Prototype Air Cleaning System for a Firing Range

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January 1985

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EXECUTIVE SUMMARY

This report recommends air cleaning system components for the U.S. Army Ballistics Research Laboratory's new large-caliber firing range, which is used for testing depleted uranium (DU) penetrators. The new air cleaning system must have lower operating costs during the life of the system compared to that anticipated for the existing air cleaning system. The existing system consists of three banks of filters in series; the first two banks are prefilters and the last are high-efficiency particulate air (HEPA) filters. The principal disadvantage of the existing filters is that they are not cleanable and reusable. The filters must be replaced frequently to maintain proper functioning of the ventilation system.

Pacific Northwest Laboratory focused the search for alternate air cleaning equipment on devices that do not employ liquids as part of the particle collection mechanism (e.g., liquids are used in many types of scrubbers). Collected dry particles were assumed preferable to a liquid waste stream. The dry particle collection devices identified included electrostatic precipitators; inertial separators using turning vanes or cyclones; and several devices employing a filter medium such as baghouses, cartridge houses, cleanable filters, and noncleanable filters similar to those in the existing system. The configurations and principles of operation of these devices are thoroughly described in the report.

The economics of practical air cleaning systems employing the dry particle collection devices were evaluated in 294 different combinations. The economic evaluation accounted for several factors including costs of equipment and its installation; labor, materials, and energy costs of operation and maintenance; costs of disposing of low-level radioactive wastes generated by operating the equipment; and the particle collection performance of the devices used in each system configuration considered. To evaluate how particle collection performance affects operating costs, a special method was devised and tested against operating data at other similar firing ranges. To assist the evaluation and to

set performance criteria, data were obtained on the characteristics of the airborne particles to be collected and operating experiences at the other similar firing ranges.

The economic evaluation showed that systems employing no high-efficiency cleanable particle collection devices would have 20-year life cycle costs in the range of \$5 to \$8 million. In contrast, those systems employing a high efficiency cleanable device at the first particle collection stage, would have 20-year life cycle costs in the range of \$400 to \$800 thousand. The recommended system configuration consists of a high-efficiency cartridge filter with automatic cleaning followed by the last two stages of disposable filters in the existing filter system. The HEPA filter bank is recommended as the last stage to achieve the desired ultimate efficiency and to act as a final barrier to particle release. The high-efficiency prefilter would be retained upstream of the HEPA stage to collect the bulk of the particles penetrating the cartridge filter, especially if it should fail catastrophically because of excessive explosive overpressurization. Retaining this prefilter would extend the functional life of the HEPA stage. The existing filter housing should be relocated to make room for the cartridge house and used to house the two final filter banks and the existing fan.

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INTRODUCTION

The Ballistics Research Laboratory (BRL), a component of the U.S. Army Research and Development Command (ARDC), has contracted with Pacific Northwest Laboratory (PNL) to supply a prototype air cleaning system for a new indoor large-caliber range where depleted uranium (DU) munitions are tested. Pacific Northwest Laboratory's objective was to modify or replace the existing air cleaning system to reduce operating and waste management costs without losing particulate containment capability. Another desired benefit was to reduce the aerosol clearance time in the target building from that experienced at BRL's older range.

This final report of the feasibility study phase details the methodology and rationale behind the recommendation of an air cleaning system. This report was preceded by reports on the performance of air cleaning systems at existing ranges (Bamberger 1983a^(a)), the characteristics of the effluent particles (Mishima 1983a,b^(b); Bamberger 1983b^(c)) and the performance criteria for the prototype system (Glissmeyer 1984^(d)). In this report the performance criteria and the candidate emission control systems are briefly summarized. The factors addressed in the cost analysis are detailed and the cost estimates for the candidate systems are discussed. The cost analysis for each candidate system and the method used to calculate the filtration performance of combined devices are detailed in the Appendices. The advantages and disadvantages of each system are discussed and air cleaning system recommendations are made.

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- (a) Bamberger, J. A. 1983a. Task 2 Report: Performance of Existing Air Cleaning Systems, Informal Report to U.S. Army Ballistics Research Laboratory, prepared by Pacific Northwest Laboratory, Richland, Washington.
 - (b) Mishima, J. 1983a. Task 3 Report: Effluent Characterization. Informal Report to U.S. Army Ballistics Research Laboratory, prepared by Pacific Northwest Laboratory, Richland, Washington.
Mishima, J. 1983b. Addendum to Task 3 Report. Informal Report to U.S. Army Ballistics Research Laboratory, prepared by Pacific Northwest Laboratory, Richland, Washington.
 - (c) Bamberger, J. A. 1983b. Particle Size and Concentration vs Time Data, Informal Report to U.S. Army Ballistics Research Laboratory, prepared by Pacific Northwest Laboratory, Richland, Washington.
 - (d) Glissmeyer, J. A. 1984. Development of a Prototype Air Cleaning System for a New Target Building, Task 4: Prototype System Criteria. Informal Report to U.S. Army Ballistics Research Laboratory, prepared by Pacific Northwest Laboratory, Richland, Washington.

PERFORMANCE REQUIREMENTS

The minimum performance requirements for the air cleaning system (ACS) were developed in the Prototype System Criteria (PSC) report.^(a) The requirements addressed included airflow rate, filtering efficiency, and structural characteristics. Table 1 summarizes the conclusions of that report.

FLOW CAPACITY

The design air flow, 24,000 actual cubic feet per minute (acfm) and the present internal volume of the firing range should result in a clearance time of around 60 min to an acceptable concentration level for DU particles of 0.02 mg/m^3 . This clearance time is on the border of acceptability for range operation and is the result of incoming clean air being mixed poorly with the volume inside the target bay. The clearance time for the target bay, given perfect mixing, would be about 24 min. Ballistics Research Laboratory suggested doubling the airflow to shorten the clearance time; however, this would double the cost of the ACS and require structural modifications to avoid a large pressure loss through the ventilation system. By partly opening up the front of the target-fragment shield or extending the ventilation exhaust intakes toward the fragment shield, the mixing could be substantially improved. This was discussed extensively in the PSC report, and the recommendation was made to continue to use the original flow rate in this study.

The existing fan has inadequate pressure capacity [11 in. water gauge (WG) at 24,000 acfm] to maintain the design airflow, because the sum of the pressure drops across the structure and fully loaded filter banks is estimated as 15 in. WG. In the PSC we recommended that bellmouths be added at ventilation intakes and the 2-ft orifices be removed from the shock attenuators. These modifications would reduce the required fan pressure capacity to around 11 in. WG. When selecting new ACS components, the effects of system pressure drops on the cost analysis were considered.

(a) Glissmeyer, J. A. 1984. Development of a Prototype Air Cleaning System for a New Target Building, Task 4: Prototype System Criteria. Informal Report to U.S. Army Ballistics Research, prepared by Pacific Northwest Laboratory, Richland, Washington.

TABLE 1. Summarized System Performance Criteria

1. Flow Capacity 24,000 acfm (680 acmm) constant
2. Operation Continuous during 8 h/day
ambient temperature, humidity
3. Dust Characteristics
 - a. 4.9 kg per shot
 - b. 300 shots/yr, maximum of 4 shots in any day
 - c. Size distribution: see text and Table 2
 - d. Composition: 20 wt% UO_2
70 wt% U_3O_8
9 wt% FeO_x
1 wt% SiO_x , AlO_x , TiO_x , H_2O , HNO_3 , KOH , H_2SO_4
4. Peak Pressure Pulse 3 psi for 0.5 to 1.5 s
5. Minimum System Filtering Efficiency 99.998% at 0.5 g/m^3 inlet concentration
6. Minimum New Prefiltration Efficiency at 0.5 g/m^3 inlet concentration, finest aerosol
 - 99% if bank 2 replaced
 - 91% if bank 2 retained
7. Maximum Clearance Time 60 min to 0.02 mg/m^3 interior concentration

OPERATION

Because the range will be operated under all weather conditions and because the make-up air is not heated or otherwise conditioned, the air in the ventilation system will be at ambient temperature and humidity. Therefore, there is little need for the ACS to be insulated or heated in most cases. However, condensation may possibly occur at high humidity and pressure drop through the system. If condensation occurs during test firings, the condensate may be somewhat corrosive because acidic and basic fumes are present from the

burning propellant (see Table 1). Hence, corrosion resistant materials or finishes may be required on the ACS interior. Also, because the ACS is currently outdoors on a concrete pad near the shore of Chesapeake Bay, the new equipment should be appropriately weatherproofed.

Because liquid radioactive wastes cannot be processed on site, only devices for dry collection of particles are considered to be applicable. Particles will be retained on the media or transferred to disposal containers. If collected particles are temporarily stored in hoppers, the hoppers should be designed to minimize reentrainment of the particles into the ventilation air. Appropriate operating procedures must be instituted to minimize worker exposure to the waste DU particles in the containers.

The preferred candidate ACS should be designed so that the collection media can be inspected and changed out on the clean side (downstream side) of the system and out of the weather. Used media should be easy to remove and contain so that the external and inhalation exposure to personnel are minimized. If media access is external to the device, the entire ACS may need to be enclosed to facilitate all-weather maintenance.

CONTAINMENT INTEGRITY

All components of the ACS must be designed to withstand both the maximum vacuum that the fans can exert and the pressure pulses generated by the estimated 6000 test firings that will occur during the 20-year life of the equipment. The peak pressure pulse is estimated to be 3.0 psig with a duration of 1.5 s, at the inlet of the ACS. The maximum vacuum pressure requirement of any of the proposed ACSs is 27.2 in. WG if the recommended structural modifications mentioned earlier are implemented -- otherwise, the maximum pressure is 31 in. WG. These pressure extremes (+3 psig, -31 in. WG or about -1 psig) must not disrupt the collection media or the air-tight seals at critical locations in the ACS (e.g., access doors, media, ductwork joints, or other seals that could allow leakage to the atmosphere or bypassing the particle removal stages). The ACS eventually chosen, or additions thereto, will be required to pass a leak test on site. We recommend that the vended system be pressurized to 3 psig and

the measured leak rate not exceed a set criterion. The leak criterion and the test method are outlined in ANSI/ASME (1980a) standard N509-1980 and ANSI/ASME (1980b) standard N510-1980.

If new filter banks are required, a 2-ft separation and a screen should be placed between each bank to prevent media from a failed filter from damaging or plugging downstream filters. The critical filter seals should be on the downstream side so the pressure wave will not work against the seal. A working space should also be constructed between the banks to permit close inspection of filter seals.

The structure will be located outdoors and will need to withstand wind and snow loads experienced in the area. The exterior finish should protect the structure against corrosion induced by the elements. The air cleaner will mate with the existing shock attenuators and possibly the filter house. Access must be provided for interior cleaning and inspection of wear and corrosion.

AEROSOL CHARACTERISTICS

The composition of the aerosol generated during test firings was summarized in Table 1. Three particle size distributions were considered for use in evaluating ACS performance. These size distributions were measured during test firings using cascade impactors, which quantify uranium mass as a function of aerodynamic particle size. The measurements are expressed as log-normal distributions with the parameters listed in Table 2.

Figure 1 shows these size distributions as log-normal probability plots. Measurements 1 and 3 were made adjacent to the targets during outdoor tests (Glissmeyer and Mishima 1979), and Measurement 2 (Chambers et al. 1982) was made adjacent to targets inside a target bay at BRL's enclosed range (see the PSC report for a detailed discussion). None of these measurements were made under conditions that exactly simulated those expected at the ACS; therefore, we cannot predict the actual size distribution of the aerosol challenging the ACS. Because the filtering efficiencies tend to be lower for smaller particles, we chose to use the finest size distribution (Measurement 3, Table 2) for assessing the performance of candidate ACSs. Using the finest size

TABLE 2. Size Distribution Summary

Measurement	Mass Mean Aerodynamic Particle Diameter, μm	Geometric Standard Deviation
1	2.7	6.3
2	1.6	13.0
3	0.81	22.9

distribution may result in underestimating filtration performance and over-estimating the cost of operating the system. However, this method will be applied uniformly to all devices to avoid giving unfair advantage to any system and to preserve the relative cost ranking of each candidate.

FIGURE 1. Depleted Uranium Size Distribution

CANDIDATE SYSTEMS

The basic assumptions for selecting equipment were that 1) particle collection should not produce a liquid effluent requiring treatment, and 2) the final control device will be a bank of high-efficiency particulate air (HEPA) filters to act as a final polishing and safety stage. Therefore, the candidate ACSs consist of a primary device for dry particle collection followed by one or more banks of disposable filters, the last bank being HEPA filters. These systems are described only briefly here; thorough descriptions and illustrations can be found in the appendices. The fifteen candidate types are listed in Table 3.

TABLE 3. Candidate Air Cleaning Systems

1. Existing Disposable Filters
2. Existing Disposable Filters With Extended Surface Filter
in Place of Bank 2
3. Rolling Prefilter + Disposable Filters
4. Peeled-Roll Filter + Disposable Filters
5. Pulse-Jet Baghouse + Disposable Filters with standard felt media
or with coated media
6. Shaker Baghouse + Disposable Filters with standard fabric media
or with coated felt media
7. Electrostatically Augmented Baghouse + Disposable Filters
8. Cartridge House + Disposable Filters with standard media
or with coated media
9. Cyclones + Disposable Filters
10. Electrostatic Precipitator + Disposable Filters
11. Vaned Inertial Separator + Pulsed Panel Filter
+ Disposable Filters
12. Cleanable High-Efficiency Filter + Disposable Filters

The existing filters are the disposable type consisting of three banks of 24 filters each. The first bank has 2-in.-deep pleated filters rated 25% efficient by ASHRAE 52-76 (1976) dust spot test, the second bank has 11.5-in.-deep pleated filters rated 95% efficient by ASHRAE 52-76 dust spot test, and the third has 11.5-in.-deep pleated HEPA filters. Each filter is 2 ft high and 2 ft wide, and the banks are three filters high and eight filters wide. The filter frames are made of sheet metal and, together with the fan, are housed in a 12-gauge galvanized steel building on a 22-ft-square pad. Figure 2 shows the layout of the filter house.

We assumed that for most of the candidate systems the existing filter house will be used and one or more of the filter banks will be employed downstream of the primary device; however, the fan may be of greater static pressure capacity and relocated outside the housing. The primary device will probably displace the filter housing and fan to an adjacent pad as illustrated in Figure 3.

In baghouses, particles are collected on the surface of a tubular or flat fabric bag. The bag is periodically cleaned by shaking or by pulsing compressed air through the bag. Seventeen vendors provided cost information for baghouses, mostly for those cleaned with compressed air (pulse-jet). The cartridge house is functionally identical to, but more compact than, the pulse-jet baghouse. Instead of collecting particles on fabric bags, they are collected on a cellulose mat that is pleated and formed into a cartridge similar to the carburetor air-cleaners of trucks.

The electrostatic precipitator (ESP) charges aerosols by corona discharge at electrodes. The charged particles then migrate to oppositely charged plates. Particles built-up on the collection plates are removed by agitating the plates with rappers or acoustically induced vibration. The particles then fall into a hopper for transfer to containers. Four vendors provided information on eight ESPs suitable for this study.

In a cyclone, the airflow is caused to move in a tornadic fashion. Large particles move to the outer wall by centrifugal force and are moved downward to a hopper by gravity. Three vendors provided information on cyclones for this study.

FIGURE 2. Existing Filter House

FIGURE 3. Possible Orientation of Air Cleaning Equipment

A rolling prefilter is mechanically similar to the film advance system in a camera. There are two reels--one has new media wrapped on it and the other takes up the exposed media. Particles are collected on the media that is stretched flat between the two reels as the air passes through. Periodically, the reels are advanced to expose new media to the air. When the new media are exhausted, the reels are replaced. The peeled roll filter is similar in that it uses clean- and used-media reels; however, the airflow passes radially inward through the layers of media wound on the clean media reel and then out through the end of the reel's core. Because the air passes through many layers of media, the filtration efficiency is greater than that of the rolling prefilter although the media are essentially the same. When the outer layer becomes loaded with particles, the layer is wound onto the other reel. Several media units are contained in a single housing. Collected particles are retained on the media of the rolling filters and are disposed of with the media. The pressure waves caused by test firing may dislodge some particles from the media and cause them to drop to the floor of the housing.

The extended surface filter is a prefilter that fits into the same holding frame as the existing second prefilter. The medium is a thick glass-fiber pad shaped into pockets or envelopes that are about 30 in. deep. The efficiency is about the same as the current second prefilter, but this filter has greater particle-holding capacity.

The cleanable high-efficiency filter contains one or two banks of high-efficiency filters that look similar to the HEPA filter used in the existing system. The filters differ from the HEPAs in that they have a thin coating on the particle collection side so particles cannot penetrate into the fibers of the media. The medium acts as a support for the porous coating, which does the filtering. The filters are cleaned in place using either a vacuum system or pulses of compressed air. Two vendors were found that supply this type of equipment.

In the pulsed panel device, the cleanable filter panels are housed in a steel box with hoppers beneath. The filter medium is very similar to the medium-efficiency prefilter in bank 2 of the existing system except the media are not pleated as deeply and the individual filter dimensions are 2 ft x 4 ft x 3 in. For the design airflow, the pulsed panel device would contain 24 panel filters. The filters are cleaned periodically with pulses of compressed air flowing in the direction opposite to the airflow.

The vaned inertial separator is rated at about 80% efficiency under ASHRAE 52-76 (1976). Ninety percent of the airflow is sharply turned through vanes, while 10% of the airflow proceeds in a straight line. Large particles cannot follow the rapid change in direction and follow the 10% airflow in a straight line. The 10% airflow, now more heavily laden with particles, is passed through a pulsed panel unit that will remove 80% to 90% of the particles. The airflows from the vaned inertial separator and the pulsed panel are recombined and passed through a second pulsed panel with a 24,000 acfm capacity. Two vendors were found to manufacture the vaned inertial separators.

Each combination of primary device and disposable filters was considered as a candidate ACS. Usually, four estimates were generated for the cost and performance of each ACS. Each estimate was for a different combination of disposable filters to be used downstream. The four combinations were banks 1, 2, and 3; banks 2 and 3; bank 3; and banks 1 and 3. Different vendors were contacted to obtain cost estimates for equipment they recommended. From the information gathered, different cost and performance estimates for candidate ACSs were made following the methods discussed in the next section.

