simple Organic Fuels								
Butane (C ₄ H ₁₀)	573	370	45.7	0.078 (± 0.003)	2.7 (± 0.3)	—	—	5
Benzene (C ₆ H ₆)	874	500	40.1	0.085 (± 0.002)	2.7 (± 0.3)	4.0	1460	5,31,38
Hexane (C ₆ H ₁₄)	650	450	44.7	0.074 (± 0.005)	1.9 (± 0.4)	—	1300	5,38,39
Heptane (C ₇ H ₁₆)	675	505	44.6	0.101 (± 0.009)	1.1 (± 0.3)	—	—	22,33
Xylene (C ₈ H ₁₀)	870	555	40.8	0.090 (± 0.007)	1.4 (± 0.3)	—	—	5
Acetone (C ₃ H ₆ O)	791	570	25.8	0.041 (± 0.003)	1.9 (± 0.3)	0.8	—	9,29,37
Dioxane (C ₄ H ₈ O ₂)	1035	530	26.2	0.018 ^a	5.4 ^a	—	—	33
Diethyl ether (C ₄ H ₁₀ O)	714	385	34.2	0.085 (± 0.018)	0.7 (± 0.3)	—	—	3
Petroleum Products								
Benzine	740	—	44.7	0.048 (± 0.002)	3.6 (± 0.4)	—	—	3
Gasoline	740	330	43.7	0.055 (± 0.002)	2.1 (± 0.3)	2.0	1450	3,18,24,31,38,39
Kerosene	820	670	43.2	0.039 (± 0.003)	3.5 (± 0.8)	2.6	1480	3,21
JP-4	760	—	43.5	0.051 (± 0.002)	3.6 (± 0.1) ^a	—	1220	3,16,21,34
JP-5	810	700	43.0	0.054 (± 0.002)	1.6 (± 0.3)	0.5	1250	8,14,15,32
Transformer oil, hydrocarbon	760	—	46.4	0.039 ^a	0.7 ^a	—	1500	22
Fuel oil, heavy	940-1000	—	39.7	0.035 (± 0.003)	1.7 (± 0.6)	—	—	3,6
Crude oil	830-880	—	42.5-42.7	0.022-0.045	2.8 (± 0.4)	—	—	3,38
Solids								
Polymethyl- methacrylate	1184	1611	24.9	0.020 (± 0.002)	3.3 (± 0.8)	1.3	1260	12,26

^a Value independent of diameter in turbulent regime

^b Only two data points available

^c Data from [14] excluded; otherwise $\dot{m}_{\infty}^* = 0.064$ (± 0.010) and $h\delta = 5.3$ (± 6.0)

For each entry, measured burning rates (kg per m² per s) are listed, along with pool diameter D (m).

- Ref. 1 LNG: 0.053 (D=0.32), 0.048 (D=0.34), 0.043 (D=0.75), 0.033 (D=1.2), 0.13 (D=3.0), 0.040 (D=4.1), 0.039 (D=6.5)
- Ref. 3 Diethyl ether: 0.023 (D=0.3), 0.033 (D=0.5), 0.046 (D=1.4), 0.073 (D=2.8), 0.026 (D=0.2), 0.028 (D=0.25), 0.029 to 0.033 (D=0.3), 0.046 (D=0.5), 0.043 (D=0.8), 0.049 (D=1.2), 0.048 (D=1.4), 0.064 (D=2.8), 0.046 (D=4.8), 0.044 (D=12.9)
- Gasoline: 0.044 (D=1.3)
- Kerosene: 0.022 (D=0.3), 0.022 (D=0.25), 0.023 to 0.024 (D=0.3), 0.031 (D=0.8), 0.033 (D=1.4), 0.037 (D=2.8), 0.049 (D=12.9)
- Fuel oil, heavy: 0.023 (D=1.3), 0.038 (D=2.8), 0.037 (D=12.9)
- Crude oil: 0.012 (D=0.2), 0.021 (D=0.5), 0.021 (D=1.4), 0.022 (D=2.8)
- Ref. 4 LNG: 0.030 (D=0.28), 0.042 (D=0.75), 0.047 (D=1.32)
- Ref. 5 Liquid H₂: 0.064 (D=0.075), 0.101 (D=0.15), 0.147 (D=0.33)
- Methane: 0.013 (D=0.3), 0.018 (D=0.75), 0.022 (D=1.22), 0.024 (D=1.8)
- Benzene: 0.044 (D=0.3), 0.064 (D=0.8), 0.067 (D=0.75)
- Benzene: 0.047 (D=0.3), 0.064 (D=0.33), 0.077 (D=0.75), 0.075 to 0.083 (D=1.22)
- Hexane: 0.037 (D=0.3), 0.060 (D=0.5), 0.083 (D=0.75), 0.073 (D=1.22)
- Xylene: 0.027 (D=0.3), 0.053 (D=0.75), 0.067 (D=1.22)
- Ref. 6 Fuel oil, heavy: 0.023 (D=0.84), 0.033 (D=2.7)
- Ref. 7 Ethanol: 0.018 (D=0.33)
- Ref. 8 JP-4: 0.043 (D=0.72), 0.064 (D=1.1), 0.064 (D=17.1)
- Ref. 9 Methanol: 0.018 (D=0.25), 0.013 (D=0.22), 0.013 (D=0.28)
- Ethanol: 0.013 (D=0.25), 0.013 (D=0.32), 0.013 (D=0.33)
- Acetone: 0.018 (D=0.25), 0.019 (D=0.3)
- Ref. 13 Cyclohexane: 0.110 (D=0.2), 0.165 (D=0.3)
- Ref. 14 Average: 0.106 (D=0.6 to 2.4)
- JP-4: 0.106 (D=0.6 to 2.4)
- Ref. 18 JP-4: 0.061 (D=0.2), 1.8, 2.2, 3.0, 8.0, 10.1
- Ref. 20 LPG: 0.063 (D=0.34), 0.046 (D=0.77), 0.067 (D=1.7), 0.102 (D=3.4), 0.090 (D=6.9), 0.111 (D=14)
- Ref. 21 Kerosene: 0.026 (D=0.3)
- JP-4: 0.026 (D=0.3)
- Ref. 22 Methanol: 0.020 (D=1.3), 0.021 (D=1.7), 0.021 (D=2.4)
- Hexane: 0.067 (D=1.2), 0.073 (D=1.7)
- Transformer oil, hydrocarbon: 0.022 (D=1.2), 0.027 (D=1.7)
- Ref. 24 Ethanol: 0.018 (D=0.33)
- Gasoline: 0.023 (D=0.25)
- Ref. 26 PMMA: 0.029 (D=0.25), 0.018 (D=0.34), 0.017 (D=0.52), 0.018 (D=0.89), 0.018 (D=0.85), 0.020 (D=1.4)
- Ref. 27 Hexane: 0.028 (D=0.25), 0.033 (D=0.8)
- Dioxane: 0.012 (D=0.33), 0.016 (D=0.8)
- Ref. 28 JP-4: 0.048 (D=1.22), 2.4, 3.8, 8.3
- Ref. 27 Methanol: 0.018 (D=0.6), 0.014 (D=1.82)
- Acetone: 0.023 (D=0.8), 0.026 (D=1.52)
- Ref. 28 Benzene: 0.067 (D=0.8)
- Hexane: 0.077 (D=0.8)
- Gasoline: 0.066 (D=0.8)
- Crude oil: 0.045 (D=0.8)
- Ref. 29 Hexane: 0.036 (D=0.8), 0.080 (D=1.8), 0.074 (D=3.0)
- Gasoline: 0.046 (D=0.8), 0.061 (D=1.8), 0.063 (D=3.0)

Table 7 Burning rate for the flammable liquid (Babrauskas 1983)

The approximate diameter of 210 L (55 gal) drum is 0.57 m (2 ft). Therefore, the area of the pool is 0.26 m² (2.80 ft²). Table 8 summarizes the data used to calculate the peak heat release rate of a kerosene pool fire.

Top Surface 55 gal Drum	Diameter (m)	Surface area (m ²)	Heat of Combustion (kJ/kg)	Burning Rate (kg/m ² sec)	Heat Release Rate (kW)
Kerosene	0.57	0.26	43.70 x 10 ³	0.039	440

Table 8 Heat release rate estimates for kerosene pool fire

This analysis is somewhat crude. The presence of rags could increase heat release by increasing surface area or could decrease heat release by blocking radiation. The burning rate could also be reduced by the restriction of air entrainment by the drum. Overall, the estimate of 440 kW (417 Btu/sec) is expected to provide a conservatively high estimate of heat release rate.

4.4 Summary of the Predicated Heat Release Rates

A summary of the heat release based on the t-squared fire growth (see Section 4.2) for each of the fuel type and configuration is presented in Table 9. The burning rate histories were determined based on the these calculation, and are presented in Figures 16 through 19. These results have been used as the input for the CFAST simulation to appraise the thermal effects from fire to the structure.

Values for maximum/peak heat release were calculated for the fire scenarios described in Section 4.3. It should be noted that the selection of fire growth rate for each fuel package is calculated assuming a t-squared fire growth rate as described in Section 4.2. Multiple object fires used the same fire growth rate with a maximum heat release rate based on the number of objects in the fuel packages.

Figure 16 Heat release estimates based on the exhaust flow rates

Figure 17 Heat release estimates for wood pallet fire

Figure 18 Heat release estimates for plywood box fire

Figure 19 Heat release estimates for kerosene pool fire

Fuel Type and Configuration	Peak Heat Release Rate (kW)	Standard Fire Growth Factor, α , NFPA 92B-1990 (kW/sec ²)	Time to Reach Peak Heat Release (sec)
Floor exhaust 291-T system on only	49 x 10 ³	0.0444 - Fast	1050
Roof exhaust 221-T-13 system on only	70 x 10 ³	0.0444 - Fast	1255
Both exhaust 291-T and 221-T-13 systems on	120 x 10 ³	0.0444 - Fast	1644
Wood pallet stack (4 ft high)	3,750*	0.0444 - Fast	300
Plywood box filled with ordinary combustible	1,200*	0.0444 - Fast	170
55 gallon drum filled with flammable liquid soaked rags	440*	0.0444 - Fast	100

* Peak heat release rates given are for a single item.

Table 9 Summary of heat release rate results

Based on the current information and knowledge of burning rates of combustible fuels, estimates of the heat release rate of the potential fuel element appear to conservatively represent the potential hazard.

5.0 ESTIMATING POTENTIAL FIRE EXPOSURE

5.1 General

The potential for ignition and fire spread exists in the canyon and railroad inventory due to radiative heating from the burning of wood and other items described in Section 4. This emitted radiant energy from the flame could be enough to ignite other materials in the area. An analysis was performed to determine the extent to which such a fire would likely induce ignition of nearby materials causing an increase in total heat release rates.

