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# Potential for Hepa Filter Damage From Water Spray Systems in Filter Plenums

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# POTENTIAL FOR HEPA FILTER DAMAGE FROM WATER SPRAY SYSTEMS IN FILTER PLENUMS*

by

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Abstract

The water spray systems in high efficiency particulate air (HEPA) filter plenums that are used in nearly all Department of Energy (DOE) facilities for protection against fire was designed under the assumption that the HEPA filters would not be damaged by the water sprays.[1] The most likely scenario for filter damage involves filter plugging by the water spray, followed by the fan blowing out the filter medium. A number of controlled laboratory tests that were previously conducted in the late 1980s are reviewed in this paper to provide a technical basis for the potential HEPA filter damage by the water spray system in HEPA filter plenums.

In addition to the laboratory tests, the scenario for HEPA filter damage during fires has also occurred in the field. A fire in a four-stage, HEPA filter plenum at Rocky Flats in 1980 caused the first three stages of HEPA filters to blow out of their housing and the fourth stage to severely bow. Details of this recently declassified fire are presented in this paper.[2] Although these previous findings suggest serious potential problems exist with the current water spray system in filter plenums, additional studies are required to confirm unequivocally that DOE's critical facilities are at risk.

## I. Introduction

One of the most serious issues dealing with HEPA filters in DOE nuclear facilities is the potential for HEPA filter rupture during accidental fires and the resulting release of radioactive smoke. This potential is not addressed in most Safety Analysis Reports (SARs) and Environmental Impact Statements (EISs) prepared for DOE facilities. The common practice in SARs and EISs is to use the HEPA filter efficiencies stated on page 22 of the Elder Report:

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1 Rocky Flats Safe Sites of Colorado, P.O. Box 464, Golden, CO 80402
2 U.S. Department of Energy, Defense Programs(DP-45), Germantown, MD 20874

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99.9% efficiency for the first stage HEPA filter and 99.8% efficiency for every filter stage thereafter under every accident condition.[3] Elder obtained these values from unpublished minutes of a meeting held in Albuquerque on December 9, 1971 to discuss HEPA filter efficiency values to be used under normal and accident conditions.[4] The selected values have no technical support and were based on the personal opinions of the twelve people attending the meeting (representatives from the Atomic Energy Commission (AEC) and the Albuquerque Operations Office). One stipulation on the use of the efficiency values, not included in the Elder report, was that "SARs show that the integrity of the filters will be maintained throughout the duration of the accident."[4] Unfortunately, most SARs and EISs use the Elder HEPA efficiency values without establishing that the filter integrity will be maintained. In contrast to the current practice of using a constant 99.9% or 99.8% efficiency for all conditions, more recent guidance recommends that the HEPA filter efficiency should be determined on a case-by-case basis and can have 0% efficiency in some cases.[5]

The use of water sprays inside HEPA filter plunums was the engineering solution to fires that had occurred at the Rocky Flats Plant. On September 11, 1957 a fire had spread through the ventilation system and threatened the final HEPA filter bank of 700, 1,000 cfm HEPA filters.[6] Firefighters used 2 1/2 inch hose lines to put out the fire. The HEPA filters were combustible and used media made from cellulose and asbestos fibers. Over 400 of the 700 HEPA filters in the final bank burned through, and almost every filter was ruined.[6] Following this fire, all combustible HEPA filters in AEC facilities were replaced with non-combustible glass fiber filters. A second major fire occurred at Rocky Flats on May 11, 1969.[6] The fire engulfed many glove boxes, burning many tons of plastic windows, and spread through the ventilation system. The fire broke through the glove box HEPA filters, intermediate filter banks, and the first stage of the final HEPA filter bank. Firemen were able to put out the fire within four hours and before the final stage was breached.[6] This fire was the most expensive ($27 million) in AEC and DOE history. Following this fire, studies were conducted to evaluate various fire protection systems for HEPA filters. These studies, which are reviewed in this paper, led to the use of water sprays inside HEPA filter plenums. However, another fire occurred at Rocky Flats on July 2, 1980 in which sprinklers were used, but the fire still resulted in extensive HEPA filter damage. An analysis of this fire in this report raises questions about the use of water sprays for protecting HEPA filters from fires.

## II. Typical Water Spray System in Filter Plenums

DOE has prepared a standard on Fire Protection Design Criteria in which the water spray system shown in Figure 1 is recommended for use in HEPA filter plenums.[7] The Design Criteria document formalizes a design that has been used extensively throughout DOE facilities for many years since the 1969 Rocky Flats fire. The fire protection system consists of a heat detector at the plenum inlet, an automatic deluge spray head followed by a demister stage, and manual spray nozzles directed at the first of a two-stage HEPA filter bank. The function of the automatic deluge spray is to provide a uniform sheet of water over the entire cross section of the plenum in order to cool hot intake air. Figure 2 shows the typical spray nozzles used for the deluge spray (Figure 2A) and for the HEPA filter spray (Figure 2B). The deluge nozzle directs a flat, 180° fan-shaped spray pattern toward the floor where the water enters a drain, whereas the HEPA filter spray nozzle directs a 360° cloud of fine mist against the face of HEPA filters. Figure 3 shows a photograph of a deluge spray nozzle mounted on the ceiling of a 4x4 HEPA filter plenum and located close to the inlet of the metal mesh demisters. A second deluge spray nozzle is not seen in the photograph. The deluge spray is generated at 0.25 gpm per square foot of filter area, or 16 gpm for the 16 2'x2' demisters in Figure 3. Any water droplets carried in the air stream are removed by the demisters.