COST ANALYSIS METHOD

Because this application of an air cleaning system is unique and applicable data on the performance of the filters are lacking, it must be realized that costs attributed to the different ACS configurations are estimates based on several imponderables. Such factors considered in this study were the particle collection efficiency of devices, individually or in series, and the frequency of mechanical repairs. The former proved to be the most significant because several important items hinge on the question of efficiency. Included in this category are the life of media, frequency of media replacement, media disposal, and the disposal of collected dust. We have used the best efficiency data available to us from the literature or vendors; however, in most cases, extrapolations beyond the data were required and are noted where they appear. Estimates of maintenance and repairs were obtained largely from vendors. Estimating methods were applied uniformly to identify the relative ranking of the candidate ACSs, even though the estimates were inexact overall. In most cases the ACSs include all or a part of the existing filter banks as after- or polishing-filters. To explore which filter banks should be retained, cost estimates were generated for each practical combination of the existing after-filters with candidate devices.

COSTS ADDRESSED

A complete estimate of procurement, operating, and maintenance costs of each ACS was attempted. The cost elements addressed were

- media life -- how long the media lasts
- media replacement -- replacement and disposal of media
- waste disposal -- disposal of collected powder
- first costs -- initial investment in equipment and installation
- maintenance -- operation, maintenance, and repairs of ACS
- electrical power -- power requirements of fan and auxiliaries.

The general method of estimating these elements will be explained in the following subsections. Labor costs are assessed under the topics to which the labor is applied.

COST ASSUMPTIONS

The several assumptions that we used as a starting point for cost estimating are enumerated in Table 4. We also assumed that HEPA filters will be retained as the last device in an ACS for a polishing and safety stage. These assumptions are used several times in the estimating method. Other assumptions are introduced as they pertain to specific method elements.

MEDIA LIFE

The life expectancy of the media is a concern in all of the devices except cyclones or ESPs. Mechanical media failure resulting in particle leakage is the principal factor determining the life of cleanable media. The filtration efficiency of cleanable media affects only the subsequent disposable filters, because it determines the challenge aerosol. For disposable filters, the filtering efficiency and the particle-holding capacity are equally important to media life. Therefore, the question of media life is approached differently for the two media types.

Disposable Filters

The approach developed was applied to all of the types of disposable filters investigated: the rolling filters, existing filters, and extended-surface filters. To estimate media life, both the filtration efficiency as a function of aerodynamic particle size and the dust holding capacity at the final operating pressure drop must be known; however, data covering the entire range of interest were generally not available and extrapolations were required. The data on efficiency and dust capacity for the individual devices are discussed in Appendices B through J.

The particle size range of interest was subdivided into seven size brackets, equally spaced logarithmically. The mass of particles in each bracket was estimated from the size distribution plots (Figure 1) as shown in Table 5. All of the particles in a given bracket were assumed to behave as particles the size of the bracket midpoint. The collection efficiency of each device was obtained for each size bracket midpoint. The amount of particles collected by and penetrating a device was computed for each size bracket. The

TABLE 4. Assumptions Used for Cost Estimating

<u>Variables</u>	<u>Assumed Values</u>
Labor rate for BRL personnel	\$31/man-hr
Power cost	\$0.04/kWh
Waste disposal cost including container, shipping fees, labor, burial fees	\$25/ft ³
ACS equipment life	20 year
Test firings that ACS will be exposed to	6000
Average weight of test round	4.9 kg
Average aerosol mass per test	4.9 kg
Bulk density of the collected dust	1.5 g/cm ³
Annual operating time for ACS (365 day x 5/7 - 10 holiday) x 8 hr/day =	2006 hr

total amounts collected and penetrated were computed by summing the bracket values. To estimate the fraction of filter life (life fraction, LF) used by a test shot, the vendor's estimated particle-holding capacity was divided into the mass of particles collected during a test firing. The inverse of this value is the average estimated number of shots to which the device could be exposed before replacement. The penetrated particle mass distribution per size bracket was used as the input aerosol to the next stage of filtration. This approach was used to estimate the useful life of a disposable filter as an individual unit or as a bank of units in series.

An example of the application of this method is shown in Appendix A. The dust holding capacities, filter collection efficiencies, and calculations using this method are detailed in the appropriate appendices covering each candidate

TABLE 5. Particle Size Distributions--Percent Mass Per Size Bracket

Bracket	Bracket Midpoint Size, μm	Mass Distribution, %		
		No. 1	No. 2	No. 3
1	0.1	7.3	20	31
2	0.32	12.7	14	14
3	1.0	20.5	18	15
4	3.2	25.5	17	13
5	10.0	19.0	14	11
6	32.0	10.3	9	7
7	100.0	4.7	8	9

ACS. This method was first tested on the existing filters and resulted in the filter replacement frequencies shown at the bottom of Table 6. Table 7 shows the disposable filter life experienced at existing ranges. Comparing the values for disposable filter life shows that the estimates calculated using this method were within the range experienced at other ranges, giving us some confidence in the method. As stated in the performance requirements, the finest size distribution (Table 5, No. 3) was used in this study to estimate media life and particle penetration.

Cleanable Media

Estimates of media life for the cleanable media devices were obtained from the equipment manufacturers, who usually do not make the media they supply except for the cleanable high-efficiency filters. The estimates from the manufacturers are based on extensive experience with their users. The controlling factor for these devices is mechanical wear resulting in filter media failure. Most often these devices are used in harsh industrial ventilation environments where aerosol concentrations are higher and more continuous than expected for the firing range. Most vendors felt that the aerosol loading at the firing range is light compared to their typical applications. The life estimates for each device using cleanable media are detailed in the appropriate appendices and are summarized in Table 6.

TABLE 6. Calculated Media Life

<u>Device</u>	<u>Life Expectancy, months</u>
Common Rolling Filter	1
Peeled-Roll Filter	84
Pulse-Jet Baghouse: Standard Felt	24
Coated Felt	27
Electrostatically Augmented Baghouse	24
Cartridge House	24
Cleanable High-Efficiency Filter	80-120
Pulsed Panels	1
Shaker Baghouse	60
	<u>No. Shots</u>
25% ASHRAE Prefilter	4
95% ASHRAE Prefilters	4
HEPA Filters	31
95% ASHRAE Extended Surface Filter	8

TABLE 7. Actual Filter Life Experience

<u>Range</u>	<u>Shots Per Year</u>	<u>Range of Filter Life, Rounds/Change</u>		
		<u>1st Prefilters</u>	<u>2nd Prefilters</u>	<u>HEPAs</u>
Other Site	230	1-2	10-20	100-200
BRL	180	1-6	1-6	5-60

To estimate the characteristics of the challenge aerosol that is passed to units downstream and the quantities of dust to be transferred to disposal containers, the calculation method described above for the disposable filters was also applied to most cleanable media devices. For pulse-jet baghouses an alternate method based on current research was used for estimating the downstream aerosol size distribution. The alternate method, detailed in Appendix C, discards the notion of collection efficiency and relates penetration flux to the media area, dust cake on the media, and the frequency of cleaning.

MEDIA REPLACEMENT

To estimate the cost of replacing filter media, several factors were taken into account:

- the cost of new media
- the cost of disposing of used media
- the labor to change the media
- the volume of the compacted media
- the labor to compact the used media.

How we handled these factors for each type of media is discussed in the following subsections.

Cleanable Media and Peeled-Roll Filter

The cost of new media (CM) for these devices was determined by multiplying the number of media units (NU; bags, rolls, etc.) by the cost per unit (CU) and the number of replacement sets (RS) required in 20 years.

$$CM = NU \times CU \times RS \quad (1)$$

The cost of the original set of media was included in the prices of the equipment from the vendors.

The cost of media disposal (CMD) was calculated in three steps. First the volume of a set of compacted media (MVOL) was determined by multiplying the original volume by the percent compaction. Second, the number of media units that could be compacted and packaged for burial per man-hour was estimated (MCOM). The total media disposal cost was then calculated by

$$CMD = [(MVOL \times \$25/\text{ft}^3) + (NU \times \$31/\text{man-hr} / MCOM)] \times (RS + 1) \quad (2)$$

The man-hours (TCH) required to change each type of media were calculated by estimating the time for two persons to change one media unit and multiplying by the number of units in a complete set. It was assumed that two persons would be involved at any time for safety. The cost for all media changes (CMCH) in 20 years was then calculated by

$$\text{CMCH} = \$31/\text{man-hr} \times \text{TCH} \times (\text{RS} + 1) \quad (3)$$

The RS + 1 factor was used in Equations (2) and (3) because the original set of media must also be handled and disposed.

Disposable and Rolling Filters

The method for computing media replacement, disposal, and change-out costs for the disposable and rolling filter media types (other than the peeled roll) is identical to that outlined for the cleanable media except the RS and RS + 1 factors are replaced with the total number of media sets used, which can be calculated by 6000 shots $\times$ LF (the fraction of media life used by one test shot). The cost-estimating equations are combined and implemented in the FILTER code. FILTER produces the cost and the number of filter changes for the use of any combination of disposable filters as part of the ACS.

Combined System

The media replacement costs for both the cleanable and disposable devices were combined as shown in the appendices.

MAINTENANCE

Maintenance costs associated with media replacement were discussed above. The remaining maintenance topics--waste disposal, equipment repairs, and operating labor--are described in the following subsections.

Waste Disposal

The major waste disposal problem, other than disposing of the media, is disposal of the powder or dust collected in the hoppers used in most of the candidate ACSs. The powder will be a mixture of about the same composition as the airborne particles shown in Table 1. Because the principal component will be DU, precautions must be taken to control the radiological and toxicological hazards. Powder collected in the hoppers will be transferred to a container via some type of airlock valve. The container will have to meet Department of Transportation (DOT) requirements and will probably be a Type A container--a 17C, 17H, or 17EH drum. For purposes of estimation, the following are assumed: 1) a 55-gal drum (7.35 ft³) will be used; 2) 2 hr of labor will be involved in

filling each drum; 3) powder bulk density is equal to that of uranium oxide (1.5 g/cm^3); 4) a cost of $\$25/\text{ft}^3$ includes the container, shipping, and burial costs. Allowing some head-space, each drum will contain about 300 kg of powder. For example, if 4.9 kg dust were collected per shot, then the method for computing powder disposal cost is shown in Equation (4).

$$\begin{aligned}
 \text{20-yr Dust Disposal Cost} &= \frac{4.9 \text{ kg dust to hopper}}{\text{shot}} \times 6000 \text{ shot} \times \frac{\text{drum}}{300 \text{ kg dust}} \\
 &\times \frac{\$25}{\text{ft}^3} \times \frac{7.35 \text{ ft}^3}{\text{drum}} + \frac{2 \text{ man-hr}}{\text{drumfill}} \times \frac{\$31}{\text{man-hr}} \\
 &= \$24,083 \qquad (4)
 \end{aligned}$$

Because the quantity of powder collected in the hopper varies with the equipment, individual costs of dust disposal for each ACS were estimated in the appendices.

REPAIRS

The expected repair costs addressed in this study include compressor maintenance, pulse valve rebuilds, cleaning-cycle control board replacement, blower repair, and a 16-man-hr allowance for miscellaneous annual repairs. The estimating methods for these costs are described below, and the maintenance cost tables in the Appendices contain columns that show which of these repair costs were included in the total cost estimate for each ACS.

For compressor maintenance and repairs, we assumed 8 man-hr/yr would be required. This equates to $8 \text{ hr/yr} \times 20 \text{ yr} \times \$31/\text{hr} = \$4960$. For miscellaneous annual maintenance or repairs we assumed 16 man-hr/yr or $\$9920$. For replacement of the cleaning-cycle control board, we assumed the replacement requires 4 man-hours and the electronics board will cost $\$500$. The cost for replacing the board is then $(4 \text{ hr} \times \$31/\text{hr}) + \$500 = \$624$. Two of the ACSs require the use of a medium pressure air blower instead of a compressor. We assumed blower

motor repairs may require 16 man-hr and \$1500 for parts for a total of $(16 \text{ hr} \times \$31/\text{hr}) + \$1500 = \$1996$. We also assumed that control board and blower repairs would occur only once during the facility life.

Most vendors have advised that the purge valves, which open to emit pulses of compressed air for media cleaning, must be rebuilt frequently. They suggested a preventative maintenance program of rebuilds every 2 years. Usually, each pulse system includes two valves--a solenoid valve and a diaphragm valve--and a rebuild kit costs \$43 per pair of valves. The worksheets in the appendices list the number of pulse valve pairs per equipment configuration where appropriate. If they are rebuilt every 2 years, the valves will be rebuilt eight times during the equipment life (repair won't be necessary before decommissioning). We have assumed each rebuild will require 8 man-hr; thus, the labor cost is $(8 \text{ rebuilds}) \times (8 \text{ man-hr}) \times (\$31/\text{man-hr}) = \$1984$. The parts cost is $(\text{number valve pairs}) \times (\$43/\text{kit}) \times (8 \text{ rebuilds})$ and is computed for each ACS as appropriate in the appendices.

OPERATION

To estimate the labor cost of operating the ACSs, we have estimated the time involved for daily start-up and shutdown, annual inspection, and annual housekeeping. For the daily operation, we assumed 20 min was required to start and shutdown the existing ACS. For the candidate ACS we added additional time for more complicated equipment. The approach for inspection and housekeeping was similar; one day for housekeeping and a half-day for inspection of the existing system per year. For the other systems additional time was allotted for more complicated equipment. Table 8 lists the amount of time required for daily operating and annual inspection and housekeeping labor for each ACS. The cost of the labor is estimated using Equation (5).

$$\begin{aligned} \text{Operation Labor Cost} = & 20 \text{ yr} \times \frac{\$31}{\text{man-hr}} \times \left(\text{Housekeeping} \frac{\text{day}}{\text{yr}} + \text{Inspection} \frac{\text{day}}{\text{yr}} \right) \times \frac{8 \text{ man-hr}}{\text{day}} \\ & + \left(\text{Operation} \frac{\text{min}}{\text{day}} \times \frac{2006 \text{ man-hr}}{\text{yr}} \times \frac{\text{day}}{8 \text{ hr}} \times \frac{\text{hr}}{60 \text{ min}} \right) \end{aligned} \quad (5)$$

TABLE 8. Operating Labor

System	Housekeeping man-days/yr	Inspection	Start-Up and Shut Down, min/day
Existing Filters	1	0.5	20
Pulse-Jet Baghouse	1	1	30
Shaker Baghouse	1	2	30
Electrostatic Baghouse	1	2	40
Cartridge House	1	1	30
Vendor O, Cleanable High-Efficiency Filter	1	1.5	30
Vendor S, 1-stage Cleanable High-Efficiency Filter	1	2	40
Vendor S, 2-stage Cleanable High-Efficiency Filter	1	2	45
Electrostatic Precipitator	1	1	30
Cyclone	1	0.5	20
Peeled-Roll Filter	2	1	20
Pulsed Panel	2	1	30
Rolling Prefilter	2	0.5	20
Vaned Inertial Separator + Pulsed Panel Filter	2	1.5	30

FIRST COSTS

The first cost, or initial capital investment, includes the costs of equipment design, fabrication, freight, and installation. Auxiliary equipment such as air compressors and hopper valves are also part of the first cost. In all cases the cost of design and fabrication was estimated by the equipment vendors. The type of hopper valves and paint finishes varied between vendors because we had not selected a preferred type. When the hopper valves were not included, we added \$1500/hopper to the vendor's cost to cover the price of motorized airlock valves. The material of construction for most system components was mild steel.

Some vendors supplied us with the cost of ductwork, fan, flow-rate controls, installation, concrete, and electrical work; however, most did not. To put these varied cost estimates on a common ground for installation, we asked Kaiser Engineers Hanford Company, in Richland, Washington, to generate cost estimates. These estimates, summarized in Appendix L, included flow-rate controls, fans for various pressure requirements, air compressors, concrete pads, sheds, drum handling equipment, freight, ductwork of various types, installation labor, and leak testing in the field. How these were applied to the different ACSs is detailed in the appendix on each type. For all devices except cyclones and precipitators, these estimates were used for the auxiliary equipment, freight, and installation costs. Vendor estimates were used for the cyclones and precipitators.

ELECTRICAL POWER

Power costs for the range are not part of the direct operating costs to BRL; however, power costs were estimated to provide a basis for selection between ACSs with otherwise comparable costs. Included in our estimates were the power for operating the fan, the control device, and the auxiliary equipment such as compressors or blowers.

Fans

The power cost for operating the fan was estimated directly from the system pressure drop using the method of Burchsted, Fuller and Kahn (1976, p. 24) and very conservative fan and motor efficiencies.

$$\begin{aligned} \text{Fan Power Cost} &= \text{Air Flow, acfm} \times \frac{2006 \text{ hr}}{\text{yr}} \times 20 \text{ yr} \times \text{pressure drop, in. WG} \times \frac{\$0.04}{\text{kWh}} \\ &\quad \times \frac{1}{0.55 \text{ fan efficiency}} \times \frac{1}{0.85 \text{ motor efficiency}} \times \frac{1}{8520 \text{ conversion factor}} \end{aligned} \quad (6)$$

The pressure drop for each ACS was estimated by adding that of each control device to the 2.2 in. WG assumed for the range structure and ductwork.

Continuous Equipment

The ESPs are the only continuous users of electricity other than the ventilation fan. Power requirements in terms of kilowatts were obtained from the vendors. The power cost was then computed by multiplying kilowatts by the number of operating hours and the use rate, \$0.04/kWh.

Intermittent Auxiliaries

Most auxiliary devices operate only intermittently during the cleaning cycle. The operating fraction, operating hr/hr, for these devices was estimated and the horsepower (hp) requirements were furnished by vendors. The power cost was then computed using Equation (7).

$$\begin{aligned} \text{Auxiliary Power Cost} &= \text{Operating Fraction} \frac{\text{hr}}{\text{hr}} \times \text{Auxiliary hp} \times \frac{2006 \text{ hr}}{\text{yr}} \times 20 \text{ yr} \\ &\times \frac{0.7457 \text{ kW}}{\text{hp}} \times \frac{\$0.04}{\text{kWh}} \end{aligned} \quad (7)$$

TOTAL COSTS

Following the method outlined, the costs over 20 year of acquiring, maintaining, and operating each candidate ACS were computed. The resulting data are tabulated in the appendices according to the type of primary control device. Total costs were estimated for 294 different systems for the 15 types of primary control devices. The most promising configuration for each primary control device was selected and will be discussed in the next section.