5.2 Radiative Heat Flux to Target Fuels

To determine the potential of one item or fuel package igniting another and producing a collective fire, a point source radiative heat transfer model was used Modak (1977, 1981) (Figure 20a). The radiative model calculates the incident heat flux on a external target based on the emitted radiative heat flux and is based on the following assumptions:

- (1) the flame can be represented by a small isotropic point source of radiant energy;
- (2) the energy radiated from the flame is a specified fraction of energy released during combustion.

Expressed mathematically, the radiant heat flux at any distance from the source is given by

$$\dot{q}_r'' = \frac{\chi_r \dot{Q}}{4 \pi R^2} \quad 4$$

where $\dot{q}_r''$ = incident heat flux per unit area on target fuel (kW/m²),
 χ_r = radiative fraction for the fuel and is relative to the total energy released. It is not constant for the fuel, but generally varies from 0.15 to 0.60 (McCaffrey 1981),
 $\dot{Q}$ = heat release from exposing burning material (energy release rate of fire) (kW), and
 R = distance between the effective center of the fire and the nearest surface of the target fuel (m).

Target fluxes were estimated in accordance with Figures 9 and 10, canyon and railroad tunnel inventory layout. Table 10 provides a summary of the analysis performed using Modak (1981, 1977) correlation. All the specified distances from the fire to the target are approximate because the layout of the inventory is not to scale.

Figure 20a Fire heat flux to target
Point source thermal radiation model

Location	Target fuel	Separation distance between fire source and target fuel - R* (m)	Fire source	Radiative fraction c_r^{**} (McCaffery, 1981)	Fire heat release rate (kW)	Heat flux per unit area on target fuel, (kW/m ²)
13L, canyon	Wood pallet	2	1.22 m high wood pallet stack	0.35	3,750	26
13L, canyon	Drum	3.5	1.22 m high wood pallet stack	0.35	3,750	9
3R, canyon	Wooden box	2	1.22 m high wood pallet stack	0.35	3,750	26
3R, canyon	Wood pallet	3	1.22 m high wood pallet stack	0.35	3,750	12
Repackaging area, railroad tunnel	Repackaged (LLW)	3	plywood box filled with combustibles	0.35	1,200	4
Repackaging area, railroad tunnel	Repackaged (RMW)	1	55 gallon drum filled with flammable liquid soaked rags	0.35	440	12

* Separation distances between fire source and target fuel are not to scale in the canyon and railroad tunnel inventory.

** Most fuels have radiative fraction between 0.25 - 0.40.

Table 10 Summary of the radiative heat flux to target fuel

This incident heat flux on a target may result in the ignition of a previously unignited fuel package. If material is heated long enough and the radiative heat flux on a target fuel exceeds the critical or minimum heat flux, then that item is considered to be ignited. As each item is ignited, the size of the fire increases, and the compartment temperature increases. Heat fluxes required for ignition are discussed in Section 5.3.

5.3 Ignition During a Continuous Heat Flux

The potential for ignition of nearby material from fires was evaluated based on the work of Quintiere and Harkleroad (1985). For a continuous heat flux on a solid, the ignition is based on the concept of a critical or minimum surface temperature. This is called the ignition temperature. It is related to the flash point at which the flow of volatile gases is sufficient to allow flame to persist at the surface. From theoretical considerations and data on many materials, we can characterize conditions for ignition. Most common combustible materials have a range of ignition temperatures of approximately 300 to 400°C (572 to 752°F). This corresponds to a minimum or critical radiant heat flux for ignition of approximately 10 to 30 kW/m² (0.88 to 2.65 Btu/ft²sec). Below these heat fluxes, an object will not ignite, and above these heat fluxes, the time to ignite will decrease with increasing heat flux. Ignition temperature can be considered to be a property of the solid, but it is not truly constant and can vary with the rate of heating. Surface temperature rise due to an imposed heat flux, q , on a thick solid is estimated by

$$T_{ig} - T_i = \frac{\dot{q}_r'' \sqrt{t_{ig}}}{\sqrt{\frac{\pi}{4} k \rho c}} \quad 5$$

- where T_{ig} = final surface temperature at ignition time t_{ig} (°C),
 T_i = initial surface temperature (ambient) (°C),
 q_r = incident radiative heat flux (kW)
 $k\rho c$ = thermal inertia (conductivity x density x specific heat) ((kW/m²K)² sec),
 t_{ig} = ignition time (sec).

In case of infinite thickness with continuous heating, a minimum radiative heat flux for the ignition is given by

$$\dot{q}_{critical}'' = h_{overall} (T_{ig} - T_i) \quad 6$$

where $\dot{q}_{critical}$ = minimum or critical temperature for ignition (kW/m²),
 $h_{overall}$ = over all heat transfer coefficient (kW/m²-K),
 T_{ig} = ignition temperature (°C), and
 T_i = ambient temperature (°C).

This implies no heat conduction into the solid and that the energy balance on the surface must be sufficient to achieve a surface temperature equal to the ignition temperature. For explicit reradiation for a surface emissivity of one,

$$\dot{q}_{critical}'' = \sigma (T_{ig}^4 - T_i^4) + h_{conv} (T_{ig} - T_i) \quad 7$$

where h_{conv} = convection heat transfer coefficient (kW/m²-K),
 σ = Stefan-Boltzmann constant (5.669 x 10⁻¹¹ kW/m²-K⁴),

and the ignition time for the thick solid can be estimated by

$$t_{ig} = \frac{\pi}{4} k\rho c \frac{(T_{ig} - T_i)^2}{(\dot{q}_r'')^2} \quad 8$$

where t_{ig} = ignition time (sec),
 $k\rho c$ = thermal inertia ((kW/m²K)² sec), and
 $\dot{q}_r$ = incident radiative heat flux (kW).

Light weight foam materials may have $k\rho c$ values as low as $0.01 [(kW/m^2K)^2sec]$ whereas a value of 1 $[(kW/m^2K)^2 sec]$ might be an upper limit for more dense common furnishing and construction materials. For this class of materials, the ignition time is estimated from the Equation 8 or derived from the literature. Table 11 provides ignition properties of some common combustibles. The data demonstrate the thermophysical properties and ignition susceptibility of solid materials.

Target fluxes were estimated (see Table 10) for the distances from the fire to the target ranging from 1 to 3.5 m (0.3 to 11.50 ft). Critical limits for incident heat flux by target combustibles range from 10-30 kW/m^2 (0.88 to 2.65 Btu/ft^2sec) (for plywood see Figure 20b, Quintiere and Harkleroad 1985). If the ignition is calculated to possibly occur the heat release rate of the target source is added to the initial source (see Table 12).

<p>(1) Canyon Location 13L - heat release rate 3,750 kW (3556 Btu/sec) burning one stack of wood pallets Calculated heat flux - 26 kW/m^2 (2.28 Btu/ft^2sec) to target fuel (wood pallet) Ignition is possible in this location Total heat release rate - 15,000 kW (14226 Btu/sec) burning of four stacks of wood pallets</p>
<p>(2) Canyon Location 3R - heat release rate 3,750 kW (3556 Btu/sec) burning one stack of wood pallets Calculated heat flux - 12 kW/m^2 (1.05 Btu/ft^2sec) to target fuel (wood pallet) Ignition is possible in this location Total heat release rate - 7,500 kW (7113 Btu/sec) burning of two stack of wood pallets</p>
<p>(3) Canyon Location 3R - heat release rate 3,750 kW (3556 Btu/sec) burning one stack of wood pallets Calculated heat flux - 26 kW/m^2 (2.28 Btu/ft^2sec)to target fuel (plywood box) Ignition is possible in this location Total heat release rate - 1,200 kW (1138 Btu/sec) burning of one plywood box</p>
<p>(4) Railroad tunnel 55 gallon drum filled with flammable liquid soaked rags - heat release rate 440 kW (0.41×10^3 Btu/sec) Calculated heat flux - 12 kW/m^2 (1.05 Btu/ft^2sec)to target fuel 210 L (55 gallon) drum Ignition is possible in this location Total heat release rate - 3,520 kW (3338 Btu/sec) burning of eight 210 L (55 gallon) drum</p>

Table 12 Total heat release rate estimates

Material	q_{ext} (W/cm ²)	C (s/mm) ^{1/2} (cm ² /W)	q_{ext}^a (W/cm ²)	q_{ext}^b (W/cm ²)	$\dot{h}$ (s ^{-1/2})	t_{in} (s)
Plywood, plain, 0.635 cm	0.4	1.8	1.2	1.6	0.07	190
Plywood, plain, 1.27 cm	0.3	1.5	1.4	1.6	0.07	225
Plywood, FR, 1.27 cm	...	...	...	4.4	0.10	110
Hardboard, 0.35 mm	0.4	5.8	1.0	1.0	0.03	1190
Hardboard, 3.175 mm	0.1	2.2	1.3	1.4	0.05	420
Hardboard (S159M)	0.1	1.8	1.5	...	...	...
Hardboard, gloss paint, 3.4 mm	1.1	4.1	1.8	1.7	0.05	468
Hardboard, nitrocellulose paint	0.4	2.0	2.1	1.7	0.06	306
Particle board, 1.27-cm stock	0.9	3.2	1.7	1.8	0.05	342
Douglas Fir particle board, 1.27 cm	0.6	2.0	1.7	1.6	0.05	395
Chipboard (S118M)	0.4	2.2	1.6	...	...	...
Wood panel (S178M)	0.4	1.1	1.6	...	...	...
Fiber insulation board	0.6	3.4	1.4	1.4	0.07	205
Fiberboard, low density (S119M)	0.1	1.3	1.2	...	...	...
Polysocyanurate, 5.08 cm	0.9	0.4	1.7	2.1	0.36	8
Polystyrene, 5.08 cm	...	...	...	4.6	0.14	53
Polysulfone (S353M)	0.2	1.0	0.9	...	...	...
Polycarbonate, 1.52 mm	2.2	1.5	3.0	3.0	0.06	260
Foam, rigid, 2.54 cm	0.6	0.6	2.0	2.0	0.32	100
Foam, flexible, 2.54 cm	0.2	1.2	1.2	1.6	0.09	132
PMMA Type G, 1.27 cm	0.1	2.0	1.6	1.5	0.05	456
PMMA polycast, 1.59 mm	0.3	3.4	1.0	0.9	0.04	462
Carpet #1 (wool, stock)	2.1	1.5	2.5	2.3	0.18	32
Carpet #2 (wool, untreated)	1.2	1.2	1.6	2.0	0.11	83
Carpet #2 (wool, treated)	1.4	3.2	1.6	2.2	0.12	72
Carpet (nylon/wool blend)	0.8	1.7	1.8	1.8	0.06	248
Carpet (acrylic)	0.4	1.8	1.1	1.0	0.06	250
Gypsum board, common, 1.27 mm	1.9	0.9	3.5	3.5	0.11	87
Gypsum board, FR, 1.27 cm	1.0	1.1	2.1	2.8	0.10	95
Gypsum board, wall paper (S142M)	0.7	5.8	1.0	1.8	0.07	208
Mineral wool, textile paper (S160M)	0.2	1.2	1.7	...	...	...
Asphalt shingle	0.3	2.7	1.6	1.5	0.06	306
Fiberglass shingle	1.8	1.5	2.7	2.1	0.08	161
GRP, 2.24 mm	0.1	1.3	2.0	1.6	0.09	132
GRP, 1.14 mm	1.4	2.9	1.6	1.7	0.06	279
Aircraft panel epoxy fiberite	...	...	...	2.8	0.13	57

Note: GPR = glass-reinforced polyester, FR = fire-retardant treatment.

