CHAPTER 10

FIRE PROTECTION

10.1 Introduction

A separate chapter on fire protection is included in this Handbook because fire is the dominant public risk accident in nuclear facilities. This chapter focuses on fire prevention and protection of the ventilation systems in industrial and Government facilities such as energy production reactors, fuel processing and reprocessing facilities, research establishments, special applications facilities, waste processing plants, and storage and salvage sites. High-efficiency particulate air (HEPA) filters are extremely susceptible to damage when exposed to the effects of fire, smoke, and water; it is the intent of this chapter to provide the designer with the experience gained over the years from hard lessons learned in protecting HEPA filters from fire. Fire protection for ventilation systems in commercial nuclear power plants is outside the scope of this chapter.

The presence of water around fissionable materials is a potential cause of undesired nuclear criticality. The primary agent used in the protection of HEPA filters from fire also happens to be water. This appears on the surface to be a conflict, but the professionals in both subject areas have largely come to an understanding of how the objectives of both fire protection and criticality safety can be achieved. The successful prevention of fire damage and undesired criticality often involves human or procedural aspects that are difficult to quantify, so careful analysis and coordination between these two important subject areas is of particular importance in these situations. Appropriate guidance has been developed and can be found in the DOE Fire Protection Design Standard, DOE-STD-1066-99.[1]

There are also two major issues with protecting confinement ventilation systems from the effects of fire: the effect of water on the integrity of HEPA filter median and the potential of a criticality incident occurring with the use of water in the vicinity of fissile materials. Experts have carefully developed the guidelines in this chapter with consideration for both of these issues. Study of the history of fire and fire suppression system behavior in actual fires and in research and testing has shown that HEPA filter media integrity can be assured by following the recommendations in this Handbook. The prevention of criticality occurrences is more situation-specific, however. While fire protection and criticality experts do agree on general acceptability of means of fire protection of fissile materials, each specific situation must be evaluated individually by qualified persons in both the fire protection and criticality safety fields. None of the criticality mishaps known to have occurred in the world has been caused by water from a fire suppression system, but some fires have caused extensive damage and contamination because water-based fire suppression systems were not present.

The ventilation air cleaning system of a nuclear facility is responsible for confining the radioactive smoke that results from fires. There are three major objectives to fighting fires in or around ventilation systems in nuclear facilities: (1) to keep the confinement ventilation system operable; (2) to suppress the fire; and (3) (if the filtration function is no longer operable) to prevent the release of radioactive materials that may have accumulated on the filters.

A confinement ventilation system must be designed to fulfill its purpose, i.e., to prevent harmful products (radioactive or otherwise) from escaping the system (sometimes referred to as the confinement) or facility, impacting the public or workers, and doing environmental damage. This chapter describes methods to ensure that confinement ventilation systems are designed, maintained, and operated in a manner to provide optimum protection against fires that could cause the confinement ventilation system to fail in its primary function.

The potential effects of fire in or around confinement ventilation systems are: (1) penetration of the system, and (2) release of hazardous materials to interior spaces outside the confinement volume. Large fires in confinement ventilation systems will produce heat- and smoke-filled combustion products that can degrade ventilation circuit components, ignite exposed materials, and/or plug the filters that prevent release of the toxic components produced during normal operations, thus causing loss of confinement. [Note: Hot gas transport can soften HEPA filter sealants, thereby weakening filter media in their frames. This, combined with the pressure differential, can blow out the filters, resulting in confinement loss][1]. Ignition of combustibles in gloveboxes or rooms can result in flaming brands and glowing embers. They may be lifted and carried by the design airflow to filter banks where they can burn through unprotected filters or ignite dust coating the interior of the ducts or trapped by filters. In either event, the unprotected filters would no longer be functional. If a fuel/air mixture filling even a small volume of a confinement system is ignited, the resulting pressure pulse can explosively breach the system. Such events are generally limited to the local elements of a system because of pressure pulse attenuation in the ducts and rapid fuel consumption during the explosion.

Fires that start inside ventilation systems have different characteristics than those that start outside the system, depending on how they are ignited. The performance of ventilation systems after ignition is determined by the system design and the safety measures provided by codes and standards.

In this chapter, topics such as fire hazards and effects, and analytical techniques are discussed, followed by a description of recommended fire safety features. In addition, a number of lessons learned from past fires at both DOE sites and commercial nuclear facilities are discussed. This chapter also refers the reader to the recognized codes and standards to be used in the fire protection design process and does not conflict with those codes and standards. The user should recognize that this is a handbook and not a design standard.

10.2 Fire History

Fires in nuclear facilities have been caused by a variety of energy sources, including electrical energy and spontaneous combustion of pyrophoric metals. While fixed fire suppression systems or operator intervention have limited the size and consequences of most of these fires, some did propagate and cause significant damage and material release. There have been numerous occurrences of fire in nuclear facilities since the beginning of the Manhattan Project and many lessons learned from those fires. Some lessons have been learned at great expense. A brief history is discussed here in the hope that the lessons will not be forgotten or ignored by facility designers and operators.

The most significant fires involving the HEPA filters of confinement ventilation systems have occurred at the Rocky Flats Plant. In 1957, pyrophoric ignition of plutonium in a production line ignited combustible cellulose filters in the production box and spread from there via laminated plexiglass window materials and other unknown combustible materials in the ventilation system to involve and destroy combustible HEPA filters in the final filter stage. Delays in fighting this fire were due to radiation safety concerns and delays in using water due to criticality concerns allowed it grow. It was extinguished soon after water was used, but a buildup of combustible vapors and dusts in the ventilation ductwork and the final filter stage ignited and resulted in a small explosion. This severely damaged the HEPA filters in the final filter stage and allowed the second-highest known plutonium release at Rocky Flats to occur.[2, 3] A significant portion of the plutonium released from this fire was deposited offsite.[3] As a result of this event, fire-resistant glass fiber HEPA filters were researched, developed, and put into service in the nuclear industry.

Another fire occurred at Rocky Flats in 1969 in a production line glovebox.[2, 3] The exact cause of this fire is unknown, but the area of origin included a storage cabinet that housed small, open metal containers filled with plutonium machine turnings. The cabinets, which were constructed of high-density pressed wood shielding material and plastic, were included in the production line to reduce radiation exposure to workers. Heat detectors originally installed in the glovebox were removed to the underside of the glovebox floor to accommodate the cabinet. A fire detector alarm alerted the fire department. When the firefighters arrived, the building was smoke-filled, indicating the fire had escaped the confinement system. While localized contamination was detected outside the building, no measurable contamination escaped the site.

History of Fire Involving Confinement Ventilation Systems

The following is a partial list of fires known to have occurred in nuclear facilities, involving nuclear materials, and having some interaction with the facility confinement ventilation system or some other significance. These come from U.S. Atomic Energy Commission (AEC) Serious Accident Reports. The AEC was a predecessor of the U.S. Department of Energy. This list is by no means comprehensive or complete.

1. *Fire in Ventilating System Filters.* AEC, Serious Accidents, Issue No. 83, July 27, 1955

   This fire involved a large bank of paper HEPA filters in wood frames (CWS Filters). Following extinguishment of a fire that had been caused by sparks from welding, re-ignition occurred on each of the following 2 days. About 2.5 tons of carbon dioxide was used to control the fire. Although no radiation hazard was involved, suppressing this fire was difficult due to the reactivity of the dust (specifics not given) in the ductwork with water.

2. *Serious Ventilating System Incidents.* AEC, Serious Accidents, Issue No. 110, November 8, 1956

   Fire started from spontaneous combustion in zirconium powder that had accumulated in ductwork incurring $150,000 in damage.

   Six hundred grams of hydride powder in plastic bags spontaneously ignited near the intake of a 6 feet × 6 feet filtering unit incurring $21,093 in damage.

   Laboratory scale testing being run in oxides generated by combustion in air of NaK, were carried by the ventilating system to a combustible filter. For unknown reasons, the NaK began splattering and ignited the filters. A loss of $8,400 was reported.

3. *Fire in British Windscale Facility.* AEC, Serious Accidents, Issue No. 128, October 15, 1957

   The fire started in the British graphite-moderated, air-cooled reactor at Windscale. Stack gas filters were very effective in removing particulate matter from the airstream, and the radioactive contamination of the surrounding area appears primarily concerned with iodine dispersed over about 200 square miles of farmland.

4. *Explosion in Glove-Box Line of Plutonium Facility.* AEC, Serious Accidents, Issue No. 129, October 28, 1957

   Vapor from a flammable lubricating and rust preventative chemical being used on a machine in the glovebox line circulated throughout all the boxes, and sparks from an electric brush being used on another machine ignited the vapors and caused an explosion. Loss not stated.

5. *Small Metallic Plutonium Fire Leads to Major Property Damage Loss.* AEC, Serious Accidents, Issue No. 130, November 27, 1957

   A small amount of plutonium spontaneously ignited within a dry box in a so-called "fireproof" building that was relatively free of combustible material. More than $300K in losses were incurred. This is the fire that occurred in September 1957, where most of the filter banks were destroyed. The initial fire released a significant quantity of flammable vapors into the confinement ventilation system, which subsequently ignited and exploded.

6. *Filter Fire.* AEC, Serious Accidents, Issue No. 41, December 2, 1958 and Serious Accidents, Issue No. 144, March 9, 1959

   Fire started in a fume hood in a chemical laboratory involving an experiment with perchloric acid. The fire involved a combustible filter under the hood and traveled through the exhaust system, reaching the main filter bank on the second floor of the building. Loss estimated at $12,000.

7. *Drybox Explosion Disperses Polonium Contamination.* AEC, Serious Accidents, Issue No. 148, October 8, 1959

   After normal working hours, an explosion occurred in a sample hood that dispersed some polonium-containing solution. The cause is not precisely known. Loss unknown.

8. *Ventilating Air Filter Clogs During Fire.* AEC, Serious Accidents, Issue No. 151, October 28, 1959

   A fire in a room under construction at an AEC plant occurred. The ventilating system had been placed in service for the room even though the room was not yet complete. The filters soon became plugged with smoke and soot. The firefighters entered the obscured room and "chopped" out the filters. The smoke soon cleared from the room, but had radioactive contamination been present, it would have been exhausted out the ventilation system

9. *Plastic Windows and a $125,000 Sprinkler Head.* AEC, Serious Accidents, Issue No. 152, October 29, 1959

   Fire occurred in a chemical laboratory in a walk-in type of hood, involving plastic doors and windows. A sprinkler head controlled the fire and limited the damage to about $350.

10. *Radiochemical Plant Explosion releases Plutonium Contamination Outside Facility.* AEC, Serious Accidents Issue No. 162, March 30, 1960

    This explosion occurred in a radiochemical pilot plant being used for processing spent power reactor fuel. A small amount of plutonium was dispersed, contaminating nearby buildings and grounds. Loss was about $360K, which includes decontamination costs.

11. *Could Sprinkler Protection Have Reduced This $200,000 Radiochemistry Building Fire Loss?* AEC, Serious Accidents, Issue No. 175, April 5, 1961

    A fire occurred on the inside of a cavern drybox designed for working with high levels of radioactivity. The fire spread to other areas within the cavern involving plastics and wood. A minor amount of radioactivity was dispersed. The loss was about $200,000.

12. *Polyester Fibrous Glass Duct Fire causes $43K Damage.* AEC, Serious Accidents, Issue No. 216, January 31, 1964

    Fire started in combustible laboratory fume hood ducting. The ducting was of polyester resin-bonded fibrous structure. The fire began around a hot plate in a fume hood and then extended into the ductwork. Fire damage was limited to the general area of ducting but smoke damage was extensive in this 4,500 square foot, one-story and basement facility. Smoke damage may have been exacerbated by the exhaust fanes having been turned off during the fire. The exhaust system was not filtered.

13. *Filter Box Fire.* AEC, Serious Accidents, Issue No. 217, February 7, 1964

    This fire occurred in a filter box on the roof of a nuclear facility. The burning filters were manually removed from the box by firefighters who then used carbon dioxide and dry chemical fire extinguishers to extinguish the fire. Some smoke backed up into the plant as a result of shutting off the blower fans. The fire was determined to have been caused by fine uranium chips which spontaneously ignited and were drawn into the ventilation system. The burning uranium chips ignited the metal mesh in the roughing filters and then the "absolute" filters as they are called in the report. The roughing filters had been cleaned 6 weeks previously and there was no evidence of buildup of dust in the ductwork itself. The "absolute" filters were less than one year old. A recommendation of this report was the use of fire-resistive "absolute" filters.

14. *Fire and the Reaction of Nitric Acid with Plutonium Ion Exchange Resin Leads to Major Property Damage.* AEC, Serious Accidents, Issue No. 237, December 4, 1964

    At 1:23 am, a sudden reversal of airflow was noted in the facility during plutonium purification operations. The purification operation was shut down immediately. The presence of a fire was discovered after about 30 minutes. The use of water was not recommended due to criticality safety concerns. The fire was extinguished in about 1.5 hours through the use of about 500 pounds of sodium bicarbonate. It was later estimated that, if water fog had been used, it could have been extinguished in 5 minutes. The fire spread through open gratings to involve all four floors of the facility. The direct and indirect loss was estimated at $397K. Although no direct mention is made of confinement ventilation system performance, this is being included as it was a significant fire in a nuclear facility.