DISCUSSION

The appendices describe the operating principles of the several types of air cleaning devices listed in Table 3. They also give detailed cost estimates for operating the air cleaning systems for the 20-year expected life. Cost estimates were generated for each device in all of the practical combinations of the existing filter banks. In this section the costs of operating the candidate systems will be compared.

One configuration of each candidate system is used in the comparison. It was stated previously that HEPA filters are assumed to be used as the final stage of filtration to serve as a polishing stage and as a final barrier to particle release. It is further assumed that the HEPA stage will require a medium- to high-efficiency prefilter that will collect the bulk of particles penetrating the first device. This ensures that the HEPA stage can remain functional even if the first filtration device fails catastrophically in an accident that might conceivably be caused by explosive overpressurization of the system during a test firing. When power costs are excluded from consideration, the 20-year equipment, maintenance, and operating costs were most often least expensive when the three existing filter banks were used downstream of the first device. The cost difference between using the last two instead of the three existing filter banks was more significant for systems with total costs over \$1 million than for the less expensive ones (for which the difference was usually negligible). The system configurations considered for intercomparison are listed in Table 9. Summarized cost estimates for these systems were computed as shown in Appendix L and the results are shown in Table 9.

The first two columns of Table 9 list the configuration recommended for each device. The initial investment values given include equipment acquisition, installation, freight, ventilation fans, controls, and certain desirable accessories for waste handling (drum scale and truck). The filtration penetration estimates are for the device plus the filter banks as a system. Given the uncertainties in filter efficiency data, the penetration estimates are probably accurate to 1 to 2 orders of magnitude. Maintenance costs include parts and labor for operation, repairs, housekeeping, and removal and installation of

TABLE 9. Cost Summary for Candidate Air Cleaning Systems

System		Initial Investment, \$K	Calculated System Fractional Penetration	Maintenance			Power	
Device	Filter Bank			Total Labor, man-hr	Total Parts, \$K	Total Maintenance, \$K	mWh	\$K
Cartridge, Coated Media	2,3	129	5.0E-08	3542	8	118	3475	139
Cleanable High-Efficiency Filter, 1 Stage	2,3	187	2.0E-07	3884	3	124	5750	230
Cleanable High-Efficiency Filter, 2 Stage		197	6.3E-07	4638	2	146	3850	154
Electrostatic Baghouse	2,3	167	6.3E-07	4946	3	157	4000	160
Baghouse, Pulse-Jet, Standard Felt	2,3	157	2.0E-09	4748	8	155	4000	160
Baghouse, Shaker, Standard Sateen	2,3	134	1.0E-08	6192	1	192	2950	118
Baghouse, Pulse-Jet, Coated Felt	2,3	157	3.8E-10	4434	8	145	4000	160
Cartridge, Standard	2,3	129	5.0E-06	3732	8	123	3475	139
Vaned Inertial Separator	2,3	119	7.0E-06	4158	2	131	4525	181
ESP	2,3	466	1.6E-06	3427	1	107	3100	124
Pulsed Panel	2,3	100	9.0E-06	4096	2	129	3275	131
Peeled-Roll Filter	2,3	253	1.1E-04	8047	1	250	4825	193
Cyclone	1,2,3	112	1.1E-04	8447	0	262	6575	263
Standard Rolling Filter	1,2,3	31	1.1E-04	10585	1	329	2950	118
Existing System	1,2,3	20	1.1E-04	12041	0	373	3200	128
Extended Surface at Bank 2	1,2,3	10	2.5E-04	16470	0	511	2700	108

System	Replacement Media, \$K	Waste Disposal		Excluding Power		
		man-hr	Vol, ft ³	Total \$K	Operating, \$K	Operating + Initial, \$K
Cartridge, Coated Media	40	252	1043	34	191	320
Cleanable High-Efficiency Filter, 1 Stage	14	204	749	25	163	350
Cleanable High-Efficiency Filter, 2 Stage	15	205	776	26	186	383
Electrostatic Baghouse	20	214	1075	34	210	377
Baghouse, Pulse-Jet, Standard Felt	60	259	1400	43	257	414
Baghouse, Shaker, Standard Sateen	49	221	1247	38	279	413
Baghouse, Pulse-Jet, Coated Felt	94	208	1100	34	273	430
Cartridge, Standard	122	347	1528	49	294	423
Vaned Inertial Separator	216	440	1807	59	406	525
ESP	51	255	1004	33	191	657
Pulsed Panel	249	477	2008	65	443	543
Peeled-Roll Filter	2649	3138	15345	481	3380	3633
Cyclone	3031	3739	17607	556	3848	3960
Standard Rolling Filter	3482	4814	19633	640	4451	4482
Existing System	3631	5661	20920	698	4703	4723
Extended Surface at Bank 2	3640	4640	33064	970	5121	5131

filters. The power costs take into account the ventilation fan and any auxiliary equipment required by each system. Media replacement includes the purchase of filter media--both cleanable and disposable. The waste disposal estimate includes the labor involved in compacting, handling, and disposing of filter media and DU containing dust, and the cost of packaging, shipping, and disposing of the waste at a commercial site for low-level radioactive wastes. The totals in the last three columns exclude the cost of power as requested by BRL. The operating cost is the sum of all the costs discussed except the initial procurement. The operating cost plus the initial procurement is the total number of constant dollars that would be spent on the system during the 20-year facility life. Amortizing the operating costs over 20 years at 4% interest and adding the initial investment yields the life cycle cost estimate in the last column.

The systems in Table 9 were listed in order of ascending life cycle cost. There were two distinct groupings costwise with about an order of magnitude difference in total cost between the two. The expensive group was characterized by systems where most of the filtration duty is performed using disposable filters. This was true even of the cyclone system because the cyclone's low efficiency for the challenge aerosol puts the filtration burden on the disposable filters. The average life cycle cost for this group was about \$6500K.

The less expensive group was characterized by performing most of the filtration with a high-efficiency device using cleanable filters or no filters at all as was the case for the ESP. The average life cycle cost for this group was \$570K. The most important distinction between the two groups was the cost entailed in the usage and disposal of throw-away filters. Another significant difference, but of lesser impact, was the relative average costs of maintenance, \$139K and \$345K for the first eleven and the last five systems, respectively. It should also be noted that none of the expensive group of systems met BRL's efficiency criterion of 99.998% (penetration less than 2.0×10^{-6}), although they were close to meeting the criterion within the accuracy of the available data. The expensive group was then eliminated from further consideration.

Several of the candidate systems in the less expensive group were eliminated for operational reasons. The vaned inertial separator and pulsed panel systems were eliminated because of the inconvenience and potential inhalation hazard inherent in requiring that the filter panels be changed by entering the contaminated hopper portion of the pulsed panels.

The ESP had the lowest estimated maintenance cost (\$107K) of the remaining systems; however, the ESP had a significantly higher initial cost which outweighed the maintenance advantage. We also suspected that the ESP would be more susceptible to 'puffing', briefly reduced efficiency for the instant of pressurization following a test shot, than would devices using filter media.

The shaker baghouse was eliminated for several reasons. First, it relies entirely on a dust cake for filtration, which would be disrupted during cleaning and probably during each test firing pressure pulse. Smith, Cushing and Carr (1981) showed that shaker efficiency declines significantly following cleaning until such time as a dust cake is rebuilt, which would be a long time in the firing range case because the dust concentration is essentially atmospheric. Second, the pressure pulse could severely damage the unsupported filter bags. The filter bags are inflated by the ventilation airflow and the only supports to the fabric are rings sewn into the fabric at intervals. The brief pressurization following a test shot may overstress an inflated bag. This also applies to the electrostatically augmented baghouse because it has a similar fabric support configuration. An additional drawback of the shaker baghouse was the very large number of bags (960) that would eventually require replacement.

The remaining devices, in order of initial cost, were

1. Cartridge House (\$129K)
2. Pulse-Jet Baghouse (\$157K)
3. Cleanable High-Efficiency Filter (\$187 to 197K)

Table 10 lists the advantages and disadvantages for these remaining candidate systems.

TABLE 10. Advantages and Disadvantages For Remaining Candidate Systems

	Advantage	Disadvantage
Cartridge House	1 Filter removal from clean side out of weather	1 Standard high pressure housing unavailable
	2 Extensive user experience	
	3 Broad vendor support	
	4 Filters compact easy to change	
	5 Lowest initial cost	
	6 Compact housing	
Pulse-Jet Baghouse	1 Filter removal from clean side, out of weather,	1 Walk-in filter access requires high bay
	2 Extensive user experience	2 Filters awkward to change because of support cage
	3 Broad vendor support	3 Highest number of filter elements to change
	4 Standard high pressure models available	
	5 Fewest door seals	
Cleanable High-Efficiency	1 Convenient filter changeout	1 No existing systems of comparable capacity
	2 Fewest filter elements	2 Many door seals that could leak
	3 Compact housing	3 Most expensive
	4 Bagout system for filters	4 Single vendor filter supply
	5 Eliminate existing filters with two-stage housing	5 No standard high-pressure models
	6 Two stages of filters with slightly larger housing	6 Single-stage models had highest pressure drop

CONCLUSIONS

The cartridge house system with walk-in filter access is recommended for this firing range application. Initial test firings using the existing filter house resulted in failure of the original joints in the front and back walls, which have since been rebuilt. Because of that failure, the cartridge house will be fabricated of 0.25-in. steel and must pass a leak test at the design pressure of +3 psig. We anticipate that the cartridge house will attenuate the pressure pulse transmitted to the filter house.

It is unknown how much the cost of a cartridge house may be increased by the requirement for heavier steel. If the estimated cost is double or triple the costs estimated for this study, it may be well to reconsider the pulse-jet baghouse as the next choice because standard high pressure models are available within the range of prices given in this study (see Tables C.5a and C.6a in Appendix C). The cartridge house was recommended as the first choice because of its compact size and small number of filter elements relative to the baghouse. The cleanable high-efficiency filter units were recommended as the third choice because vendor support is limited to the original manufacturer, systems of comparable capacity have not been built before, and there are many door seals subject to leakage.

The existing filter house, or a suitable replacement, should be attached downstream of the cartridge house to enable the use of the 95%-rated prefilters and the HEPA filters. A single cartridge filter was adapted to the prefilter bank of another range for some preliminary testing. After several test shots the filter appeared undamaged from the pressure pulse.

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APPENDIX A

MODELING FILTER EFFICIENCY

APPENDIX A

MODELING FILTER EFFICIENCY

To begin calculating the quantities of particles collected and penetrating the filter media, the particle size range of interest was divided into seven, equally wide, logarithmic size brackets (i.e., the difference between the logarithms of the upper and lower bracket limits is the same for each bracket). The mass fraction of the aerosol in each bracket was obtained from the plot of log (particle aerodynamic diameter) versus cumulative mass percentage on a probability scale as shown in Figure 1 of the main text. The aerosol mass percent in each bracket was shown in Table 5 for each size distribution. The aerosol in each bracket was assumed to behave as if it were of the same particle size as the midpoint. Data on the collection efficiency of the filters were obtained for the particle sizes associated with the bracket midpoints. Extrapolation beyond the range of literature data was often required. The aerosol mass/bracket was multiplied by the collection efficiency for each bracket to calculate the mass collected. The mass collected from a bracket subtracted from the initial mass was the bracket mass penetrating the filter. Total masses collected and penetrating a filter were obtained by summing the values from each bracket. The penetrating mass per bracket served as the initial mass distribution for the next filter stage. Table A.1 shows an example performance calculation for the three existing filter banks in series using Size Distribution 3. The initial mass distribution, fractional efficiency, mass collected and penetrated for each stage and size bracket are shown. Also shown are the overall and cumulative efficiency for each stage.

Table A.1 illustrates how the cost of filter usage was calculated. The table shows the vendor's estimate for the maximum amount of dust that may be collected on a bank of 24 filters at the pressure drop that requires filter replacement. The mass collected by a filter stage was divided by the dust capacity to estimate the fraction of filter life, or life fraction, LF, used in the test. The inverse of the life fraction, $1/LF$, is the number of tests the

filter can be exposed to before replacement and is shown in the table as 'Shot Life'. While this method may be simple, the results in the table for Shot Life were within the range experienced, giving us some confidence in applying the method.

As shown in Appendix B, the cost of new media, disposal of the used media, and media change out was estimated as \$267, \$1949, and \$4291 for stages 1, 2, and 3, respectively, for one filter bank change. The life fraction multiplied by the bank cost is the cost incurred for the test. This can be multiplied by the number of tests expected in twenty years to estimate the cost during the facility life. The life fraction times the number of tests in 20 years is the number of times the filter bank will be changed. Table A.1 shows the results of these calculations for the existing filter system.

This approach, using a combined bank cost including all the costs associated with replacing a filter bank, was used only for the disposable filters (like those in the existing system) and for the conventional rolling filter. This method was coded for use on a personal computer and is called FILTER. The costs of using the cleanable media and the peeled-roll filter were estimated separately in the worksheets in Appendices B-J and added to the estimated cost of the disposable filters.

A different approach was used to estimate the particle quantity and size distribution exiting a pulse-jet baghouse. This approach is developed in detail in Appendix C.

TABLE A.1. Efficiency and Cost Calculation for Size Distribution No. 3

Size Midpoint Diameter, μm	Distribution		Bank One--25% ASHRAE Filters		
	Mass, %	Initial Grams	Fractional Efficiency	Grams Collected	Grams Penetrated
0.1	31	1519	0.0001	1.519E-01	1.519E+03
0.32	14	686	0.0001	6.860E-02	6.860E+02
1	15	735	0.007	5.145E+00	7.299E+02
3.2	13	637	0.82	5.223E+02	1.147E+02
10	11	539	0.983	5.298E+02	9.163E+00
32	7	343	0.995	3.413E+02	1.715E+00
100	9	441	0.9972	4.398E+02	1.235E+00
Total		4900		1.838E+03	3.062E+03
Cumulative Total				1.838E+03	
Stage Efficiency				3.752E-01	
Cumulative Efficiency				3.752E-01	
Max Load, g				6720	
Shot Life, shots				3.65	
Bank Replacement Cost				\$267	
20-yr Cost by Bank				\$438,307	
System 20-yr Cost					
Bank Changes in 20 yr				1642	

Size Midpoint Diameter, μm	Bank Two--95% ASHRAE Filters			Bank Three--HEPA Filters		
	Fractional Efficiency	Grams Collected	Grams Penetrated	Fractional Efficiency	Grams Collected	Grams Penetrated
0.1	0.83	1.261E+03	2.582E+02	0.998	2.577E+02	5.164E-01
0.32	0.94	6.448E+02	4.116E+01	0.99968	4.114E+01	1.317E-02
1	0.987	7.204E+02	9.488E+00	0.9999	9.487E+00	9.488E-04
3.2	0.998	1.144E+02	2.293E-01	0.99999	2.293E-01	2.293E-06
10	0.9994	9.158E+00	5.498E-03	1	5.498E-03	0.000E+00
32	0.9996	1.714E+00	6.860E-04	1	6.860E-04	0.000E+00
100	0.9997	1.234E+00	3.704E-04	1	3.704E-04	0.000E+00
Total		2.752E+03	3.091E+02		3.086E+02	5.305E-01
Cumulative Total		4.591E+03			4.899E+03	
Stage Efficiency		8.990E-01			9.983E-01	
Cumulative Efficiency		9.369E-01			9.999E-01	
Max Load, g		9600			9600	
Shot Life, shots		3.49			31.11	
Bank Replacement Cost		\$1,949			\$4,291	
20-yr Cost by Bank		\$3,352,674			\$827,502	
System 20-yr Cost					\$4,618,483	
Bank Changes in 20 yr		1720			193	

APPENDIX B

DISPOSABLE FILTERS

APPENDIX B

DISPOSABLE FILTERS

This appendix addresses the disposable (noncleanable, nonreusable) type of filters like those in the existing filter house. The existing filtration unit consists of three banks of disposable filters in series. Twenty-four filters are in each bank--three filters high by eight filters wide. The filters are enclosed in a housing with five access doors as shown in Figure 2. The double-width, double-inlet fan, with a 60-hp motor, is rated at 24,000 acfm at 11 in. WG and is also enclosed in the housing. Electrically driven opposed-blade dampers are located at the inlet and outlet of the housing to provide some measure of isolation when the system is shutdown. The dampers drive to their full-open position when the fan is started. The housing has a 12-gauge inner wall with reinforcing channels.

EXISTING FILTERS

The first filter bank consists of Product W2 prefilters that have a pleated cotton media and an ASHRAE rating of 25%.^(a) The dimensions of a single filter are 24 x 24 x 2 in., giving a volume of 0.67 ft³. Product W2 has a cardboard frame and the media is reinforced with hardware cloth.

The second filter bank contains Product W3 filters that have a pleated glass-fiber media reinforced with hardware cloth and cardboard separators. The filter rating is 95% ASHRAE.^(a) The frame enclosing the media is galvanized steel and is 24 x 24 x 12 in., giving a volume of 4 ft³.

The first two banks of filters are mounted in a side-loading frame. The second bank is immediately behind the first bank. The first prefilter slides into the frame along a channel. The second prefilter individually mounts in holders, which load at the side of the frame and slide along a track.

(a) These ratings are per ASHRAE 52-76 (1976) Standard Dust Spot Test.

The final bank consists of HEPA filters, which have a rated collection efficiency of 99.97% for a 0.3- μ m dioctylphthalate (DOP) test aerosol. The dimensions of a HEPA filter are the same as those of the second prefilter and the media is enclosed in a galvanized steel frame. The media is pleated glass-fiber paper that has aluminum separators between the pleats. The filter-mounting frame side doors permit personnel entry and individual installation and clamping of the filters.