^a From spread data.

^b From ignition data.

^c Flame spread was not measurable.

^d Data were not taken.

^e Values are only significant to two places.

Table 11 Ignition and flame spread characteristics under constant heat flux
(Quintiere and Harkleroad, 1985)

Figure 20b Representative test data on ignition for plywood based on LIFT test (Quintiere and Harkleroad 1984)

Based on the target heat flux, calculations indicate that at location 13L in the canyon 26 kW/m² radiant flux occurs from the one stack of wood pallet. This flux would ignite three stacks of wood pallets to raise the fire intensity to a total 15,000 kW (14,226 Btu/sec) (Table 12). Similarly, at location 3R in the canyon, the susceptibility of ignition of a stack of wood pallets and a wood box likely result in a total heat release rate of 8,700 kW (8,252 Btu/sec). The radiant heat flux from a 210 L (55 gal) drum fire in railroad tunnel to another 210 L (55 gal) drum filled with liquid flammable soaked rags raises the radiant heat flux was sufficient to ignite all drums in this location, i.e., 8 drums. In this case, a total heat release is approximately 3,520 kW (3,338 Btu/sec).

6.0 METHOD OF COMPARTMENT FIRE ANALYSIS

6.1 General

A multi-zone computer model, CFAST, is utilized for fire simulation. CFAST was developed at National Institute of Standard and Technology (NIST) (Peacock et al., 1993) and is capable of modeling steady or non-steady burning rates in multiple compartment configurations. The simulated ideal fires are user specified but are internally controlled in the model by fuel and air supply rates. The basic equations in the model describe the mass and energy transfer from zone to zone in a fire driven environment. The general form of the model is to divide each compartment into two zones: an upper zone which contains a hot layer, and a lower layer which is relatively cool. Mass and energy transfer between the zones is provided by the fire plume, mixing at the vents, radiation between layers, and heat transfer into the boundary surfaces. Overall, zone modeling using CFAST is based on the application of mass and energy conservation principles (control volume) to homogeneous upper and lower gas regions in multi-compartment systems.

Input data include the physical dimensions of the compartment, construction materials, physical properties of these materials, vents openings, ventilation systems, fire growth rates, and the position of the specified fire (see Table 13, CFAST input data for the canyon and tunnel).

Output results include smoke layer temperatures, the level of the position of the interface between the upper and lower layers, vents flows, gas species concentrations, differential pressure, and mass flows.

6.2 Fire Modeling

6.2.1 Fire Scenario Analyses

Fire modeling involves analysis of the impact of a fire in the canyon and railroad tunnel. The fuel arrays selected for fire hazard impact analysis were chosen based on fuel/combustible data and the site configuration as described in Section 3. The following fire scenario are examined:

- (1) Fire initiated in wood pallets at location 13L in the canyon deck inventory;
- (2) Fire initiated in wood pallets at location 3R in the canyon deck inventory;
- (3) Fire initiated in plywood box in the tunnel; and
- (4) Fire initiated in 55 gallon drums filled with liquid flammable oil soaked rags.

A series of computer analyses were performed to examine the thermal effects of the fire scenarios on the T-Plant canyon and railroad tunnel. Table 13 depicts the input data used for the CFAST computer program in order to perform the analysis.

(1) Compartment information and geometry:
Canyon - 245 m x 12 m x 12 m (804 ft x 40 ft x 40 ft) (width x depth x height) Railroad tunnel: 64 m x 6 m x 8 m (210 ft x 20 ft x 20 ft) (width x depth x height)
(2) Vent connection (horizontal and vertical flow connections between compartment in the structure include doors between compartments or windows in the compartments between compartments or to the outdoors). Canyon - One 2 m wide supply fan opening to the outdoor Railroad tunnel - One 20 m (66 ft) long by 0.10 m (4 in.) wide entrance door opening to the out door. Railroad tunnel - One 4.90 m (16 in.) wide by 6.70 m (22 ft) high vertical (ceiling) vent to the canyon.
(3) Mechanical ventilation system Canyon - Mass flow rate for 291-T exhaust system - 14 m ³ /sec (30,000 cfm) Mass flow rate for 221-T-13 exhaust system - 16 m ³ /sec (42,000 cfm) Mass flow for both exhaust systems - 34 m ³ /sec (72,000 cfm)
(4) Thermal properties The thermophysical properties of the enclosing surfaces, i.e., wall, ceiling and floor for the canyon and railroad tunnel are described by the concrete.
(5) Fire specification The fire specifications is describe the fire source in the simulation. The location, position, chemical properties of the fuel, area and height of the fire, heat of combustion, mass loss rate, and rate of heat release with fire time included in the input file. The heat release rates of the specified fire were estimated in Section 4 and 5 are the input for the CFAST fire simulation.

Table 13 Description of the CFAST input data file

6.2.2 Maximum Thermal Insult Analysis

The intensity of the fire is limited by the amount of oxygen available for the fire to consume. This oxygen is limited by the airflow in and out of the compartment and the resident oxygen in the compartment. In Section 4, it was calculated that sufficient air is available to support a fire in the 49-120 MW (47×10^3 to 114×10^3 Btu/sec) range. However, the actual scenarios developed and analyzed in Section 6.2.1 are limited to a maximum of approximately 15 MW (14,226 Btu/sec).

Therefore, to examine the maximum thermal insult to the structure, fires with a constant heat release rate of 49 to 120 MW (47×10^3 to 114×10^3 Btu/sec) were analyzed. This is the most significant fire in the canyon which is limited only by the exhaust flow rate from the canyon. Three ventilation scenarios have been identified for analysis:

- (1) floor exhaust fan on only, 291-T exhaust fan system;
- (2) roof exhaust fan on only, 221-T-13 exhaust fan system; and
- (3) floor and roof exhaust on, 291-T and 221-T-13 exhaust systems.

7.0 RESULTS AND DISCUSSION ON FIRE MODELING

7.1 Maximum Thermal Effects to the Structure

Results from the CFAST simulation of the maximum heat release rate supported by the existing ventilation are included in Table 14 for the three fire scenarios in Section 6.2.2. This analysis shows that flashover condition cannot be achieved in the canyon due to the ventilation rate and wall heat loss characteristics. Based on the actual fuels present, this analysis is vastly conservative and is included only to demonstrate that flashover of the space is not possible.

7.2 Resulting Conditions at the Canyon Based on Wood Pallet Fire at Location 13L

Table 15 provides a summary of the calculated room fire environment due to a wood pallet fire at location 13L in the canyon. Smoke layer temperature histories and smoke interface position are provided in Figure 21 for the three ventilation conditions. The maximum upper gas layer temperature 112°C (234°F) was achieved during forced ventilation of hot gases from the compartment. The smoke interface position corresponding to this temperature is 3.0 m (10 ft) above the floor. A 15,000 kW (14,226 Btu/sec) peak heat release rate was used in this case as discussed in Section 5.3 (Table 13).

Fire Scenario	Peak Heat Release Rate Q (kW)	Time (s)		Mass Flow (kg/s)				Critical Hazard Parameters													
		Peak t_{PEAK} (s)	Total Duration t_D (s)	Flow Out (kg/s)		Flow In (kg/s)		Canyon							Railroad Tunnel						
				Exhaust flow Canyon	Exhaust flow Tunnel	Vent flow Canyon	Vent flow Tunnel	Smoke Layer Temperature (°C)		Interface Position (m)	Differential Pressure (Pa)	O ₂ Concentration (%)	CO ₂ Concentration (%)	H ₂ O Concentration (%)	Smoke Layer Temperature (°C)		Interface Position (m)	Differential Pressure (Pa)	O ₂ Concentration (%)	CO ₂ Concentration (%)	H ₂ O Concentration (%)
								Upper	Lower						Upper	Lower					
291-T exhaust system on only	49x10 ³	1050	3000	11.46	-	2.33	7.44	216	110	0.27	-5.30	0.44	5.28	28	85	30	6.2	-11	0.96	5	27
221-T-13 exhaust system on only	70x10 ³	1255	2400	16.38	-	3.46	8.20	236	88	0.25	-7.40	0.30	5.18	28	119	30	6.2	-13	0.80	5	27
Both exhaust system on	120x10 ³	1644	1800	25.45	-	7.3	10.80	283	145	0.25	-16.30	0.163	4.98	10	95	30	6.2	-23	0.68	5	27

Table 14 Calculated values of critical hazard parameters based on exhaust flow rates. Fire origin canyon

Fire Scenario	Peak Heat Release Rate Q (kW)	Time (s)		Mass Flow (kg/h)				Critical Hazard Parameters													
		Peak t_{peak} (s)	Total Duration t_b (s)	Flow Out (kg/h)		Flow In (kg/h)		Canyon							Railroad Tunnel						
				Exhaust flow Canyon	Exhaust flow Tunnel	Vent flow Canyon	Vent flow Tunnel	Smoke Layer Temperature (°C)		Interface Position (m)	Differential Pressure (Pa)	O ₂ Concentration (%)	CO ₂ Concentration (%)	H ₂ O Concentration (%)	Smoke Layer Temperature (°C)		Interface Position (m)	Differential Pressure (Pa)	O ₂ Concentration (%)	CO ₂ Concentration (%)	H ₂ O Concentration (%)
								Upper	Lower						Upper	Lower					
291-T exhaust system on only	15x10 ³	582	660	14.75	-	6.90	7.76	112	36	1.0	-11.0	19.0	0.48	2.60	27	27	8	-12.0	20.70	0	0
221-T-13 exhaust system on only	15x10 ³	582	660	20.60	-	9.10	9.80	112	35	3.0	-18.0	19.0	0.47	2.50	27	27	8	-19.0	20.70	0	0
Both exhaust system on	15x10 ³	582	660	35.0	-	16.50	17.30	112	34	3.0	-59.0	19.0	0.47	2.50	27	27	8	-59.30	20.70	0	0

Table 15 Calculated values of critical hazard parameters based on wood pallet fire in the canyon at location 13L

Smoke layer temperature

291-T exhaust system on only

Smoke layer temperature

221-T-13 exhaust system on only

Smoke layer temperature

Both exhaust system on

Figure 21 Calculated smoke layer temperature and smoke interface position in the canyon due to wood pallet fire at location 13L

7.3 Resulting Conditions at the Canyon Based on Wood Pallet Fire at Location 3R

Table 16 provides estimates of room condition resulting from a fire at location 3R in the canyon. As illustrated in Figure 22, the maximum hot gas layer temperature 88.0°C (190°F) was achieved. The depth of the hot gas layer is 4.60 m (15 ft) above the floor. A 8,700 kW (8,252 Btu/sec) peak heat release rate was used for fire simulation.