15. *Explosion Within Glovebox Disperses Contamination.* AEC, Serious Accidents, Issue No. 242, January 11, 1965

    A methanol-air mixture in a glovebox ignited and exploded, pressurizing the glovebox and tearing off six gloves. Plutonium oxide discharged from the open ports and spread throughout the operating areas of the building. Some workers were contaminated to varying degrees. No mention is made of any contamination being released from the building.

16. *Burning Plutonium Chips Explode in Carbon Tetrachloride Degreasing Bath.* AEC, Serious Accidents, Issue No. 246, March 12, 1965

    Plutonium chips immersed in carbon tetrachloride within a glovebox spontaneously ignited and burned during operations. During the performance of the procedure in place to handle burning plutonium chips in a container, some of the burning chips fell into a carbon tetrachloride bath in the glovebox, causing an explosion with a shock wave. This ruptured the glovebox and dispersed plutonium throughout the glovebox line. There was no direct impact on HEPA filters.

17. *Cutting Wheel residues in Plutonium Waste Cause Explosion.* AEC, Serious Accidents, Issue No 258, December 17, 1965

    During an operation involving oxidation of plutonium waste in a nitrogen-inerted glovebox, in which a small amount of oxygen was introduced in a bell jar containing plutonium chips under partial vacuum, the plutonium in the jar began to smoke and then an explosion occurred within the jar. Contamination was limited to fragments thrown about the interior of the glovebox.

18. *Hazardous Solvent Causes Explosion in a Glovebox.* AEC, Serious Accidents, Issue No. 261, February 1966

    During cleaning operations, using acetone, in a glovebox where plutonium was being processed, an explosion occurred that blew out three gloves. The ensuing fire was extinguished with a 20-pound dry chemical fire extinguisher. Some workers were contaminated, and contamination was spread throughout the room. No contamination was detected outside of the building.

19. *Maintenance on Plutonium Machining Coolant Lines Leads to $17,500 Fire. Building 776/777, Rocky Flats, 1965*, AEC, Serious Accidents, Issue No. 262, March 4, 1966

    Metallic plutonium lathe operations, utilizing a circulating oil cooling system, were being conducted within a glovebox. During normal operations, oil that splashed or dripped accumulated in a drip pan with a valve in its drain line. This valve was normally open, allowing the drain pan oil to flow back to the suction side of the circulating pump. The drain line became clogged and attempts were made to unclog it by first flushing it with carbon tetrachloride (unsuccessfully), then by using a welding rod to probe and clear it. Some paper towels and a plastic pan were placed around the pipe to catch oil and prevent the spread of contamination. During the probing, sparks were noticed when the rod contacted something metallic in the line. Because the probing did not appear to be having much effect, a center punch was inserted into the drain line and struck by a hammer. The first blow caused a light spark; the second blow caused a lot of sparking accompanied by a fireball, igniting the plastic pan and paper towels. The copper drain line began to glow, indicating a fire within it. This fire was controlled using a fire extinguisher. Contamination from the fire spread throughout the Building 776 and 25,000 square feet of Building 777.

20. *Fire During Glovebox Cleanup Leads to $23,000 Damage Via Contamination Spread.* AEC, Serious Accidents, Issue No. 269, July 8, 1966

    During operations to remove the paint from the inside of a glovebox in preparation for its disposal, fire involving flammable solvents occurred in the airlock for the glovebox system. Unsuccessful attempts were made to extinguish the fire by firefighters using carbon dioxide fire extinguishers, but the fire was ultimately controlled by introducing solid carbon dioxide. Contamination was spread throughout the ventilation system ductwork and over two floors of the building.

21. *Fire Damages Hot Cell Window.* AEC, Serious Accidents, Issue No. 275, November 4, 1966

    An operation involving NaK in a shielded hot cell ignited some alcohol being used. A total-flooding carbon dioxide extinguishing system was manually actuated which extinguished the fire. The HEPA filters received some particulate contamination but not to the extent that they became plugged. The window in the hot cell was cracked due to the heat from the alcohol fire. No significant amount of contamination occurred.

22. *Glovebox Explosion Causes $42,000 Damage and Plutonium 238 Contamination Spread.* AEC, Serious Accidents, Issue No. 293, August 26, 1968

    An explosion in a series of gloveboxes where plutonium 238-contaminated wastes were being dried caused extensive damage to the gloveboxes and room. Contamination was spread into adjoining rooms and corridors. The explosion was caused by the overheating of rubber gloves, releasing flammable vapors that ignited.

23. *Waste Incinerator Incident Affirms Fire-Resistive Filter Value.* AEC, Serious Accidents, Issue No. 292, July 31, 1968

    During normal operations within a glovebox that was part of the incinerator operation, smoke from the feed-end of the incinerator indicated inadequate airflow was going through the glovebox. Maintenance personnel called to correct the problem discovered that the filter-box port cover was hot and its wood frame was smoldering. The fire department was called and the fire in the filter frame was extinguished using carbon dioxide. The filter was removed for inspection. Only the top of the four wooden sides of it were unburned. The filter medium collapse was attributed to the application of the carbon dioxide fire extinguisher. No burning of the filter medium was observed. The secondary filters in this frame were unaffected by this incident. No contamination was spread as a result of this fire.

24. *Fire - Rocky Flats Plant - May 11, 1969.* AEC, Serious Accidents, Issue No. 306, December 1, 1969

    This fire occurred one afternoon in a glovebox line in Buildings 776-777. It moved rapidly through the glovebox line due to large quantities of combustible polymer shielding in place. Carbon dioxide was unsuccessfully used to try to extinguish the fire initially. Water was used as a suppression agent by the fire department only as a last resort. Extensive damage occurred. Some contamination was detected on the roof of an adjoining building, released due to a minor HEPA filter failure. Most contamination was tracked out by firefighters during suppression operations.

25. *Incinerator Fire at Rocky Flats, July 2,1980.* Investigation Report, July 31, 1980[4]

    Incinerator operators noted a temperature rise above normal in the operation of an incinerator in Building 771 at Rocky Flats in the late morning. A temperature overheat alarm occurred in the incinerator plenum about an hour and 15 minutes later. About 90 minutes after the initial temperature rise indication, the operators received a phone call and noted other indications that there was a fire in the plenum of the incinerator. Incinerator shutdown was initiated and the fire was mostly extinguished by a water deluge system. The fire department completed extinguishing the fire. It was noted in the investigation report that two of the four causes of the fire were nitric acid attacking the urethane sealing the HEPA filter media to the frames, and the accumulation of metal fines on the HEPA filter media material. The nitrated urethane seals exhibited a temperature rise that may have ignited the metal fines on the filter media. This incident resulted in slight contamination inside the building, with no release external to the building.

26. *Fire in TRISTAN Experiment at HFBR at BNL, March 31, 1994*[5]

    This fire occurred in an experiment on the experiment level of the High Flux Beam reactor at Brookhaven National Laboratory on Thursday, March 31, 1994. It spread light contamination through the experiment level of the reactor.

27. *Cerro Grande fire effects on HEPA filters at LANL* May 4, 2000[6]

    On May 4, 2000, a prescribed burn at Bandelier National Monument, New Mexico escaped control and ultimately burned nearly 50,000 acres in and around the town of Los Alamos and Los Alamos National Laboratory (LANL). The thick smoke from this fire impacted the confinement ventilation system operations at several LANL facilities. The confinement ventilation systems in some nuclear facilities were shut down or placed on minimum ventilation to prevent filter clogging. Some facilities whose confinement ventilation systems were not shut down experienced filter clogging and had to replace filters. The facilities that shut down or went to minimum operation subsequently had re-entry and restart issues they had to address. No contamination escaped from LANL facilities as a result of these actions.

28. *Cutting Operations Ignite Residue In Bottom Of Glovebox*, Rocky Flats Environmental Technology Site, Building 371, May 6, 2003

    Exploratory cutting operations on the top of a glovebox in Building 371 at Rocky Flats Environmental Technology Site (RFETS) ignited legacy combustibles in the bottom of a large, two-story glovebox that also contained a service elevator. Fire extinguishers were used to extinguish the fire, but upon stirring of the materials by the workers the fire re-ignited. The fire department arrived soon thereafter and used 600 to 800 gallons of water form hose streams to fully extinguish the fire. Some of the firefighters received skin contamination. This incident was still under investigation at the time of the writing of this document.

10.3 Requirements and Guidelines

Decisions regarding the extent and nature of fire safety features for confinement ventilation systems are predicated to a significant degree on the regulatory environment governing the facility. That environment can be characterized as being regulated by DOE or the NRC. The applicability of any fire safety criteria to a particular design will depend on the nature of the license application (for an NRC-regulated facility), the contract (for a Federal facility) and the governing regulations (e.g., 10 CFR Part 70).[7] Proceeding with an individual design should not progress until the technical (safety) basis is clearly established.

Fire protection requirements and guidelines for confinement ventilation systems are delineated in a number of NRC and DOE source documents. These include NRC Regulatory Guides, Standard Review Plans, Branch Technical Positions, and supplementary staff position papers. DOE directives include DOE Order 420.1A, *Facility Safety*,[8] its *Implementation Guide for Fire Protection*,[9] and DOE-STD-1066-99.[1]

While these criteria are expected to be implemented, a "variance" approval process exists within both the NRC and DOE. The process generally includes a documented description of the condition, the justification for literal nonconformance, and approval by the fire protection "authority having jurisdiction" (AHJ).

Despite the differences in scope between NRC and DOE fire safety directives related to confinement ventilation systems, the following are significant common requirements:

- Compliance with applicable industry standards such as those promulgated by the National Fire Protection Association (NFPA). Prominent among these is the 800 series of standards on fire protection for nuclear facilities and NFPA Standard 90A, Installation of Air Conditioning and Ventilation Systems."[10] [Note: Cost-effective alternative means of compliance are permitted under established "equivalency" provisions.]

- Development of a comprehensive Fire Hazards Analysis (FHA). The FHA is required to consider—under all operating modes—the potential adverse impact of the spread of combustion products through the ventilation system.

- Implementation of combustible materials and ignition source controls to minimize the potential for fire.

- Use of generally noncombustible structural elements and "listed" fire protection system components that are subjected to a quality assurance (QA)/quality control (QC) program.

- Provision of fire protection defense-in-depth. This means that multiple fire safety features are available in the event that one is rendered inoperable.

- Reliance on both active (e.g., fire detectors and sprinklers) and passive (e.g., fire barriers) fire safety features.

- A comprehensive inspection, testing, and maintenance program for installed fire safety features.

- A trained staff capable of responding in a timely and effective manner to fires and related emergencies.

Specific fire safety features that are stipulated in this body of criteria are considered acceptable minimums and should be treated exactly as such**.** There may be, and often are, circumstances that warrant provision of additional protective measures to compensate for elevated fire hazards or unusual risks. Such hazards and risks may be revealed in conjunction with formulation of the FHA, application of fire modeling techniques, and analysis of engineering survey results, as well as after development of the Documented Safety Analysis.

An issue that has created a degree of regulatory inconsistency concerns the retroactive application of industry standards. DOE has established the concept of "codes of record," defined as the codes and standards that were in force at the time a facility design commenced.

Questions regarding the applicability of individual fire safety directives to a particular confinement ventilation design, as well as requests for interpretation of the provision of industry standards to such designs, should be directed to the cognizant NRC or DOE fire protection AHJ.

10.4 Enclosure Fire Modeling in Fire Hazards Analysis

DOE has developed a useful framework for analyzing the fire hazard in a facility. This framework considers all of the aspects of fire and its impact on facility personnel, continuity of operation, the environment, and the public. The occurrence and spread of fire is a complex process that cuts across many design and operational disciplines, making its control throughout the lifetime of a facility problematic in some respects.

The FHA should contain a conservative assessment of the following features of a confinement ventilation system:

- Description of construction,
- Identification of high-value property,
- Description of fire hazards (including a design basis fire and its effects on the confinement ventilation system) and the limits of the ability of the confinement ventilation system to withstand fires more severe than the design basis fire,
- Protection of essential safety class systems,
- Life safety considerations,
- Critical process equipment,
- Identification of the damage potential: Maximum Credible Fire Loss (MCFL) and Maximum Possible Fire Loss (MPFL),
- Analysis of fire department/brigade response and its adequacy,
- Potential for recovery from a fire,
- Potential for a toxic, biological, and/or radiation incident due to a fire,
- Analysis of emergency planning and its ability to mitigate a fire in a confinement ventilation system,
- Security and safeguards considerations related to fire protection,
- Impacts of natural hazards (earthquake, flood, wind) on fire safety, and
- Exposure fire potential, particularly as related to the potential for breaching the confinement ventilation system due to a fire that is external to the system.

The FHA considers everything involved in the design and operation of the facility. The essential analysis tools are predictive models that can be applied to define the ranges of hazards from design basis events (DBEs). An FHA can be applied during the design phase of new facilities and/or in conjunction with changes or modifications of existing operations.

Use of Fire Modeling in FHAs

Validated and verified fire models approved by DOE for use in Authorization Basis documents must be used.