Alternate Two-Inch-Deep Prefilters

Four different prefilters sized to replace the existing first bank of prefilters were investigated; however, none appeared to have any efficiency or particle loading advantage so they were not given further consideration in this study.

Alternate High-efficiency Filters

The use of extended-surface deep-pleat filters was investigated as an alternative to the existing second prefilter with comparable efficiency but higher airflow capacity. Derating these filters to 1000 acfm presumably would allow greater particle loading capacity. Four manufacturers listed extended-surface filters of varying collection efficiencies and airflow rates in their catalogs. The flow rate increases with the surface area. The loading capacity of the filters is also related to the surface area available and, therefore, the filters with the longest bags (consistent with the space limitations of the current filter framing, 36 in.) were investigated.

All the items investigated are fairly similar. All four filters use fine diameter glass-fiber mats. Three of these extended surface filters had the same pressure drop capability as the existing second prefilter. The filters considered had collection efficiencies of 90% ASHRAE 52-76 (1976). The filter lengths varied from 30 to 33 in., and the media surface areas ranged from 66.2 to 120 ft². Figure B.1 illustrates this type of filter.

FIGURE B.1. Typical Extended-Surface Filter

EFFICIENCY

The efficiency data for the existing prefilters and the extended surface filters were extrapolated from the manufacturers literature, and the filter-loading data at the maximum operating pressure drops were obtained from communications with the manufacturers. Efficiency data for the generic HEPA filter data were obtained from Burchsted, Fuller, and Kahn (1976, Figure 2.8). The data are summarized in Table B.1.

COST ESTIMATING

The disposal cost of the disposable filters depends largely on their compacted volume. Recently, each of the existing first and second prefilters were compacted into a 55-gal. drum (internal volume 7.35 ft^3). The initial volume for this quantity of filters was 84 ft^3 . The filters compacted to 0.088 of their original volume, which was the value used for the second prefilters.

TABLE B.1. Fractional Efficiency and Loading Data for Existing Filters

Particle Diameter, μm	Fractional Efficiency			
	First Prefilter	Second Prefilter	HEPA Filter	Extended Surface Product A1
0.1	0.0001*	0.83*	0.998	0.62*
0.32	0.0001*	0.94*	0.99968	0.77
1.0	0.007*	0.987*	0.9999*	0.92
3.2	0.82	0.998	0.99999*	0.99*
10.0	0.983	0.9994	1.0*	0.999*
32.0	0.995	0.9996	1.0*	0.9999*
100.0	0.9972	0.9997	1.0*	0.99999*
Loading Data				
Maximum Pressure Drop, in. WG	1.0	4.0	4.0	4.0
Maximum Load, g	280	400	400	750

* indicates an extrapolation beyond available data.

Because of an error early in this study, a compacted fraction of 0.067 was used for first prefilters. (This resulted in underestimating the cost of changing this bank by \$7, which was not considered to be of serious consequence.) For the HEPA filters, we assumed the compacted volume was 25% of the original volume--higher than for the others because the casing is heavy sheetmetal rather than cardboard or light sheetmetal. A compacted volume of 10% was assumed for the extended surface filter. The cost of replacing a bank of each filter type was calculated as shown in Table B.2. These costs served as bank replacement cost inputs to FILTER.

The initial investment costs for these systems were just the cost of the airflow controls, \$10K. It was assumed that the extended surface filter would fit in the existing filter frame. Table B.3 shows the estimates for 20 year's maintenance, which was the same for both approaches. Filter replacement and disposal costs were omitted because they were estimated by FILTER. The only item under repairs was the 16 man hour annual allowance for miscellaneous unspecified repairs.

TABLE B.2. Cost of Replacing Banks of Disposable Filters

First Prefilter, 25% ASHRAE

New filters = 24 x \$6.15 =	148
Change out labor = 2 man-hr x \$31/man-hr =	62
Compactor operator = 1 man-hr x \$31/man-hr =	31
Disposal = 16 ft ³ x 0.067 x \$24.26/ft ³ =	26
Total =	\$267

Second Prefilter, 95% ASHRAE

New filters = 24 x \$67.50 =	1620
Change out labor = 2 man-hr x \$31/man-hr =	62
Compactor operator = 2 man-hr x \$31/man-hr =	62
Disposal = 96 ft ³ x 0.088 x \$24.26/ft ³ =	205
Total =	1949

HEPA

New filters = 24 x \$130 =	3120
Change out labor = 16 man-hr x \$31/man-hr =	496
Compactor operator = 3 man-hr x \$31/man-hr =	93
Disposal = 96 ft ³ x 0.25 x \$24.26/ft ³ =	582
Total =	4291

Extended Surface Filter, 90% ASHRAE

New Filters = 24 x \$102 =	2448
Change out labor = 4 months x \$31/man-hr =	124
Compactor operator = 2 man-hr x \$31/man-hr =	62
Disposal = 0.1 x 24 x 2 ft x 2 ft x 2.7 ft x \$25/ft ³ =	648
Total =	\$3282

TABLE B.3. Disposable Filter Twenty-Year Maintenance

Device	Type	Repair Codes C P A E B	Misc. Repairs, \$K	Housekeeping Inspection, day/yr	Start-up Shutdown, min/day	Operating Labor, \$K	Subtotal Maintenance, \$K	Auxiliary Power \$K
Existing Filter Banks		1	9.92	1.5	20	59.26	69	0.00
Extended-Surface Filter @ Bank 2		1	9.92	1.5	20	59.26	69	0.00

Table B.4 shows various performance data and total costs for each disposable filter bank combination. The disposable filter replacement cost is the 20 yr cost of new filters and disposal of used filters as estimated by FILTER. The total number of times a filter bank replacement may occur and the overall system filtration efficiency was also estimated by FILTER and listed in the table. System pressure drop accounts for the building ductwork and the maximum load on the disposable filters. The fan cost estimated for two of the cases was for upgrading the existing fan for the required vacuum capacity. Total maintenance and acquisition costs for each combination are the sum of maintenance from Table B.3, the airflow control cost (\$10K), disposable filter useage and fan costs. Power costs are calculated and added to the equipment and maintenance cost.

The estimated cost for operating the existing system during 20 years and 6000 shots of 4.9-kg ammunition was \$4618K for filter replacement, \$69K for maintenance and operation, \$10K to upgrade the fan, and \$10K for flow controls, adding to a total of \$4707K without power. Power would add about another \$128K.

Cost estimates were generated for operating with fewer filter banks, but they are to be ignored because the combined efficiency is well below the criterion. The efficiency estimated for the existing system was 99.989%, which is also below the criterion but is probably a conservative estimate. An estimate was made of the effect of underestimating the efficiency of the first prefilter in the 0.1-, 0.32-, and 1- μ m size brackets. These efficiencies were increased from 0.0001 to 0.5, 0.0001 to 0.1, and 0.007 to 0.5 for those brackets, respectively. The resulting filter replacement cost decreased from \$4618K to \$3251K, which is still a very sizeable cost when compared to the cleanable media systems with a high-efficiency primary stage.

The costs of some hypothetical three-bank combinations were estimated. An ideal system might be to use two stages of 95% ASHRAE prefilters followed by a HEPA stage where the prefilters would cost the same as the 25% ASHRAE prefilter. For this system the overall efficiency increased to near the criterion, 0.999982, and the cost for 20 years was estimated at \$1.5M. A second

TABLE B.4. Twenty-Year Total Costs by Filter Bank Combination
for Disposable Filters

	Bank Combination	Disposable Filter Replacement	Number Bank Changes	System Efficiency, %	System ΔP , in. WG	Fan Cost, \$K	Total First Cost, \$K	Fan Power, \$K	Equipment and Maintenance, \$K	Power, \$K	Total, \$K
Existing Filter Banks	1.2.3	4618	3555	99.989	13.2	10	20	128	4707	128	4835
	2.3	6422	3062	99.989	12.2	10	20	118	6511	118	6629
	3	13132	3061	99.932	11	0	10	106	8719	106	8826
	1.3	8640	3553	99.932	11	0	10	106	8719	106	8826
Extended-Surface Filter at Bank 2	1.2.3	5041	2893	99.975	11.2		10	108	5120	108	5228

hypothetical system with one bank of 95% ASHRAE prefilters followed by two HEPA banks resulted in an estimated efficiency and cost of 0.99999979 and \$6.4M, respectively.

Using the extended surface filter resulted in an estimated 20-year total cost higher than that of the existing system because the unit cost of the filter is higher than the 95% ASHRAE filter it replaces. Apparently, the extended-surface filter would result in a cost saving only if its unit cost were less than the filters replaced, and it had equal or better performance.

It has been assumed for this study that the existing housing and one or more of its filter banks would be used in the prototype system. Two problems, however, are that there are no flow controls and the fan is probably undersized. A third problem is that the housing is always at the maximum fan vacuum capacity because the fan is in the interior of the housing. If fan bearings are inspected while the fan is operating, personnel must enter the housing--a difficult task while it is under vacuum.

If the filter housing is to be used, the fan vacuum capacity probably must be increased. The fan manufacturer indicates that the fan vacuum capacity can be increased to around 13 in. WG by using a larger motor. If the vacuum requirement is greater still, the existing fan should be removed and the replacement fan should be a single-inlet type located outside the housing. Flow controls in the form of a vortex damper or speed control would be incorporated. This would enable external inspection of the fan and the housing would be only at the vacuum absolutely required for the airflow at any set of filter loading conditions.

Two additional factors need to be considered. One is the ability of the housing to handle the increased structural load of the vacuum. The other is the ability of the housing to remain leak tight during the 3-psi pressure pulses. However, if another filter device is used upstream, the pressure pulse will probably be dampened in magnitude and time.

If it becomes desirable to replace the filter housing, more vendor inquiries would be necessary to supplement the cost analysis. One vendor indicated they would furnish a bag-in/bag-out side-loading filter housing of T-304

stainless steel that would meet ANSI Standard 509 and 510 specifications (ANSI/ASME 1980a; ANSI/ASME 1980b) for aerosol and pressure leakage in nuclear facility air cleaning systems. If furnished with the same type of filters as the existing system, the new housing would cost about \$38.5K with 24 filters per bank. Alternate sizes discussed were 18 and 48 filters per bank at \$28.5K and \$80K, respectively.

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APPENDIX C

BAGHOUSES

APPENDIX C

BAGHOUSES

DESCRIPTION

A device where particles are removed from the airflow by entrapment on a fabric substrate shaped in the form of tubes or envelopes is commonly called a baghouse. Depending on the vendor's choice of total fabric area and the length of the bags, the number of bags required ranged from 110 to 960 with an average of about 264 bags and 4400 ft² of cloth. The vendors consulted recommended three types of baghouses: pulse-jet, shaker, and electrostatically enhanced. Each of these types are described in greater detail following a brief discussion of the fabrics used.

FABRICS

For ambient temperature filtration, two main fabric types are used--felt and woven. Several compositions of these types are available with special characteristics suited for the application, such as resistance to acid fume. As a rule, felt bags are used in pulse-jet baghouses and woven bags are used in shaker baghouses because of the different requirements and stresses on the fabric.

The woven fabrics come in a few different weaves, but all require the buildup of a dust cake, which performs the actual filtration. The fabric serves as a support for the cake, as shown in Figure C.1. After a cake is established, the efficiency is very high compared to other devices. If immediate high efficiency is required or the dust loading is very light, a dust is artificially entrained in the airstream to coat the fabric. The dust, called a filter aid, is often lime.

The felt is made by needling fibers into the weave of a strong woven backing, or scrim. Particle filtration occurs both on the fibers and on the dust cake that eventually builds as illustrated in Figure C.1. Once a dust cake is established, it is hypothesized that particle penetration through these fabric

FIGURE C.1. Particle Collection on Woven and Felt Bag Media
(after Beachler and Jahnke 1981)

types is caused by seepage due to the shock of cleaning. It is reasonable to presume that the pressure wave from the test firings will also cause seepage.

One fabric manufacturer attempts to retard the seepage by applying a type of Teflon® coating to the surface of the fabric. The coating has been demonstrated to filter and retain the particles on the outer surface of the fabric. When the coated bags are cleaned, the bag surface is smooth compared to the cakey surface of the other bag types. Presumably, this type of media would retain less surface contamination on cleaning than the other types. The manufacturer claims longer bag life, higher efficiency, lower operating pressure drop, and a reduction in the cloth area required. A drawback to this fabric is its higher cost and fragility. The coated polyester felt bags, as they are known, cost about six times as much as conventional polyester felt bags. This

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cost study was done for both conventional and coated bags. When coated bags are installed, care must be taken not to abrade the coating on the exterior of the bags.

PULSE-JET

In the pulse-jet baghouse the media is usually in the shape of a long cylindrical tube; closed at one end with the open end anchored at the top in a tube sheet. Air usually passes from the outside of the bag to the inside and out the open end. The interior of the bag is supported by a heavy-gauge wire cage. Figure C.2 is a cutaway drawing of the typical pulse-jet baghouse. Collected dust is cleaned from the fabric periodically by pulses of compressed air directed downward through a venturi at the open end of the bag. The shock of the pulse dislodges particles that have agglomerated to a large enough size to fall into the hopper or to a point lower on the bag. One or more rows of bags are cleaned at a time while the baghouse is online. The snapping of the fabric back onto the cage is one main cause of fabric wear. Another cause of fabric wear is the abrasion by particles. Most baghouses have inlet diffusers to prevent abrasion caused by the high velocity impingement of particles on the fabric.

The dirty-air inlet may be in the hopper region or just below the tube sheet so that the airflow along the bags can be either generally upwards or downwards. Access to the baghouse interior is usually through an inspection hatches at the hopper and at the clean-air plenum on the top. Bags are usually inspected and changed from the clean-air side, which is through the top access. There are usually several hinged doors on the clean-air plenum to gain access to all the bags. This design would require a covering of some kind to permit all-weather access. An alternate design, offered by all but one vendor, is to have a walk-in clean air plenum. The plenum, with a single entry, would be tall enough for the removal of the cages. The walk-in plenum is preferred to enable all-weather access and to reduce the potential for leaky seals; however, the baghouse housing is taller than otherwise, but the access elevation remains the same with or without the walk-in.

FIGURE C.2. Pulse-Jet Baghouse Cross Section

One manufacturer builds a pulse-jet baghouse with the bags inverted over a tube sheet. The airflow is from inside to the outside of the bag. The compressed-air pulse nozzle and venturi are at the bottom of the bag. The cleaning pulse is directed downward through the venturi, creating a suction on the bag, which blows the dirt laden air into a vented hopper specially designed to prevent reentrainment. At the hopper vent, a single bag discharges to atmosphere, but could be ducted back to the clean-air plenum. The top of the walk-in plenum is at the same elevation as the top of the bags, thus reducing the headroom requirement of the other pulse-jet baghouses. The walkway inside the plenum is between the rows of bags, which allows close inspection, but possibly increases the potential for exposure during bag changes.

Most baghouses are constructed of 12- to 14-gauge steel; however, most vendors recommended thicker steel and additional bracing to withstand the pressure pulses. Some vendors manufacture cylindrical baghouses to American Society of Mechanical Engineers (ASME) Pressure Vessel Codes like that pictured in Figure C.3. This type is also available with a walk-in plenum, but the number of bags is limited, so two units in parallel would be required.

The air for cleaning pulses is usually provided by an external air compressor. The compressed air must be dry so freezing condensate will not damage the pulsing valves or the fabric. The compressor packages selected for this study were complete with air driers and heat lagging on the piping. Insulation and heating are also available for the valve mechanisms or the entire baghouse. This option was generally ignored in this cost study unless it was part of the standard unit. The baghouses come equipped with standard cleaning cycle timers that operate at regular intervals or on a demand signal such as pressure drop.

One vendor recommended a baghouse with a high-pressure blower instead of a compressor. The blower pumps air into a manifold rotating in the horizontal plane above the tube sheet with nozzles aligned above the openings of a group of bags. The blower draws its supply from the clean-air plenum. Similar designs are available from other vendors. In one design the rotating manifold also blocks normal airflow in adjacent bags to attempt to prevent particles from being pulsed onto the neighboring bags. Because of the rotating manifold,

FIGURE C.3. High Pressure Pulse-Jet Baghouse

this type of baghouse is cylindrical and is commonly offered with walk-in plenums and cyclonic inlet sections for the removal of very large particles.

SHAKER

In a shaker baghouse, the bags are suspended at the top, closed end and the open end is anchored in a tube sheet at the bottom, directly above the hopper,

as shown in Figure C.4. The airflow is from inside to outside the bag and particles are collected in a dust cake in the bag interior. Each row of bags is anchored at the top on a boom. When cleaning is required, a mechanism causes the boom to rock from side to side, shaking the bags and causing agglomerated particles to fall to the hopper. A shaker unit large enough for 24,000 acfm would be assembled from modules or compartments, each with its own hopper, because the compartment being cleaned and its hopper must be taken offline. The bags are accessed for inspection and changing through a hatch in the side of each compartment that opens onto a walkway between the rows of bags. Generally, larger amounts of cloth are used in shaker baghouses than in pulse-jets because woven fabrics are used for the bags.

Filtration relies on the built-up dust cake; thus, efficiency decreases when bags are cleaned. Presumably, the pressure pulse of the test firing would also dislodge the cake, decreasing efficiency. The one vendor recommending this type thinks that sufficient dust cake would remain after the firing and cleaning so that recoating the bags artificially would not be required.

ELECTROSTATICALLY ENHANCED

The electrostatically enhanced baghouse places a static charge on the particles to enhance collection efficiency and agglomeration. Figure C.5 shows a cutaway of the baghouse showing a charging section beneath the collection bags. The charging section is like the first stage of a two-stage tubular electrostatic precipitator described in Appendix F. Above the charging section, the bags are inverted over the tube sheet and the airflow is from inside to outside the bag. The bag fabric is a standard felt; polyester felt is recommended for this application. The compressed air nozzle and venturi are just below the tube sheet and mouths of the bag and above the charging section. The cleaning pulse is directed downward through the venturi, creating a suction on the bag, and blows the dirt-laden air through the charging section to the hopper. The air jet also cleans the charging section. In addition to access openings like those of a pulse-jet baghouse, a third access door is provided in the charging section to facilitate maintenance there.