7.4 Resulting Conditions at the Railroad Tunnel Based on the Plywood Box Fire

Results of plywood box fire simulation are provided in Table 17. Hot gas layer temperature histories and smoke depth position in the canyon and railroad tunnel are illustrated in Figures 23a through 23c for different ventilation conditions. A peak hot gas layer temperature of 39°C (102°F) in the canyon and 67°C (153°F) in the tunnel is calculated. The smoke layer position in the canyon at 39°C (102°F) is 11 m (36 ft) above the floor and in the tunnel at 67°C (153°F) is 5.0 m (16 ft) above the floor. A 1,200 kW (1,138 Btu/sec) peak heat release rate was used for fire simulation.

7.5 Resulting Conditions at the Railroad Tunnel Based on the 55 Gallon Drum Fire

The effects of a fire involving 55 gallon drums filled with flammable liquid soaked rags calculated by CFAST are presented in Table 18. Hot gas layer temperature histories and smoke depth position in the canyon and railroad tunnel are illustrated in Figures 24a through 24c for different ventilation conditions. A peak hot gas layer temperature of 52°C (126°F) in the canyon and 116°C in the tunnel is estimated. The smoke layer position in the canyon at 52°C (126°F) is 9.80 m (32 ft) above the floor and in the tunnel at 116°C (241°F) the smoke depth of the hot gas layer is 5.0 m (16 ft) above the floor. A 3,520 kW (3,338 Btu/sec) peak heat release rate was used for fire simulation.

Fire Scenario	Peak Heat Release Rate Q (kW)	Time (s)		Mass Flow (kg/h)				Critical Hazard Parameters											
				Flow Out (kg/h)		Flow In (kg/h)		Canyon					Railroad Tunnel						
		Peak t_{max} (s)	Total Duration t_p (s)	Exhaust flow Canyon	Exhaust flow Tunnel	Vent flow Canyon	Vent flow Tunnel	Interface Position (m)	Differential Pressure (Pa)	O ₂ Concentration (%)	CO ₂ Concentration (%)	H ₂ O Concentration (%)	Smoke Layer Temperature (°C)		Interface Position (m)	Differential Pressure (Pa)	O ₂ Concentration (%)	CO ₂ Concentration (%)	H ₂ O Concentration (%)
													Upper	Lower					
291-T exhaust system on only	8,700	442	660	15.60	-	5.45	6.0	2.30	-6.70	19.50	0.33	1.75	87.0	33.0	8	-7.30	20.70	0	0
221-T-13 exhaust system on only	8,700	442	660	20.60	-	8.70	9.30	4.60	-16.50	19.50	0.33	1.75	88.0	32.0	8	-17.0	20.70	0	0
Both exhaust system on	8,700	442	660	39.40	-	16.50	17.20	4.60	-59.0	19.50	0.33	1.75	88.0	32.0	8	-59.0	20.70	0	0

Table 16 Calculated values of critical hazard parameters based on wood pallet fire in the canyon at location 3R

Smoke layer temperature

Smoke interface position

291-T exhaust system on only

Smoke layer temperature

Smoke interface position

221-T-13 exhaust system on only

Smoke layer temperature

Smoke interface position

Both exhaust system on

Figure 22 Calculated smoke layer temperature and smoke interface position in the canyon due to wood pallet fire at location 3R

Fire Scenario	Peak Heat Release Rate Q (kW)	Time (s)		Mass Flow (kg/h)				Critical Hazard Parameters													
		Peak t_{peak} (s)	Total Duration t_b (s)	Flow Out (kg/h)		Flow In (kg/h)		Canyon							Railroad Tunnel						
				Exhaust flow Canyon	Exhaust flow Tunnel	Vent flow Canyon	Vent flow Tunnel	Smoke Layer Temperature (°C)		Interface Position (m)	Differential Pressure (Pa)	O ₂ Concentration (%)	CO ₂ Concentration (%)	H ₂ O Concentration (%)	Smoke Layer Temperature (°C)		Interface Position (m)	Differential Pressure (Pa)	O ₂ Concentration (%)	CO ₂ Concentration (%)	H ₂ O Concentration (%)
								Upper	Lower						Upper	Lower					
291-T exhaust system on only	1,200	165	1200	16.38	-	7.16	9.0	35.0	27.2	5.50	-11.2	20.2	0.15	0.60	67.0	28.0	5.0	-16.0	20.20	0.13	0.80
221-T-13 exhaust system on only	1,200	165	1200	23.40	-	11.0	12.50	39.0	27.2	11.0	-26.30	20.2	0.10	0.50	65.0	28.0	5.20	-31.0	20.20	0.174	0.75
Both exhaust system on	1,200	165	1200	39.78	-	21.30	22.70	36.0	27.2	9.10	-103.0	20.2	7x10 ⁻²	0.40	63.0	28.0	5.70	-99.0	20.20	0.12	0.62

Table 17 Calculated values of critical hazard parameters based on plywood box fire in the railroad tunnel

Canyon and tunnel smoke layer temperature

Canyon and tunnel smoke interface position

Figure 23a Calculated smoke layer temperature and smoke interface position in the canyon and railroad tunnel due to plywood box fire in the tunnel. 291-T exhaust system on only

Canyon and tunnel smoke layer temperature

Canyon and tunnel smoke interface position

Figure 23b Calculated smoke layer temperature and smoke interface position in the canyon and railroad tunnel due to plywood box fire in the tunnel. 221-T-13 exhaust system on only

Canyon and tunnel smoke layer temperature

Canyon and tunnel smoke interface position

Figure 23c Calculated smoke layer temperature and smoke interface position in the canyon and railroad tunnel due to plywood box fire in the tunnel. Both exhaust system on

Canyon and tunnel smoke layer temperature

Canyon and tunnel smoke interface position

Figure 24a Calculated smoke layer temperature and smoke interface position in the canyon and railroad tunnel due to 55 gallon drum filled with flammable liquid soaked rags fire in the tunnel. 291-T exhaust system on only

Fire Scenario	Peak Heat Release Rate Q (kW)	Time (s)		Mass Flow (kg/s)				Critical Hazard Parameters													
		Peak t_{peak} (s)	Total Duration t_o (s)	Flow Out (kg/s)		Flow In (kg/s)		Canyon							Railroad Tunnel						
				Exhaust flow Canyon	Exhaust flow Tunnel	Vent flow Canyon	Vent flow Tunnel	Smoke Layer Temperature (°C)		Interface Position (m)	Differential Pressure (Pa)	O ₂ Concentration (%)	CO ₂ Concentration (%)	H ₂ O Concentration (%)	Smoke Layer Temperature (°C)		Interface Position (m)	Differential Pressure (Pa)	O ₂ Concentration (%)	CO ₂ Concentration (%)	H ₂ O Concentration (%)
								Upper	Lower						Upper	Lower					
291-T exhaust system on only	3,520	282	1000	16.38	-	9.11	5.81	46.0	28.0	5.50	-7.50	20.0	0.25	1.30	118.0	29.50	5.0	-16.50	19.40	0.35	1.90
221-T-13 exhaust system on only	3,520	282	1000	23.40	-	9.70	12.10	52.0	28.0	9.80	-20.50	20.0	0.25	1.35	116.0	29.0	5.10	-29.0	19.50	0.33	1.80
Both exhaust system on	3,520	282	1000	39.78	-	19.60	21.40	48.0	28.0	8.20	-20.0	20.0	0.20	1.0	111.0	28.0	5.50	-91.0	19.60	0.30	1.50

Table 18 Calculated values of critical hazard parameters based on 55 gallon drum filled with flammable liquid soaked fire in the railroad tunnel

Canyon and tunnel smoke layer temperature

Canyon and tunnel smoke interface position

Figure 24b Calculated smoke layer temperature and smoke interface position in the canyon and railroad tunnel due to 55 gallon drum filled with flammable liquid soaked rags fire in the tunnel. 221-T-13 exhaust system on only

Canyon and tunnel smoke layer temperature

Canyon and tunnel smoke interface position

Figure 24c Calculated smoke layer temperature and smoke interface position in the canyon and railroad tunnel due to 55 gallon drum filled with flammable liquid soaked rags fire in the tunnel. Both exhaust system on

7.6 Summary of CFAST Modeling Results

The modeling performed using CFAST demonstrates that the identified fire sources can not generate fire conditions which would be expected to pose a thermal hazard to the structure. Local thermal exposures may of course be more significant in these scenarios, and times for smoke layer development are at least several minutes. As such, these fires do not appear to present significant hazard to the building structure.

8.0 HEPA FILTER PERFORMANCE

HEPA filters can withstand short periods of high temperature exposure 400°C (752°F) and long term exposure to lower temperatures 120°C (248°F) (DOE, 1993). Determination of the effects of the fire on the exhaust ventilation system is based on the failure of the HEPA filters or breach of the system. Breaching of the system can be caused by high temperature exposure to the HEPA filters, i.e., 135°C (275°F). According to one manufacturer of the HEPA filters (Flanders Filters (003-8-04-00-NU-GG-F)), HEPA's are fire resistant to spot temperatures up to 648°C (1198°F).

8.1 HEPA Filter Clogging

HEPA filters are provided in the exhaust system to filter out contaminants. Clogging of a HEPA filter will potentially prevent air from being exhausted and, therefore, eliminate the negative pressure required in contaminated areas.

The fire could affect the ability of the HEPA filter due to formation of aerosol under ventilation conditions. The aerosols are composed mainly of soot particles. The degree of filter plugging appeared to be directly related to the fuel load, fuel type, and air available for ventilation.

A complete analysis of filter clogging requires very detailed ventilation system data which in many cases, as for this facility, are not available. As such, simpler methods are required to

evaluate the effect of fire on HEPA filters. A review of the literature and the development of simple methods of analysis are included in Appendix A.

Based on the review of HEPA filter loading included in Appendix A, the amount of fuel burned which will cause filter clogging can be estimated. This is done on the basis of the number of HEPA filters available in parallel. No credit is taken for multiple stages since it is assumed that the important aspect of filter clogging is the increase in resistance and the accompanying reduction in flow which can cause loss of containment.

Table 19 summarized mass of fuel burned to causes HEPA filter failure in the T-Plant floor and roof exhaust ventilation system based on the existing filter area identified by the T-Plant facility management (WHC, September 1994). The floor exhaust system extracts 30,000 cfm air from the canyon and exhausts through four 6 ft by 6 ft banks of HEPA filters to outside. The roof exhaust system consists of an exhaust fan rated at 42,000 cfm that extracts canyon air through a 228 ft² bank of HEPA filters. The estimations for mass of fuel burned are based on the correlations developed in Appendix A. These results show that a limit of two stacks of wood pallets or two plywood boxes filled with combustibles or two 55 gallon drums filled with flammable liquid soaked rags is required in a single area of T-Plant inventory to prevent clogging of HEPAs in exhaust ventilation system during a fire.