Fire models for FHAs range from simple algorithms that predict thermodynamic changes in enclosures to complex programs that can account for heat, mass transfer, and smoke production in multiple enclosures. Many mathematical models have been installed in software codes and are available on the Internet bulletin boards of various government agencies. These codes can predict the development and spread of fire and smoke conditions through multiple rooms, and can account for changes in the structure and composition of enclosures. Application of these models requires considerable understanding of their use and limitations, statements of which are usually included in the instructional text published with the software codes. Reduction of complex models to simple terms supported by empirical data is often useful in predicting uncomplicated systems.

10.5 Fire Phenomena

Fire is a complex phenomenon that involves the initiation of an event and subsequent actions that can mitigate or exacerbate the event's effects. The matrix in **Table 10.1** covers: (1) the initiation and generation of harmful products from a fire; (2) the means by which these harmful effects are transported throughout the confinement ventilation system are discussed; and (3) the impacts of these harmful effects on the main components of the confinement ventilation system are discussed. The material in this section indicates the fire hazards that must be mitigated. The techniques for mitigation are presented in the next section.

Table 10.1 – Fire Phenomena Matrix

	Heat	***Smoke***	***Related Effects***
Generation	Fire growth	Initial aerosol makeup	Water vapor, chemical releases, deflagrations
Transport	Temps in ducts	Change in aerosol with time and temperature	Change with movement through ducts
Effects on filters	Media failure	Filter media plugging	Filter media plugging and failure

10.5.1 Fires Occurring Outside a Confinement Ventilation System

Fires occurring outside a confinement ventilation system generate heat that exposes the outside of ducting as well as produce combustion products that are drawn into the confinement ventilation system when it operates as intended. These combustion products will affect the components of the confinement ventilation system.

10.5.1.1 Generation of Heat, Smoke, and Related Products

Thermal Effects from Fire Initiation and Growth

Hot gases from a fire that originates outside of the confinement ventilation system will be entrained within it and will be conveyed via the duct system to the filter banks. While a certain amount of heat dissipation and dilution will occur, over time the gases may cause steady deterioration of the filter medium and may ignite combustible framing. The designer of nuclear air cleaning systems must accurately characterize the design basis fire. This characterization can be subjective, (i.e., the thermal effects of a fire are determined on the basis of judgment and experience) or the thermal effects of a fire on HEPA filters can be calculated by qualified individuals using fire models. In the latter case, the chosen fire must be sufficiently conservative (i.e., severe) to be an upper boundary for the mitigative features protecting the function of the confinement ventilation system.

Smoke Generation

Smoke contains particulates that can pose a significant "plugging" threat to HEPA filters. Smoke is a suspension of solid and/or liquid particles and gases resulting from combustion and pyrolysis. Soot is an intrinsic part of smoke. However, the term "soot" can be further refined to mean finely divided particles, mainly carbon, produced and/or deposited during incomplete combustion of organic materials. Moreover, the amount of smoke generated from any material is strongly influenced by the same conditions that effect combustion efficiency. In general, smoke is a heterogeneous combination of solid and liquid particles of varying size and composition. Their instantaneous character depends on the material of origin, combustion conditions, environment, and flow dynamics. The sizes of particulates vary from 0.002 to 0.5 µm, depending on the experience described above. Conditions related to incomplete combustion generally result in an aerosol distribution of larger mean particulate size. However, if the smoke concentration is high, particle agglomeration (smoke aging) proceeds rapidly, as does fallout and surface deposition.

Agglomerated smoke aerosols can attain diameters as large as 10 µm in plumes from fires; however, visibility is most influenced by particulates with diameters of -1.0 µm. Collections of data on smoke production rates (g of soot/g of material burned) are available and can be used to estimate visible obscuration and smoke detector response time.

Water Generation

The quantity of water generated in the fire is as important as the soot and other particulates. Water vapor can condense on the particulates in smoke, both increasing their average diameters and leading to increased agglomeration resulting in generally larger particulates. Larger particulates lead to more rapid HEPA filter plugging.

Calculating the aspects of the phenomenon of water generation from combustion is an extension of the processes described by Gottuk and Roby.[11]

Generation of Combustion Products from External Fires

Many methods exist to establish the thermal history of gaseous and particulate combustion products from a postulated fire (in most cases, the type of fire experienced in a nuclear facility would be a ventilation-controlled fire, rather than a fuel-controlled fire).

Once the masses of smoke and water generated for a given fire have been established, the temperature that occurs at the HEPA filter will determine how much water remains in the gaseous state or how much is condensed.

10.5.1.2 Transport of Heat, Smoke, and Related Products

Heat Loss in Ducts

Hot gas from fires may enter the exhaust duct system and lead to excessive temperatures at the HEPA filters if not mitigated. The two primary tools for analyzing the cooling of hot exhaust gas are: (1) dilution analysis with additional exhaust streams, and (2) duct cooling by convective and radiative heat transport.

As the combustion products from a fire travel through the length of a duct, losses occur (see **Figure 10.1**). Thermal energy is added or lost through the walls of the duct according to the temperature differential between the products of combustion gases in the duct and the atmosphere external to the duct. Solid and liquid particulates are deposited along the duct interior surfaces according to a number of factors.

Alvares[12] studied heat transport in gases traveling through ducts to determine the losses in a duct external to a facility. Most ducts are not external to a facility, so the designer must consider this in the analysis.

Because confinement systems are part of the enclosures that support operations with nuclear materials, computer codes have been developed to predict the results of accidents on the internal conditions within the system. For fire events, the room fire models discussed above can serve as the source term for codes that treat the response of components within the confinement ventilation system. Modeling tools are available (e.g., CFAST) to help analyze heat transport in the ducts.

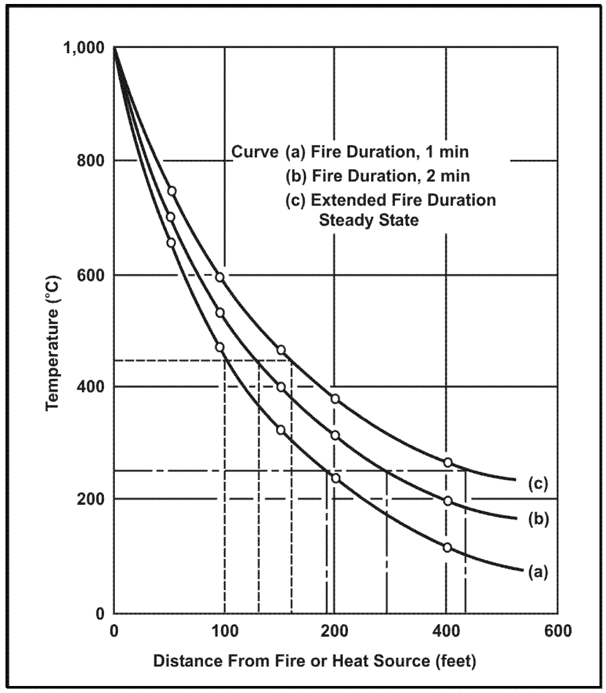

Figure 10.1 – Cooling Rate of Air in a 12-inch Diameter Duct Carrying 1,000 cfm of Air with Inlet Temperature of 1,000 Degrees Celsius

The phenomena noted in this section will be adequately mitigated by implementation of the fire protection provisions of DOE Standard 1066-99.[1] In those rare instances when it can be clearly demonstrated in a comprehensive FHA that these fire hazards are insignificant, alternate fire protection configurations can be considered.

Smoke and Water Loss in Ducts

A significant quantity of smoke and water may settle out in the ventilation ducts. In one configuration where the duct was located outside the fire area, Alvares[12] observed that about 60 percent of the aerosol mass (including water) was lost between the duct entrance and the HEPA inlet (about 19 feet for a 2-foot × 2-foot cross-section duct).[12]

Transport of related combustion products (e.g., smoke particulates) can be modeled using available techniques. Analysis methods for the entrainment and transport of these products in confined situations such as ducts are generally well understood. The form and dispersion characteristics of the combustion products in question also must be understood. Once this is done, the effects on the HEPA filters can be shown with time.

10.5.1.3 Effects on Filters of Heat, Smoke, and Related Products

The impact of fires on the integrity of the HEPA filters can be determined through a sequence of analyses to establish: (1) the dynamics of the design basis fire; (2) the generation of smoke, water, and heat (temperature) that enters the confinement ventilation system; (3) the mitigation of smoke, water, and heat through the ducting to the HEPA filters; and (4) the response of the HEPA filters to the smoke, water, and heat that reach them. The interaction of smoke, water, and heat play a major role in the plugging of HEPA filters, as well as the consequent rise in filter pressure drop and possible reduction in exhaust flow. This sequence of analysis will determine the potential of the design basis fire for causing structural damage to the HEPA filters and thereby increasing the filter penetration. Finally, the impact of the smoke and water loading and the air temperature on the HEPA filters must be determined.

HEPA Filter Response to Temperature

Fire-resistant HEPA filters must meet the requirements of Underwriters Laboratory (UL)-586, *High-Efficiency, Particulate, Air Filter Units*.[13] Prefilters must meet the requirements of UL-900, *Performance of Air Filter Units*.[14] These UL test methods qualify the construction materials for the filter, frame, and gaskets. To be listed by UL under UL-586[13] as a HEPA filter unit, HEPA filters are required to meet the following three criteria:

- Withstand 750 ± 50 degrees Fahrenheit heated airflow for 5 minutes at not less than 40 percent of rated capacity.

- Have a greater than 97 percent test aerosol efficiency after exposure to the hot air test and cooling.

- Withstand a spot-flame test in which a Bunsen burner flame at 1,750 ± 50 degrees Fahrenheit is placed on the filter with no after-burning when the flame is removed.

For the spot flame test, a horizontal Bunsen burner is touched to the filter at three locations for 5 minutes at each site. Afterwards, the burner flame is moved to touch the filter frame, filter pack, and sealing materials. To pass the test, flaming on the downstream side of the filter must cease within 2 minutes after removal of the burner flame. Although this test indicates the fire performance of the filter, it is a small-scale test with a limited, controlled heat source that does not replicate the temperatures experienced during actual exposure to a more severe, full-scale fire. Many fires can reach higher temperatures and more severe conditions than this test fire.

Extended exposure to temperatures above 800 degrees Fahrenheit will cause destruction of the casing of wood-cased filters and warping of the casing of steel-cased filters, allowing unfiltered air to bypass the filter. The medium of HEPA filters is thin (0.015 inch) and can be destroyed by incandescent sparks, flaming trash, or burning dust on its surface.

Although HEPA filters can withstand a temperature of 750 degrees Fahrenheit for an extremely limited time, they should not be subjected to continuous exposure to temperatures higher than 250 degrees Fahrenheit. Longer filter life and more reliable service, as well as a greater operational safety factor, can be obtained when normal operating temperatures are below 200 degrees Fahrenheit and higher temperature extremes are avoided.

Continuous operation of HEPA filters at higher temperatures is limited primarily by the filter sealant used to seal the filter core into the filter case. At higher temperatures, the sealants lose their strength, causing the filters to fail. For example, standard urethane seals are suitable for service at 250 degrees Fahrenheit, while some silicone seals can withstand 500 degrees Fahrenheit.

Because different sealants are available and different filter manufacturers rate their filters for different temperatures, the best practice for ventilation system designers and operators is to determine the manufacturer's limiting continuous service temperature if continuous operation at high temperatures is necessary. A decision to operate above 200 degrees Fahrenheit should be accompanied by controls requiring replacement filters that have been proven to be acceptable for above-normal temperatures.

HEPA Filter Response to Smoke and Water Loading

Water from combustion plays a major role in potential HEPA filter clogging with smoke aerosols. The temperature at the HEPA filter is important for determining the extent of water condensation from the fire exhaust. The HEPA filter-plugging studies suggest using the following approach to analyze the potential of fires to plug HEPA filters.

With the design basis fire and its combustion products previously established, transport of the hot gases, smoke particulates, and water vapor through the duct system must be established. The characteristics of the combustion products penetrating the prefilter or demister must be determined next. This process will yield a mass of smoke aerosols for comparison to a reference mass holding capacity for HEPA filters. The amount of water condensing on the smoke deposits is determined from the temperature at the HEPA filters and from the combustion water loading.

The nature of the aerosols has a major effect on plugging of all filters, including deep-bed sand (DBS) filters, prefilters, and HEPA filters. Previous studies have shown that, in addition to the mass of the smoke aerosols, the particle size and the state of the aerosol (liquid or solid) significantly affect HEPA filter clogging.

Figure 10.2 and **Table 10.2** illustrate some of the effects of particulates on HEPA filters.

In related tests using rolling prefilters (the media roll advances through the test duct as it plugs), Bergman et al.,[15] showed that, once a fire and the ventilation system have reached the point where the smoke generated can plug a HEPA filter, plugging can occur within 1 min, as seen in **Figure 10.3**. Tests 2 through 5 showed that they were not effective in protecting the HEPA filter from plugging until the prefilter efficiency was a minimum of 90 percent for milli-µm particles. **Figure 10.4** shows the efficiency for the different filter media used in the tests in Figure 10.3. Test 5, with insufficient media replacement in the roll, illustrates how rapidly the HEPA filter plugs when directly exposed to the proper aerosols. The plugging potential of the smoke aerosols is so great that it dominates all other parameters.