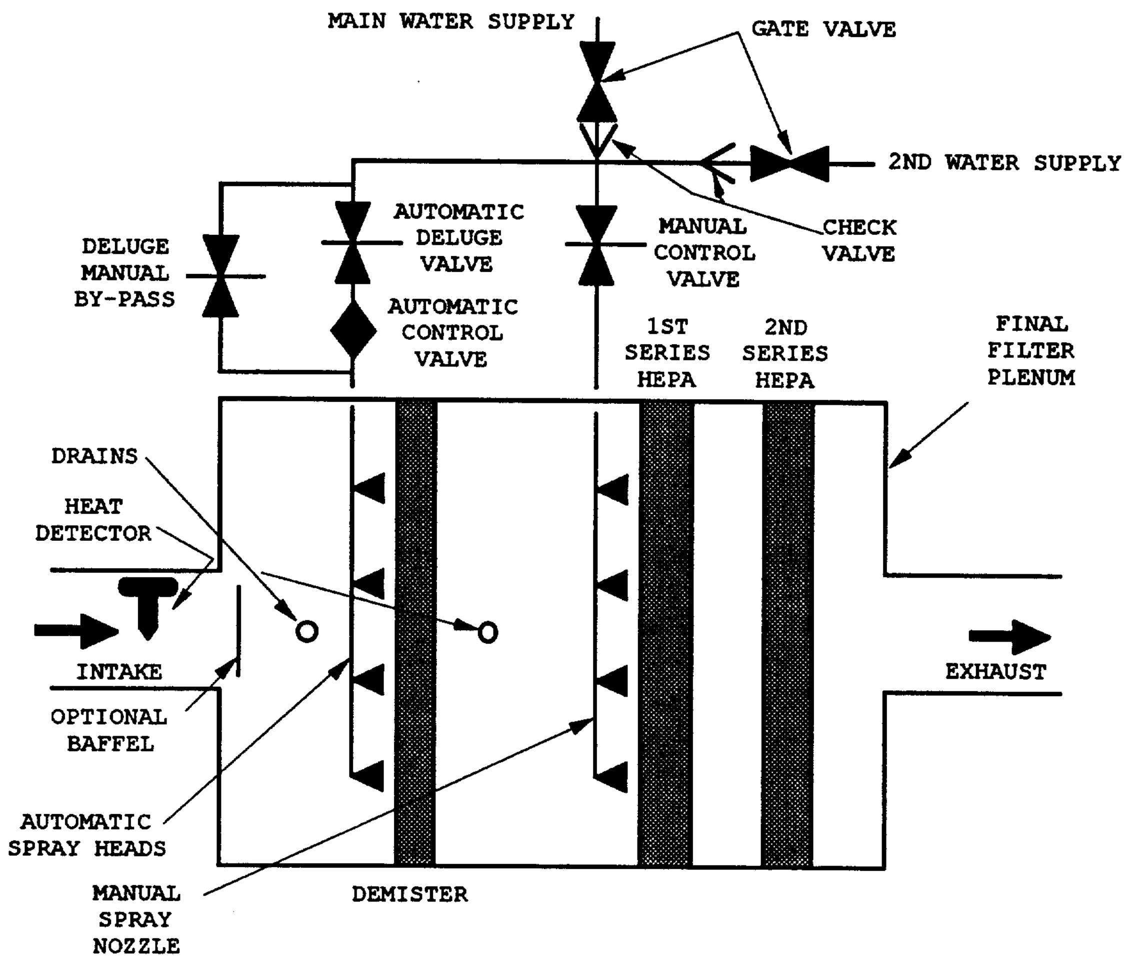
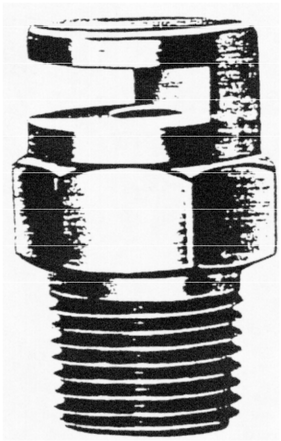
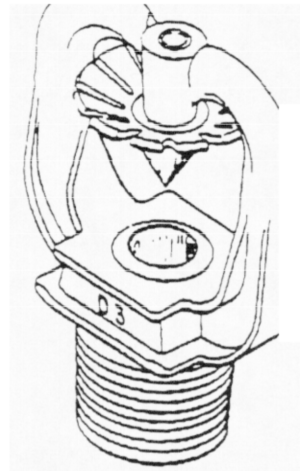



Figure 1 Diagram of the fire protection system for HEPA filter plenums widely used in DOE facilities and specified in DOE Standard on Fire Protection Design Criteria, DOE-STD-1066-XX [7]



(A)



(B)

Figure 2. Drawings of typical spray nozzles used for (A) the deluge spray and (B) the HEPA filter spray. The deluge spray nozzle grenerates a flat, 180° fan-shaped spray pattern. The HEPA filter spray nozzle generates a 360° cloud of fine mist.

Manual spray nozzles, like the one shown in Figure 2(B), are directed at the first stage HEPA filters to put out potential fires should they occur. However, since the HEPA filters are easily damaged by direct water sprays, the selected nozzles must generate a fine water mist. Figure 4 shows a photograph of a manual spray nozzle mounted on the ceiling of the filter plenum with the spray nozzle directed against the first stage HEPA filters. A second spray nozzle is not seen in the photograph. The water flow through both nozzles is 0.25 gpm per square foot of filter area, or 16 gpm for the 16, 2'x2' HEPA filters. Some facilities periodically test the water spray and unavoidably wet the HEPA filters. This practice reduces the strength of the HEPA media as described later in this report and should be avoided.

In preparing the Fire Protection Design Criteria, the DOE fire protection engineers recognized the potential of the water sprays to damage the HEPA filters.[7] To mitigate this potential, the standard recommends throttling back the fan controls or providing redundant filters. Unfortunately, there are no studies to support these recommendations.

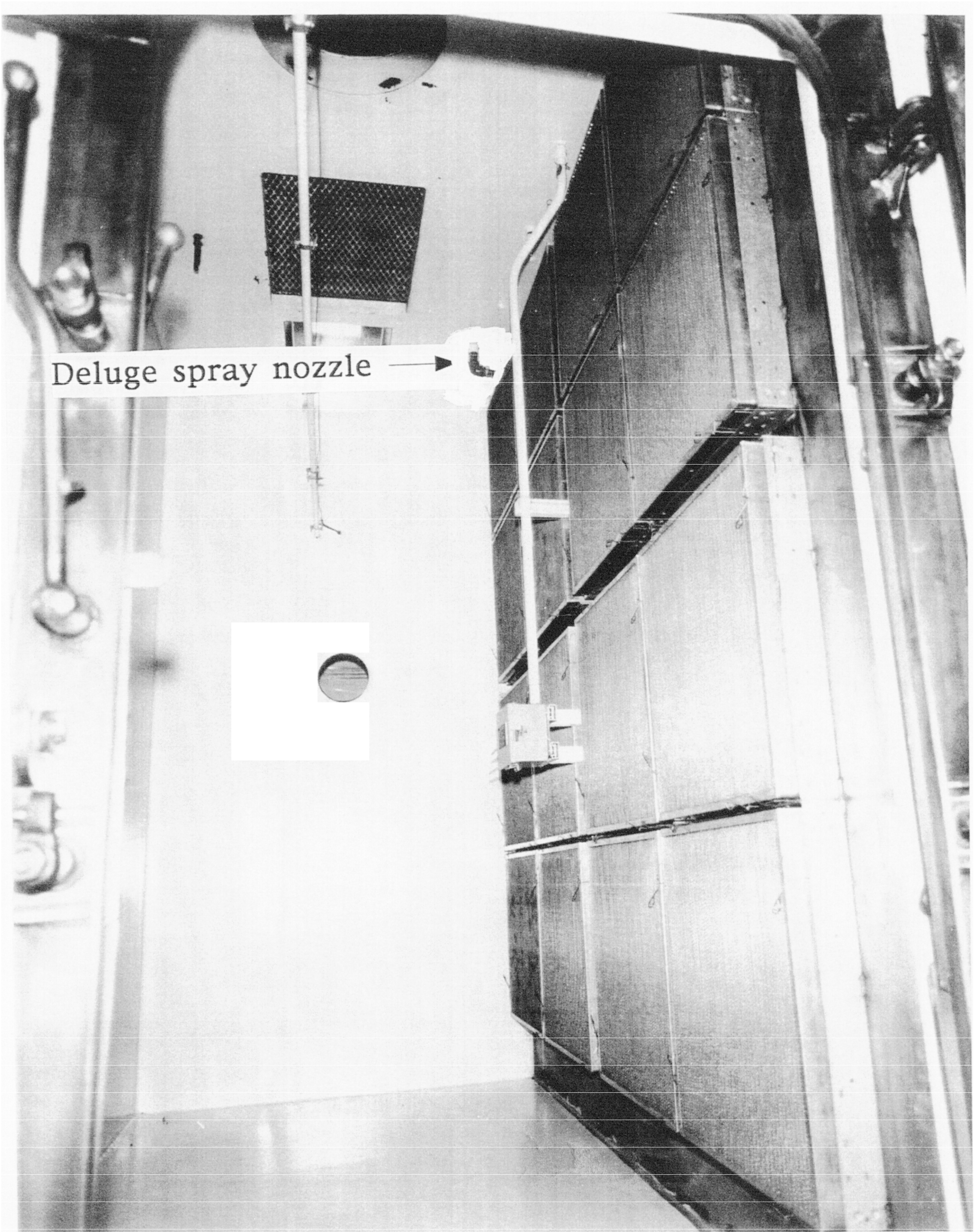



Figure 3. Photograph of a deluge spray nozzle mounted on the ceiling of a 4x4 HEPA filter plenum and located close to the inlet of the metal mesh demisters. The access door to the demister stage was opened for the photograph.