Table 20 provides a summary of the results for mass of fuel burned for floor and roof exhaust ventilation system in terms of fuel packages, separation distance, and target heat fluxes in the T-Plant inventory. Heat flux from burning two stacks of wood pallets with separation distance of 20 ft cannot ignite another stack of pallet in the inventory, but burning of three stacks of wood pallets with same separation distance will ignite other stacks of wood pallets. If the separation distance for three stacks of pallets increases from 20 ft to 25 ft, the target heat flux is within the range of no ignition limit, but three stacks of wood pallets will potentially clog the HEPA filters in exhaust ventilation system.

Fuel	Mass fuel burned M_b	Recommended number of fuel packages allowed with separation distance
Wood	970 (kg/floor filter) 2138 (lb/floor filter)	Two stacks of wood pallets or two plywood boxes filled with combustibles at 20 ft separation distance (Eqi. mass for two pallets or boxes= 750 kg)
	1534 (kg/roof filter) 3382 (lb/roof filter)	Three stacks of wood pallets at 25 ft separation distance (Eqi. mass for three pallets=1050 kg) Three plywood filled with combustibles at 20 ft separation distance (Eqi. mass for three boxes=1050 kg)
70/30 n-Dodecane/TBP (Flammable & Combustible Liquid)	184 (kg/floor filter) 406 (lb/floor filter)	Two 55 gallon drums filled with flammable liquid soaked rags at 20 ft separation distance (Eqi. mass for two drums = 180 kg)
	300 (kg/roof filter) 661 (lb/roof filter)	Three 55 gallon drums filled with flammable liquid soaked rags at 20 ft separation distance (Eqi. mass for three drums = 270 kg)

Table 19 Mass of fuel burned to causes HEPA filter failure in T-Plant exhaust ventilation system

Therefore, only two stacks of wood pallets are allowed in the one location of T-Plant inventory. The target heat flux from burning one, two, or three plywood boxes or 55 gallon drums filled with flammable liquid soaked rags with separation distance of 20 ft is within the range of no ignition limit, but three burning of three plywood box or 55 gallon drums filled with flammable liquid soaked rags potentially clog the exhaust ventilation system; therefore, only two plywood box are allowed in a single location in inventory.

Fire source	Heat release rate (kW)	Target fuel	Separation distance between fire source and target fuel (m)	Radiative fraction γ_r^* (McCaffery 1981)	Heat flux** per unit area on target fuel (kW/m ²)	Ignition to target fuel	Eqi. mass of fuel (kg)	Mass of fuel burned M_b (kg/floor filter)	Mass of fuel burned M_b (kg/roof filter)
One stack of wood pallet	3,750	Wood pallet	6 (20 ft)	0.35	3.0	no	350	970	1534
Two stacks of wood pallets	7,500	Wood pallet	6 (20 ft)	0.35	5.80	no	700	970	1534
Three stacks of wood pallets	11,250	Wood pallet	6 (20 ft)	0.35	8.70	yes	1050	970	1534
Three stacks of wood pallets	11,250	Wood pallet	7.60 (25 ft)	0.35	5.40	no	1050	970	1534
Four stacks of wood pallets	15,000	Wood pallet	6 (20 ft)	0.35	11.60	yes	1534	970	1534
One stack of wood pallet	3,750	Wood pallet	6 (20 ft)	0.35	3.0	no	350	970	1534
One plywood box filled with combustibles	1,200	Repackaged LLW	6 (20 ft)	0.35	0.92	no	350	970	1534
Two plywood boxes filled with combustibles	2,400	Repackaged LLW	6 (20 ft)	0.35	1.85	no	700	970	1534
Three plywood boxes filled with combustibles	3,600	Repackaged LLW	6 (20 ft)	0.35	2.80	no	1050	970	1534
One 55 gallon drum filled with flammable liquid soaked rags	440	Repackaged RMW	6 (20 ft)	0.35	0.34	no	90	184	300
Two 55 gallon drums filled with flammable liquid soaked rags	880	Repackaged RMW	6 (20 ft)	0.35	0.68	no	180	184	300

* Most fuels have radiative fraction between 0.25 - 0.40

** Point source heat transfer model

Table 20 Mass of fuel burned for floor and roof exhaust ventilation system in terms of fuel packages and separation distance

8.2 Thermal Effects HEPA Filter Limits

Based on the results of the CFAST modeling, the thermal hazards to HEPA filters are negligibly small. Predicted compartment temperatures are less than HEPA filter temperature limits and heat losses in the exhaust ducts are significant.

9.0 Estimating Sprinkler Actuation Time in the Canyon and Railroad Tunnel

No sprinklers are currently installed in T-Plant. The provided calculations are intended to evaluate the potential value of ceiling mounted sprinklers.

Sprinkler response is dependent on the thermal characteristics of the sprinkler, its installation geometry, and fire exposure. Estimates of sprinkler response time were calculated using a computer model, DETACT-QS, as included in FPEtool (Nelson, 1990). Input parameters included the ceiling height (H), sprinkler head radial distance from the axis of the fire (r), the activation temperature (T_p), ambient temperature (T_a), the response time Index (RTI) of the sprinkler, and the growth rate of the fire. Input parameters used for this assessment are shown in Table 21.

Location	Fire growth rate, α (kW/m ²)	Ceiling height, H (m)	Radial* distance, r (m)	Sprinkler activation temperature, T_g (°C)	Ambient temperature, T_a (°C)	Response time index, RTI (m/sec) ^{1/2}
Canyon	0.044 (fast)	12 (40 ft)	2.15 (7 ft)	71 (160 °F)	25	165 300 (ft/sec) ^{1/2}
Tunnel	0.044 (fast)	8 (26 ft)	2.15 (7 ft)	71 (160 °F)	25	165 300 (ft/sec) ^{1/2}

* Calculated from sprinkler spacing selected as 10 ft.

Table 21 Input parameter for sprinkler activation

To determine the potential of a sprinkler being swept by the fire plume, an analysis is performed using Alpert's correlation (Evans, 1988) to evaluate the minimum heat release of a fire needed to raise the gas temperature at 71°C (160°F) in the canyon and tunnel.

The correlations developed by Alpert are as follows:

$$T_g - T_o = \frac{16.9 Q^{2/3}}{H^{5/3}} \quad \text{for } \frac{r}{H} \leq 0.18 \quad (9)$$

$$T_g - T_o = \frac{5.38 \left(\frac{Q}{r}\right)^{2/3}}{H} \quad \text{for } \frac{r}{H} > 0.18 \quad (10)$$

The calculations for heat release rate required to activate sprinkler system are provided in Table 22.

Location	Ceiling height, H (m)	Radial* distance, r (m)	Sprinkler activation temperature, T _g (°C)	Ambient temperature, T _∞ (°C)	Response time index, RTI (m/sec) ^{1/2}	r/H	Heat release rate (kW)
Canyon	12 (40 ft)	2.15 (7 ft)	71 (160°F)	25	165 300 (ft/sec) ^{1/2}	0.17 ≤ 0.18	2240 (Eq.9)
Tunnel	8 (26 ft)	2.15 (7 ft)	71 (160°F)	25	165 300 (ft/sec) ^{1/2}	0.26 > 0.18	1220 (Eq.10)

Table 22 Minimum heat release rate required to activate sprinkler system

Sprinkler type and location	Time to sprinkler activation (sec)	Fire size (kW)	Sprinkler actuation temperature (°C)
Conventional Canyon	∞	2240 (min)	71
	289	3865 (fast)	71
Conventional Tunnel	∞	1220 (min)	71
	239	2660 (fast)	71

Table 23 Sprinkler response conditions in the canyon and railroad tunnel

The results of the sprinkler activation calculations are shown in Table 23. Fast growing fires are detected in the tunnel and canyon in about 4 and 5 minutes, respectively. Of course, some fires of interest not grow to this size. While the activation times are longer, these fires can be detected if they exceed the minimum fire sizes of 1220 and 2240 kW for the tunnel and canyon, respectively.

Of major concern are the fuel packages which can cause HEPA filter failure but cannot activate sprinklers. For purpose of fire effects modeling, we have used conservatively high heat release rates. However, with regard to sprinkler activation, the conservation approach is to use maximum heat release rates. Thus, the worst case fires are lower heat release rates with long durations.

For pallet stacks fires which have a maximum heat release rate of 3750 kW, it is expected that heat release rates below the 2240 kW needed for activation of sprinkler in the canyon is unlikely, especially since two pallet stacks are not sufficient to cause HEPA filter failure.

The box storage maximum heat release was estimated at 600 to 1200 kW by two different methods. Using the lower of these values in the canyon could lead to a three box fire which could not activate sprinklers but could cause HEPA filter failure. As such, sprinklers may not effective for plywood box filled with combustibles storage.

Finally, the drum storage is the worst case for sprinkler. Drum burning rates may be much less than the maximum estimated here. As such, it is very probable that the heat release rate from three or more drums will be less than the fire site required for sprinkler

activation in either the tunnel or canyon. As such, sprinklers are of no value for either location for drum fires.

This analysis of sprinkler activation indicate that ceiling mounted sprinklers may not be effective in preventing HEPA filters failures due to fire.

10.0 Summary

A fire hazard (FH) analysis was performed for Building 221-T, T-Plant Complex canyon and railroad tunnel at the at the Department of Energy (DOE) Site, Richland, Washington. The analysis was conducted to determine the fire hazards associated with the combustible material storage in the building. The fuel arrays selected for the fire hazard impact were based on fuel/combustible data and situations provided by T-Plant facility. The results are presented in terms of the impact of fire on the building structure, content, and exhaust ventilation system. Quantification of radioactive release and their dispersion were not considered.

Results from the CFAST simulation using the maximum heat release rate supported by the existing exhaust ventilation shows that flashover condition cannot be achieved in the canyon due to the ventilation rate and wall heat loss characteristics.

The calculated compartment fire environment due to a wood pallet fire at location 13L in the canyon shows that the hot gas layer temperature of 112°C (234°F) is expected due to a 15,000 kW (14,226 Btu/sec) heat release rate with a smoke depth of 3.8 m (12.5 ft) above the compartment floor.

The maximum smoke layer temperature from CFAST simulation due to a 8,700 kW (8,252 Btu/sec) fire in the canyon at location 3R is 87.4°C (189°F) with a smoke position of 3.3 m (11 ft) above the floor. The impact from this size of fire is less significant than the fire at location 13L.

Fire involved a plywood box in the tunnel due to a 1,200 kW (1,138 Btu/sec) heat release rate is rise the canyon temperature only about 39°C (102°F), and a 68°C (154°F) smoke

temperature is expected in the tunnel. The smoke interface positions are 11 m (36 ft) and 4.8 m (16 ft), respectively.

A fire involved 210 L (55 gal) drums filled with flammable liquid soaked rags in the tunnel with a heat release rate of 3,520 kW (3,338 Btu/sec) raises temperature of the canyon up to 54°C (129°F), and the temperature rise in the tunnel is 115°C (239°F). The smoke layer position from this fire in the canyon 11 m (36 ft) above the floor and in the tunnel is 4.8 m (16 ft) above the floor.