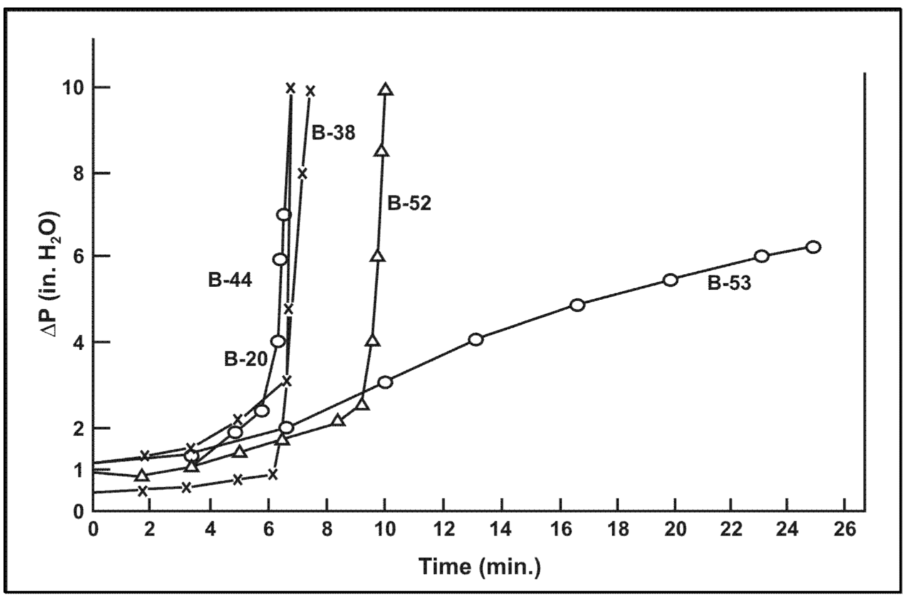

Figure 10.2 – Aerosol Loading of HEPA Filters by Smoke from Composite Cribs for the Different Conditions Shown in Table 10.2 (composite cribs consist of 40 percent wood, 14 percent PVC, 29 percent FRP, 9 percent PMMA, and 8 percent polycarbonate)[16]

Table 10.2 – Test Conditions for the HEPA Plugging Measurements in Figure 10.4 [16]

Test	*HEPA Size (cfm)*	*Exhaust Flow (cfm)*	*Fuel Burn Rate (g/min)*	*Smoke Concentration (g/m3)*	*Temperature at HEPA (degrees Celsius)*	*HEPA wt. Gain (g)*
B-44	1,000	500	3,000	6.4	65	470
B-20	500	500	1,200	4.8	86	—
B-38	500	1,000	3,000	8.6	105	574
B-52 (free burn)	500	500	1,500	7.6	70	106
B-53	500	1,000	1,680	8.4	110	550

Figure 10.5 shows an electron micrograph of the aerosols generated from composite burns. The deposits show the smoke aerosols were liquid because of the drop-like spheroid coating the fibers. The deposits have solidified because any liquid would not have remained in the high vacuum of the scanning electron microscope. Filter plugging with solid aerosols, as shown in **Figure 10.6**, does not show the same rapid increase in pressure drop as the liquid aerosols.[16]

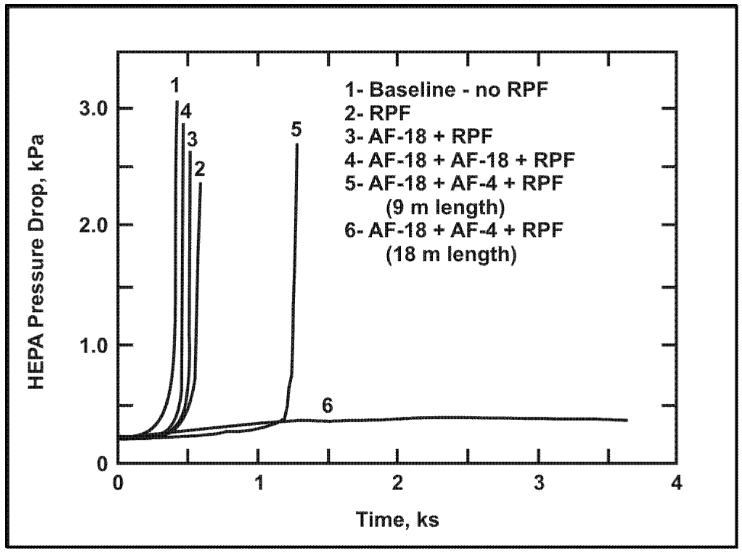

Figure 10.3 – HEPA Filter Plugging by Smoke Aerosols with Various Rolling Prefilters [15]

Prior Filter Exposure that Impacts Filter Response

Water Exposure. Water is an effective method for reducing temperature, but HEPA filters are not designed to operate when wet and will suffer structural damage. The HEPA filter medium is treated with water-repellent chemicals. Tests have shown a reduction in water repellency effectiveness with each wetting of the medium. The tensile strength of the filter medium can be reduced to failure levels with as little as one wetting. **Figures 10.7** and **10.8** further illustrate the relationships between particulates, temperature, and water-saturated air. A properly designed fire suppression system will include demisters to prevent water from reaching functional filters. HEPA filters exposed to water should be replaced immediately. HEPA filters that potentially could be exposed to water should be replaced within 5 years—immediately if actually exposed.

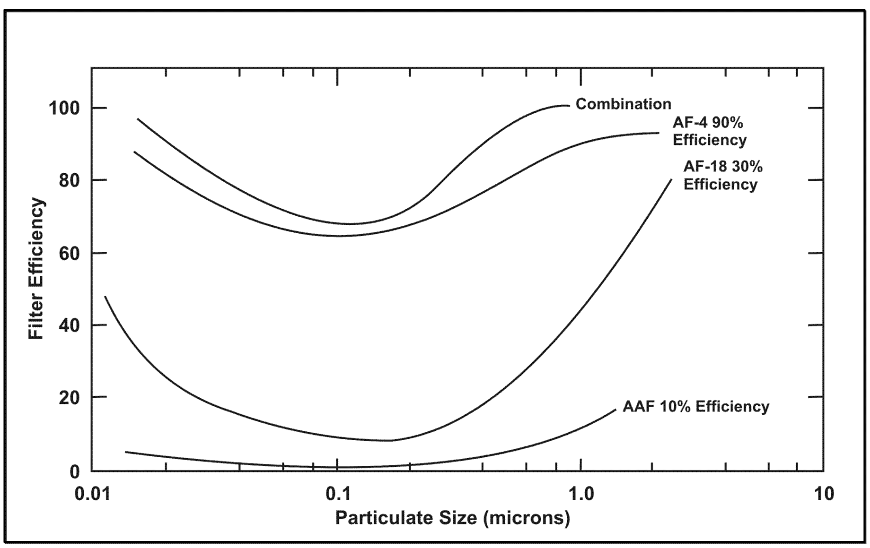

Figure 10.4 – Efficiency of Different Layers of Prefilters as a Function of Particle Size. (Efficiency Values Refer to the ASHRAE Dust Spot Efficiency. [15]***)***

Other Filter Types

Not all filter types are as subject to the thermal and combustibility effects as typical HEPA filters with combustible media. Plugging from smoke particulates can be a concern for all types of filters, however.

Figure 10.5 – Scanning Electron Micrograph of HEPA Filter Media Loaded with Smoke Aerosols from Composite Crib Fires. (Note: the drop-like globules attached to the filter fibers that suggest the liquid nature of the aerosol)[17]

10.5.1.4 Effects on Physical Integrity of the Confinement Ventilation System Components

Fires external to the confinement ventilation system may not only damage the HEPA filters inside the confinement ventilation system, they also may damage the integrity of the confinement ventilation system ductwork and enclosures. If the confinement ventilation system ductwork or enclosures are breached, some or all of the functionality of the confinement ventilation system will be impaired. This must be considered in the design of the physical components and the fire suppression systems provided in the facility.

10.5.1.5 Effects of Wildland Fires

Although documented evidence is lacking, recent wildland fire experience such as at the Cerro Grande fire in Los Alamos in 2001 demonstrated the potential for smoke to adversely affect confinement ventilation systems. Facilities in areas where this type of event may occur are required to analyze the hazard in their authorization basis documents. During the 2001 Cerro Grande fire, some confinement ventilation systems in facilities at the Los Alamos National Laboratory were shut down to prevent the rupture of HEPA filters due to clogging from smoke. Other external situations (such as volcanic eruptions or the dust from denuded landscapes) can also create abnormally dusty conditions that cause clogging of prefilters and HEPA filters and present serious threats to confinement ventilation systems. System designers and operators should implement features that minimize the probability of having to shut down confinement ventilation systems in other than extreme emergency situations. During emergency situations, if the Incident Commander determines that a confinement ventilation system has been breached and radioactive material is being released, a decision should be made whether to shut the confinement ventilation system down completely or operate it in a manner that would minimize the impact. These hazards may reveal the need for additional safeguards, including but not limited to, administrative controls of the removal of natural vegetation and other combustibles near filter inlets, installing smoke removal systems such as an electrostatic precipitator prefilter or installing additional filtration to preclude ingress of particulate into the building. NFPA Standard 1144, *Protection of Life and*

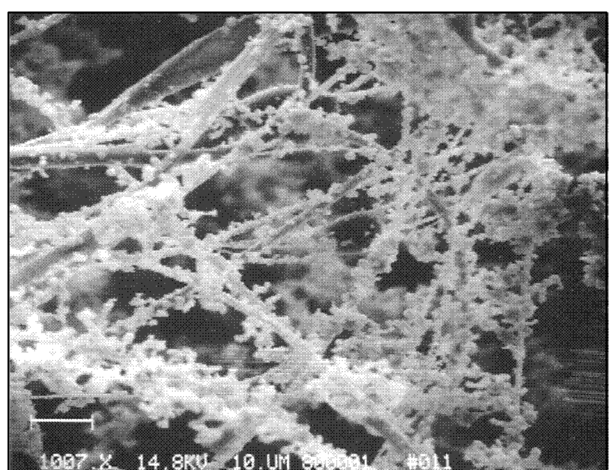

Figure 10.6 – Scanning Electron Micrograph of Sodium Chloride Aerosols on Glass Fiber Prefilter.[18]

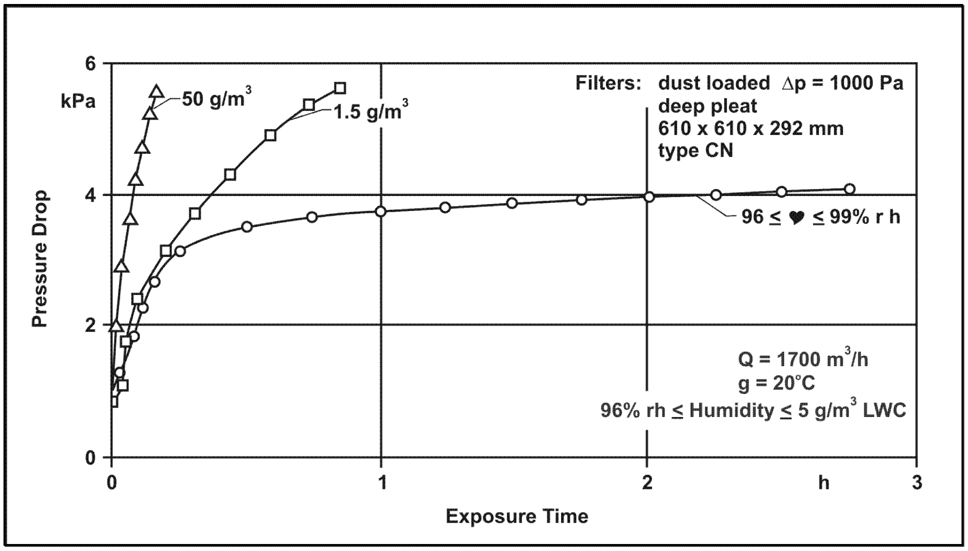

Figure 10.7 Illustration of Rapid Pressure Drop Increase with Water Saturated Air [19]

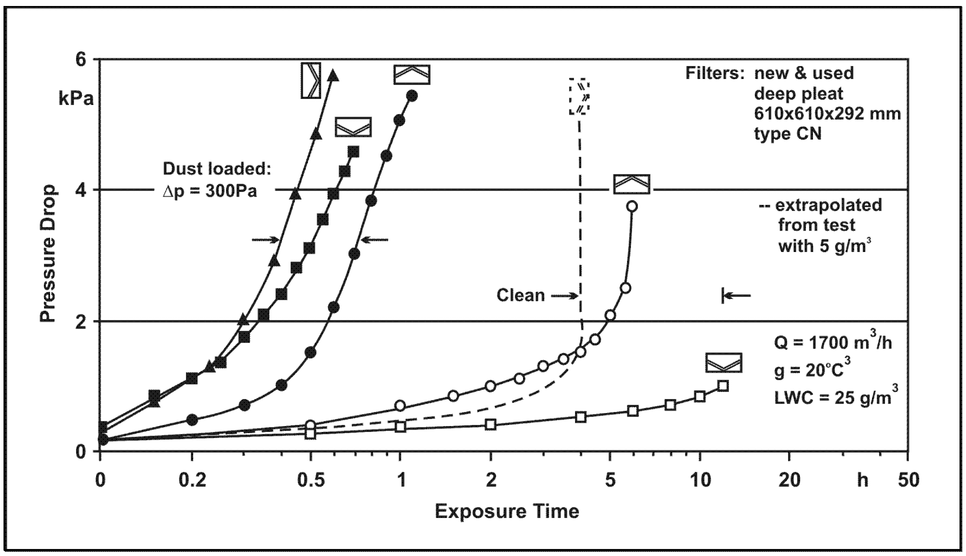

Figure 10.8 – Rapid Filter Plugging Due to Moisture Deposition on Particle-loaded HEPA Filters [19]

Property from Wildfire,[20] provides guidance on minimum defensible spaces around all buildings. High-hazard facilities would be expected to have defensible spaces exceeding these minimum values.