FIGURE C.4. Cross Section of a Shaker Baghouse
(after Beachler and Jahnke 1981)

FIGURE C.5. Electrostatically Augmented Baghouse

BAGHOUSE EFFICIENCY MODELING

Pulse-Jet

Sixteen vendors recommended the use of a pulse-jet baghouse with polyester felt bags--plain or Teflon® coated. The other respondent recommended a shaker baghouse. Few data were available on the fractional efficiency of either type of baghouse. The Fabric Filter Manual (FFM) (1983) notes that unless such data were obtained over a period of operation, including the various stages of filter performance, the data would not be useful. The FFM further states that without pilot testing, the prediction of fractional efficiency has no practical

significance because the factors such as dust load, fabric type, fabric area, cleaning mechanism, cleaning frequency, and dust characteristics can vary greatly between applications. Nevertheless, an attempt will be made to evaluate baghouse performance for this cost analysis; however, a fair amount of uncertainty exists about the results. We will consider the pulse-jet baghouse first.

Particle penetration data for various fabric types measured under comparable experimental conditions were unavailable. The manufacturer of coated felt bags furnished measurements of the particle penetration of mixed lead oxide and granite dust as a function of Feret's diameter^(a) at a face velocity of 10 ft/min while being pulse cleaned at 1-min intervals. Fractional penetrations for Feret's diameters of 0.12 to 84.2 μm were reported for unconditioned bags (no previous dust loading) and conditioned bags. These data were plotted and values obtained for the sizes of interest are shown in Table C.1. Note that the higher efficiency for the conditioned fabric results because a dust cake was built-up.

TABLE C.1. Fractional Efficiency Data for Teflon® Coated Felt Bags

Particle Diameter (Feret's), μm	Teflon®-Coated Bags, 10 ft/min Superficial Velocity	
	Unconditioned	Conditioned
0.1	0.944*	0.99540*
0.32	0.9715	0.99690
1	0.9959	0.999690
3.2	0.99994	0.999960
10	0.99996*	0.99999*
32	0.99999*	0.99999*
100	0.99999*	0.99999*

* Extrapolated

(a) Feret's diameter is defined as the distance between two tangents on opposite sides of the particle and perpendicular to the bottom of the microscope field (Feret 1931). Particle size measurements using this technique are not directly comparable to the more desirable aerodynamic equivalent diameter, which is the diameter of a sphere of water that would fall at a velocity equal to the actual particle.

Similar fractional efficiency data for standard polyester felt in a pulse-jet baghouse are lacking. Data were found, however, for both the uncoated and coated felt bags that had been obtained using a particle seepage approach. Recent work by Leith and Ellenbecker (1983) postulates that pulse-jet baghouse emissions result from gradual particle seepage through the bags caused by the snapping action of the fabric when cleaned. Thus, no immediate linkage appears between upstream and downstream aerosol characteristics. Particle seepage would vary as a function of particle size, mass of dust per unit area of fabric, the time between cleaning pulses, the fabric dynamics during cleaning, and the fabric characteristics.

Flux (aerosol mass per unit fabric area per time) was measured as a function of particle diameter (Feret's) for fly ash, granite, and limestone dusts using a three-bag baghouse. Singed, Teflon®-coated, and plain polyester felt bags were conditioned with dust for 20 hr with continuous pulse cleaning at 1-min intervals. The three superficial filtration velocities (flow rate/cloth area) used were 50, 75, and 100 mm/s (10, 15, and 20 ft/min). The data used in this cost study (Table C.2) were taken from a plot of flux versus particle size with bag type as a parameter. The flux data had been averaged for the three dusts and superficial filtration velocities. The flux units used were mass per unit fabric area per time.

TABLE C.2. Unit Flux by Particle Size

Particle Diameter (Feret's), μm	Flux, $\text{kg m}^{-2}\text{s}^{-1}$	
	Teflon®-Coated	Plain
0.1	1.5×10^{-12}	5.0×10^{-12}
0.32	2.0×10^{-11}	1.9×10^{-10}
1.0	2.0×10^{-10}	2.0×10^{-9}
3.2	6.0×10^{-10}	1.0×10^{-8}
10	6.0×10^{-10}	1.0×10^{-8}
32	1.1×10^{-10} *	4.0×10^{-9} *
100	1.0×10^{-12} *	1.9×10^{-10} *

* Indicates value extrapolated beyond data.

To scale these experimental results to the firing range case and to be consistent with the experiment, a 1-min interval between cleaning pulses was assumed. At the firing range, the bulk of the dust load is generated by the intermittent test firings. Unlike the experimental conditions where cleaning was continuous and online, the demand for bag cleaning in this case will probably be intermittent and may not need to be online.

Online cleaning relies on the agglomeration of particles in a dust cake on the fabric. The agglomerated particles, when pulsed off the fabric, fall through what is typically rising air to the hopper or at least to a point lower on the bag. When the dust cake particles do not agglomerate, some vendors recommend taking the baghouse or a compartment offline during cleaning so there is no airflow to inhibit particle settling. Other vendors recommend that dirty air enter the baghouse near the top and flow downward. Offline cleaning may reduce emissions to the level typical of a shaker baghouse, which requires offline cleaning. To simulate the worst case, we assumed that the cleaning will be online.

According to the seepage theory, more frequent cleaning results in higher emissions if other factors are equal. How much cleaning will be required at the firing range is an impossible question to answer without pilot testing. Some common strategies to automate intermittent online cleaning are

1. cleaning pulses set to occur at regular intervals between manual ON and OFF commands
2. a preset number of cleaning pulses to be initiated by a manual ON command
3. a preset number of pulses to be initiated by a differential baghouse pressure switch.

Strategies 1 and 2 can be used anytime (e.g., daily, weekly, after hours, or after every shot). Some manufacturers were of the opinion that the predicted dust loading was very light and cleaning would not be needed after every shot. Strategy 3 would probably result in the least frequent cleaning. Given a constant airflow, the buildup of dust per unit fabric area and hence baghouse differential pressure, are proportional to the amount of aerosol generated and inversely proportional to the cloth area. Also, particle flux is directly proportional to cloth area and the frequency of cleaning pulses; therefore, under

Strategy 3, the combined cloth area effects may cancel and be unimportant to overall emissions. Strategy 3 is the online cleaning method we recommend, but we cannot predict the amount of cleaning required and hence the emissions with any confidence. We assumed that for the worst case, cleaning will be started when every round is fired and cease at the end of the clearance time. This is shown to maximize emissions and will penalize baghouses with greater fabric area.

Because the unit flux by particle size is fixed for each fabric, the particle size distribution is fixed with a somewhat larger mass mean size for plain felt than for the coated felt. Leith and Ellenbecker (1983) showed that the particle size with maximum flux was about 1 μm for the Teflon®-coated felt and 8 μm for the plain felt, and that the maximum flux was about three orders of magnitude higher for the plain felt than for the coated.

The FILTER model (see Appendix A) was adapted to use the flux data in Table C.2 to make a new version, FILTER.BAG. The flux for each size bracket was determined by multiplying each flux value by the cloth area and the length of cleaning time expressed as pulses (1 pulse/60 s).

$$\text{Flux, g} = \frac{\text{Particle Flux}}{\frac{\text{kg}}{\text{m}^2 \text{ s}}} \times \frac{\text{Cloth Area}}{\text{ft}^2} \times \text{Pulses} \times \frac{1000 \text{ g}}{\text{kg}} \times \frac{60 \text{ s}}{\text{Pulse}} \times \frac{\text{m}^2}{10.764 \text{ ft}^2} \quad (\text{C.1})$$

Aerosol concentrations were examined that had been measured at 1-min intervals at the exhaust point of a target bay during 10 test rounds. After 45 min, the amount of additional aerosol passing that point was insignificant; therefore, it was assumed that if a baghouse were in operation, it would not have been cleaning for longer than 45 min. The test round fired was 3400 g. The number of cleaning pulses is then estimated by the integer value of Equation C.2.

$$\text{Pulses} = \frac{\text{Projectile Weight, g}}{3400 \text{ g}} \times 45 \quad (\text{C.2})$$

After the number of pulses was calculated, the flux per particle size bracket was calculated using Equation (C.1). The dust collected by the baghouse is calculated by summing the fluxes and subtracting from the input aerosol mass. The calculation of operating cost for the after filters proceeds as described in Appendix A with the flux per bracket as the input size distribution.

System filtration efficiencies exceeded the criterion given in Table 1 in all cases. A brief summary of baghouse efficiency, system efficiency, downstream disposable (after-filter) cost, and after-filter bank changes is shown in Table C.3 for comparison with the results using the fractional efficiency data for coated felt. (The efficiency value of 1.0 is interpreted not as 1.0, but as exceeding the value that could be expressed within allowed significant digits.) The estimates, when expressed as penetrations, are probably only accurate to one or two orders of magnitude. Because the after-filter costs predicted with the fractional efficiency method were intermediate to after-filter costs predicted with the flux method, the data from the flux method will be used in this cost study as representative of extremes. This will also allow us to consider the economic merits of two types of fabric.

SHAKER

The only data found on the fractional efficiency of a shaker baghouse were obtained at an Electric Power Research Institute pilot plant for studying the application of air cleaning devices at coal-fired generating stations (Smith, Cushing and Carr 1981). Particle sizing was performed using an electrical mobility analyzer and a cascade impactor, so the size data are considered to be aerodynamic size. The particles sampled in their study were fly ash. The data are listed in Table C.4. The lowest efficiency in their study was for particles in the range of 7 to 8 μm . The authors also noted that during and after shaking, the emission of the fraction around 1 to 2 μm increased considerably. This disappeared after the dust cake had reestablished itself. It is not known if cleaning cycles were included in the experimental time interval.

Calculations using FILTER showed an overall shaker efficiency of about 0.99984, for Size Distribution No. 3 (see Table 5 in main text), which was slightly better than the best results for the pulse-jet shown in Table C.3.

TABLE C.3. Summary of Baghouse Performance Results

Baghouse Efficiency	Fractional Efficiency Method	Flux Method	
	Coated Felt	Coated Felt	Plain Felt
Minimum	0.998	0.9991	0.985
Maximum	0.998	0.9997	0.995
<u>System Efficiency</u>			
Minimum	0.999997	0.99999998	0.9999998
Maximum	0.9999995	1.0	0.99999998
<u>After-Filter Cost, \$K</u>			
Minimum	13	1.7	28
Average	19	3.1	51
Maximum	25	5.6	93
<u>After-Filter Bank Changes</u>			
Minimum	6	1.5	34
Maximum	6	2	128

TABLE C.4. Shaker and Electrostatic Baghouse Filtering Efficiency

Particle Diameter, μm	Filtering Efficiency	
	Shaker	Electrostatic
0.1	0.999985*	0.994*
0.32	0.999985	0.99965
1.0	0.999937	0.999963
3.2	0.99957	0.999988
10.0	0.99925	0.999977
32.0	0.9999	0.9999957*
100.0	0.999987*	0.9999992*
Baghouse Efficiency, Size Distribution No. 3	0.99984	0.9981
Maximum Unit Pressure Drop, in. WG	2.0	6.0

* Indicates value extrapolated beyond data.

There is some uncertainty whether the fractional efficiency would be as good at the firing range where the pressure pulses could disturb the dust cake. The cost estimates for the shaker were made using this data and the lesser efficiency of the conditioned coated felt listed in Table C.1 for comparison.

Electrostatically Enhanced Baghouse

The efficiency data for the electrostatically enhanced baghouse were obtained from Felix and McCain (1979) and are listed in Table C.4. The particle size data were aerodynamic size as obtained from cascade impactor samples. The baghouse collection efficiency calculated with FILTER, 0.9981, was better than that for a standard baghouse with the plain felt fabric (Table C.3).

COST ESTIMATING

Tables C.5a and C.5b summarize the descriptive information about the baghouses considered. Included are the shape--cylindrical or box--and whether a high pressure design was used (Hi P); the type of access for changing bags [walk-in above tube sheet (TI) and on side wall (SI), hatch located above tube sheet (TH) and in side wall (SH)]; bag length; number of bags; area of cloth; cubic feet of cloth assuming a 1/8 in. thickness and no compaction; wall thickness of the casing; the vendor's estimate of compressed air required for cleaning; horsepower of compressor to supply the required air; and the number of solenoid and diaphragm valve pairs in the cleaning system. The tables also show the average, maxima, and minima of most parameters.

Tables C.6a and C.6b summarize the initial investment costs to acquire the baghouses including the vendor-supplied baghouse cost and our estimates of erection and compressor costs. (Note that from here on the tables will differ in format because of the different computational needs for the equipment.) Table C.6a also includes the power cost of operating the compressor for 20 years assuming it would operate 20% of the time. Averages, minima, and maxima are indicated for each parameter. The erection (installation) costs were estimated as shown in Table C.7.

TABLE C.5a. Descriptive Summary of Pulse-Jet Baghouses

Maker	Type	Bag Access	Bag Length, ft	Number Bags	Cloth, ft ²	Cloth, ft ³	Wall Thickness, in.	Compressor		No. Valves
								Air, acfm at 100 psi	hp	
M	Box	TI	12	196	3077	32	0.134	30	7	14
D	Box	TH	12	172	3236	34	0.105	12	5	32
R	Cyl	TI	12	162	3890	40	0.135	0	15	0
U	Box	TH	8	280	3520	37	0.188	8	3	8
E	Cyl	TH	12	202	3810	40	0.134	61	20	16
T	Box	SH	6.5	308	2400	25	0.134	42	10	12
R	Box	TI	12	182	3380	35	0.135	50	20	13
Q	Hi P Cyl	TI	10	198	3114	32	0.188	45	10	36
M	Hi P Cyl	TI	12	200	3120	32	0.25	42	10	14
HH	Hi P Cyl	TI	10	228	3692	38	60	20	24	
Z	Box	TI	10	340	4000	42	0.105	62	20	20
X	Box	TH	12	325	6125	64	0.1046	78	20	25
N	Box	TI	9	336	4939	51	0.105	66	20	24
H	Box	TI	20	160	5031	52	0.25	30	7	10
CC	Box	TI	14	224	4928	51	0.188	50	20	16
GG	Box	TI	8	400	6250	65	0.105	40	10	25
FF	Box	SI	8	280	6000	62	0.105	5	3	36
V	Hi P Box	TI	10	294	4000	42	0.38	71	20	21
JJ	Hi P Box	TI	8	438	5500	57	0.25	70	20	25
FF	Box	SI	8	360	8000	83	0.105	5	3	48
Average				264	4401	46	0.1550	41	13	21
Minimum				160	2400	24.96	0.0000	0	3	0
Maximum				438	8000	83.2	0.3800	78	20	48

Note: Cyl = cylinder, Hi P = high pressure

TABLE C.5b. Descriptive Summary of Shaker and Electrostatically Enhanced Baghouses

Device	Media Access	Bag Length, ft	Number Media Units	Media, ft ²	Compressed Media, ft ³ /set	Wall Thickness, in.	Dust to Hopper Per Shot, g	Run Fraction, hr/hr	Auxiliary Equipment, hp
Standard Shaker	SI	7	960	8392	87	0.0747	4900	0	0
Shaker With Coated Bags	SI	7	960	8392	87	0.0747	4900	0	0
Electrostatic Augmented	SI	12	110	2750	29	0.188	4900	0.5	5

The first costs for the shaker are not as first supplied by the vendor. The vendor's baghouse estimate was \$33K, but without the extra strength required for this application and without the hopper valves needed for each of the twelve compartments. An additional \$1K was added per valve and \$20K for the stronger construction giving a total of \$65K. For the shaker with coated media, another \$33K was added to cover the cost of the 960 coated bags. For the other baghouses, we frequently had to add our own estimates for accessory items such as the hopper valves.

TABLE C.6a. Pulse-Jet Baghouse First Costs, Excluding Fan

Maker	Baghouse w/bags, \$K	Compressor, \$K	Erection Pad, Duct etc., \$K	Subtotal, \$K
M	33	9.9	61.3	104
D	33	5.6	61.3	100
R	58	0	58.5	116
U	35	5.5	61.3	102
E	42	14.8	61.3	119
T	36	10	61.3	107
R	54	14.8	61.3	131
Q	69	10	61.3	140
M	85	10	61.3	156
HH	70	14.8	61.3	146
Z	41	14.8	61.3	117
X	43	14.8	61.3	119
N	58	14.8	61.3	134
H	110	9.9	61.3	181
CC	100	14.8	61.3	176
GG	80	10	61.3	151
FF	55	5.5	61.3	122
V	165	14.8	61.3	241
JJ	115	14.8	61.3	191
FF	65	5.5	61.3	132
Average	67.35	10.76	61.16	139.27
Minimum	33.00	0.00	58.50	99.90
Maximum	165.00	14.80	61.30	241.10

TABLE C.6b. Shaker and Electrostatically Augmented Baghouse First Costs, Excluding Fan

Device	Unit, \$K	Auxiliary Equipment, \$K	Erection Pad, Duct etc., \$K	Special Installation, \$K	Subtotal, \$K
Standard Shaker	65	0	58.5	0	123.50
Shaker With Coated Bags	88	0	58.5	0	146.50
Electrostatic Augmented	83	5.6	61.3	0	149.90

TABLE C.7. Installation Costs For Baghouses

<u>Item</u>	<u>Electrostatically Enhanced and Pulse-Jet, \$</u>	<u>Shaker, \$</u>
Pad 22 x 30 ft	4700	4700
Compressor Shelter	2800	2800
Hopper shed	5300	5300
7-gauge stainless steel ducts plus erection	20900	20900
Electrical	6400	6400
Freight	1200	1200
Pressure test	1900	1900
Drum scale	8100	8100
Flow controls	10000	10000
Total	\$61300	\$58500

Tables C.8a and C.8b show the estimates for maintenance costs for 20 years of operation in terms of current dollars. The basic cost and operating assumptions were those listed in pages 12-23 in the main report. For all 20 of the pulse-jet baghouses, the maintenance costs were computed for both standard and coated polyester felts. Most vendors seemed to feel that the standard felt bag life would be considerably longer than in applications where dust loads are heavy and cleaning continuous; therefore, they estimated about a 2-year bag life. The 2-year bag life translates into a requirement for purchasing nine replacement sets of bags and installing, changing, and disposing of 10 sets during the 20-year anticipated life. The maker of the coated felt claimed a substantially longer bag life and a lower pressure drop than that for standard. For this study, that claim was tempered with skepticism and a 2.25-year bag life was assumed. Therefore, eight sets will be handled during facility life and seven replacement sets will be purchased. The bag life for the electrostatic baghouse was assumed to be the same as the standard felt, 2 years. The manufacturer of the shaker baghouse claimed a bag life of 10 years; a 5-year value was used for this study resulting in installation and disposal of four sets of bags and procurement of three sets. In Table C.8 maintenance costs include the cost of replacement bags, bag installation and disposal, collected dust disposal, equipment repairs, and operation.