Table 19 summarizes the mass of fuel burned which causes HEPA filter failure in the T-Plant based on the existing filter area identified by the T-Plant facility management (WHC, September 1994). The estimations for mass of fuel burned are based on the correlations developed in Appendix A. These results show that two stacks of wood pallets, two plywood boxes filled with combustibles, or two 55 gallon drums filled with flammable liquid soaked rags at separation distance of 20 ft are allowed in single areas of the T-Plant inventory to prevent clogging of HEPA's in exhaust ventilation system during a fire.

Based on these limits on fuel packages to prevent HEPA failure, calculations were performed to assess the required spacing between fuel packages to prevent ignition. Twenty feet was found to be a suitable spacing.

Sprinkler response time was estimated using DETACT computer model for the fire located in the canyon and railroad tunnel that grow as t -squared, fast fire. The calculations are based on conventional fixed temperature sprinkler with rated temperature of 71°C (160°F) and spacing of 10 ft. The results of the sprinkler activation calculations are shown that pallet fires are detected in the tunnel and canyon in about 4 and 5 minutes, respectively. Of course, some fires of interest not grow to the size of these pallet fires. While the activation times are longer, these fires can be detected if they exceed the minimum fire sizes of 1220 and 2240 kW for the tunnel and canyon, respectively.

For pallet stacks fires which have a maximum heat release rate of 3750 kW, it are expected that heat release rates below the 2240 kW needed for activation of sprinkler in the

canyon is unlikely, especially since two pallet stacks are not sufficient to cause HEPA filter failure.

The box storage maximum heat release was estimated at 600 to 1200 kW by two different methods. Using the lower of these values in the canyon could lead to a three box fire which could not activate sprinklers but could cause HEPA filter failure. As such, sprinklers may not be effective for plywood box filled with combustibles storage.

Finally, the drum storage is the worst case for sprinkler. Two drums is at the HEPA filter limit, but this fire could not activate sprinklers in either the tunnel or the canyon. Sprinklers are of no value for either location for drum fires. Overall, ceiling mounted sprinklers cannot be used to increase the fuel package limits established for boxes and drums to prevent HEPA filter failure.

11.0 CONCLUSIONS

The following conclusions are based on the analysis documented in this report:

- (1) Several of the candidate fire scenarios were quantified to allow assessment of the potential impact on the building, its contents, and exhaust ventilation system.
- (2) The thermal impact of the fire in the canyon and tunnel environment would be minor due to the compartment size and ventilation system.
- (3) In all fire scenarios, the heat release rate is limited below that which could result in significant damage to the structure.
- (4) The potential for the release of hazardous products of radioactive waste exists due to HEPA filter failure. Based on a review of literature results, limits on fuel packages to two pallet stacks, two boxes, or two drums are needed to prevent HEPA filter failures due to fire.

- (5) Results of the analysis of steady state fire scenario demonstrated that maximum possible fire (120 MW) (114×10^3 Btu/sec) could not raise the upper layer temperature in the space to a level that could result in flashover.
- (6) The separation distance of 20 ft between fuel packages is sufficient to prevent ignition to nearby fuel packages because corresponding heat flux is within the range of no ignition limit. This is based on the fuel package limits required to prevent HEPA failure.
- (7) Installation of ceiling mounted sprinklers in the canyon and railroad tunnel is not expected to be effective in allowing increased fuel package limits for boxes and drums.

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APPENDIX - A

REVIEW - SMOKE AEROSOL EXPOSURE TO HEPA FILTERS

Appendix - A
Review - Smoke Aerosol Exposure To HEPA Filters

A-1 Introduction

A review was made of the literature on the behavior of High Efficiency Particulate Air (HEPA) filters when exposed to smoke aerosols. The intent was to provide information useful in assessing the potential risk associated with fire smoke loading in nuclear air cleaning systems. Data, formulas, and method are presented and discussed.

Accidental fires involving liquid and solid fuels in industrial process and/or nuclear facilities can pose a serious fire hazard. The ventilation systems for nuclear facilities include HEPA filtration to provide safeguards for the confinement of radioactive material. The systems are necessarily negative pressure systems, i.e., the air moving fan is the last component of the ventilation circuit, and ventilated enclosures have negative pressure relative to the ambient atmospheric pressure. Upstream of the fan is the final HEPA filter station to confine radioactive materials within the process plant.

The susceptibility of HEPA filters to fire effects was demonstrated by the occurrence of an insignificant release of radioactive contaminants during the second fire at Rocky Flats in 1969. In this event, investigators concluded that the final HEPA filter in a specific ventilation circuit failed resulting in the loss of containment.

The results of the literature review indicate that filter failure or air cleaning system malfunction is due primarily to the increase in filter pressure drop resulting from filter plugging by smoke during the fire.

Performance and regulation requirements on fire prevention and fire protection in smoke ventilation systems for HEPA filters are covered in various references (Burchsted et al. (1976), Burgess (1989), Donovan (1985), Brown (1993), and Goodfellow (1985)).

By definition a HEPA is a "throwaway, extended-medium, dry type filter" having the following characteristics (Goodfellow (1985)).

- (1) A minimum particle removal efficiency of 99.99% for 0.3 micron particles.
- (2) A maximum resistance, when clean, of 0.25 kPa (1 inch of water) when operated at rated airflow capacity.
- (3) A rigid casing extending the full depth of the medium.

Common air filters used in conventional air cleaning applications are unable to decontaminate air to the levels required to meet the maximum permissible concentration values that have been established for radioactive substances in air. The lowest threshold limit values specified for most chemical contaminants in air are at least two orders of magnitude higher than the maximum permissible concentration of any radioactive material. HEPA filter must be used to meet these very low levels. The primary factor in filter replacement is pressure drop. Typically, HEPA filters are replaced when the pressure drop exceeds 1 kPa (4 in. of water). By specifications, HEPA filter must have sufficient structure pressure to withstand a continuously applied overpressure of 1.25 kPa (5 in. of water) or higher for at least 900 seconds without visible damage or loss of efficiency. A peak pressure differential of 2.5 kPa (10 in. of water) across the HEPA filter causes failure, thus causing degradation in overall system performance. Normal practice is to have an overall pressure drop over the filter system of not more than about 1 kPa (4 in. of water) since fan power costs become excessive beyond this and significant losses of filtration performance.

A number of studies on the clogging of HEPA filter due to collection of combustion aerosol particles within the filtration media in reprocessing plants have been conducted through testing. These were performed at Lawrence Livermore National Laboratory (LLNL), Japan Atomic Energy Research Institute (JAERI), Los Alamos National Laboratory, Pacific Northwest Laboratory (PNL), and Kernforschungszentrum Karlsruhe (KfK). The experiments performed demonstrate the consequences of a fire on the integrity of HEPA filters due to smoke plugging. In this review, these data will be interpreted in the context of available filter model/correlation methods.

A-2 Filtration Models

Filtration models are either concepts or mathematical relationships that describe or predict filter performance. The common measures of filter performance are pressure drop, collection efficiency, and life. This discussion includes a very brief summary of the filter models used for representing the effects of fire aerosols on filter flows.

A-2.1 Resistance Model

For purposes of predicting ventilation flow rate, it is necessary to represent the effect of filter loading on the filter flow resistance, R , and the flow through the filter, Q , is given by

$$Q = \frac{\Delta P}{R}$$

Data on filter resistance can be represented as

$$\frac{R}{R_o} = 1 + \alpha_R M_a + \beta_R M_a^2 \quad A1$$

where R = filter resistance,
 R_o = clean filter resistance,
 M_a = mass of soot on the filter,
 α_R = model constant, and
 β_R = model constant.

Since Equation A1 requires that soot yields or soot generation rates be known, it is convenient correlate data based on the material burned rather than the soot yield generated.

If we recognize that soot yield, ψ_s , is defined as

$$\psi_s = \frac{m_{soot}}{M_b} \quad A2$$

where m_{soot} = mass of soot generated, and
 M_b = mass of the fuel burned.

Equation A1 can be expressed as

$$\frac{R}{R_o} = 1 + \alpha_R (\psi_s M_b) + \beta_R (\psi_s M_b)^2 \quad A3$$

A-2.2 Pressure Drop Model

While filter resistance is the relevant parameter for ventilation flow prediction, several investigators have not included both pressure drop and flow rate data in their testing. Therefore, data are correlated on the basis of pressure drop, in analogy with resistance as

$$\frac{\Delta P}{\Delta P_o} = 1 + \alpha_p M_a + \beta_p M_a^2 \quad A4$$

where ΔP = pressure drop across filter,
 ΔP_o = initial pressure drop of clean filter,
 α_p = pressure based filter constant, and
 β_p = pressure based filter constant.

Here again, this can be expressed in terms of mass burned.

$$\frac{\Delta P}{\Delta P_o} = 1 + \alpha_p (\psi_s M_b) + \beta_p (\psi_s^2 M_b^2) \quad A5$$

A-2.3 Flow Reduction Method

Simple estimates of the quantity of fuel which upon burning seriously degrade ventilation system performance are often required. Alvares et al. (1978, 1980) have correlated their data in the form of mass burned to cause a 50 percent reduction in ventilation system flow. While 50 percent reduction in flow is a somewhat arbitrary endpoint, it certainly is indicative of serious effects. This correlation takes the form

$$C = \dot{m}_b t_{plug} \quad A6$$

where $\dot{m}_b$ = burning rate,
 t_{plug} = time to reduce flow by 50 percent, and
 C = mass burned up to the time 50 percent flow reduction was realized.

A-3 Filter Clogging Definition

Based on Equation A1 and a complete hydraulic description of the ventilation system, the HEPA flow can be predicted in a fire incident. Unfortunately, it is often not possible to provide such detailed description of the ventilation system. As such, it is necessary to define operational definitions of filter failure. Several such definitions have been developed by various investigators.

Alvares et al. (1978, 1980) have developed the correlation of 50 percent flow reduction as failure criteria. This criteria or definition of failure is inherent in Equation A6, and Alvares et al. data reduction methods.

Fenton et al. (1983) have defined $R/R_0 = 12$ as filter failure. Their definition corresponds to a filter pressure drop of 2.5 kPa (10 inches of water). The rationale for this criterion is not given.

A final correlation which can be used a pressure drop of 2.5 kPa (10 inches of water) over the filter. This criterion is derived from pressure drops across filters which can cause structural

failure of the filter, leading of course to loss of filter function. Based on a normal clean filter pressure drop of about 0.25 kPa (1 inch of water), this is very similar to the Fenton et al. criterion. However appropriate $\Delta P/\Delta P_0$ or $\Delta R/\Delta R_0$ equals 10-12 may be for experimental studies, it is not appropriate for hazard analysis.