10.5.2 Fires Occurring within Confinement Ventilation Systems

Fire may originate from sources within the confinement ventilation system (e.g., glovebox-sized operations and small hot-cells). The effects of fires occurring within confinement ventilation systems, although similar to those resulting from fires external to the confinement ventilation system, may be different and thus require different controls.

10.5.2.1 Generation of Heat, Smoke, and Related Products

Fire events occurring inside a confinement ventilation system may appear in a number of physical forms. Fire may occur in ordinary combustible material. The amount of combustible material within a confinement ventilation system generally would not be as much as in a larger room, so the fire growth characteristics may be somewhat altered.

Fire may occur in the radioactive materials in a confinement ventilation system, or a fire involving ordinary combustibles may subsequently involve radioactive materials. A fire involving a flammable liquid or gas used inside a confinement ventilation system also may occur. These events may take the form of a flame front moving rapidly through a flammable vapor, a flame front moving rapidly enough to deflagrate and produce some overpressure, or even a detonation if the conditions for such phenomena exist.

Filter fires can occur due to either decomposition of combustible dust deposits within the filter, organic decomposition of chemical residue carried by the airstream from upstream processes, or spark/ember introduction from an upstream source. While introducing a water spray within or prior to the duct inlet can prevent the latter condition, fires originating at the filter itself cannot be satisfactorily mitigated by automatic suppression methods. Consequently, reliance is placed on the manual deluge system and fire department response.

Industrial and institutional loss experience has shown that over a period of time even "office dust" accumulations can form highly combustible residues on filters that are sufficient to cause damage if ignited. It also has been established that the concentration of these fuels need not be high to cause severe damage due to the fragility of the media. Fire-retardant chemical preparations for the filter media may initially make ignition difficult, particularly on clean media. However, this retardant material tends to become less effective over time and does nothing to retard or reduce the combustibility of dust or residue deposits from the airstream itself.

Administrative controls and alarm interlocks are designed to alert operators about impending change-out intervals that have been established to maintain dust or residue inventories below radiological actions points. It is not feasible, however, to eliminate the potential for direct filter fires or to practically reduce residue levels below those that may damage the filter itself.

10.5.2.2 Transport of Heat, Smoke, and Related Products

The transport of hot gases, smoke, water vapor, and chemicals from an internal fire through a confinement ventilation system can be modeled in much the same way as is done for an external fire. A fire occurring within the confinement ventilation system may affect the transport mechanism by altering the airflow through the system more than an external fire.

The transport mechanism also may be affected if the actual structural confinement barrier of the confinement ventilation system is involved in the fire and is contributing to its spread. The accumulation of dust and debris inside the air cleaning system ductwork over long periods of operation provides a mechanism for transporting flames from an ignition source to the filters, and also can produce soot that can clog filters in a fire.

10.5.2.3 Effects on Filters of Heat, Smoke, and Related Products

The effects of the products of combustion reaching the HEPA filters are the same for internal and external fires. The same physical parameters affect the manner in which the filters are threatened.

10.6 Fire Hazard Controls and Design Features

10.6.1 Objectives and Requirements

There are three major objectives for fire protection of confinement ventilation system:

- To prevent fires from affecting the operation of the ventilation system;
- To protect the filtration function; and
- To prevent the release of material that has accumulated on filters.

General Requirements

General requirements for the control of fire hazards that may affect the confinement ventilation system are formalized in NFPA Standards 9010[9] and 801, *Fire Protection for Facilities Handling Radioactive Materials*,[21] DOE Order 420.1A,[9] and DOE Standard 1066-99.[1]

Special hazards may cause exposure of the filters to the following: highly combustible dust loading; pyrophoric materials; chemically reactive, explosive, or corrosive vapors; or high-moisture conditions that may cause rapid degradation of HEPA filters. These should be evaluated on a case-by-case basis by a fire protection engineer who understands the process sufficiently to determine the protection warranted.

A comprehensive fire protection scheme for filter housings will include the following principles:

- The ventilation system filter housing construction materials should be noncombustible.
- Process hazards inside and outside the ventilation filter housings should be controlled.
- General area sprinklers should be provided within all process areas.
- The final filter housing should be separated from the general building area by fire-rated construction.
- Automatic water spray should be installed upstream of a demister and before the first-stage filters.
- Manual water spray should be installed at the first-stage HEPA filter.
- Fire detection systems should be installed in the final filter housing to allow early warning and activation of the extinguishing systems.
- Automatic flammable gas detection should be provided in filter housings where flammable or combustible processes are performed.

The FHA for a confinement ventilation system may indicate the need for further fire protection measures.

10.6.2 General Fire Hazard Control Features

10.6.2.1 Fuel Control

The flammability of materials must be considered in designing the confinement ventilation system. This is a first line of defense against fire, without which any ignition will lead to a dangerous situation.

The NFPA Standards and DOE fire protection requirements provide guidance on how to do this. The FHA also should address the issue of materials flammability.

If the process involves the presence of flammable vapors or liquids, the allowable concentration of flammable vapors inside the filter enclosure must be limited and controlled. The maximum permissible concentration (MPC) of flammable vapors is 25 percent of the lower flammable limit.

Control of Energy Sources

Ignition sources inside the filter enclosures must be limited to those necessary for operating the system. Electrical systems must be installed in accordance with NFPA 70, the *National Electrical Code*.[22] The presence of flammable gases or vapors in the operation of the confinement ventilation system will require specialized electrical equipment to prevent their ignition.

A number of flame-producing incidents have occurred while using aerosol generating devices (sometimes used in filter testing). Most of these incidents involved replacement aerosols with a lower auto-ignition temperature than dioxytl phithalate (DOP). In one incident, the aerosol liquid flow through the heater was initiated prior to establishing carrier airflow as recommended by the manufacturer. It ignited, shooting a flame of several feet from the discharge port. Fortunately there were no injuries, and equipment damage was limited to scorched insulation. The manufacturer modified the aerosol generator to reduce the heater block set point below the auto-ignition temperature of the polyalphaolefin (PAO) being used, and the air valve was modified to maintain minimal flow with the valve closed. Some generators use inert gas instead of air, but this does not always avoid ignition. While shutting down a generator, the operator heard a loud "pop" and observed smoke from the generator. An investigation revealed that flames were produced if the nitrogen flow was interrupted before the aerosol liquid flow was shut off. A safety cover was installed to prevent inadvertently shutting off the nitrogen switch, and the hose adapter was modified to preclude flaming if nitrogen was lost. In another incident, several discharge hoses erupted in flame when the generator ran out of aerosol liquid and the operators refilled the generator without deactivating it, allowing air to enter the system. Neither the manufacturer's instructions nor the operating procedure cautioned against this. The aerosol generators used are not approved by either Factory Mutual (FM) Global or UL to verify the safety for the intended use.

Challenge aerosols are not interchangeable. A new hazard analysis should be performed if the aerosol is changed. Equipment tolerances and emergency cut-outs should be evaluated. The manufacturer should be consulted. Training must emphasize procedural control, particularly valve sequencing. Critical warnings should be included in the operating procedures and on the instrument. Where valve sequencing is the only barrier preventing ignition, instruments should be replaced or modified by the manufacturer to make improper sequencing impossible.

Controlling Oxygen

Some operations use atmospheres inerted with nitrogen or argon as a flammability control. This is discussed for specific situations later in this section.

10.6.2.2 Passive Design Features and Fire Hazard Controls

Duct Runs

The design of the duct runs can greatly influence the effect of a fire in the facility or within the ductwork on the ability of the confinement ventilation system to perform its function. This section will address the physical configuration aspects of the ducts and filter housings. Ductwork and related equipment are required to comply with the criteria of NFPA 90A[10], *Installation of Air Conditioning and Ventilation Systems* and NFPA 91, *Standard for Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Noncombustible Particulate Solids.*[23] These standards provide explicit requirements for integrating the ventilation system with the building construction, as well as operational guidance for systems inspection, cleaning, and maintenance. Other sections address the active fire protection or cooling systems that may be needed to maintain confinement ventilation system functionality.

Another significant consideration in the design and layout of an air cleaning system is provision of separate systems for each building fire area. Buildings are subdivided into discrete fire areas to limit fire damage to only one area. If fire area boundaries are penetrated to allow passage of the air cleaning ducts, the possibility of fire spreading to multiple fire areas is introduced, potentially resulting in much more extensive fire damage.

Duct Response to Fire

There may be situations where fire dampers cannot be installed at firewall duct penetrations because of the need to maintain confinement ventilation. In some cases, ducting may traverse other fire areas before reaching the filter banks. The quality of the duct construction and installation are the most important factors in maintaining the integrity of the ducting. A number of factors need to be considered:

- Where the duct penetrates a firewall, distortion during a fire may allow flames to pass through the wall around the outside the duct. Investigators[24, 25] performed full-scale fire testing that provided insight into the performance of reinforced ducting under limited fire exposures.

- Conductive heat transfer through the duct may ignite combustible materials in adjacent fire areas. This can be mitigated by insulating or enclosing the duct as determined by the FHA.

- Duct collapse can occur due to weakening of the duct or the hangers when heated. Additional hangers and/or reinforcement will mitigate this potential problem.

- Where there are duct openings in a nonfire space, the FHA should consider the potential for fire spread and the need for additional safeguards.

Air Supply and Extraction

The method of air supply and extraction profoundly influences the efficiency with which a fire burns. Most gloveboxes are designed so that the air supply enters at the bottom on one side of the box and exits at the top on the other side. This design ensures that a vigorous fire will persist so long as fuel and air are available. If, the ventilation pattern is reversed and air enters at the top of the box and exits at the bottom, however, combustion products will mix with the supply air to weaken and ultimately extinguish the fire. This tactic is effective for all but very large enclosures.

Entrance Filters

Because the duct-entrance filter is the major dust collector, it is also the primary component in which a fire could occur. Protection of the HEPA filter downstream from sparks and burning fragments from the duct-entrance filter may be needed if the distance between them is not great. If it is less than 20 to 30 feet, a fine (20 to 30 mesh) screen may be installed downstream of the duct-entrance filter (such screens must be located where they are convenient for periodic cleaning). Because lint tends to bridge the openings, screens, and coarse filters (e.g., furnace filters), installation of fine-mesh screens on the face of the duct-entrance filter is not recommended; however, this does not preclude installation of a mesh screen for physical protection of the filter. For glovebox and hot cell applications, the duct-entrance filter should be designed for withdrawal into and replacement from the contained space. The filter should also be afforded maximum protection against the effects of or ignition by a fire in the contained space.

Prefilters

Prefilters are usually provided in the central filter house in addition to or instead of duct-entrance filters. Again, fire is more likely to occur in the prefilter than in the HEPA filter downstream. Prefilters should never be mounted directly on the face of the HEPA filter or on the opposite side of a common mounting frame with the HEPA filter (i.e., back to back). A spacing of at least 36 inches between the downstream face of the prefilter and the upstream face of the HEPA filter is recommended—not only for maintainability, but also to provide space where burning fragments and sparks can burn out or settle to the floor of the filter house.

Filter Housings

HEPA filter housings should be protected from facility fires by fire-rated construction. High temperatures in exhaust filter housings can be minimized by long runs of duct preceding the housings, by intake of dilution air from streams from other contained or occupied spaces of the building, or by cooling the outside of the duct with water spray. Cooling via water spray installed inside the duct has been employed in some applications (discussed in Section 10.6.2.3). The intent is to place the HEPA filters where they are least likely to be exposed to heat, hot sparks, and burning embers from a potential fire in the process line.

Fire Screens

A fire screen is a noncombustible sheet of meshed metal similar to a roughing filter that is intended to reduce the potential for transporting glowing embers/burning brands through the airstream from the fire source to the filter banks. The screen should be installed upstream from the prefilter(s) and ahead of the filter housings. Specific design criteria for fire screens can be found in DOE Standard 1066-99.[1]

Materials

Ideally, all construction materials used in confinement ventilation system enclosures should be noncombustible. Use of noncombustible materials for the enclosure will help limit the total amount of fuel available to burn if a fire occurs. If suitable noncombustible materials cannot be used because of process, shielding, corrosion-resistance, or other special purpose requirements, attempts should be made to minimize the quantity and surface area of the installed combustible materials. If a combustible duct material is utilized, installation of automatic sprinklers may be required according to DOE, NFPA, or FM Global requirements.

The preferred construction materials for ductwork are steel, stainless steel, or galvanized steel. If fiberglass ductwork is needed because of corrosion issues, special ductwork that meets the flame-spread criteria in NFPA 90A[10] is required. Acoustic linings or duct silencing materials are combustible and are not permitted inside air cleaning system ductwork.