TABLE C.8a. Twenty-Year Maintenance Costs for Pulse-Jet Baghouses

Maker	Man-hr Per Bag Change	Ten Changes Standard Bag Labor, \$K	Standard Bag Disposal, \$K/20 yr	Eight Changes Coated Bag Labor, \$K	Coated Bag Disposal, \$K/20 yr	Dust Disposal, \$K/6000 shots	Repair Codes					Misc. Repairs, \$K
							C	P	A	E	B	
M	98	30.38	8.25	24.30	6.60	24.08	1	1	1	1		22.30
D	86	26.66	8.64	21.33	6.91	24.08	1	1	1	1		28.50
R	81	25.11	10.32	20.09	8.26	24.08			1	1	1	12.54
U	140	43.40	9.51	34.72	7.61	24.08	1	1	1	1		20.24
E	101	31.31	10.17	25.05	8.13	24.08	1	1	1	1		22.99
T	154	47.74	6.64	38.19	5.31	24.08	1	1	1	1		21.62
R	91	28.21	9.02	22.57	7.22	24.08	1	1	1	1		21.96
Q	99	30.69	8.35	24.55	6.68	24.08	1	1	1	1		29.87
M	100	31.00	8.37	24.80	6.70	24.08	1	1	1	1		22.30
HH	114	35.34	9.89	28.27	7.91	24.08	1	1	1	1		25.74
Z	170	52.70	10.84	42.16	8.67	24.08	1	1	1	1		24.37
X	163	50.38	16.34	40.30	13.08	24.08	1	1	1	1		26.09
N	168	52.08	13.28	41.66	10.62	24.08	1	1	1	1		25.74
H	80	24.80	13.29	19.84	10.63	24.08	1	1	1	1		20.93
CC	112	34.72	13.10	27.78	10.48	24.08	1	1	1	1		22.99
GG	200	62.00	16.77	49.60	13.41	24.08	1	1	1	1		26.09
FF	140	43.40	15.96	34.72	12.77	24.08	1	1	1	1		29.87
V	147	45.57	10.78	36.46	8.62	24.08	1	1	1	1		24.71
JJ	219	67.89	14.87	54.31	11.89	24.08	1	1	1	1		26.09
FF	180	55.80	21.27	44.64	17.01	24.08	1	1	1	1		34.00
Average	132.13	40.96	11.78	32.77	9.43	24.08						24.45
Minimum	80.00	24.80	6.64	19.84	5.31	24.08						12.54
Maximum	219.00	67.89	21.27	54.31	17.01	24.08						34.00

Repair Code Key

C - annual compressor maintenance

P - semi-annual pulse valve rebuilds

A - annual miscellaneous maintenance

E - one time replacement of cleaning cycle control electronics

B - one time bearing and other repair of blower

A "1" under the repair code column indicates that the repair is applicable to the device and is accounted for in the cost estimate.

TABLE C.8a. (contd)

Maker	Housekeeping & Inspection, day/yr	Start-up Shutdown, min/day	Operation Labor, \$K	Standard Bag, \$K/9 sets	Coated Bag, \$K/7 sets	Subtotal Maintenance Standard Bag	Coated Bag	Compressor Power, \$K
M	2	30	87.65	11.71	57.34	184	222	1.68
O	2	30	87.65	10.28	62.43	186	231	1.20
R	2	30	87.65	9.68	58.80	169	211	3.59
U	2	30	87.65	13.83	73.44	199	248	0.72
E	2	30	87.65	12.07	59.09	188	227	4.79
T	2	30	87.65	14.28	79.77	202	257	2.39
R	2	30	87.65	10.88	66.06	182	230	4.79
Q	2	30	87.65	11.08	50.70	192	224	2.39
M	2	30	87.65	11.95	58.51	185	224	2.39
HH	2	30	87.65	12.76	58.38	195	232	4.79
Z	2	30	87.65	19.03	87.06	219	274	4.79
X	2	30	87.65	19.42	95.07	224	286	4.79
N	2	30	87.65	17.78	105.72	221	295	4.79
H	2	30	87.65	14.33	75.75	185	239	1.68
CC	2	30	87.65	17.14	87.45	200	260	4.79
GG	2	30	87.65	19.76	104.92	236	306	2.39
FF	2	30	87.65	37.80	199.92	239	389	0.72
V	2	30	87.65	16.46	75.28	209	257	4.79
JJ	2	30	87.65	21.64	114.88	242	319	4.79
FF	2	30	87.65	48.60	257.04	271	464	0.72
Average	2	30	87.65	17.52	91.38	206.45	269.76	3.15
Minimum	2	30	87.65	9.68	50.70	169.39	211.42	0.72
Maximum	2	30	87.65	48.60	257.04	271.40	464.43	4.79

TABLE C.8b. Twenty-Year Maintenance Costs for Shaker and Electrostatically Augmented Baghouses

Device	Replacement Media, sets/20 yr	Media Replacement, \$/20 yr	Man-hr Per Media Change	Media Change Labor, \$K	Media Disposal, \$/20 yr	Dust Disposal, \$/6000 Shots	Repair Codes					Misc. Repairs, \$/K	Housekeeping Inspection, days/yr	Start-up Shutdown, min/day	Operation Labor, \$/K	Subtotal Maintenance, \$/K	Auxiliary Power, \$/K
							C	P	A	E	B						
Standard Shaker	5	47.86	480	89.28	13.79	24.08	1	1				10.54	3	30	92.61	278.17	0.00
Shaker With Coated Bags	5	165.02	480	89.28	13.79	24.08	1	1				10.54	3	30	92.61	395.34	0.00
Electrostatic Augmented	9	8.91	55	17.05	7.39	24.08	1	1	1	1		20.24	3	40	118.52	195.20	2.99

Repair Code Key

C - annual compressor maintenance

P - semi-annual pulse valve rebuilds

A - annual miscellaneous maintenance

E - one time replacement of cleaning cycle control electronics

B - one time bearing and other repair of blower

A "1" under the repair code column indicates that the repair is applicable to the device and is accounted for in the cost estimate.

The labor to change a set of bags was based on an estimate of 0.5 man-hr per bag. The bag disposal cost was based on the uncompacted bag volume from Table C.5, the number of bag sets per 20 years, and the assumption that 240 bags could be packed into a drum per hour. (The vendors felt that while the bags could be compacted, they would probably return to their original size unless they were restrained. It was assumed here that the compactor would at least efficiently pack the rolled bags into a drum, leaving essentially no void space.) The 20-year cost of replacement bags was based on bag prices received from vendors for the standard and coated polyester felts, respectively. The methods for estimating repairs and operation costs was outlined in the body of the report. The repairs applicable to each device are indicated by a '1' under the appropriate repair code.

Table C.9 lists the 20-year cost of procuring, changing, and disposing of the disposable after-filters for each combination of after-filter bank, baghouse, and fabric type considered. For each baghouse, we give estimates for each of four practical combinations of after-filters; each after-filter type is denoted by the current bank that the type of filter occupies in the existing filter house. Thus, the 20-year cost of using the existing filters in series following the Vendor V baghouse is under the columns headed with bank combination '1, 2, 3' for both the coated and standard polyester felts; namely, \$1.0K and \$14.9K respectively. (After-filter costs were calculated for baghouses with 1000 and 8000 ft² of cloth area using FILTER.BAG. The table entries are linear interpolations based on cloth area.) Also indicated are the averages for all after-filter combinations, all baghouses, and both fabric types. Notice that because of its greater collection efficiency, the cost of using after-filters is lower for the coated media than for the standard media by about \$48K in 20 years on the average. This cost advantage is offset by the higher coated media cost as is shown in the next table.

Table C.9 also lists the number of times a filter bank will be changed in 20 years and the maximum operating pressure drop across the entire ventilation system. Vendors estimated that maximum pressure drops across the baghouses would range from 4 to 6 in. WG (i.e., the pressure at which the cleaning cycle

TABLE C.9. Disposable Filter Usage for Pulse-Jet Baghouses

Disposable Filter Usage, \$K/20 yr											
Maker	Coated Bag With Banks					Standard Polyester With Banks					Grand Average
	1,2,3	2,3	3	1,3	Average	1,2,3	2,3	3	1,3	Average	
M	0.77	2.06	4.53	1.31	2.17	11.44	35.39	77.54	18.09	35.61	18.89
D	0.81	2.17	4.76	1.38	2.28	12.03	37.21	81.54	19.03	37.45	19.87
R	0.97	2.60	5.72	1.66	2.74	14.47	44.73	98.02	22.87	45.02	23.88
U	0.88	2.36	5.18	1.50	2.48	13.09	40.48	88.70	20.70	40.74	21.61
E	0.95	2.55	5.60	1.62	2.68	14.17	43.81	96.01	22.40	44.10	23.39
T	0.60	1.61	3.53	1.02	1.69	8.92	27.60	60.48	14.11	27.78	14.73
R	0.85	2.26	4.97	1.44	2.38	12.57	38.87	85.17	19.87	39.12	20.75
Q	0.78	2.09	4.58	1.33	2.19	11.58	35.81	78.47	18.31	36.04	19.12
M	0.78	2.09	4.59	1.33	2.20	11.60	35.88	78.62	18.35	36.11	19.15
HH	0.93	2.47	5.43	1.57	2.60	13.73	42.46	93.03	21.71	42.73	22.67
Z	1.00	2.68	5.88	1.70	2.82	14.88	46.00	100.80	23.52	46.30	24.56
X	1.54	4.10	9.01	2.61	4.31	22.78	70.44	154.35	36.02	70.89	37.60
N	1.24	3.31	7.26	2.10	3.48	18.37	56.80	124.46	29.04	57.17	30.32
H	1.26	3.37	7.40	2.14	3.54	18.71	57.86	126.78	29.58	58.23	30.89
CC	1.24	3.30	7.25	2.10	3.47	18.33	56.67	124.18	28.98	57.04	30.26
GG	1.57	4.18	9.19	2.66	4.40	23.25	71.87	157.50	36.75	72.34	38.37
FF	1.50	4.02	8.82	2.56	4.23	22.32	69.00	151.20	35.28	69.45	36.84
V	1.00	2.68	5.88	1.70	2.82	14.88	46.00	100.80	23.52	46.30	24.56
JJ	1.38	3.68	8.09	2.34	3.87	20.46	63.25	138.60	32.34	63.66	33.77
FF	2.01	5.35	11.76	3.41	5.63	29.76	92.00	201.60	47.04	92.60	49.12
Average	1.10	2.95	6.47	1.87	3.10	16.37	50.61	110.89	25.88	50.93	27.02
Minimum	0.60	1.61	3.53	1.02	1.69	8.92	27.60	60.48	14.11	27.78	14.73
Maximum	2.01	5.35	11.76	3.41	5.63	29.76	92.00	201.60	47.04	92.60	49.12
Avg. Bank Changes	2	1.5	1.5	2	1.75	34.6	25.4	25.4	34.6	30	15.875
ΔP	17.2	16.2	12.2	13.2	14.7	17.2	16.2	12.2	13.2	14.7	14.7
Fan, \$K	17.5	17.5	10	10	14	17.5	17.5	10	10	14	13.75
Fan Power, \$K	166	157	118	128	142.14	166	157	118	128	142.14	142.14

would probably be initiated and which would occur no oftener than once per shot). To be on the conservative side, 6 in. WG was used to add to the remainder of the system; however, a properly sized fabric area could probably be operated at a lower value. The assumed pressure drops for the rest of the system were 1, 4, 4, and 2.2 for the first and second prefilters, HEPA filters, and structure, respectively. These filter pressure drops are the maxima at which change out is initiated, so the pressure estimate was made assuming each stage of filtration was at its fully loaded condition simultaneously. The maximum pressure drop was used to size the required fan, which cost is shown in the table. The \$10K cost of the fan in some configurations indicates that the existing fan was used with a larger motor. The cost of the fan for the selected configuration must be added to the first cost shown in Table C.7. The cost of the electricity to run the fan is also shown in Table C.9.

Table C.10 brings together all the costs for the pulse-jet baghouses listed on Tables C.5, C.6, C.8, and C.9. The table shows the total 20-year cost for each baghouse, fabric, and after-filter combination and their averages, maxima and minima, with power costs excluded. The power cost for the fan and average compressor capacity are given for the typical baghouse combination with each after-filter configuration and fabric type. The power cost is then added to the averages, maxima, and minima. Notice that the cost difference between using coated or standard polyester felt was at most \$48K or 11%, which is probably less than the accuracy of the estimates. It may make little difference in cost which of these polyester felts is used. The difference would be in the subjective factor of how many times a filter bank must be changed--2 or 30 times on the average for the coated and standard felt, respectively. High-pressure baghouses were available with total costs both above and below the average. The variability between baghouses is partly due to the differences in first costs and partly due to the differences in fabric area. The latter source of variability occurs because the method used to calculate baghouse emissions (and hence cost of after-filters) is assumed to be a linear function of fabric area. This source of variability was only important in the case of the standard fabric, and in actual practice may not be important at all.

TABLE C.10. Total Twenty-Year Cost for Pulse-Jet Baghouses

Pulse-Jet Baghouse Cost, \$K/20 yr											
Maker	Coated Bags With Banks					Polyester Felt With Banks					Grand Average
	1,2,3	2,3	3	1,3	Average	1,2,3	2,3	3	1,3	Average	
M	345	346	341	338	343	318	342	376	317	338	340
D	349	350	346	342	347	315	340	377	315	337	342
R	346	348	343	339	344	318	348	394	318	344	344
U	368	370	365	361	366	332	359	400	332	355	361
E	364	366	361	357	362	338	368	413	339	365	363
T	382	383	377	375	379	336	354	380	333	351	365
R	378	380	375	371	376	342	369	407	342	365	371
Q	382	383	378	375	380	361	385	420	360	382	381
M	398	400	395	391	396	371	395	430	370	391	394
HH	397	398	394	390	394	373	402	445	373	398	396
Z	409	411	407	402	407	368	399	446	369	395	401
X	424	427	424	418	423	383	431	507	389	427	425
N	448	450	447	442	447	391	429	489	394	426	436
H	439	441	437	432	437	402	442	503	406	438	438
CC	455	457	454	449	454	412	450	510	415	447	450
GG	476	479	476	470	475	428	477	555	434	474	474
FF	530	532	530	523	529	400	447	522	406	444	486
V	516	518	514	510	514	483	514	561	484	510	512
JJ	529	531	528	522	528	471	514	582	476	511	519
FF	616	619	618	610	616	450	513	615	460	510	563
Average	428	429	425	421	426	380	414	467	382	410	418
Minimum	345	346	341	338	343	315	340	376	315	337	340
Maximum	616	619	618	610	616	483	514	615	484	511	563
20 yr											
Power, \$K	169	160	121	131	145	169	160	121	131	145	145
Power + Avg	597	589	547	552	571	549	574	588	512	556	563
Power + Min	514	506	462	469	488	485	500	497	446	482	485
Power + Max	785	779	739	740	761	652	674	736	615	669	715
Average											
Bank											
Changes	2	1.5	1.5	2	2	34.6	25.4	25.4	34.6	30	16

The shaker and electrostatic baghouse data shown in Table C.11 contain the disposable filter usage, number of times a filter bank must be changed, system efficiency, system total pressure drop, fan cost, total first cost (including fan) and fan power cost for 20 years of operation and for each combination of disposable filter banks. The table also summarizes with the totals for equipment and maintenance exclusive of power; total power cost; and total of equipment, maintenance, and power for the same combinations for 20 years. The replacement costs for disposable filters were calculated using FILTER. Note that the estimated total cost for the shaker generated using coated felt efficiency data was about \$150K more than when Felix and McCain's (1979) data were used.

RECOMMENDATION

To compare equipment types, a recommendation for the average costs of each type was made assuming the suitability of the existing filter housing for mounting the disposable filters. This was a tentative assumption pending structural analysis results.

For a pulse-jet baghouse with coated media, the configuration with banks 1 and 3 as after-filters resulted in the lowest cost exclusive of power. It would seem prudent to have some type of good prefilter ahead of the HEPA should the baghouse fail; however, a somewhat more efficient prefilter than the existing 1st prefilter would be preferred. Thus, ignoring power cost, the best choice may be with banks 2 and 3 as after-filters at a slight extra cost of \$9K over 20 years. The same reasoning applied to the electrostatic and the shaker baghouses results in recommending the bank 2, 3 after-filter configuration for those devices as well. Because of the pressure pulse accompanying each test firing, it seems unlikely that a stable cake could be maintained on the shaker's woven fabric at the time most critical to filtration; therefore, it may be more reasonable to assume the operating cost to be better represented by the data generated with the coated media.