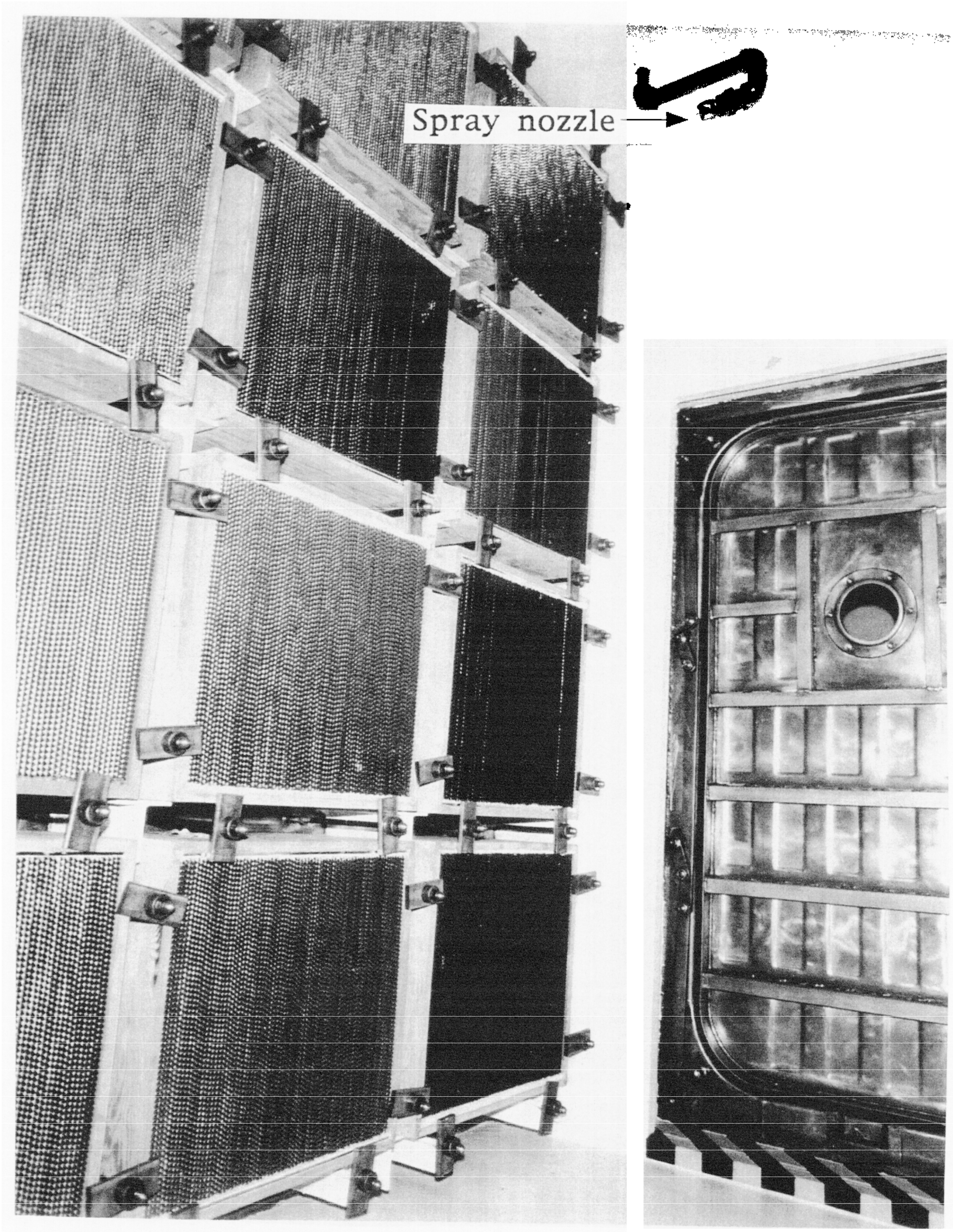



Figure 4. Photograph of a manual spray nozzle mounted on the ceiling of the filter plenum with the spray nozzle directed against the first stage HEPA filters.

## III. Studies Conducted in 1970s On Water Spray Systems Were Incomplete

Several studies were conducted after the 1969 Rocky Flats fire to develop engineering solutions that prevent or mitigate the destruction of HEPA filters in filter plenums during ventilation fires. Although these studies demonstrated the performance of various technologies such as water sprays and demisters, no baseline studies were performed to attempt to destroy the HEPA filters under fire conditions that simulated the 1969 Rocky Flats fire. Thus, it was not possible to assess what benefit the fire protection counter measures had on the HEPA filters.

Cartwright et al conducted 13 full-scale tests on a 2-stage, 3x4 HEPA filter plenum (12 HEPA filters per stage) that was specially built for this study at Rocky Flats.(8) A separate structure was built to house an incinerator that injected hot exhaust into the filter plenum. Only new 2'x2'x1' HEPA filters were used in that study. The authors found that using water sprays directly on HEPA filters would soak the filter and create holes in the media and therefore recommended that direct water sprays be controlled manually and only used under extreme emergencies. They also found that a deflector plate on the inlet pipe and a water curtain followed by a prefilter reduced the gas temperature and prevented most of the sparks and water spray from reaching the HEPA filters. Unfortunately the test conditions in that study were very mild and not representative of potential, worst case conditions. The pressure drop across the HEPA filters in this study was quite low (values ranged from 0.3-0.7 inches) and could not cause any structural damage. No baseline tests were conducted to see the effect of the fire tests on HEPA filters alone.

Domning conducted full scale tests to evaluate water spray heat exchanges for protecting HEPA filters under fire conditions.(9) He conducted two tests using water sprays on a filter plenum consisting of a single stage of 12 new HEPA filters for each test. In one test, the water spray was directed against an inlet deflection plate and in the second, directly on the 12 HEPA filters. The water flow rate was 0.25 gpm per square foot of filter area. The analysis of the test results showed that the added water spray increased filter plugging compared to plugging by smoke alone. The pressure drop across the HEPA filters was so low (0.3-0.4 inches) that no structural damage was seen.

Gaskill and Murrow conducted 13 tests in which they studied cooling hot gases with various water spray and demister configurations upstream of single, new HEPA filters.(10) They used a propane burner to generate the high temperature air stream. Although they showed that a water spray with demister was effective in reducing the gas temperature, they had no baseline tests with HEPA filters without the water spray/demister system. Moreover, none of the tests showed filter plugging by water because the temperature at the HEPA filter was above the boiling point of water. In addition, since new HEPA filters were used in the study, the filters had the factory treatment of water repellency, which prevents them from plugging with water.