Filter Construction

Wood is frequently used for HEPA filter casings. For this application, the wood is required to have undergone a fire retardant treatment that results in a flame spread of 25 or less and a smoke-developed rating of 50 or less when tested to American Society for Testing and Materials (ASTM) Standard E-84.[26] This test measures the speed at which flames will travel across the surface of the material being tested. As a comparison, the flame spread of red oak boards is 100, while the flame spread of concrete or unpainted steel is zero. Thus, even with the fire retardant treatment, wooden filter frames will burn in a sufficiently severe exposure fire.

Duct entrances and prefilters are required to be classified as Class 1 Air Filter units in accordance with UL Standard 900.[14] This is a different test method than is used for HEPA filters and is intended to evaluate the combustibility and amount of smoke generated for air filter units of both washable and throwaway types when they are clean. Class 1 filters, when exposed to flames, do not contribute fuel to the fire and will emit only limited quantities of smoke. Class 2 Filters burn moderately and emit moderate amounts of smoke. Either filter class will burn vigorously if it becomes dust loaded.

Fire Barriers

HEPA filter housings located within nuclear or hazardous process buildings are required to be separated from the remainder of the building by a minimum of 2-hour-rated fire barriers. This requirement is intended to ensure HEPA filters are protected from fires occurring in the process building. One common type of 2-hour-rated barrier is constructed of 8-inch-thick concrete block walls and a poured concrete ceiling. Another way to provide this level of protection is to locate the filter housing outside of the process building. If the filter housing is located in a separate building, no specialized fire barriers are necessary, provided the housing is located at least 20 feet from the process buildings and the exterior walls of the buildings have no unprotected openings. If the filter housing is located less than 20 feet but more than 5 feet from the process building, the filter housing is required to be constructed as a 1-hour-rated fire barrier. Filter housings are required to be installed in 2-hour-rated firewalls if they are less than 5 feet from the process buildings.

Small filter housings, which have a leading-edge surface area of 16 square feet or less, are not required to be separated from the rest of the building, provided the building has area-wide automatic sprinklers and the housing has an internal fire suppression system.

Penetrations through the air cleaning system enclosure fire barriers are only permitted for services necessary to the operation of the filtering system. Where penetrations cannot be avoided, the openings created through the fire barrier must be properly sealed with approved, fire-rated, noncombustible penetration seal materials. Penetration seals are tested and approved under the requirements of ASTM E-814, *Fire Tests of Through Penetration Fire Stops.*[27] The penetration seals must also be compatible with and capable of continued exposure to the types of materials and atmospheres present inside the filter enclosure. Doors in 2-hour-rated enclosures are required to be Class B fire door assemblies. Doors in 1-hour-rated enclosures are required to be Class C fire door assemblies. The requirements for construction and installation of fire doors are found in NFPA 80, *Fire Doors and Windows.*[28] HVAC ducts that penetrate 2-hour-rated enclosures must be protected with UL-listed fire dampers. HVAC ducts that penetrate 1-hour-rated enclosures are not required to have fire dampers. In some cases, it is necessary for ductwork that is part of the nuclear air cleaning system to penetrate fire-rated barriers. Fire dampers cannot be installed in these ducts because their operation during a fire would cause the dampers to close, sealing off the ductwork. This would prevent the filtration system from continuing to operate. Because the air cleaning system is required to be functional at all times, an alternative method of fire protection must be provided. It is recommended that a fire protection engineer be consulted to evaluate such configurations on a case-by-case basis. [Note: DOE has granted an exemption on the use of fire dampers for certain configurations of ductwork in an existing building where alterations would have been difficult due to highly contaminated conditions.] Each of the above features requires the design to be adjusted to the process under consideration. When changes are made to the process, each of the design features needs to be reviewed to ensure that nothing has been introduced that would make the fire system ineffective.

10.6.2.3 Active Design Features and Fire Hazard Controls

One of the goals of the nuclear industry has been to provide gloveboxes, caves, canyons, hot cells, fume hoods, and other radiological confinement areas with practical ventilation exhaust systems that can remain in service through a fire and can contain all the radioactive contamination made airborne by the fire. It has been established by both consensus standards and industry/government regulations that ventilation components in nuclear air cleaning systems should continue to perform their safety functions effectively under all conditions by confining radioactive or other potentially dangerous materials. To realize this for fire protection purposes, it is necessary to protect the filter housing in the exhaust system from heat, smoke, and burning material that would be generated during a fire scenario. In the event of fire, the release of contaminated smoke through a ruptured or damaged filter housing may have more serious consequences than any potential casualty losses from the fire itself.

Fire Dampers

Fire dampers in ductwork penetrating fire-rated construction should not be utilized in confinement ventilation systems with the following design features: (1) where the ducting is a integral part of the nuclear air filter system, and (2) where equipment is required to continuously function. Such duct material penetration of fire-rated construction without fire dampers should: (1) be made part of the fire-rated construction by either wrapping, spraying, or enclosing the duct with an approved material, or by other means of separating the duct material from other parts of the building with equivalent required fire-rated construction by either wrapping, spraying, or enclosing the duct with an approved material; or (2) be qualified by an engineering analysis for a 2-hour fire-rated exposure to the duct at the penetration location where the duct maintains integrity at the duct penetration with no flame penetration through the fire wall after a 2-hour fire exposure.[21]

Fire Detection Systems

Detection equipment for early warning of fire conditions must be provided in all HEPA filter housings. Rate anticipation heat detectors are most commonly used because of their good stability, low maintenance requirements, and relatively quick response to heat.

Sampling types of smoke detection systems has been suggested as a means to provide early warning, however, precautions must be taken to ensure they do not provide a leak path that bypasses the filters.

Alternative fire detection methods are possible depending on the specific design of the filter enclosure. If flammable liquids or gases are used and the possibility of explosion exists, rapid detection using flame detection devices may be needed.

NFPA Standard 72[29] provides the requirements for the installation of fire detection devices and systems.

Automatic Fire Suppression Systems

Prior to the Brown's Ferry nuclear power plant fire in 1975, the use of water on electrical fires was not considered a safe practice by the nuclear power industry. Following the Brown's Ferry fire (see NRC NUREG-0050, *Recommendations Related to the Brown's Ferry Fire*),[30] in Factory Mutual (now FM Global) and other organizations performed studies to test the use of water in electrical spaces (see Electric Power

Research Institute (EPRI) NP-1881[31] and EPRI NP-2660).[32] In addition, Sandia National Laboratories (SNL) performed tests on cable tray protection schemes (see NRC NUREG/CR-2377,[33] NUREG/CR-2607,[34] and NUREG/CR-3656).[35] These studies by Factory Mutual and other organizations showed that fighting fires in grouped cables could be accomplished efficiently using water (these tests were done on unenergized electrical cables, however, the conclusions on the use of water as an efficient extinguishing agent were confirmed). Following the Brown's Ferry fire and the tests performed by Factory Mutual, SNL, and others, the inhibition against using water to put out fires in all spaces with electrical equipment seemed to subside, and fire protection engineers made more deliberate assessments of the type of electrical occupancy when considering use of water as a fire suppressant.[36, 37]

Automatic fire suppression systems throughout a facility will control a fire in its early stages of growth, thus mitigating fire effects that could affect the functionality of the confinement ventilation system. Wet pipe sprinkler systems are the most common type of automatic fire suppression system and have a proven experience record of fire extinguishment. Other types exist and are described further in this section. Activation of a suppression system will extinguish an incipient fire and automatically alert dispatchers or the fire department.

Consideration must be given during the design phase to testing and maintenance of fire suppression and fire detection systems throughout the life of the system/facility. Consideration also must be given to avoiding interference with or inhibition of the safety function of other safety features (i.e., water addition/criticality controls, HEPA filters, etc.).

Wet Pipe Sprinkler Systems

Wet pipe sprinkler systems are used to control the fire potential in the areas being exhausted by the confinement ventilation system. They will control the fire to limit the threat to the facility and the HEPA filters, and also will prevent physical fire damage to the ductwork of the confinement ventilation system.

The need for wet pipe sprinkler protection is established by DOE or NRC requirements, or the FHA. The design requirements for these systems are contained in NFPA Standard 13, *Installation Of Sprinkler Systems*.[38]

Deluge and Water Spray Systems

A deluge sprinkler system is one in which the sprinklers are normally open and water flow is controlled by a valve in the line leading to the sprinkler heads. When this valve is opened, water is discharged from all the open sprinklers at the same time.

Two types of deluge systems are required for protection of HEPA filter housings. The first type, automatically-actuated deluge systems, are located upstream of the demisters. This type of system is also called a water curtain, as it consists of closely spaced, open-head, deluge nozzles connected to piping located in front of and above the demisters. When the system is activated, all of the nozzles spray water simultaneously downward, forming a wall of water. This system is intended to cool incoming air, hot sparks, and flames before the prefilters are threatened. The water curtain is located upstream of the demisters so the water spray carryover can be diverted to prevent moisture from reaching the downstream HEPA filters.

Operation of an automatic deluge spray system is initiated by a fire detection system located in the ducting—usually heat detectors. The detection system opens a deluge valve, allowing water flow to the nozzles. The spray nozzles are either open sprinkler heads from which the fusible link has been removed or special purpose nozzles designed to produce a particular pattern. The automatic system is also equipped with a locked bypass valve that can be manually opened if the detection system or the deluge valve fail to operate. Closed-head pilot sprinklers are sometimes used in place of an electrically-operated heat detection system to open the deluge valve to the nozzles. In this case, the pilot sprinklers serve only as temperature sensors and do not spray water.

Fires produce smoke that can cause rapid clogging of filters. Because the automatic spray deluge system functions much like the scrubbers that are used to clean smoke stack exhaust, there is an expectation that the automatic system may also reduce smoke clogging. However, the nozzles are not optimized for smoke reduction. In limited research with spray nozzles, it was found that smoke clogging decreased in some cases, but increased in others. Therefore, premature manual activation of the spray deluge system to reduce smoke is not recommended without further research to quantify results for specific arrangements and combustible contents. Operational procedures such as shutting down or throttling back the blowers to prevent rupture of clogged filters during a fire should be addressed in the authorization basis documents. The generic operational procedures provided here resulted from studies at a DOE site and are applicable to the procedures at most sites. Use of these procedures should be preceded by a thorough design review to ensure their specific applicability.

Demisters must be installed between the automatic spray nozzles and the HEPA filters. Demisters are specially configured metal panels that redirect the water droplet trajectory toward the floor of the enclosure. Performance criteria for demisters are contained elsewhere in this handbook. The demisters must be positioned at least 3 feet upstream of the HEPA filters, and approximately 6 inches downstream of the automatic deluge nozzles.

The second type of deluge system is a manual deluge spray system. This system is operated only if the filters begin to burn because it discharges water directly onto the first filter system. Burning cannot only breach the filters, but may also release particulate that has accumulated on the filters over time. Facilities without this manual system must rely on firefighters to attack HEPA filter fires with hose streams. The manual deluge system is intended to avoid unnecessary exposure of firefighters who must otherwise enter the hazardous environment within the housing, and also to ensure a more gentle application of water to make it possible for some filter stages to survive. The manual control valve for the manual deluge spray system is normally locked in the closed position and only accessible to firefighters. Fire department training programs should address operating procedures for these valves.

The potential for nozzle plugging or corrosion in housing deluge systems should be considered during design. Potential remedies include, but are not limited to, strainers, blow-off caps, and corrosion control measures such as use of special corrosion-resistant materials or coatings.

The automatic extinguishing systems must be designed to comply with the requirements of NFPA 13[38] and NFPA 15, *Water Spray Fixed Systems For Fire Protection*.[39] These standards provide the requirements for designing the system and selecting components, as well as associated installation requirements. Research conducted by Dow Chemical Company following the 1969 filter housing fire at Rocky Flats determined that the minimum water supply for the system must be hydraulically calculated to provide at least 0.25 gpm/ft^2 over the entire face area of the filters, or 1 gpm per 500 cfm of airflow, whichever is greater. The water curtain must be located 6 in. before the demisters. Standard deluge-type sprinkler heads must be installed on the piping at a minimum spacing of 4-foot intervals. The system must be activated by the rate-compensated heat detection system or by pilot-operated sprinklers. A manually operated release must also be installed on the deluge valve in the event a malfunction in the releasing system occurs. The use of corrosion-resistant deluge heads and piping should be considered for all installations.

Water Mist Systems

New watermist technologies are being developed that use fine water sprays to efficiently control, suppress, or extinguish fire using limited volumes of water. Their suitability for use in confinement ventilation systems has not been demonstrated at this time (refer to NFPA 750, *Standard on Water Mist Fire Protection Systems).*[40]

Sprinklers within Ductwork

Provision of wet-pipe sprinkler systems within ducts or filter housings is the exception rather than the rule, however, deluge sprinkler systems are routinely provided on carbon-filled adsorption systems in nuclear power reactors. On deluge systems for adsorption filters, fog nozzles with as fine a droplet-size distribution as possible are recommended for maximum cooling and smoke-particle capture. To limit the volume of water discharged, consideration should be given to an automatic recycling deluge system.