TABLE C.11. Total Twenty-Year Cost for Shaker and Electrostatically Augmented Baghouse Costs

Shaker and Electrostatic Baghouse Costs, \$K/20 yr											
Maker	Bank Combination	Filter Replacement, \$K	Number Bank Changes	System Efficiency, %	System ΔP in. WG	Fan Cost, \$K	Total First Cost, \$K	Fan Power, \$K	Equipment and Maintenance, \$K	Power, \$K	Total
Standard Shaker Baghouse	1,2,3	0.30	1	99.999999	13.2	10	134	128	412	128	540
	2,3	1.00	1	99.999999	12.2	10	134	118	413	118	531
	3	2.10	1	99.999998	11	0	124	106	404	106	510
	1,3	0.50	1	99.999998	11	0	124	106	402	106	509
Shaker w/ Coated Bags	1,2,3	13.30	6	99.999951	13.2	10	157	128	565	128	693
	2,3	13.40	6	99.999951	12.2	10	157	118	565	118	683
	3	25.10	6	99.9997	11	0	147	106	567	106	673
	1,3	25.00	6	99.9997	11	0	147	106	567	106	673
Electrostatically Augmented	1,2,3	13.70	35	99.999937	17.2	18	167	166	377	169	547
	2,3	13.70	35	99.999937	16.2	18	167	157	377	160	537
	3	25.20	35	99.99962	12.2	10	160	118	381	121	502
	1,3	25.10	35	99.99962	13.2	10	160	128	381	131	512

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APPENDIX D

CARTRIDGE HOUSES

CARTRIDGE HOUSES

A cartridge house collects particles on filter media made of a treated cellulose paper that is pleated and formed into a cylindrical cartridge. The cartridge is very similar in appearance to a truck carburetor air-cleaner. It is about 12 in. in diameter by 24 in. high. Figure D.1 shows a typical cartridge house with several cartridges mounted below a tube sheet in a configuration similar to a pulse-jet baghouse. Dirty air enters near the bottom of the hopper and passes upward and through the cartridge to be exhausted at the top of the housing. Particles collected on the cartridges are removed by pulses of clean air directed through the cartridge in a direction opposite to the normal airflow. The removed particles that have agglomerated to a sufficiently large size settle into the hopper by gravity. Venturis between the compressed air nozzles and the cartridges amplify the cleaning airflow over the amount injected by the compressed air system.

In the standard configuration (Figure D.1), the cartridges are accessed by opening a door on the dirty-air side of the housing. Various mechanisms are used for clamping the cartridges against the tube sheet to make an airtight seal. One type requires a person to partly enter the housing to unfasten a bolt at the bottom of each cartridge. Another type has a lever operated mechanism for clamping entire rows of cartridges simultaneously. The lever is mounted just inside the access door. When the cartridges are loosened, they can be slid off the ends of a pair of rails and placed in a plastic bag.

A second configuration has a walk-in plenum on top of the tube sheet. A person enters the plenum, which is on the clean side of the cartridges, and removes the cartridges up through the tube sheet; however, the venturis and compressed-air pipes must be removed first. Figure D.2 shows a variation on the walk-in plenum where the cartridges are located on both sides of a central aisle. The venturis and compressed-air lines are beneath the cartridges. Cleaning pulses are directed downward through the venturis to suck the particles from the cartridges and blow them down into a special hopper that prevents reentrainment. The rows of cartridges are also compartmentalized to prevent removed particles from migrating to neighboring cartridges during cleaning.

FIGURE D.1. Typical Cartridge House

Figure D.3 shows another design where cartridges are mounted on a slight angle to the horizontal plane. The clean-air side, tube sheet, and pulse cleaning pipes are at the back of the cabinet. Pairs of cartridges are accessed through hatches on the front of the cabinet. This design has several more seals that must be checked for airtightness; however, with a modified hatch design, it lends itself to a type of bagout method for cartridge changes similar to that used in gloveboxes in the nuclear industry. The dirty airflow is from the top to the back of the cabinet, which would enhance the movement of particles to the hopper during pulse cleaning. The cartridges are also compartmentalized to reduce the tendency to blow particles to adjacent cartridges during cleaning.

FIGURE D.2. Walk-in Cartridge House

The cartridge houses are made of painted carbon steel. Most are a single housing except some that are available as multiple units in parallel or series.

EFFICIENCY

Two types of treated-cellulose paper cartridges are available. The standard media is available through all the vendors contacted. Efficiency data for these media were obtained from a vendor where measurements had been made using cascade impactors for a welding fume application. The particle size data were

FIGURE D.3. Horizontal Mount Cartridge House

in terms of aerodynamic particle size. A coated-cellulose cartridge media is also available. The fractional efficiency data for the coated media were obtained using an optical particle sizer and a calcium carbonate aerosol at a concentration of 2.3 g/m^3 upstream of the filter. Both sets of data were obtained during normal operation with regular cleaning cycles included; however, they are not as comparable as desired because of the different measurement methods used. The data, listed in Table D.1, show a greater efficiency for the coated than for the standard media. These data were used in the FILTER code to estimate usage of the downstream disposable filters. Cartridges with either type of media cost essentially the same.

TABLE D.1. Filter Efficiency for Cartridges

Particle Diameter, μm	Standard	Coated
0.1	0.955*	0.99955*
0.32	0.9971	0.999897*
1.0	0.99919	0.999977
3.2	0.999795	0.999985
10.0	0.999725*	0.999946*
32.0	0.999833*	0.9999725*
100.0	0.9999*	0.99999*

*Indicates value extrapolated beyond data.

COST ESTIMATING

Table D.2 summarizes the descriptive information about the cartridge houses considered. Included are the maker, type of access for changing cartridges, number of cartridges, surface area of the filter media, wall thickness of the cabinet, compressed-air capacity required for cleaning mechanism, horsepower of the compressor, and the number of pulse valves that will require periodic maintenance.

Table D.3 shows the estimated acquisition costs for the six cartridge houses. The initial cost of the cartridge house includes the first set of cartridge filters. The compressor estimate includes the air drier and heat tracing to prevent possible moisture freezing in the pulse valves in the winter.

TABLE D.2. Descriptive Summary of Cartridge Houses

Maker	Cartridge Access	Number of Cartridges	Cloth, ft ²	Wall, in.	Compressor		No. Valves
					Air SCFM at 100 psi	hp	
AA	SH ^(a)	46	9890	0.1046	12	5	23
DD	TI ^(b)	72	15480	0.12	24	7	12
E	SH	56	12040	0.13	50	15	14
BB	SH	60	12900	0.1046	18	6	30
Z	SH	72	15480	0.13	32	7	12
FF	TI	72	15480	0.1046	2	3	12
Average		63	13545	0.12	23	7	17
Minimum		46	9890	0.10	2	3	12
Maximum		72	15480	0.13	50	15	30

(a) SH = cartridge access via hatch on side wall.

(b) TI = Walk-in access above tube cartridge.

TABLE D.3. Cartridge House Acquisition Costs, Excluding Fan

Maker	Cartridge House w/bags, \$K	Compressor, \$K	Erection Pad, Duct etc., \$K	Subtotal, \$K
AA	23	5.6	61.3	89.9
DD	30	9.9	61.3	101.2
E	29	14.8	61.3	105.4
BB	38	9.9	61.3	109.4
Z	42	9.9	61.3	112.7
FF	49	5.5	61.3	115.8
Average	35.17	9.27	61.30	105.73
Minimum	23.00	5.50	61.30	89.90
Maximum	49.00	14.80	61.30	115.80

The erection cost assumes an installation outdoors with no building to cover the overall air cleaning system. Compressor and erection cost estimates are shown in Appendix K. Table D.4 lists the items included in the erection estimate.

TABLE D.4. Installation Costs of Cartridge House

<u>Item</u>	<u>Cost, \$</u>
Pad 22 x 30 ft	4700
Compressor shelter	2800
Hopper shed	5300
Seven-gauge ducts and erection	20900
Electrical	6400
Freight	1200
Pressure test	1900
Drum scale	8100
Flow controls	10000
Total	61300

Table D.5 shows the estimated maintenance costs for a 20-year life. The general method for these estimates was described in the main report (pages 12-23). Additional assumptions beyond those stated in the main report were

- cartridges cost \$65 each
- cartridge compacts to 25% of original volume (1.92 ft^3)
- twelve cartridges can be compacted per man-hr
- cartridges have 2-year life, per manufacturers' data
- compressor operates 20% of the time
- cartridge changing requires 0.25 man-hr each.

In addition to the total estimated maintenance, Table D.6 includes the cost of compressor operation.

Table D.6 shows the estimates made by FILTER for the cost of operating the downstream disposable filters in various combinations for both types of media for 6000 test shots and 4900 g of challenge aerosol.

Fan requirements vary according to the combination of downstream banks of disposable filters. Table D.7 lists the estimated static pressure requirement, fan cost, and 20-year fan power cost for each combination of filter banks. The individual maximum pressure drops assumed were 1, 4, 4, 4, and 2.2 in. WG for the existing first prefilter, second prefilter and HEPA filter banks, cartridge house, and ductwork/shock attenuator system, respectively.

TABLE D.5. Twenty-Year Maintenance and Compressor Power Costs

Maker	Man-hr/ Cartridge Change	20-Yr Changeout Labor, \$K	Cartridge Disposal, \$K/20 yr	Dust Disposal, \$K/6000 Shots	Repair Codes C P A E B	Misc. Repairs, \$K	Housekeeping and Inspection, day/yr	Start-up Shutdown, min/day	Operation Labor, \$K	Cartridge Replacement, \$K/9 Sets	Subtotal Cartridge Maintenance, \$K	Compressor Power, \$K
AA	12	3.57	6.71	24.08	1 1 1 1	25.40	2	30	87.65	26.91	174	1.20
DD	18	5.58	10.50	24.08	1 1 1 1	21.62	2	30	87.65	42.12	192	1.68
E	14	4.34	8.17	24.08	1 1 1 1	22.30	2	30	87.65	32.76	179	3.59
BB	15	4.65	8.75	24.08	1 1 1 1	27.81	2	30	87.65	35.10	188	1.44
Z	18	5.58	10.50	24.08	1 1 1 1	21.62	2	30	87.65	42.12	192	1.68
FF	18	5.58	10.50	24.08	1 1 1 1	21.62	2	30	87.65	42.12	192	0.72
Average	16	4.88	9.19	24.08		23.39	2	30	87.65	36.86	186	1.72
Minimum	12	3.57	6.71	24.08		21.62	2	30	87.65	26.91	174	0.72
Maximum	18	5.58	10.50	24.08		27.81	2	30	87.65	42.12	192	3.59

Repair Code Key

C - annual compressor maintenance

P - semi-annual pulse valve rebuilds

A - annual miscellaneous maintenance

E - one time replacement of cleaning cycle control electronics

B - one time bearing and other repair of blower

A "1" under the repair code column indicates that the repair is applicable to the device and is accounted for in the cost estimate.

TABLE D.6. Estimated Usage Costs of Disposable Filters
Downstream from Cartridge Houses

Downstream Disposable Filter Bank Combination	Filter Usage Costs, \$K		Number Of Times A Filter Bank Will Be Changed	
	Coated Media	Standard Media	Coated Media	Standard Media
1,2,3	1.1	104	1	45
2,3	1.2	104	1	45
3	2.2	191	1	45
1,3	2.1	190	1	45

TABLE D.7. Fan Requirements for Cartridge Houses

	Filter Bank Combination			
	1,2,3	2,3	3	1,3
System Pressure Drop, in. WG	15.2	14.2	10.2	11.2
Fan Cost, \$K	17	16	0	0
Fan 20-yr Power Cost, \$K	147	137	99	108

Table D.8 summarizes the 20-year cost of acquiring and operating the six cartridge houses using standard cartridge media. Each entry in the maker versus bank combination matrix is the sum of acquisition, maintenance, disposable filter usage, and fan costs for the given configuration. Average, maxima, and minima for these total costs are also shown. The 20-year total power costs shown are the sum of the fan power cost and the average compressor power cost for all the units from Table D.5. The compressor power cost was only about 1% of the total power. The sum of the power cost and the equipment and maintenance average, maxima, and minima costs are also given in the table. Table D.9 shows the same data assuming coated media were used.

TABLE D.8. Total Twenty-Year Cost of Cartridge Houses Using Standard Media

Maker	\$K by After-Filter Bank Combination				Average
	1,2,3	2,3	3	1,3	
AA	385	384	455	454	420
DD	414	413	484	483	448
E	406	405	476	475	440
BB	418	417	488	487	453
Z	425	424	495	494	460
FF	428	427	498	497	463
Average	413	412	483	482	447
Minimum	385	384	455	454	420
Maximum	428	427	498	497	463
Power	149	139	100	110	125
Power + Avg	561	551	583	592	572
Power + Min	534	523	556	564	544
Power + Max	577	566	599	607	587

TABLE D.9. Total Twenty-Year Cost of Cartridge Houses Using Coated Media

Maker	\$K by After-Filter Bank Combination				Average
	1,2,3	2,3	3	1,3	
AA	282	281	266	266	274
DD	311	310	295	295	303
E	303	302	287	287	295
BB	316	315	300	300	307
Z	322	321	306	306	314
FF	325	325	310	309	317
Average	310	309	294	294	302
Minimum	282	281	266	266	274
Maximum	325	325	310	309	317
Power	149	139	100	110	125
Power + Avg	459	448	394	404	426
Power + Min	431	420	367	376	399
Power + Max	474	464	410	419	442

APPENDIX E

CYCLONES

APPENDIX E

CYCLONES

E.1 DESCRIPTION

Cyclones separate particulates from the gas stream by transforming the flow stream into a confined vortex. Particles enter the cyclone following the gas streamlines. Flow through the cyclone vortex produces a tangential motion forcing the particles across the streamlines towards the collector wall. When the particles enter the boundary layer close to the cyclone wall they lose kinetic energy by viscous shear and mechanical friction. The two opposing forces involved are an outward centrifugal force, imparted by the rotation of the gas stream and an inward drag force which is a function of the particle density, diameter and shape. Any particle for which the centrifugal force is greater than the drag force will reach the wall and can be collected.

Cyclones are primarily used to collect large diameter, $>10\text{-}\mu\text{m}$ particles. To increase the collection efficiency for smaller particles, high-performance cyclones have been developed. High-performance cyclones have smaller inlet and outlet areas with smaller body diameter and longer overall length than conventional cyclones. The pressure drop across a high-performance cyclone is usually greater than 10 in. WG. Several small diameter cyclones operating in parallel also increase collection efficiency. As a last resort to increase efficiency, cyclones may be operated in series; however, the resulting pressure drop and energy requirements are extremely high. Figure E.1 shows a typical cyclone configuration.

Quotes and cyclone system configurations for the air cleaning system were obtained from three cyclone manufacturers. More than twenty cyclone manufacturers were initially contacted and invited to provide designs for the system. System designs for two collection efficiencies were requested: 90% and 60% to 70%, for the aerosol size distribution with 30% of the particles $<1\text{ }\mu\text{m}$ and 30% $>7\text{ }\mu\text{m}$ (Size Distribution No. 1, Tables 2 and 5 of the main text). None of the manufacturers would specify a system for 90% collection

FIGURE E.1. Typical Cyclone Configuration (after Beachler and Jahnke 1981)

efficiency because 30% of the aerosol was $<1\ \mu\text{m}$ in diameter. Each of the vendors was able to specify a cyclone for 60% to 70% particulate collection (essentially all the particulate $\geq 1\ \mu\text{m}$ in diameter). One proposed a single 123-in.-diameter high-performance cyclone. Another proposed four 35-in.-diameter cyclones in parallel, and a third proposed sixteen 27.5-in.-diameter cyclones in parallel. Table E.1 shows the overall space requirements of the cyclone systems. Pressure drops for the cyclones, also listed in the table, are much higher than for most air filters discussed in this report, 11 to 16 in. WG.

The cyclone systems are constructed out of welded steel and require no maintenance over their 20-year projected life. The valve at the hopper outlet is the only moving part and requires periodic lubrication. For collection of an extremely abrasive particulate, wear plates can be installed at the cyclone inlet. The plates, which are replaced every 5 to 10 years as necessary, are not required for the aerosol in question.

TABLE E.1. Cyclone System Specifications

	<u>Product T</u>	<u>Product F</u>	<u>Product Q</u>
Number of Cyclones	1	4	16
Body Diameter, in.	123	35	27.5
Inlet Height, in.	75	--	11
Inlet Width, in.	17	15 ^(a)	22.37
Outlet Length, in.	--	--	16
Outlet Diameter, in.	33.5	18	36
Cylinder Length, in.	--	--	56.5
Cone and Hopper Length, in.	234	--	137
Total Length, in.	293	123	193.5
Inlet Elevation, ft ^(b)	27.2	15	14.5
Outlet Elevation, ft ^(b)	30.1	18	16
Pad Size, ft x ft	7 x 7	10 x 25	20 x 30
Weight, lb	10,400	5,000	10,000
AP, in. WG	16	12	10.7
Construction	--	14-gage mild steel	10-gage hot rolled steel

(a) Diameter

(b) Assumes hopper outlet 4 ft above ground

The cyclone systems' costs are listed in Table E.2. The single cyclone costs half as much as the two multiclones. No installation costs were provided for Product T or Product F. Very little site assembly is required for these systems. The units are placed on the pad and the connecting ductwork is attached. The Product Q requires site assembly of four inlet and outlet manifolds, 16 product receivers, and 16 collection barrels. The installation cost provided for Product Q was \$165,000. At startup, the pressure drops across each of the multiclones are balanced to ensure equal flow through each of the units. The flow balance should be checked biannually.

TABLE E.2. Cyclone Costs

	<u>Product T</u>	<u>Product F</u>	<u>Product Q</u>
Cyclone System Cost	\$16,000	\$32,000	\$ 37,366
Installation and Site Assembly	--	--	165,000
Freight ^(a)	2,080	1,000	2,000

(a) Estimated at \$20/100 lb.

E.2 Collection Efficiency

The vendors were asked to supply system collection efficiency as a function of particle size. Product F and Product T provided particle cut diameter^(a) and Product Q provided a system total collection efficiency along with some fractional efficiencies as a function of Stokes equivalent diameter. The particle cut diameters were converted to collection efficiency as a function of particle size using Size Distribution 1 and the Lapple Method (Beachler and Jahnke 1981). The fractional efficiencies are listed in Table E.3.

The Lapple Method is one of the older methods of calculating cyclone fractional efficiency. The method was documented in 1951 before the development of high-performance cyclones. The method was applied to the Product F and Product T cyclones because the vendors did not provide any collection efficiency data as a function of particle size. Using the cut diameters of 3.0 μm and 2.4 μm for Product F and Product T, total collection efficiencies of 49.34% and 53.73% resulted, respectively. The vendors were asked to provide cyclones with collection efficiencies ranging from 60% to 70% assuming Size Distribution 1 (Table 5 from main text). However, because Size Distribution No. 3 (Table 5) was used, cyclones were assumed to have smaller cut diameters in order to achieve the required collection efficiencies. Therefore, 2.0- μm and 1.5- μm cut diameters were used for Product F and Product T, respectively. These curves

(a) The particle cut diameter is that diameter for which the cyclone has 50% collection efficiency.