For hazard analysis, one must assume that the filter is already as dirty as is allowed at the time of the fire. Normally, filters are replaced at a pressure drop of 1 kPa (4 inch of water). Thus, the fire need only increase ΔP from 1 kPa to 2.5 kPa (4 inch to 10 inch of water) rather than 0.25 kPa to 2.5 kPa (1 inch to 10 inch of water). Thus, we need to determine the mass of fuel which increase ΔP from 1 kPa to 2.5 kPa (4 inch to 10 inch of water) for purpose of evaluation the worst case found in practice. Using Equation A5, we have the following as the fuel equivalent, $M_{b,dirt}$, needed to reach $\Delta P/\Delta P_0 = 4$

$$\frac{\Delta P}{\Delta P_0} = 1 + \alpha_p \psi_s M_b$$

$$4 = 1 + \alpha_p \psi_s M_{b,dirt}$$

$$M_{b,dirt} = \frac{3}{\alpha_p \psi_s}$$

At $\Delta P/\Delta P_0 = 10$ we have

$$10 = 1 + \alpha_p \psi_s M_{b,gross}$$

The mass burned to change $\Delta P/\Delta P_0$ from 1 kPa to 2.5 kPa (4 inch to 10 inch of water) is

$$M_{b,gross} = \frac{9}{\alpha_p \psi_s}$$

$$M_b = M_{b, gross} - M_{b, dirt} = \frac{9 - 3}{\alpha_p \psi_p}$$

$$M_b = \frac{6}{\alpha_p \psi_p} \quad A7$$

This value for fuel burned to cause failure can also be used as a criterion for failure based on initially dirty filters. The value is 2/3 that which would occur for clean filters.

A-4 Review of Available Filter Clogging Data

In this section, we review the available data for filter performance during fires. The data will be examined in the context of filter models used by the investigators.

Alvares et al. (1978, 1980) conducted a series of experiments which illustrate the filter plugging rate for various combustible material that are common in nuclear facilities. Wood cribs and other potential fuels were burned in an enclosure specifically designed and instrumented for fire tests. Seven types of fuel elements from materials were selected for testing, abundant in laboratories where radioactive materials are used or stored. When airflow through filter reached half the initial flow rate they considered the filter plugged. They conducted comparative analyses with data taken at the temperature peak and again just prior to significant flow reduction. Along with this data, they measured total aerosol concentration and rough aerosol size distribution at the exit to the test cell and just upstream of the HEPA filter. Table A1 lists the values of aerosol mass and mass distribution measurements using cascade impactors positioned near the exit to the test cell and at the upstream surface of the HEPA filter. It is significant that while concentration of aerosol at the filter face is sometimes less than at the compartment, the reduction in aerosols is small.

Impactor at exit of test cell						Impactor at HEPA station			
Test	Material for crib	Conc, mg/m ³	Gross mass distribution			Conc, mg/m ³	Gross mass distribution		
			d > 3	d > 1	d < 1 ^a		d > 3	d > 1	d < 1 ^a
PB-7	Tight fir wood					0.001	82	2	16
B-2	Loose fir wood					0.005	3	60	37
B-3	PMMA-FR					0.001	3	44	53
B-11	Polycarbonate					0.0007	14	58	28
B-15	Dense fiberboard	0.002	12	71	17	0.002	6	67	27
B-17	Polyvinyl chloride	0.002	10	69	21	0.002	10	63	27
B-18	Fiber-reinforced polyester	0.001	61	21	18	0.002	56	15	29
B-20	Composite	0.006	42	57	1	0.005	25	72	3
B-21	Loose fir wood	0.013	62	32	6	0.009	49	23	28
B-28	Loose fir wood	0.006	68	25	7	0.002	89	0	11

^a d = Aerosol diameter in microns.

Table A1 Aerosol mass and mass distribution measurement (Alvares et al. 1978)

The plugging tests involved smoke generation from variety of fuels in different configuration. The material used for smoke production were selected by surveying the composition and distribution of combustible materials that were used for construction of enclosures-contained appliances, and materials that were necessary for the operational function to the facility. Selected fuels were fir, polymethylmethacrylate, polycarbonate, dense fiberboard, polyvinylchloride, fiber reinforced polyester, and composite. The tests results are presented in Alvares et al. (1978, 1980) study for all of the above materials with different configuration. The data are ambient temperature ($^{\circ}\text{C}$), relative humidity (%), exit airflow rate (L/sec), initial fuel weight (kg), final fuel weight (kg), fuel consumed (m), maximum cell temperature ($^{\circ}\text{C}$), maximum duct temperature ($^{\circ}\text{C}$), filter dry bulb temperature ($^{\circ}\text{C}$), filter wet bulb temperature ($^{\circ}\text{C}$), test cell plug temperature ($^{\circ}\text{C}$), maximum test cell temperature ($^{\circ}\text{C}$), filter plug time (sec), filter pressure drop (Pa), wet mass at upstream impactor (mg), dry mass at upstream impactor (mg), aerosol size at upstream, wet mass at downstream impactor (mg), dry mass at downstream impactor (mg), aerosol size at downstream, oxygen concentration (%), carbon monoxide concentration (%), carbon dioxide concentration (%), and methane (ppm). The bulk of the experiments were conducted with wood fuels.

Based on these results, we can estimate the amount of burned material required to cause a fifty percent reduction in airflow. A fifty percent reduction in airflow is defined as failure by clogging of the HEPA filter in Alvares et al. (1978, 1980) study.

The measured mass of wood to clog the filter are presented in Table A2. The mean and the standard deviation of C for wood shows the amount of wood required to clog the filter. Based on this analysis of test data, exhausting combustion products from burning 26 kg of wood through the HEPA filter can clog the 0.61 m x 0.61 m (2 ft x 2 ft) HEPA filter by the 50 percent reduction in flow criterion. The standard deviation in the mass burned of 14.5 kg (32 lb) indicates a wide range of experimental results. No systematic trends were observable, so that the variation is assumed to be random.

Fuel type and configuration (wood)	$\alpha_p \psi_s$ (1/kg/filter)	C (kg/filter)
PB-8 Fir, tight layers, staggered	0.153	41.40
PB-82 Fir, tight layers, staggered	0.120	46.0
B-1 Fir, loose layers, staggered	0.201	10.4
B-2 Fir, loose layers, staggered	0.421	10.80
B-13 Fir, standard crib	0.223	25.90
B-14 Fir, standard crib	0.212	51.60
B-21 Fir, standard crib, low inlet, low output vents	0.185	33.0
B-27 Fir, standard crib	0.188	-
B-28 Fir, standard crib, overload ventilation	0.268	16.0
B-29 Fir, standard crib	0.268	30.0
Mean	0.22	29.45
Standard deviation	0.082	15.10

Table A2 Analysis of Alvares et al. (1978 & 1980) results

While Alvares et al., (1978, 1980) did not analyze their data in terms of Equation A5. They did provide the data needed for such an analysis. Thus, for the wood test conducted by Alvares et al., the values of $\alpha_p \psi_s$ were determined and are reported in Table A2.

Using Equation A7 this yield

$$M_b = \frac{6}{\alpha_p \psi_s} = \frac{6}{0.22} \frac{kg}{filter}$$

$$M_b = 27 \frac{kg}{filter}$$

This is remarkable close to the 26 kg (54 lb) derived based on 50 percent flow reduction. Given the vast differences in the models, this similarity must be regarded as fortuitous.

Fenton et al. (1983) conducted experiments on HEPA filter loading by combustion products to determine how airflow resistance varies with particulate mass concentration. The combustion of two organic fuels, polystyrene (PS) and polymethylmethacrylate (PMMA), at varying conditions generated the particulate material plugging the filters.

Physical characteristics of the soot and HEPA filter plugging data were presented. Seven HEPA filters were plugged with polystyrene combustion products and four filters were plugged with polymethylmethacrylate combustion products. Details concerning the plugging process for each filter are shown in Figure A1 and A2, where the airflow resistance offered by the filter is given by

$$R = \frac{\Delta P}{Q}$$

where R = resistance,
 ΔP = pressure drop across the filter, and
 Q = airflow rate.

The actual resistance is normalized by the initial clean filter resistance, R_0 in the figures. HEPA filter resistance ratios R/R_0 , in both cases is up to a value of 14.0 for each filter. The data in Figure A1 shows the influence of the polystyrene mass burning rate on the quantity of the particulate material collected necessary for plugging. These data can be used to explain the variation in polystyrene combustion particulate mass necessary to plug the HEPA filter. Figure A2 shows the results obtained when four HEPA filter were plugged with polymethylmethacrylate combustion products.

Fenton et al. (1983) correlated their data using Equation A1. They correlated their results on the basis of the ventilation provided to the fire. Polystyrene Tests 3 and 5 were low ventilation and polymethylmethacrylate Tests 9 and 11 were low ventilation. Their correlation of data is shown in Table A3. Their results indicate that well ventilated fires generate more particulate than poorly ventilated fires.

Figure A1 Measured airflow resistance across the HEPA filters due to polystyrene combustion products (Fenton et al. 1978)

Figure A2 Measured airflow resistance across the HEPA filters due to polymethylemethacrylate combustion products (Fenton et al. 1978)

Fuel	Ventilation of fire	α_R	β_R
PS	High	0.0207	0.735×10^{-5}
PS	Low	0.0048	0.277×10^{-7}
PMMA	High	0.0477	$- 0.308 \times 10^{-4}$
PMMA	Low	0.0641	$- 0.573 \times 10^{-4}$

Table A3 Filter resistance correlation (Fenton et al. 1983)

A summary of the results for both fuels is also given in Table A4. The HEPA filters tested with polystyrene had a protective metal screen (1 cm x 1 cm) with the exception of filters numbered 6 and 7. In polymethylmethacrylate combustion products plugging tests, all four of the HEPA filters had the protective screen removed and filter number 11 incorporated asbestos separators within the filtration media in place of the aluminum separators used in all previous filters. Figure A2 shows that HEPA filter number 11 displays essentially normal behavior regarding plugging, thus indicating that the separator material does not discernably influence the plugging characteristics for polymethylmethacrylate combustion products.

Fuel type	Filter Number	Clean static pr.drop (cm of water)	Apparent mass burning rate (g/min)	Total deposited* particulate mass for plugging (g)
Polystyrene	1	2.1	19.4	527
Polystyrene	2	2.1	21.3	432
Polystyrene	3	2.1	15.4	1256
Polystyrene	4	2.1	21.7	405
Polystyrene	5	2.1	17.5	1207
Polystyrene	6	2.1	22.9	423
Polystyrene	7	2.1	21.3	391
PMMA	8	2.2	11.6	233
PMMA	9	2.2	12.4	257
PMMA	10	2.2	15.6	186
PMMA	11	2.2	13.4	309

* Plugging is defined as $R/R_0 = 12$

Table A4 Summary of combustion products plugging of HEPA filters (Fenton et al. 1983)

Reviewing together the polystyrene and polymethylmethacrylate combustion aerosol plugging of HEPA filter suggests some rough trends. First, the expected soot fractions and total particulate mass concentrations, when related to fuel mass burning rate correlate and establish a consistent trend. And second, a rough correlation exists between the particulate mass concentration and accumulated mass gain of the filter necessary for plugging.