Demisters and HEPA Filters

Water protection for HEPA filters has been controversial due to concerns about water plugging of the filters. The research that led to this concern was based on conditions that are not reflected in an actual filter installation. Specifically, the research involved soaking filters in pans of water. However, in a properly designed confinement ventilation system, demisters prevent water from the automatic deluge system from reaching the filters. Manual deluge systems are only operated after the filters begin to burn. Consequently, water damage is no longer an issue. This topic is further discussed in DOE Standard 1066-99.[1]

Fire Department Standpipe Systems

Because the possibility of a fire that can affect the filters cannot be entirely eliminated; some provision for manual fire fighting using a standpipe system (meeting the requirements of NFPA 14 *Standard for the Design and Installation of Standpipe and Hose Systems* [41] is necessary. The fire department will almost always use its own hose packs.

The use of a hose stream can only be considered when all other automatic and manual safeguards have been determined to fail. Filters cannot be saved, but hose streams may prevent fire spread to subsequent stages of filters and avoid failure of the final filter stage that could release contamination. In addition, a hose stream can serve to prevent further damage to the filter mounting frames and housing, the duct, or the building. Similar observations can be made for the common types of sprinkler systems, both automatic and manually actuated, if they are installed inside the filter housing.

Water Runoff Collection

Facilities protected by sprinklers or deluge systems must have a provision to collect and dispose of water used for fire extinguishing. In addition, design of the water drainage system has to be consistent with the characteristic of water as a neutron moderator.

Gaseous Agent Systems

Some spaces external to the ductwork of ventilation systems are protected with gaseous agent fire suppression systems. There are NFPA standards for the design of these systems that include Halon alternatives and carbon dioxide systems. Competent technical persons should be consulted to design these systems.

Flammable Gas Detection

If flammable gases are used, the FHA may require flammable gas detection equipment in the ductwork or filter housings. The installed gas detectors must be connected to an alarm system located at a continuously attended position to ensure immediate corrective actions are taken if high flammable vapor concentrations are detected. The effective design of systems to detect flammable gases depends on the gases themselves, the airflow characteristics within the confinement ventilation system, the actions that must be taken in response to unacceptable concentrations of flammable gases, and many other factors. Systems that do not adequately address the issues may either not work at all or will provide false alarms on a frequent basis which can be an equally bad situation. Competent technical persons who are knowledgeable of the hazards present and the design of such systems should be consulted to design these systems.

Protection of Carbon-Filled Adsorption Systems

To prevent loss of confinement for radioactive iodine and iodine compounds, carbon-bed temperatures must be maintained at a level where impregnants and trapped radioiodine cannot desorb. This requires the bed(s) to be large enough that specific loadings of iodine cannot exceed 2.5 mg/g of carbon, and that airflow through the bed can be maintained at some level in excess of 6 (preferably 10) linear fpm. If bed temperatures can be maintained below the level where desorption of impregnants and trapped radioiodine takes place, carbon ignition is unlikely. If a fire should start, however, total flooding or dumping of the carbon into a container of water is the only effective means of extinguishing a carbon bed fire that is known at this time. Carbon dioxide and gaseous nitrogen are ineffective against activated carbon fires because the fire feeds on the oxygen adsorbed in the pores of the carbon, and the quantity of liquid nitrogen required to provide effective cooling would be unavailable in most cases.

Combustible Metals

Metal fires, particularly fires in water-reactive metals such as sodium, present special problems. Water and inerting agents such as Halon alternatives cannot be used, and inert atmospheres such as nitrogen and carbon dioxide require practically the total exclusion of oxygen to be effective. The fire must be treated in the operating space before it can reach the ducts or filters, which requires an effective duct entrance filter, preferably one of the HEPA type if the metal dusts are finely divided. However, most of the fire-extinguishing agents that are effective against such fires produce copious clouds of dust that, when released, rapidly threaten to plug the duct entrance filter. This in turn threatens overpressurization of the glovebox or hot cell, resulting in blowback of contamination to occupied spaces of the building. Carbon microspheres[5] have been shown to be extremely effective against plutonium, sodium, uranium, sodium-potassium, magnesium, aluminum, lithium, and other types of fire that produce intense heat. The material can be dispensed automatically or manually and produces essentially no dust when dispensed either way. In addition, it has negligible chloride content (and so poses no threat to stainless steel equipment and cells), is very easy to cleanup, is inexpensive, and is readily available.

When combustible metals are being processed, the potential presence of combustible dusts in both the airstream and inside the filter enclosure should be considered in the FHA. Appropriate hazard controls should be provided as necessary (duct-entrance filters alone will not prevent dust from entering the ducting).

10.6.2.4 Discussion of Other Filter Types

Small Filter Assemblies in Plywood Enclosures

Some smaller HEPA filter assemblies are purchased as a single package. These are often self-contained in assemblies constructed of plywood or other wooden composite material. These assemblies have male duct connections on their inlet and discharge sides, and are easily dropped into place by clamping existing ducts onto them. Given the lack of fire resistive properties of these filter assemblies, it is not recommended that they be used in new construction.

High-Efficiency Metal Fiber Filter Systems

High-efficiency metal fiber (HEMF) filter systems have only been commercially available in the United States since the mid-1980s. They are made of sintered stainless steel fibers that are welded into steel housings and steel frames. These filters have been used in small, specialized exhaust systems, but have not yet been sufficiently developed to be equivalent to HEPA filters.

In contrast to HEPA filters, HEMF filters are not weakened by moisture impingement. They can also operate for longer time periods and in hotter conditions than HEPA filters because the metal filters contain no flammable components, and are inherently resistant to high temperatures. However, the finely divided filter media in a metal filter will not resist a direct flame impingement. The resistance of the metal filter to moisture and heat makes this filter attractive for fire protection purposes. Because the use of HEMF filters is relatively new to the DOE community, only limited experiential data on the behavior of these filters in actual fires is available. They are also very expensive to purchase and operate.

Radioiodine Absorber Air Cleaning Systems

Although much discussion in the nuclear community has been generated in the past 40 years regarding fire protection of absorbers, little consensus and few conclusions have been reached about the proper method of extinguishing fires in absorbers with combustible material. Available methods include: (1) using a combination of manual and automatic water spray systems, (2) limiting airflow to the absorbers, and (3) using alternative noncombustible absorber media (e.g., silver zeolite). Absorber air cleaning systems are often used in nuclear reactor emergency ventilation confinement systems where they are frequently referred to as charcoal- or carbon-type filters. Other inorganic absorber materials are available for absorber media, including silver oxide, silver nitrate, aluminum silicate, and silver zeolite. It is generally accepted that, as a minimum, absorbers should be provided with fire detection equipment.

For carbon-type filters, American Nuclear Insurers, an insurance carrier for nuclear power plants, recommends the following fire protection:

- Charcoal filters should have a hydraulically designed, automatic water spray system that uses directional, solid-cone spray nozzles controlled by an approved deluge valve. The system should be capable of being manually actuated from a suitably remote location.

- Spray nozzles for horizontal beds or drawers should be oriented above each bed or drawer and should be designed to distribute water evenly across the top of each bed or drawer at a minimum density of 0.25 gpm/ft^2.

- Spray nozzles for vertical beds should be oriented at the top of the bed and should be designed to distribute water evenly across the top of the bed at the rate of 3.2 gpm/ft^2 of charcoal bed.

- A supervised, fixed-temperature detection system should be provided and connected to an annunciator in the control room. The detectors should be located on the downstream side of the charcoal bed to facilitate timely, automatic operation of the spray systems. The spray system should be equipped with a local alarm and should be connected to an annunciator in the control room. The airflow should terminate (with the fan shut off) upon water activation.

- For the pressure vessel-type charcoal filter, where a shut-off bypass arrangement is employed around each tank, an automatic water spray system is not required. A hose connection should be available on the side of the tank to allow the introduction of water.

Deep-Bed Fiberglass Filter Systems

Early designs of deep-bed, fiberglass filters did not address filter media replacement. Fiberglass filters plug over time, resulting in combustible deposits that may contribute to fire risk. It is generally accepted that water applied to this type of filter media will extinguish the fire. Precautions should be taken when water is applied to filter media containing radioactive material to prevent the water from being released to the environment.

Deep-Bed Sand (DBS) Filter Systems

For the most part, DBS filters are fire-resistant, chemically inert, and require no special fire protection systems. Sand filters are usually accompanied by HEPA filters. When a sand filter is used in series with a HEPA filter, it should be upstream of the HEPA filter. In this position, the sand filter can protect the HEPA filter that provides the final confinement barrier. However, HEPAs have been traditionally installed prior to the sand filters for fear of sand fires carrying over and plugging the HEPAs.

Since plugging is a "worst case" scenario for both HEPA and DBS filter arrangements, both require mitigation measures. It has been largely accepted that DBS filters, while expensive to construct, decontaminate, and demolish, offer improved performance in their ability to operate in the presence of heat and fire products. However, no quantitative test results have been found to confirm that a DBS filtration system can withstand plugging by smoke particulates. While it has been empirically shown that DBS filters can resist high heat conditions, and some qualitative testing has shown a high degree of resistance to plugging compared to HEPA filters, this does not confirm how many particulates can be absorbed and the rate or conditions under which a DBS arrangement can operate without loss of efficiency. Indeed, DOE reports to this point are largely historical rather than experimental in nature. Tests on the physical properties of smoke and its effect on DBS filters need to be performed to establish obstruction limits for DBS filters.

Self-Cleaning Viscous Liquid Filters

This type of filter uses a viscous liquid for cleaning purposes. These filters should be avoided where radioactive materials are handled because they produce radioactive sludge that requires disposal. They also require special fire protection systems because of the combustible nature of the liquid.

Moving-Curtain Single-Pass Rolling Prefilters

One noteworthy type of prefilter is the moving-curtain single-pass rolling prefilter. This type of prefilter involves manually or automatically feeding a fresh filter media across the face of the filter frame while the dirty media is rewound onto a take-up roll. When the roll is exhausted, the takeup media is disposed of and a new media roll is installed. In 1980, LLNL performed fire tests involving this type of prefilter utilizing a modified commercial moving-curtain filter. The purpose of testing this type of filter was to find a way to limit or eliminate the smoke that may be produced in a fire, thus reducing the potential for the smoke to plug the HEPA filters. The tests validated that the moving-curtain single-pass rolling prefilter could reduce the potential for aerosol plugging of HEPA filters during a fire. The final test report stated that prefilters of this type were an "experimental prototype." Those considering this type of design should obtain a copy of the report and review the basis of the conclusions as they apply to a particular case.

Electrostatic Precipitator Prefilter

Another type of prefilter used at DOE facilities is the electrostatic precipitator (ESP) prefilter. This prefilter imparts an electrical charge to particles in the airflow stream, causing them to adhere to collector plates. The ESP prefilter has been used to extend the life of HEPA filters when processes involve larger-diameter airflow particles. An ESP prefilter provides some fire protection, as long as the particles resulting from the combustion products of a fire can be properly collected on the filter throughout the fire. Most commercially available ESP prefilters cannot catch the smaller airborne particles and smoke particles associated with a burning fire. However, more work needs to be done to understand which particle sizes associated with fire can be effectively filtered by an ESP prefilter. When ESP prefilters are used, they should be made of noncombustible materials and, as with any prefilter, the user should pay careful attention to preventing dust loading on the prefilter during use. In addition, ESP prefilters should not be used where explosive concentrations of gases or dusts are present.

Regenerable HEPA Filters

A study is being conducted at Savannah River Technology Center to develop a full-scale application of a regenerable HEPA filter. Previous attempts at this task were made at LLNL and involved the stainless steel matrix. These efforts proved less than satisfactory due to weight and efficiency considerations. The latest effort at Savannah River is a ceramic matrix with a sintered stainless steel coating. A backwash system is also provided for periodic in-place cleaning of the filters. This design holds a potential for long life similar to that of conventional HEPA filters, with a reduced potential for catastrophic failure due to media breakthroughs, moisture, or fires in the ventilation system. If fully validated at the demonstration level, this system could provide a solution to many fire protection issues. Whether or not this technology can be adapted to building ventilation systems with much larger airflow requirements has not been determined as of this writing. The space, pressure drop, and resistance requirements still need to be improved to make this technology useable on a widespread basis. With the development of such newer technologies, some design changes may be expected to optimize performance.

10.6.2.5 Fire Protection Concepts for Gloveboxes

Fire protection and prevention in gloveboxes is mainly accomplished via the following methods:

- Using noncombustible construction materials. (For information on gloves and windows, which are more vulnerable to fire damage, refer to DOE Standard 1066-99.[1])

- Adhering to acceptable housekeeping policies and procedures.

- Avoiding the use of flammable materials within the box wherever possible. (When no suitable nonhazardous substance can be substituted, the amount of flammables is limited to the minimum required for immediate use. The containers used for flammable substances are safest available for the planned operation.)

- Maintaining a current in-box material inventory. (The box is not used for storage. Boxes usually are inappropriate for storage, especially for chemicals.)

- Establishing a safer, nonoperative box configuration and periodically checking it to ensure that nonoperating boxes are in a safe condition. (Precautions include isolating boxes by closing fire stops, checking through-flow, checking port covers, disconnecting electrical equipment, and removing corrosives.)

- Designing the box with down-draft ventilation (high air inlet, low outlet) to inhibit combustion while still purging the box.

- Providing a protective atmosphere. (This measure is listed last because those preceding it apply to all gloveboxes, whereas inerting is used only when there is too much risk involved in operating without a protective atmosphere. Assessing the degree of risk involved in an operation is often a subjective evaluation.)

10.6.2.6 Protective Atmospheres

The inerting atmosphere system is designed for continuous operation, whereas the extinguishing system usually has a one- or two-shot, single-incident application before reservicing is required to return the system to the ready state.