Based on these early studies, fire protection engineers incorporated water sprays and demisters into HEPA filter plenums to protect the HEPA filters against fires. These fire protection systems have remained essentially constant over the years and now represent the standard in DOE facilities.(1) The main attention in these early studies was focused on the high temperature aspects of the fire. Domning's finding that water sprays increased the plugging effect of smoke aerosols was not seen as an important factor for fire protection.(9) Even after Alvares et al completed an extensive study of HEPA plugging by smoke aerosols, the major concern was still high temperatures inside the filter plenum.(11) Alvares et al showed that smoke aerosols can rapidly plug HEPA filters and that water sprays accelerate and exacerbate the effect. However, the primary result of a plugged HEPA filter is the loss of ventilation. Since the plugged HEPA filter prevented radioactive particles, as well as air, from passing through, the plugged HEPA filter produced a passive containment system. Passive containment is presently used in some DOE facilities. Thus, the concerns about HEPA failures during fire conditions seemed to be generally resolved until the mid 1980s when German researchers demonstrated that water sprays and even high humidity can cause HEPA filters to rupture.(12-14)

## IV. German Studies in 1980s Show Water Sprays Damage HEPA Filters

Ruedinger et al showed that high humidity can result in high filter pressure drop and decreased media strength, the combination of which can lead to structural damage and loss of filter efficiency.(12) They built a special test facility to study moisture effects on full-scale HEPA filters under various temperature and flow conditions. They found that the 11 deep pleated HEPA filters with an elastomeric sealant had structural failures at an average differential pressures of 20 inches and as low as 10 inches under wet conditions. The most frequent failure mode is the rupture of the downstream media pleats.

The filters with stainless steel frames and a glass fiber sealant were significantly weaker. The three filters tested failed at an average of 9.5 inches, and as low as 6.8 inches. The failure mode in these filters was the filter pack being pushed out of the frame, since the glass fiber sealant held the filter pack in place by friction.

For both filter types, there was no significant difference in the break pressure whether the filter was clean or had particle deposits. However, with particle deposits, the filter would absorb water at lower relative humidities and would rupture even with a demister to protect the HEPA filter. Ruedinger et al also showed that a new HEPA filter with no particle deposits would not rupture if a demister were used because not enough water would accumulate on the filter to raise the pressure drop to the failure point.(12) The filter failure under the humid air conditions occurred at differential pressures that were about 1/3 to 1/4 the comparable values for filter failure under dry conditions.

Ruedinger et al confirmed that the decreased strength of the wet HEPA filters is due to the decreased tensile strength of the glass HEPA media.[12] They showed that the tensile strength of a new filter paper is reduced by a factor of three due to humidity exposure. Ruedinger et al also conducted tests on new HEPA filters made from polycarbonate microfiber media and showed no structural damage up to the maximum pressure of 32 inches of water.[12] Although these filters do not meet the UL 586 requirements for the spot flame test, they are very resistant to water and acid exposure.[1]

Ricketts et al evaluated the structural limits of a variety of different HEPA types under high humidity conditions.[13] Ricketts et al tested 29 HEPA filters having the conventional US design (deep pleat with adhesive sealant) and found many filters failing at lower pressures than previously reported by Ruedinger et al.[12] Ricketts et al also showed that the primary failure mode is the rupture of the downstream pleats.[13] This mechanism is facilitated by the loosening of the filter pack and a ballooning of one or more pleats due to the pressure. Another failure mechanism is the tearing of the media near the sealing edges of the frame and results from a loosened filter pack. They found that the average failure pressure for the deep pleated filter with an adhesive sealant is 16 inches. Of the 29 filters tested, only three had failures less than 10 inches of water; one failed at 3.6 inches and two at 7 inches. In separate tests on HEPA filters using glass fiber sealants, they found that the breaking point was one half (8.8 inches) the breaking strength of the standard deep pleat filter with an adhesive sealant. The weakest filter design was the mini-pleat, where the structural failure occurred at an average pressure of 3.6 inches and a minimum of 1.6 inches.

Ricketts et al noted that particle deposits cause HEPA filters to fail at relative humidities less than 100%.[13] Although the average HEPA failure occurred at 97% relative humidity, two deep-pleated HEPA filters failed after exposure to 80% relative humidity for two hours. In contrast, clean filters require a water content greater than 100% relative humidity to induce structural failures. They found that the failure pressures were the same for filters with and without particle deposits as previously found by Ruedinger et al.[12]

Ricketts et al pointed out that the humidity causes HEPA filters to have structural failures at differential pressures that are 60% to 90% lower than the failure under dry conditions.[13] For example, a deep pleated, clean HEPA filter is structurally damaged at 13.7 inches under humid conditions and at 92 inches (3.3 psi) under dry conditions.

An important finding by Ricketts et al is that the combination of factors leads to an even greater filter deterioration than the cumulative effect of the individual factors alone.[13] Tests on the filter media showed that moisture causes a 60% decrease in tensile strength, creases cause a 45% decrease, moisture exposure with subsequent drying causes a 40% decrease, and dust loading on creased samples cause a 5% decrease. A cumulative effect of these factors would predict a residual tensile strength that is 13% of the value of a new, uncreased HEPA media. Experimental values for filter media subjected to the combination of exposures showed a residual tensile strength that was only 7% of its original value.

Ricketts et al extended their previous studies to show the effect of filter design, particle deposits, and the quantity and time of water exposure on the pressure drop of HEPA filters.(14) They showed that the standard, deep pleated HEPA filter loaded with dust to 4 inches, would reach a pressure drop of 10 inches in 8 minutes and 14 inches in 30 minutes when exposed to humid air with relative humidity between 96% and 99%. The major findings of this study were: (1) particle deposits greatly accelerate the increase in pressure drop due to moisture, (2) the greater the water content, the faster the rise in pressure drop for both clean and dust loaded filters, and (3) mini pleat filters have more rapid increases in pressure drop than deep pleat filters for the same moisture exposures.

The results of these German studies suggest that the water spray systems in filter plenums in DOE facilities may result in HEPA filter rupture during actual fire conditions. Surprisingly, the German studies did not stir much concern with fire protection engineers in the U.S.. Although the controlled laboratory studies were quite convincing, there were no examples of fires in any of the DOE facilities where the water spray caused HEPA filter failures. However, in 1995 Fretthold had issued a recently declassified report that described a 1980 fire at Rocky Flats involving water sprays and blown out HEPA filters.(2) That report confirmed the predictions of the German laboratory studies.

## V. 1980 Filter Plenum Fire at Rocky Flats Caused Extensive Filter Damage

Fretthold described the results of a fire in a HEPA filter plenum at Rocky Flats that occurred on July 2, 1980.(2) The fire occurred in a HEPA filter plenum that filtered the exhaust from an incinerator shown in the drawing in Figure 5. The exhaust from the incinerator is treated in an off-gas system in which the hot exhaust gas is first sprayed with a caustic solution to cool the gas and to neutralize the acid gases and then passed through a wet cyclone to remove suspended particles. Figure 6 shows the off-gas system. The treated exhaust then passes through a booster blower and into the incinerator filter plenum, as shown in Figure 7. A deflector cone at the plenum inlet deflects the incoming air to distribute the air more uniformly over the HEPA filters mounted 3 high and 4 across. Note that only 600 cfm passed through the plenum that had a filter capacity of 12,000 cfm. Although the filter plenum contained 4 stages of HEPA filters, the stages were incorrectly mounted back-to-back. The incinerator plenum did not have an automatic deluge spray system or a demister stage in front of the first HEPA bank. The exhaust from the incinerator plenum then enters the main building plenum.