Conclusions from this work are restricted to quantitatively establishing HEPA filter plugging characteristics for polystyrene and polymethylmethacrylate combustion aerosols. The resistance ratio is observed to be nearly linear with respect to the accumulated mass of combustion aerosol in both cases.

Based on the Fenton et al. (1983) work for PS, under well ventilated conditions about 400-500 g (0.88 to 1.1 lb) of soot cause a $R/R_0 = 12$. For PMMA, 200-300 g (0.44 to 0.66 lb) of soot are needed to yield $R/R_0 = 12$. These differences result from differences in particle size distributions. Since the soot yield of PS is much greater than PMMA, based on mass burned rather mass accumulated, one would expect PS to be for worse than PMMA. Fenton et al. (1983) did not provide systematic measurement of mass burned so that correlation on this basis is not possible.

Ballinger et al. (1988) summarizes the results of small and large scale tests conducted at Kernforschungszentrum Karlsruhe (KfK) Federal Republic of Germany, Pacific Northwest Laboratory (PNL) USA, and Japan Atomic Energy Research Institute (JAERI). Objectives of these fire tests were to obtain information on the behavior of solvent fire in a cell and on the integrity of high efficiency particulate air filters due to aerosol smoke plugging and evaluate confinement of radioactive materials released during the solvent fire containing fission products through ventilation systems equipped with HEPA filters under postulated fire conditions.

The results of numerous solvent pool fire tests conducted at KfK of different pool areas and of solvent burning rates were presented by Ballinger et al. (1988). The solvent fires includes kerosene fires as well as fires involving a mixture of a tributyl phosphate (TBP) and kerosene. The aerosols are composed mainly of soot but also contain butyl phosphoric acid and phosphoric acid in kerosene-TBP fires. In contrast to the burning rate, the aerosol formation is not constant

during the whole burning period. Fires of kerosene-TBP mixtures have substantially higher aerosol formation rates than fires of pure kerosene. The integral aerosol formation for kerosene fires is ~2% of the burned solvent, while for kerosene-TBP mixtures (70/30) it is up to 14% with maximum values of 25% shortly before the fire is extinguished. Figure A3 demonstrates the soot or aerosol yield. Increasing the TBP concentration during the fire as shown in Figure A4 increases the aerosol formation. TBP was identified as the aerosol forming substance.

The filtration of soot particles were performed using sandbed and HEPA filters in the filter test loop. Sandbed filters might be used as safety filters to reduce pressure and temperature and particle concentration during fire. They might be used as prefilters followed by HEPA filters. Therefore HEPA and sandbed filters were tested with respect to their loading capacity, pressure drop and failure limitation. The pressure increase with increasing challenge by soot particles is shown in Figure A5 for different sandbed for HEPA filters. The loading capacity per meter square ventilation cross section is higher by a factor of 3 for sandbed filter than for HEPA filter.

Results from the large fire tests conducted at Japan Atomic Energy Institute were also provided by Ballinger et al. (1988). These tests were performed with instruments to measure temperature, pressure, flow rates, pressure drop across the HEPA filter, and mole fraction of combustion gases. A laser type aerosol monitor was provided at the upper and lower streams of the HEPA filters. 100% n-Dodecane and 30 vol.% TBP in dodecane on water were used for pool fires. The range of airflow rates was 120 to 600 m³/hr, which corresponds to 3 to 6 air volume changes per hour and burning areas ranging from 0.0768 to 1.84 m² (0.82 to 19.80 ft²). A burning pan was placed on a heater plate in the cell. The solvent and water containing non-radioactive nuclei in the pan were ignited at 40°C (104°F) by a propane gas burner. The inlet airflow was controlled by a flow control valve to maintain a fixed volume change rate for each test. The airflow at the dilution duct was also controlled to maintain the nominal flow rate of 4,380 m³/h for six half size HEPA filters. The pressure drop across HEPA filters was measured to estimate the endurance of filters due to smoke loading. Figure A6 shows the pressure drop across the filter versus the smoke loading for one unit of HEPA filter (grams per half filter unit). Increases in pressure drop (ΔP) are caused by the increase in smoke loading on the filter unit

Figure A3 Aerosol formation during pool fires (Ballinger et al. 1988)

Figure A4 Solvent concentration during pool fires (Ballinger et al. 1988)

Figure A5 Measured particles mass loading and pressure drop of sandbed and HEPA filters
(Ballinger et al. 1988)

Figure A6 Measured pressure drop across the HEPA filters due to 100% n-Dodecane particulate mass loading (Ballinger et al. 1988)

in both types of solvent fire. In both cases in Figure A6, though the data is scattered, the pressure drop shows the identical trend due to smoke aerosol loading.

Ballinger et al. (1988) correlated their data using Equation A4 in the form

$$\Delta P = \Delta P_o + 0.14 M_a + 1.6 \times 10^{-4} M_a^2 \quad A8$$

where ΔP is in mm H₂O and M_a is in gram/whole filter (Note Figure A6 is expressed in gram/half filter). In these experiments 70/30 mixture of n-Dodecane/TBP were found to have yields of 0.05 (about 1/3 the German results).

Maximum pressure drop ΔP (mm of water)	Measured accumulated mass of the smoke aerosol on HEPA (m _f kg per unit)	α_p (1/kg/unit)
31.25	0.031	4.78
31.75	0.052	3.06
40.50	0.068	5.02
37.90	0.90	3.19
56.90	0.096	7.06
60.0	0.112	6.44
47.25	0.140	3.43
75.66	0.142	7.57
80.82	0.143	8.06
92.85	0.153	9.43
98.45	0.153	10.07
62.75	0.167	4.81
Mean	-	6.07
Standard deviation	-	2.39

Initial Pressure Drop = 24.0 mm of water

Table A5 Pressure drop and 100% n-Dodecane particulate mass loading results
(Ballinger et al., 1988)

Organic solvents (hydrocarbon) fires have substantially higher aerosol formation rates than wood fires. With respect to the filtration of aerosol smoke loading, the pressure drop across the

HEPA filter is also higher for solvent fires. Now we shall examine the difference in α_p for 100% n-Dodecane and wood burning. Figure A6 data are used to determine the pressure drop and smoke loading for one unit of the HEPA filter from 100% n-Dodecane pool fire. From this data, α_p is calculated using Eq. A4. Here we have chosen to use $\beta_R = 0$ for comparison with the Alvares et al. (1983) wood data.

For Alvares et al. (1978, 1980) wood data $\alpha_p \psi_s$ was 0.22. Using $\psi_s = 0.05 - 0.14$ and $\alpha_p = 6.07$ yields $\alpha_p \psi_s = 0.30 - 0.85$. For 70/30 dodecane using Equation A7, this corresponds to 7 - 20 kg (15.5 - 44 lb) of solvent per filter. Thus, while the soot yield of n-Dodecane soot is much higher than wood, the effectiveness of wood in clogging filters is nearly comparable to liquid hydrocarbon fuels.

Nisio et al. (1991) reported the effect of kg of 70/30 n-Dodecane/TBP on the pressure drop across a filter (see Figure A7). They found that a pressure drop of 2.5 kPa (10 inch of water) was achieved when 5-7 kg (11 - 15.5 lb) of solvent burned per standard filter. The 5 kg estimate is based on Test BOIL 3003 data and the 7 kg estimate is based on extrapolation of BOIL 3001 and 20A1 data. (BOIL 3001, 3003, and 20A1 are test numbers in Fig. A7.) Based on a dirty filter ($\Delta P = 1$ kPa (4 inch of water)), the mass needed to reach $\Delta P = 2.5$ kPa (10 inch of water) was 3 - 4 kg (6.6 - 8.8 lb).

A-5 Summary of Clogging Results

The mass of fuel burned which is needed to cause filter failure has been estimated based on several data sets. These results are summarized in Table A6. It is important to note that the investigator listed was the source of the data and the authors themselves did not in all cases deduce the mass burned to clog the filter.

Figure A7 Pressure drop across the front stage of six HEPA filters compared with cumulative mass weight of burned solvent per half size filter (Nisio et al. 1991)

Investigator	Fuel (kg)	Mass fuel burned per filter (kg/filter)
Alvares et al. (1978 & 1980)	wood	27 (60 lb/filter)
Ballinger et al. (1988)	70/30 n-Dodecane/TBP	7 - 20 (15.5 - 44 lb/filter)
Nisio et al. (1991)	70/30 n-Dodecane/TBP	3 - 4 (6.6 - 8.8 lb/filter)

Table A6 Summary of clogging results

Based on these results the recommendations shown in Table A7 are made. The wood value is the average value deduced by two different methods from Alvares data. The flammable/combustible value is average of minimum value deduced from the Ballinger's data and the Nisio data. While it is prudent to be conservative in the face of uncertainties, there is no obvious reason to discount the Ballinger's results. As such an average of the Ballinger and Nisio results have been used as a best estimate of the allowable fuel per filter. The conservative nature of the data treatment for flammable/combustible liquid reflects the assumptions needed in the analysis and the very limited amount of data available.

Fuel	Mass fuel burned per filter (kg/filter)	Mass fuel burned per m ² (kg/m ²)
Wood	27	72
Flammable and combustible liquid	5*	13.5

* The recommended mass fuel burned for flammable and combustible liquid, 5 kg/filter is average of 3 and 7 kg/filter from Table A6
Table A7 Mass of fuel burned per m² which causes filter failure in exhaust ventilation system

A-6 Thermal Damage to the HEPA Filter

HEPA filters can withstand short periods of high temperature exposure 400°C and long term exposure to lower temperatures 120°C (DOE, 1993). Determination of the effects of the fire on the exhaust ventilation system is based on the failure of the HEPA filters or breach of the system. According to the manufacturer the filters used, Flanders Filters (003-8-04-00-NU-GG-F) are fire resistant to spot temperature to 648°C.

Alvares et al. (1978, 1980) observed that heat losses through duct wall was sufficiently great that 10 duct diameters downstream of the fire compartment, gas temperatures were sufficiently low to prevent thermal failure of the filter. Thus, while in general duct heat transfer calculations are needed to assess thermal effects on the filters, for many duct systems filters will be more than 10 diameters away from the compartment and no thermal failure would be expected.

A-7 Smoke Aerosol Mass Accumulation Prior to the HEPA Filter

The smoke aerosol from a fire effects the filter performance by aerosol accumulation on the filter exposure surface, reduces the airflow rate. A portion of this fire generated aerosol mass is also accumulated on the surfaces of the compartment walls and exhaust duct. While some estimates of aerosol loss to surfaces are given in the experimental programs reviewed here, the results and supporting theory are not sufficiently well developed to take credit for soot deposition beyond that inherent in the tests themselves. As such, the only credit taken for soot deposition is that inherent in the experiments reviewed. Of course, the duct lengths and compartment sizes used by these investigators were relatively small so that deposition is expected to be larger in large complex systems.

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