Inerting with smothering agents may require that less than l percent oxygen be present in the glovebox atmosphere. Process and product-purity considerations may require as little as 100 ppm of total atmospheric impurities within the glovebox for successful operation. Since many of the detailed considerations are similar for high-purity and fire protection inerting, and because of the widespread application of high-purity inerting, most of this discussion will involve high-purity systems. The best single reference for design, construction, and operational information is *Inert Atmospheres 2* by White and Smith.[17]

Inert-atmosphere gloveboxes that contain radioactive material are operated at pressure differentials of 0.3 to 1.0 in.wg negative pressure relative to the surroundings. The gas flow rate is usually determined by the atmospheric purity required and the purity of the incoming gas. The box atmosphere purity can be compromised by air leakage into the box or into service connections, as well as leakage from process equipment in the box.

Filter installation requirements in inert atmosphere gloveboxes are more stringent than those for air-ventilated boxes because acceptable box air leakage rates are generally less than 0.0005 box volume/hr.[2] To attain this standard, joints and fastenings between items of equipment and materials (gaskets and seals) must have extremely low gas permeability. Full-welded joints are recommended for all permanent fixtures. Gasketed joints may deteriorate in service, imposing continuing costs for periodic testing and repair.

Low-leak systems require quality construction for all components including boxes, filters, and associated ducts. Any in-leakage associated with the filter mounting or connecting duct will adversely affect the quality of the inert atmosphere that can be maintained in the box, and thus the cost of inert gas purification. Penetrations must be minimized in both number and size. The use of smaller HEPA filters allows smaller ports for maintenance. Filter changes should be planned for times when other maintenance operations (routine or special) are taking place inside the box to reduce interruptions to operations, to reduce the loss of inert gas, and to minimize the time required to recondition box spaces.

For fire protection, the preventive step of inerting is more satisfactory, though more expensive, than extinguishing a fire if it does occur. However, oxygen must be reduced below l percent before it fails to support the burning of some pyrophoric metal.[18] The use of dry air (relative humidity less than 20 percent) reduces the hazard of pyrophoric metal fires, but does not eliminate it. Moisture in the presence of heated pyrophoric or reactive metals, such as finely divided plutonium, increases the possibility of explosion by generating hydrogen. The suitability and cost of an inert gas for the process are significant factors when selecting this type of fire control. The gas flow rate in most inert gas boxes is kept as low as possible to be consistent with required box-atmosphere purity levels; low-capacity filters are frequently used. The inert gas may be purged on a once-through basis or recirculated through a purification unit. A word of caution concerning commercially available (off-the-shelf) recirculating gloveboxes: on one occasion at a DOE installation, there was a problem with oil mists developing in the recirculating pumps and being circulated along with the inert gas. Off-the-shelf items cannot be used in a confinement-type ventilation system without evaluation, nor can they be applied as “black boxes” by those responsible for operational safety.

10.7 Operations and Maintenance Practices for Fire Protection of Confinement Ventilation Systems

10.7.1 Essential Elements

The protection of confinement ventilation systems during a fire situation depends on the reliable functioning of the procedures, systems, and barriers as they were designed and intended to function. To retain that design capability, it is critical that maintenance and surveillance of systems be accomplished on an established schedule. Procedures must be practiced, and systems must be regularly inspected to locate problems that may require alteration of the maintenance practices and operational procedures. If these things are not done, the ability of the confinement ventilation system to function when needed may be impaired.

10.7.1.1 Fire Prevention

The most critical aspect of fire prevention is fuel control. The storage of any extraneous combustible materials in filter enclosures or areas where radioactive materials are being handled must be prohibited.

Procedures for the use of flammable liquids and gases must be in place and followed. Quantities of flammable liquids and gases must be limited to only those required to perform any task.

Accumulation of dust and debris inside the confinement ventilation system ductwork over long periods of operation increases the consequences of any fires that might occur. Periodic cleaning is required to eliminate the presence of undesired fuel.

Appropriate procedures and controls must be in place and followed to prevent fire involving pyrophoric radioactive materials. Much experience exists on the start of fires in nuclear facilities and confinement ventilation systems. The lessons of the past should be applied to prevent fire from occurring in confinement ventilation systems, or where a fire occurs, a loss of the first line of defense.

10.7.1.2 Procedures

Procedures for safe operation of a facility are required by law. All hazards and necessary controls must be delineated in existing operational procedures. Fire protection procedures must complement a facility's safety documentation required by law or contractual obligations.

10.7.1.3 Inspection, Testing, and Maintenance

Inspection, testing, and maintenance requirements for fire detection and suppression systems are outlined in the NFPA standards. A program should exist that follows either the NFPA standards or a carefully thought-out alternative program that provides an equivalent degree of reliability.

Inspection, testing, and maintenance plans must have been established and implemented for all systems in the facility and its confinement ventilation system, both passive and active.

Limited life materials that will wear out in a relatively short time should be identified and replaced according to an established plan.

It is important that water-based fire suppression systems be designed such that they do not have to discharge water on HEPA filter media. Any exposure to water will significantly weaken the filter media and can result in an undesired loss of filtration due to the filter media physically failing. Systems must be designed such that they can be discharge tested without having to actually spray water on the filter media.

10.7.1.4 Impairment Planning

A program must exist to handle situations where fire detection and suppression systems are impaired. Pre-plans must be developed and instituted to guide facility operations when these systems are not functioning as they should. Impairment plans also must exist for other critical facility systems. The occurrence of an impairment is not the time to develop such plans. All impairment plans must be analyzed to identify and control to the greatest possible extent the hazards that may exist under a given condition.

Impairment plans should be exercised on a regular basis to maintain proficiency in their execution.

10.7.1.5 Modifications

Modifications in a nuclear facility must follow the protocols for Unreviewed Safety Question determination. This is a somewhat roundabout means of identifying the impact to the established safety basis and all that goes with that, but it is what the current culture understands and accepts. Configuration control must be maintained when modifications are made so that all changes are tracked across all affected documentation and all impacts are identified and understood.

10.7.1.6 Other Considerations

Emergency Planning

The successful mitigation of a fire in a nuclear facility containing a confinement ventilation system requires emergency planning and exercises involving all entities that may be called on to mitigate a fire situation. Post-fire recovery plans should exist to aid in the resumption of work in the facility after a fire.

Technical Safety Requirements Tie-in

Maintenance and operational procedures may be formalized in the nuclear facility's Technical Safety Requirements.

Quality Assurance

All aspects of operations should be tied in to the facility's Quality Assurance Program, which covers all of the areas required to produce quality work and to operate safely.

Assessments

Periodic management and independent assessment are necessary to ensure that established requirements are adequate and are properly implemented.

10.8 Generic Firefighting Procedures

The following recommendations apply to firefighting procedures and instructions. They provide a strategy that minimizes the likelihood of losing filtered, forced ventilation during a fire. These procedures were derived from extensive work at Rocky Flats and are included here because they are generically applicable to all DOE facilities where active fire protection measures are installed for filter housing protection.

A special need for nuclear facilities with confinement ventilation systems is smoke venting. Obviously, smoke cannot be vented to the exterior, but there may be methods to use the confinement ventilation system to assist in removing some smoke from the fire area to enable more rapid intervention in manual suppression of the fire.

10.8.1 Control Ventilation Configurations, Volumes, and Flow Rates in the Field

An individual who is responsible for ventilation control (and successors or alternates in case of unavailability) must be established in the facility emergency planning documentation. This individual must work in consultation with the fire department sector officer stationed in the control room or at the housing to ensure a fire emergency will be successfully mitigated with minimal impact.

Differential pressure (DP) changes in the initial filter stages must be continuously monitored, even if the DP gauge readout is exceeded. Most gauges have a maximum capability of 4 to 6 in.wg, but a rapid drop from an off-scale high reading to a lower reading will confirm stage failure, as will a significant rise in DP for the next downstream stage. Attention should be focused on the first stage and the next downstream stage until a first stage failure is indicated. A rise in DP may be due to progressive filter plugging from fire particulates or wetting of the filters from deluge spray. Because the initial filter stages are usually (but not always) viewed as sacrificial, the DP may be allowed to rise to the maximum achievable by the fan. If there is only one stage of filtration, then this is not applicable.

For housings with four stages, the SOE should monitor the second- and third-stage DP at the first indication of a loss of first-stage filter integrity. The third and fourth stage DP should be monitored if the second stage fails.

Ventilation on the affected housings should be throttled when DP across the final filter stage reaches 2 to 4 in.wg (4 in.wg is the current filter change-out criterion for normal operation).

Failure of initial stages and erosion of margin in the final filter stage is permitted if continued ventilation is necessary to support effective firefighting in the facility. If the fire department officer in charge judges that ventilation no longer provides a substantial advantage in controlling or containing the fire, and the emergency commander (generic term) validates that position, action should be taken to protect housing margin (e.g., ventilation should be discontinued at 2 in.wg DP on the final filter stage). Throttling, if selected, should be performed in a manner that maintains the actual DP reading on scale within the 2- to 4-in.wg readings at all times. In no case should ventilation be continued when 4 in.wg DP is reached across the final filter stage.

At the first indication of an explosion, the first-stage DP should be monitored for a rapid or complete loss of DP as an indication of failure. The second-stage DP should be immediately monitored under such conditions and the filters should be visually inspected if possible. If the second-stage DP is less than 0.5 in.wg, or greater than 4 in.wg, or if there is visible damage to the second stage, ventilation on the affected housing should be discontinued. The decision to shut down ventilation should be preplanned and well thought out. Explosive conditions that could clearly impact multiple stages are judged to present too great a risk to any remaining stage to warrant any attempts to maintain ventilation.

Ventilation should be restored to an affected housing only by the decision of the Emergency Commander or an approved Recovery Plan.

Restoration of ventilation should be considered likely to result in a forced convection release from the facility unless other recovery efforts have confirmed no airborne contamination is present in the facility. The decision to restore ventilation also should be preplanned and well thought out.

10.8.2 Activation of the Manual Deluge System

The manual deluge system provides an important emergency capability should the first-stage filters be in danger of being consumed by fire. However, manual deluge system activation will likely result in loss of the first stage of filters either through plugging or media failure. Consideration may be given to intermittently flowing the deluge systems with the fans shut down when doing so for short time periods. Before actuating the manual deluge system, the following recommendations should be followed:

- Direct impingement of flame or burning embers on the first stage filters should be visually confirmed, if possible.

- The manual deluge system should be activated only when it is clearly required, because activation is likely to damage the filters, could cause plugging, and could stop ventilation. Early activation of manual deluge as a precautionary measure is considered imprudent. If the viewing ports are accessible, they should be used to facilitate confirmation of filter integrity (i.e., visible flaming or smoldering of filter media). Where viewing ports are inaccessible, the inner access doors to the airlocks should be used as alternative viewing ports.

- The manual deluge system should be activated only when the fire department officer in charge decides it is necessary, based on a determination from the available evidence that flame is present in the first stage of filters.

- The person in charge of ventilation control at the facility should be authorized to initiate the manual deluge system as necessary prior to fire department arrival. Possible filter plugging and shutdown of ventilation should be anticipated once manual deluge is activated.

- The initial filter stages should be monitored for evidence of plugging or blowout of the first-stage filter (DP changes) and for evidence of either particulate buildup/wetting (DP changes) or flame (visual) on the second and subsequent stages. If flame is confirmed on any downstream stage, all fans connected to the affected housing should be secured immediately.

10.8.3 Deluge System Flow Times

The following recommendations address when the deluge system flow should be terminated.

- The housing deluge system flow should be discontinued upon visual verification by the fire department incident commander or other authorized personnel if:

  – (automatic system) there is no visible smoke in the housing upstream of the spray nozzles and temperatures in the filter housings have dropped to safe levels; or

  – (manual system) the fire involving the first stage is extinguished and the spray duration is judged to have sufficiently cooled the filter media and frame.

- Only the fire department incident commander or other authorized personnel should terminate the flow prior to meeting these criteria. Ventilation should only be restored to the affected housing following a decision by Emergency Commander or in accordance with an approved Recovery Plan.

- If filter plugging is preventing effective ventilation, removal of the plugged media should restore ventilation. However, restoration of ventilation is likely to result in a forced convection release from the facility unless other recovery efforts have confirmed there is no airborne contamination in the facility.

The removal of plugged filter media in a confinement ventilation system during a fire situation is fraught with hazards, of course, and should only be done in extreme circumstances.

10.8.4 Manual Activation of the Automatic Deluge System

Early activation of the automatic deluge system could increase the potential for the first filter stage to survive. For this reason, the automatic deluge system may be activated manually rather than waiting for high-temperature actuation where early activation provides an advantage. The decision to activate the system should be made by the fire department incident commander and/or the authorized person in charge of ventilation control at the facility based on initial assessment of the fire condition. Small fires that are under control and expected to be quickly extinguished would not challenge the HEPA filters sufficiently to warrant activation of the system. In addition, the limited available data indicate that early activation is not beneficial in reducing the potential for smoke-induced plugging for those housings equipped with fog jet nozzles for automatic deluge, and the procedures should not call for early activation of the automatic deluge system for those housings. Extensive preplanning should be conducted to define as much as possible the situations in which the automatic deluge system would be manually actuated.

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