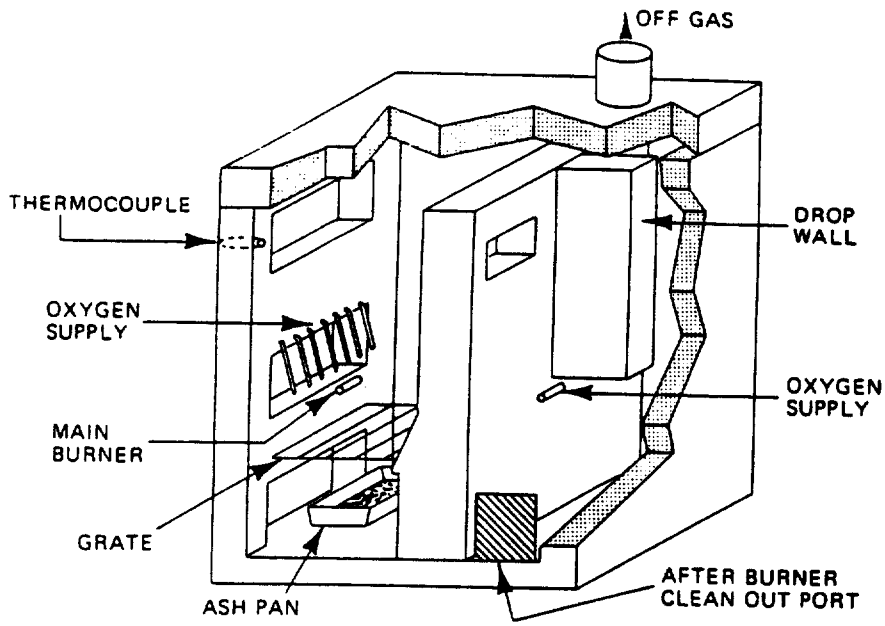



Figure 5. Drawing of the Rocky Flats incinerator.

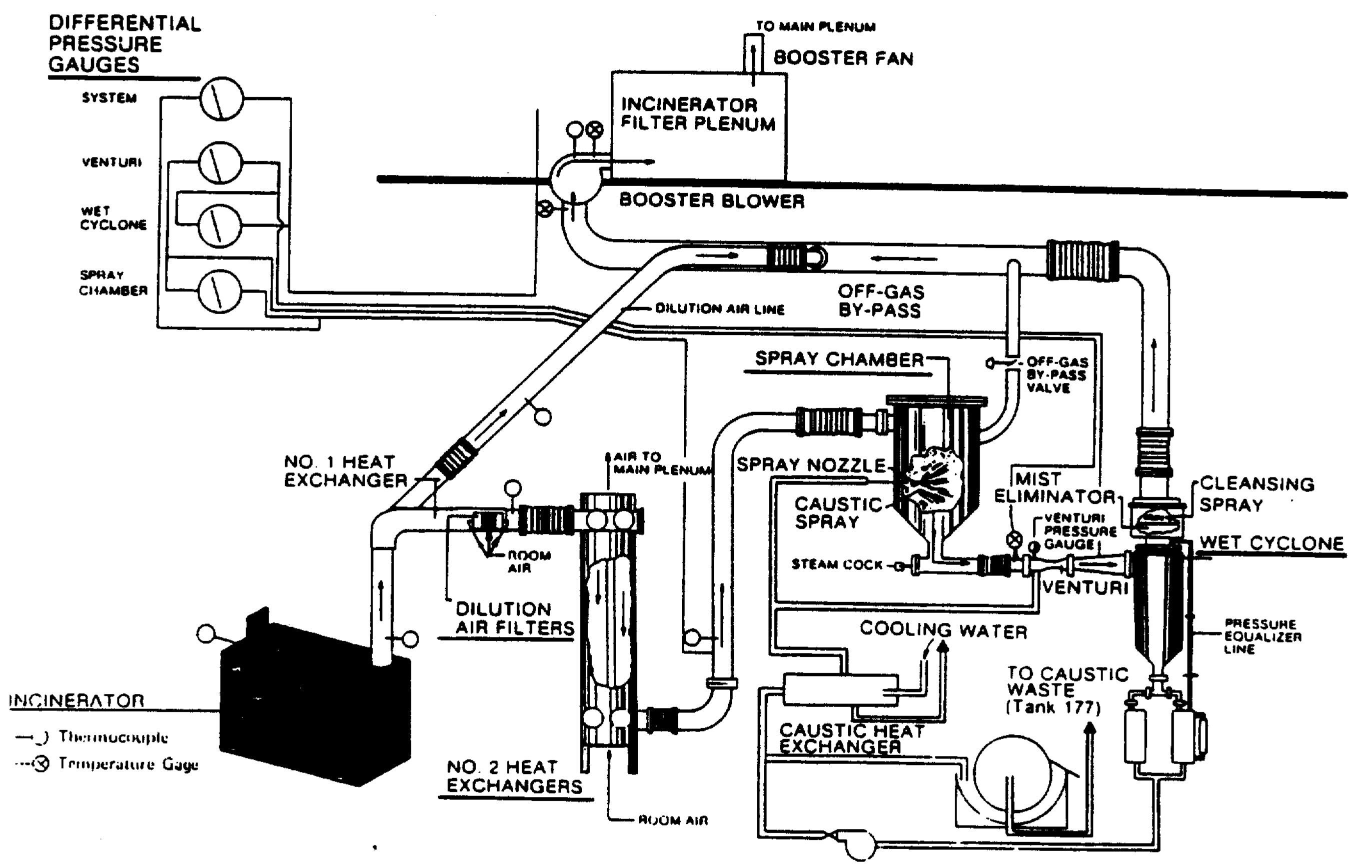



Figure 6. Schematic of the incinerator off-gas treatment system

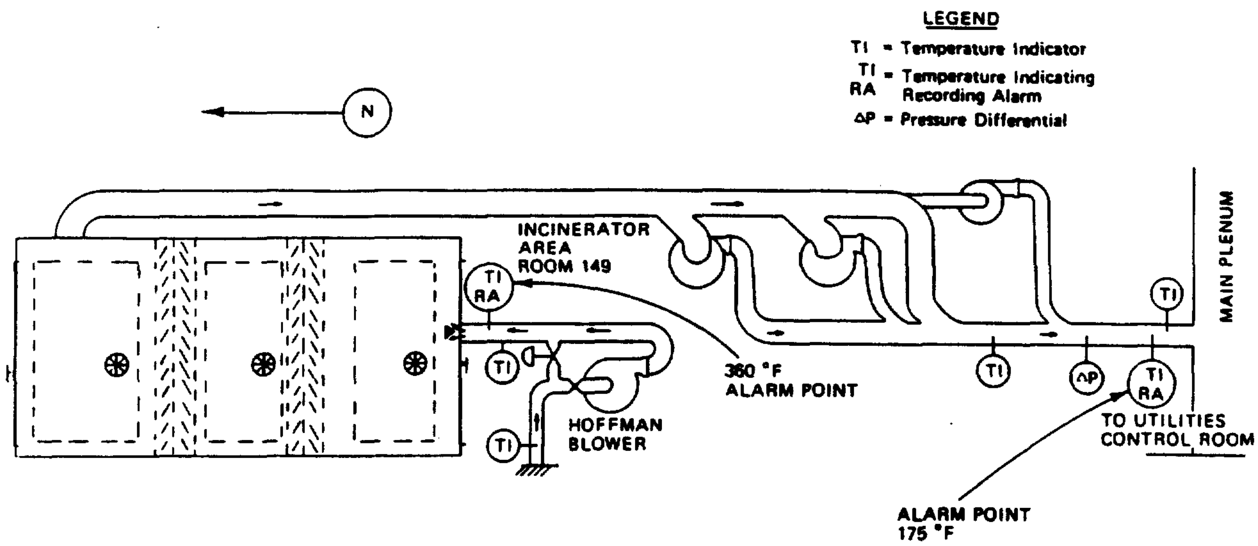



Figure 7. Incinerator filter plenum system

On July 2, 1980, a fire had occurred in the incinerator filter plenum and had extensively damaged the first three stages of HEPA filters and caused the fourth stage to severely bow.(2) A continuous recording of the plenum inlet temperature showed the temperature was constant at 100°C for several hours prior to 11:00 A.M.. At that time the inlet temperature increased linearly with time until it reached a maximum 180°C at about 12:40 A.M.. At 11:30 A.M., the production foreman inspected the filter plenum and noted the plenum inlet temperature was 70° C, the differential pressure across the HEPA filters was 0.7 inches of water, and the plenum vacuum was 7 inches of water. These were normal readings. (The automatic temperature recording at 11:30 A.M. showed the inlet temperature was 110°C, not 70°C.) At 12:34 P.M., the alarm for the incinerator filter plenum sounded as well as the main filter plenum. The deluge spray also was automatically activated in the main plenum. Responding to the incinerator fire alarm, the utilities manager observed a red glow within the incinerator plenum and then activated the manual deluge sprinklers. Shortly thereafter, firemen arrived and also noticed a red glow in the plenum and that the manual water spray had been activated. They then attempted to enter the plenum with building water hoses, but could not open the airlock doors due to the high vacuum. After reducing the air flow, the firemen entered the incinerator plenum and sprayed the HEPA filter banks with a fine water mist. Photographs of the filter plenum in Figures 8-14 showed extensive HEPA damage.

Figure 8. Photograph inside the front chamber of the filter plenum showing the air inlet with deflector cone and the damaged first stage HEPA filters.

Figure 9. Photograph showing the front side of the first stage HEPA filters.

Figure 10. Photograph inside the middle chamber of the filter plenum showing the rear side of the 2nd stage HEPA filters.

Figure 11. Photograph inside the middle chamber of the filter plenum showing the front side of the 3rd stage HEPA filters.

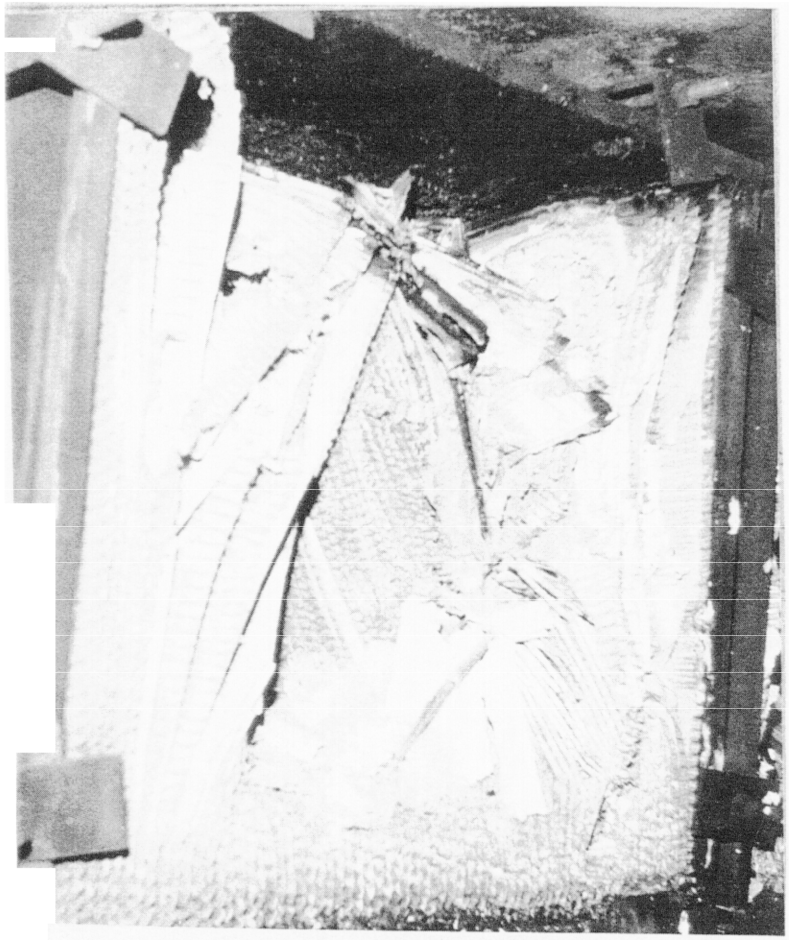


Figure 12. Photograph of the front side of a 3rd stage HEPA filter.

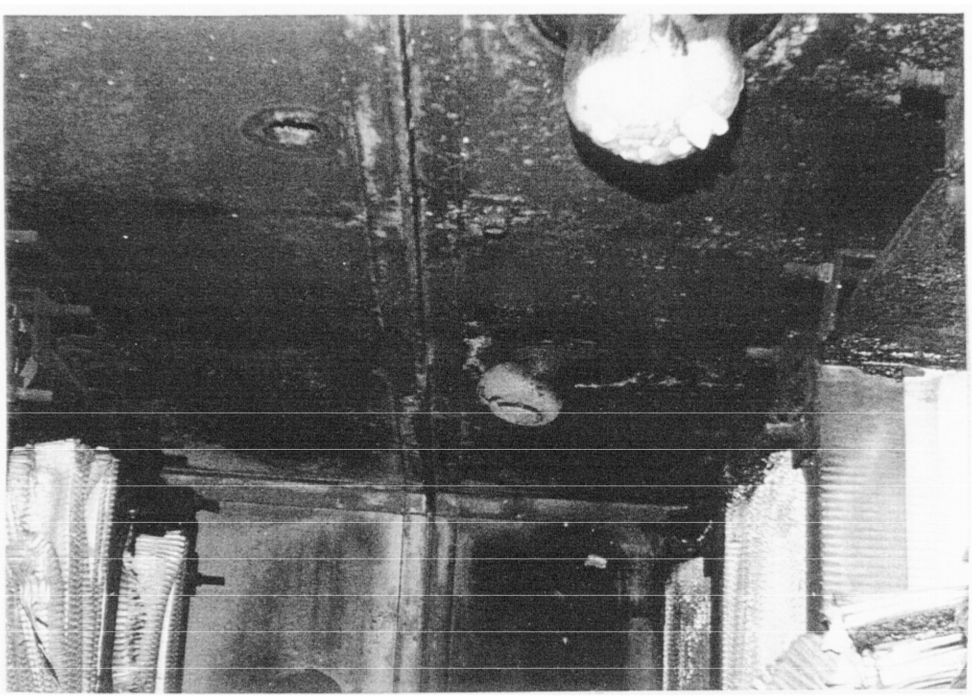


Figure 13. Photograph inside the second chamber of the filter plenum between the 2nd and 3rd HEPA stages. Note the partially melted plastic light fixture on the ceiling of the plenum.

Figure 14. Photograph of the rear side of the 4th stage HEPA filters.

The investigation following the fire concluded that the primary cause of the fire was the deteriorated off-gas bypass valve on the spray chamber shown in Figure 6.[2] The untreated hot exhaust was able to bypass the off-gas treatment and enter directly into the HEPA filter plenum. This raised the gas temperature at the plenum inlet to a maximum 180°C (356°F). In addition the investigators speculated that nitric and hydrochloric acids in the exhaust may have reacted with the urethane foam sealant used on the HEPA filters and raised the temperature even further.[2] The investigators also found metal oxide powders consisting of Cr, Fe, and Ni and as well as chlorates and nitrates on the filter media. Because the metal on the filter suggest their origin was stainless steel, the investigators concluded "This is an indication that the stainless steel duct work is being corroded by the acidic environment." From this, the investigators concluded that "All of these very fine metal particles collected on the filter media are capable of supporting combustion" and was responsible for igniting the HEPA filters.[2]

## VI. Reevaluation of the Filter Plenum Fire Shows Water Sprays Caused the HEPA Filter Blow-out

Unfortunately, the investigators did not correctly assess the cause of the fire based on the evidence. They had assumed that acid had corroded the stainless steel ducting and somehow released unoxidized metal particles that were transported in the air to the HEPA filters. The problem with the investigators' assumption is that it is not possible for acid (or oxygen, salt, or any chemical) to corrode the stainless steel and release unoxidized metal particles. If acid or oxygen reacts with the stainless steel, it quickly oxidizes the iron. The oxidized iron is seen as the typical "rust powder" on the surface of steel. The "rust" will eventually ablate from the steel surface and be carried in the air stream to the HEPA filters. This is a common observation in the off-gas from incinerators.[15] In fact, so much rust had accumulated in the prefilters at the Savannah River incinerator that the prefilters had turned an orange brown color.[15] Once the metal has oxidized, it cannot be oxidized further and therefore will not support combustion.

The only combustible component in the HEPA filters used in the Rocky Flats incinerator plenum was the sealant that held the media pack to the frame. All other components were non-flammable as recognized by the fire investigators.[2] The HEPA used metal frames, aluminum separators and the standard glass fiber paper. None of these components will support combustion. Although not seen in Figures 9-14, the sealant was burnt and charred in all of the HEPA filters. However, the sealant was only exposed to the hot air flow on the top and the bottom portions of the frame. The sealant on the two sides is protected by a layer of filter media. Thus any combustion of the sealant would be confined to the upper and lower portions of the frame. This is seen in Figures 9-11, where the sides of the filter media are still attached to the frame, but the top portion of the media pack is completely separated from the frame.

We have previously shown that the urethane sealant in current HEPA filters will char and in some cases burn during the heated air qualification test.[16] Figure 15 shows a photograph of a new HEPA filter similar to widely used HEPA filters in DOE facilities following the standard heated air and overpressure test.[16,17] The urethane sealant had completely burned through from the inlet to the exit face of the HEPA filter during the heated air test. In this test, the HEPA filter is exposed to the rated air flow heated to 700 °F (371°C) for five minutes.[17] During the test, the burning urethane was seen as a red glow with only a small flame. Following the heated air test, the burnt filter had a DOP penetration of 1.24% and therefore passed the qualification test. However with the sealant burnt through, the filter pack was loose within the frame and could easily move forward or backward. The burnt filter was then placed in the overpressure test apparatus where the pressure drop across the HEPA filter was ten inches of water.[17] That pressure had displaced the HEPA filter pack about one inch in Figure 15 and was very close to blowing out the entire pack.

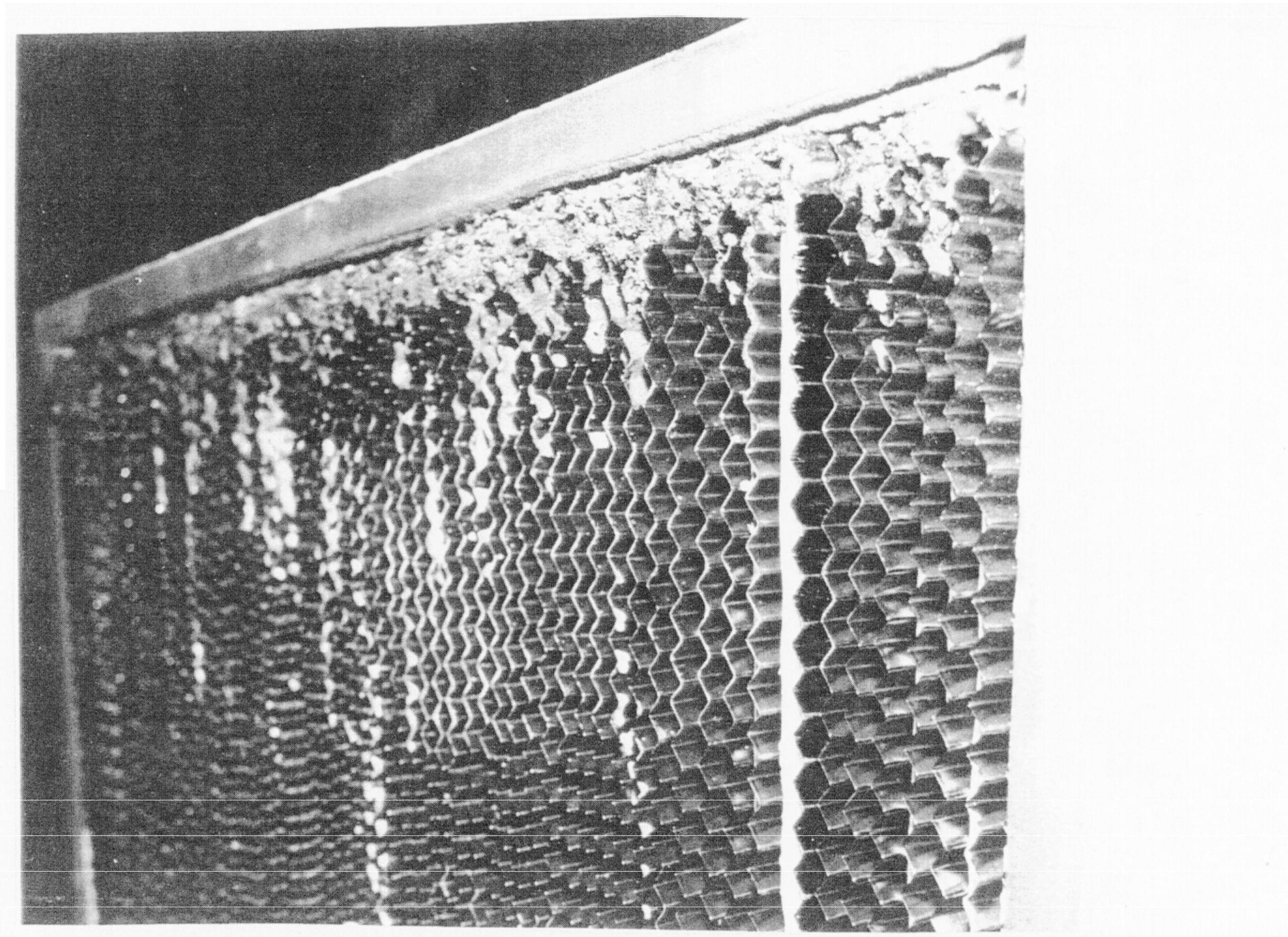


Figure 15. Photograph of the exit side of a new HEPA filter after the heated air and overpressure test. The burned urethane sealant created a separation between the filter pack and the filter frame.[16]

It is possible to reconstruct the sequence of events leading to the HEPA destruction shown in Figures 8-14 from an analysis of the photographs and the findings in previous studies. The initial step was raising the temperature of the air to a sufficient level to burn the urethane sealant. This was due to the defective by-pass valve in the off-gas treatment system. An added temperature increase may have come from the exothermic reaction between the acids and the urethane. Once the urethane sealant reached its ignition temperature, the sealant would burn. At this point, the HEPA filters would still be relatively intact. Based on our previous study, even a HEPA filter in which the sealant had burned completely through still had 99% DOE efficiency.[16] However, when the area foreman saw the red glow inside the filter plenum and turned on the water spray, the water caused the HEPA filters to plug. The effect of water plugging of HEPA filters was well documented in the German studies.[12-14] Domning and Alvares et al also showed that water sprays greatly enhance the normal filter plugging from smoke aerosols.[9,11] Bergman et al also showed that temperature or age will remove the water repellency treatment in HEPA media and thereby also result in HEPA plugging when exposed to moisture.[5] The high temperature in the filter plenum would be sufficient to drive off the water repellency treatment and result in HEPA plugging with water.

Once the filters were plugged or partially plugged, the pressure on the filters from the air flow was greatly increased and pushed against the filter pack (Recall that the firemen could not open the doors because of the negative pressure). For those filters in which the filter pack was loose from the burned urethane sealant, the pressure would cause the weakest part to be deflected. From Figures 9-12, the HEPA filter deflection began at the top of the filter where the filter pack had separated from the frame. Once the filter pack lost its integrity, blowing out the central part of the filter was easy. Note that not all of the filters suffered the same extent of destruction. Some filters showed no structural damage. The key to the filter damage was whether the filter pack was loose in the filter frame as a result of the urethane burning. Once some of the filters were blown out, the remaining filters were spared because the pressure on the filter bank was relieved when most of the air passed through the open paths.

The final filter bank was not destroyed, although some of the HEPA filters had severely bowed, as shown in Figure 14. The final HEPA stage would have experienced a lower temperature and far less water exposure then the first three banks. If the urethane sealant on the bowed HEPA filter in Figure 14 were burned out, then it would take less force to push out the HEPA pack because the top portion would be loose and not attached to the filter frame. The fact the filter pack is not blown out, but bowed, indicates the top urethane sealant was still holding the media pack to the filter frame.

Although the above scenario is consistent with the observations and previous studies, the report on the filter plenum fire stated that "the first three stages were sprayed and cooled" with fire hoses. To verify that the HEPA filter damage seen in Figures 8-14 was not due to firemen blowing out the filters with high pressure hoses, we interviewed two firemen who entered the plenum and sprayed the HEPA filters.[18] The first fireman stated that he looked through the viewing port on the inlet side of the first bank of HEPA filters and saw that the first bank was on fire, and that the HEPA filters showed large structural damage.[18] He also saw part of one HEPA filter on fire lying on the floor of the plenum. No one had entered the plenum at that time. After the air flow was turned down, he entered the downstream plenum door with a water hose having a fog nozzle, The hose was connected to the building water supply. He saw that the HEPA filters were on fire and sprayed them with the water mist, although none of the downstream HEPA filters were breached (See Figure 14). He also stated that the HEPA filter damage could not be caused by the water mist that he used.[18]

The second fireman arrived later and stated that he had entered the upstream plenum room (Figures 8 and 9) and saw the entire filter bank had been destroyed.[18] He did not spray any water on the first stage filters because there was no remaining fire. On entering the second door (Figures 10-13), he saw HEPA filters on fire and sprayed them with the water fogger. He stated that his spraying caused no further structural damage to the filters. He then entered the exhaust plenum, but since there was no fire and the HEPA filters were not damaged (Figure 14), he did not spray the filters.[18]

## VII. Conclusions

The greatest damage to the HEPA filters in the 1980 filter plenum fire was due to the water spray. The high temperature from a defective by-pass valve in the incinerator exhaust was responsible for burning the urethane sealant in the HEPA filters. This, in turn, had weakened the physical strength of the filter pack because there was no longer a mechanical bond between the filter pack and the upper side of the filter frame. We speculate that the HEPA filters in this condition would have been fully operational with minimal deterioration (some filters may have reduced efficiencies to 99%). However, when the water spray was turned on, the filter began to plug with water, which raised the filter pressure drop. This increased pressure was applied to the structurally weakened filters and blew out the filter pack in several of the HEPA filters. Most of the exhaust would then pass through the blown-out HEPA filters and result in close to 0% efficiency for that filter stage. Three of the four filter stages had blown-out HEPA filters, and the fourth stage had some filters severely bowed and ready to rupture. There was no environmental contamination from the fire since the exhaust from the incinerator filter plenum was directed into the building filter plenum, which was not damaged.

The water spray inside the filter plenum was not able to put out the fire as designed. Firemen had to enter the filter plenum with spray nozzles to extinguish the flames. The ineffectiveness of the plenum water spray is due to the inaccessibility to the burning urethane sealant. Once the urethane sealant begins burning, it is not possible to extinguish the fire with ceiling mounted spray nozzles because the water cannot make contact with the burning sealant. The HEPA filter and frame protect the burning sealant from the water spray, especially on the upper side of the HEPA filter. Figures 9-12 show the complete separation of the HEPA pack from the upper frame due to the burnt out sealant.

The 1980 filter plenum fire and the German studies on filter plugging with water sprays raise serious questions about the effectiveness of the water spray system shown in Figure 1 for protecting HEPA filter plenums from fires. The omission of key experiments in the early studies that led to the present fire protection system for filter plenums have perpetuated the belief that the system will work as designed. The early studies showed that water sprays followed by demisters are very effective in lowering the air temperature, but they did not show the system could protect HEPA filters from structural damage. No baseline studies were conducted showing damaged HEPA filters. Laboratory studies show that the current HEPA filters in DOE facilities can be structurally damaged by filter plugging from moisture and/or smoke. Once a HEPA filter is plugged, it is prone to blow-out by the pull of the system blower, especially when the filter is wet.

Although the use of a metal demister, as shown in Figures 1 and 3, improves the reliability of the fire protection system by cooling the air and removing water droplets, the HEPA filters can still be blown out because of smoke and water plugging. Ruedinger et al showed that HEPA filters can rupture due to absorbed water even when protected by demisters.[12] Ricketts et al demonstrated that if a HEPA filter has particle deposits, it can rupture at relative humidities less than 100%.[13] Since smoke aerosols can easily pass through demisters, the smoke and high humidity can result in rapid HEPA plugging and subsequent rupture.

The available studies on HEPA filter performance under fire conditions suggest there are problems with the current fire protection systems in filter plenums. Unfortunately there are no studies to confirm that the current fire protection system shown in Figure 1 will prevent the extensive filter blow-out seen in the 1980 Rocky Flats fire. German studies on filter blow out suggest that smoke and moisture can rapidly plug the filter plenum system in Figure 1 and result in filter rupture. We recommend an experimental study to confirm that the existing water spray system will work in protecting HEPA filters from rupturing during fires. Until this study is completed, we recommend that 0% efficiency be assumed for each filter stage exposed to a water spray if the blower has at least 10 inches of vacuum, disregarding the presence of a demister. This recommendation had been previously made in our guide for determining HEPA filter efficiency under accident conditions.[5]

Instead of building an elaborate system to protect the fragile HEPA filters, an alternative approach would be to build high strength HEPA filters. Germany and France have installed high efficiency steel filters in the exhaust of their commercial power plants for increased reliability.[19,20] Bergman et al have developed a cleanable high efficiency steel filter for use in DOE facilities.[21] With further development, a steel HEPA filter can replace the existing glass fiber HEPA filters. Modest incremental improvements to the existing HEPA filter can also be made such as using a non-combustible sealant and reinforced glass paper.[22]

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