TABLE E.3. Cyclone Fractional Collection Efficiencies

Company	0.1 μm	0.32 μm	1.0 μm	3.2 μm	10 μm	32 μm	100 μm	50% Cut Diameter, μm	Total Collection Efficiency, %
Product Q	0	12	39.36	99	99.9	100	100 ^(a)	~1.1 ^(b)	68.75 ^(c)
Product F	0	0.4	10.5	53	98	100	100 ^(d)	3.0 ^(c)	49.34 ^(e)
Product T	0	1.0	16	61	98	100	100 ^(d)	2.4 ^(c)	53.73 ^(e)
Recommended for Product F	0	2	22	71	99.5	100	100 ^(d)	2.0	56.77
Recommended for Product T	0.09	3.3	32	81	99.9	100	100 ^(d)	1.5	61.62

(a) Calculated from the total efficiency and Stokes Equivalent Diameters and fractional efficiencies supplied by the vendor: 1.0 μm (39.36%), 1.5 μm (92.25%), 2.0 μm (97.29%) and the Size Distribution No. 1 (Table 5).

(b) Determined from plot of fractional collection efficiency.

(c) Data supplied by vendor.

(d) Calculated from the 50% cut diameter using the Lapple Method.

(e) Calculated using the Lapple Method and Size Distribution No. 1 (Table 5).

produce total collection efficiencies closer to those specified in the original requirement, 60% to 70%. In addition they may account for cyclone design improvements made since 1951. A curve of experimental results and theoretical predictions in Beachler and Jahnke (1981) show that the Lapple theory is quite conservative for particles less than 2 μm in diameter.

The Product Q fractional efficiencies were determined from vendor data. The curve of collection efficiency as a function of particle size for the Product Q data has a much steeper slope than the Lapple curve when plotted as a cumulative log normal distribution. A 50% cut diameter of 1.1 μm for Product Q was determined from the plot.

E.3 COST ESTIMATING

A descriptive summary of some of the important characteristics of the three cyclone systems is shown in Table E.4. Included in the table are the pressure drop across just the cyclone system, excluding filters and ducts; the cut diameter; the estimated overall cyclone efficiency for the challenge aerosol size distribution (Measurement 3, see Table 5 in main text); the quantity of aerosol collected by the cyclone for the same size distribution as estimated by FILTER; the outlet elevation; and, the size of the required concrete pad. The same pad size for all cyclones was used because it is the size of a new pad needed to accommodate the existing filter house. Any excess space on the existing pad would be used to allow room for manipulating drums of collected particles.

Except for the cost associated with the disposable filters, the 20-year maintenance cost for the system is estimated in Table E.5. Cost estimates were made using the method outlined in the main report. The dust collected per shot from Table E.3 was the basis for estimating the dust disposal cost. Annual inspection, startup, and shutdown are the only other maintenance costs associated with cyclones.

Table E.6 shows the total first costs entailed in acquiring the cyclones. The vendor's cost estimate and the freight costs are taken from Table E.2. The erection cost for the Product Q cyclone was provided by the vendor. It is substantially higher than the others because of the amount of ductwork required

TABLE E.4. Summary of Cyclone Characteristics

Maker	Device	Type	Unit Pressure Drop, in. WG	Cut Diameter, μ m	Unit Efficiency, %	Grams Dust Collected Per Shot	Outlet Elevation, ft.	Pad Required, ft x ft
Q	16 Parallel	Cyclones	10.7		40.6	2325	16	20 x 30
F	4 Parallel	Cyclones	12	3	33.7	1948	18	20 x 30
T	Single	Cyclone	16	2.4	36.7	2098	30	20 x 30

TABLE E.5. Twenty-year System Maintenance

Maker	Dust Disposal, \$K/6000 Shots	Repair Codes C P A E B	Misc. Repairs, \$K	Housekeeping Inspection, day/yr	Startup Shutdown, min/day	Operation Labor, \$K	Subtotal Maintenance, \$K
Q	11.43	1	9.92	1.5	20	59.26	80.61
F	9.57	1	9.92	1.5	20	59.26	78.76
T	10.31	1	9.92	1.5	20	59.26	79.49

TABLE E.6. First Costs of Cyclones

Maker	Unit, \$K	Erection Pad, Duct, etc., \$K	Freight, \$K	Subtotal, \$K
Q	37	165	2	204.00
F	32	63.5	1	96.50
T	16	58.5	2.1	76.60

to manifold together 16 cyclones. The erection costs for the other cyclones were estimated as detailed in Appendix K and shown in Table E.7. An extra amount was added to the Product F cyclone to account for manifolding together four cyclones.

The costs associated with the disposable filters to be used downstream of the cyclones were estimated using FILTER and are listed in Table E.8 (third column) by combination of filter banks. Also shown are the number of times a filter bank replacement would occur during the 20-year lifetime, the overall

TABLE E.7. Erection Cost Estimates for Cyclones

<u>Item</u>	<u>Product F, \$</u>	<u>Product T, \$</u>
Pad 22 x 30 ft	4,700	4,700
Hopper Shed	5,300	5,300
7-Gauge Ducts and Erection	20,900	20,900
Electrical	6,400	6,400
Pressure Test	1,900	1,900
Drum Scale	8,100	8,100
Flow Controls	10,000	10,000
Extra Manifolding	<u>5,000</u>	<u> </u>
Total	\$62,300	\$57,300

system particle collection efficiency, and pressure drops. Note that the criterion efficiency established in Table 1 was not met by the calculated efficiencies. The fan costs were estimated from the pressure drop estimates and the cost estimates in Appendix K and are added to the acquisition costs from Table E.6. Power costs were estimated using the method outlined in the main report. Filter usage, initial investment, and maintenance costs are totaled for each configuration in column 9 of Table E.8, and power costs are included in the last column. Excluding power, the 20-year cost ranges from \$3.9M to \$8.1M.

For comparing costs of the different types of equipment, the estimate for the Product T cyclone with all three of the existing filter banks downstream was used. The cost estimated for the Product Q cyclone was somewhat lower; however, the need for 16 hopper dumping locations was considered a significant disadvantage, so the single Product T cyclone was selected instead. Except for the initial investment, the cyclones did not compare favorably with devices with greater efficiency for the challenge aerosol.

REFERENCE

Beachler, D. S., and J. A. Jahnke. 1981. APTI Course 413 Control of Particulate Emissions Student Manual. EPA 450/2-80-066, Northrop Services, Inc., Research Triangle Park, North Carolina.

TABLE E.8. Twenty-year Total Costs by Filter Combination

Maker	Bank Combination	Filter Replacement, \$K	Number Bank Changes	System Efficiency, %	System ΔP , in. W.G.	Fan Cost, \$K	Total First Cost, \$K	Equipment and Maintenance, \$K	Fan Power, \$K	Total, \$K
Q	1,2,3	3566	1612	99.989	21.9	27	231	3878	212	4089
	2,3	3575	1609	99.989	20.9	27	231	3887	202	4089
	3	6898	1608	99.933	16.9	18	222	7200	163	7364
	1,3	6876	1610	99.933	17.9	18	222	7178	173	7351
F	1,2,3	3887	1887	99.989	23.2	27	124	4089	224	4314
	2,3	4043	1845	99.989	22.2	27	124	4245	215	4460
	3	7908	1843	99.932	18.2	27	124	8110	176	8286
	1,3	7521	1886	99.932	19.2	27	124	7723	186	7909
T	1,2,3	3756	1779	99.989	27.2	35	112	3947	263	4210
	2,3	3858	1751	99.989	26.2	35	112	4049	253	4302
	3	7507	1749	99.93	22.2	27	104	7690	215	7905
	1,3	7254	1777	99.93	23.2	27	104	7437	224	7661

APPENDIX F

ELECTROSTATIC PRECIPITATORS

APPENDIX F

ELECTROSTATIC PRECIPITATORS

Electrostatic precipitators collect particles that become electrically charged in an intense electric field. Particulate-laden gas flows through a chamber consisting of a series of discharge electrodes spaced equidistantly between grounded collection electrodes. The particles are charged and then migrate to and are collected at the oppositely charged collection plates. The collected particles are removed from the plates by rapping. Particles fall by gravity into hoppers where they are stored before removal and final disposal.

Two types of precipitators exist: high-voltage single-stage and low-voltage two-stage. According to Beachler and Jahnke (1981), the two-stage, low-voltage units have limited use for particle emission control because the collector becomes inefficient for dust loadings greater than $7.35 \times 10^{-4} \text{ g/m}^3$. The maximum dust load anticipated for this application is 3.4 g/m^3 with a 10-min average value of 0.5 g/m^3 .

The two-stage electrostatic precipitator has separate particle charging and collection stages. In the single-stage unit the particles are charged and collected in the same stage.

Another major difference in the design of electrostatic precipitators is seen in the discharge electrode. Three major types of discharge electrode designs exist: the conventional weighted-wire electrode, the rigid frame electrode, and the needle plate electrode.

PRECIPITATOR CONFIGURATIONS

Quotes and electrostatic precipitator system configurations for the air cleaning system were obtained from five electrostatic precipitator manufacturers. More than 20 manufacturers were initially contacted and invited to provide designs for the system. Electrostatic precipitators are available for small (6,000 acfm), medium (24,000 acfm) and large (coal-fired power plants) scale applications. Companies that manufacture systems in all three categories responded to the inquiry.

Vendor K, a manufacturer of small plant and process precipitators, recommended a configuration of 12 units operating in parallel. Vendor EE, a manufacturer of intermediate size precipitators, recommended a 24,000 acfm tubular poly-stage design. Vendor KK, Vendor CC, and Vendor P all recommended modular versions of their large-scale units. Since the initial survey was conducted, Vendor P has stopped marketing its precipitators in the United States.

System designs for two collection efficiencies were requested: 91% and 99% for the aerosol size distribution, $30\% < 1 \mu\text{m}$ and $30\% > 7 \mu\text{m}$. Each vendor provided a system designed to meet each collection efficiency. Because the precipitator designs vary, each design will be discussed separately. Table F.1 compares the precipitator specifications.

TWO-STAGE PRECIPITATORS

Vendor K

Vendor K manufactures small two-stage electrostatic precipitators with separate ionization and collection stages. Several system configurations were recommended for the firing range application: drawer style, hopper style, and several self-contained units operated in parallel. Of the options presented, the hopper style system was best suited to handle the depleted uranium particulate. Figure F.1 presents Vendor K's sketch of the configuration. The design shows the units stacked three tiers high with a single hopper beneath each tier. The units are cleaned using rappers actuated by compressed air. No method was described to prevent dust reentrainment as it falls through the three tiers to the hoppers. The \$24K specified by Vendor K for annual maintenance includes dust removal from the hoppers.

Vendor K stated that the collection efficiency for the unit is essentially constant as a function of particle size. No evidence in the literature was found to support this statement, so the typical precipitator collection efficiency curve was used to describe the performance.

TABLE F.1. Comparison of the Electrostatic Precipitator Designs

	Vendor K		Vendor EE		Vendor KK		Vendor CC		Vendor P	
	91%	99%	91%	99%	91%	99%	91%	99%	91%	99%
Number of Units	12	24	1	1	1	1	1	1	1	1
Number of Fields	1	2	1	2	2	3	2	4	1	2
Number of Stages	2	2	2	2	1	1	1	1	1	1
Specific Collection Area, ft ² /1000 acfm	--	--	324	648	334	500	244	487	249	498
Plate Cleaning System	Compressed-air-actuated rappers		Compressed-air-actuated sonic horn		Compressed-air-actuated rappers		Tumbling hammers		Tumbling hammers	
Dust Collection System	Hoppers		Hoppers and screw conveyor		Hoppers		Hoppers		Hoppers	
Number of Hoppers	4	8	1	2	2	3	2	4	2	4
Pad Size, ft x ft	5 x 15	10 x 15	8 x 8	8 x 16	16.3 x 13.4	21.9 x 13.4	38 x 25	62 x 25	17 x 13	34 x 13
Weight, lb	6,000	12,000	16,000	32,000	49,000	73,000	70,000	140,000	43,400	80,000
Inlet Elevation, ft	12.5(a)		2.5	2.5	22.5(a)		20(a)		22.5(a)	
Outlet Elevation, ft	12.5(a)		17.5	17.5	22.5(a)		20(a)		22.5(a)	
ΔP, in WG	1.0	1.0	1.5	1.5	0.5	0.5	1.0	1.0	0.5	0.5
Power Requirements, kW										
Particle Charging	1.2	2.4	10	20	5.2	7.8	22	44	3.6	7.2
Purge air heaters for insu- lator compartment			8.8	17.6			2.0(c)	2.0(c)	8.0	16.0
Auxiliary					3.0(b)	3.0(b)				
Annual Maintenance, \$	24,000(d)	24,000(d)	5,000(e)	5,000(e)	1750(f)	2100(f)	1 d/yr	1 d/yr	3,500	3,500
Required Accessories	Air compressor size not specified		Air compressor 20 cfm at 80 psi		Air compressor 20 cfm at 50 psi		none		none	
Startup Time, min	10		10	30	none		none		2 hr for insulator heaters to warm up	

(a) Assumes 4-ft clearance from ground to hopper bottom.

(b) Insulator heaters 0.1 kW, vibrators 0.1 kW, rapping 0.6 kW, control system 0.8 kW, lights for safety 1.4 kW.

(c) Hopper heaters at 90 to 100°F for 1/3 of year and plate rapping.

(d) Includes dust removal.

(e) Includes man-hr and replacement parts.

(f) 0.5% of total cost.

FIGURE F.1. Vendor K System Configuration

Vendor EE

Vendor EE manufactures a tubular electrostatic precipitator. This is also a two-stage electrostatic precipitator, but the design departs from the conventional two-stage design. Figure F.2 shows a cross section of the unit. The ionizing electrode is shaped like a rod with a sharp needle at the end. The corona is generated on the needle and the remainder of the electrode acts as a nondischarging electrode, which still provides an electric field. This design provides a nonuniform electric field in the ionizing section and a uniform electric field in the collecting section.

Vendor EE recommended a one-pass unit to achieve 91% collection efficiency and a two-pass unit to achieve 99% collection efficiency. In addition, they recommend that a pilot test be run to allow the design to be further refined because a very conservative specific collection area ($324 \text{ ft}^2/1000 \text{ acfm}$ per pass) was used for the design.

Most Vendor EE systems operate wet using a continuous water mist to clean the collection surfaces. When water use is not feasible, sonic horns are used to dislodge the particulate. Compressed air requirements are 20 acfm and 80 psia to actuate the sonic horn. No users of the sonic cleaning method could be found to verify its performance.

Power requirements for the 99% collection efficiency unit are 20 kW for particle charging and 17.6 kW for pulse air heaters. Hot, dry air (150 to 180°F) is blown through the insulator compartment (200 acfm for 16 insulators) to keep the insulators dust and moisture free.

Vendor EE estimates annual maintenance costs to be \$5K. This figure includes labor and replacement parts.

SINGLE-STAGE PRECIPITATORS

Vendor KK

Vendor KK manufactures an electrostatic precipitator for industrial applications for small volume flow (3,000 to 25,000 acfm). The precipitator uses a needle/plate electrode system instead of weighted corona wires.

FIGURE F.2. Vendor EE Tubular Electrostatic Precipitator

Figure F.3 shows the design of the discharge electrodes and collection plates. Vendor KK recommended a two-field unit to achieve 91% collection efficiency and a three-field unit to achieve 99% collection efficiency. Collected dust is removed by a compressed-air-actuated plate rapping system. Compressed-air

requirements are 20 cfm at 50 psig. The precipitators are factory assembled and shipped to the site fully wired, piped, and insulated on two flatbed trucks or one rail car. The collection hoppers and attached structural leg unit are bolted to the concrete or steel foundation supplied by the owner. Then the precipitator is set on top and bolted to the hopper flange. Maintenance requirements are minimal and are estimated to be 0.5% of the total cost.

Power requirements for particle charging for the 91% and 99% collection efficiency designs range from 5.2 to 7.8 kW, with an additional 2.8 kW required to power the precipitator auxiliary systems.

Vendor CC

Vendor CC manufactures an electrostatic precipitator using a rigid frame discharge electrode with a 3/16-in.-square corona wire. Vendor CC specified a two-field precipitator to achieve 91% collection efficiency and a four-field

FIGURE F.3. Discharge Electrode Plates with Needles

precipitator to achieve 99% collection efficiency. The precipitator assembly is built as a set of modular components to allow quick field installation. One precipitator module, which includes the collecting and emitting electrodes, rapping system, high-voltage insulators, and insulator heaters, is required for each electrical field. One hopper is required under each precipitator module.

Precipitator power requirements for particle charging are 22 kW for the two-field unit and 44 kW for the four-field unit. Because these power requirements are from two to ten times larger than those of the other precipitator designs, Vendor CC was asked to recheck the requirements. No change in value or explanation for the large usage resulted. Additional power requirements for hopper heaters and rapping are 2 kW.

Vendor P

Vendor P markets a single-stage precipitator using the classic wire-weight design for the discharge electrode. Vendor P recommends a single-field unit to achieve 91% collection efficiency and a two-field unit to achieve 99% collection efficiency.

The Vendor P design also requires insulator heaters. The heaters are used to keep the insulators free of moisture by keeping their temperature above the dew point. Heated air is used to purge the insulator compartment. This prevents air from the exhaust stream from reaching the insulators.

The two-field units are factory constructed in modules for efficient site assembly. Erection time is estimated to be 150 man-hr and 300 man-hr for the two units. In addition, a cherry picker with a 6-ton capacity is required.

Cost

Table F.2 lists the precipitator system costs for this application. The value from Vendor K was not derived for a specific Vendor K system. A cost of \$5/cfm and \$10/cfm to achieve 91% and 99% particle collection was furnished. The three single-stage precipitators from Vendor KK, Vendor CC, and Vendor P all had similar relatively high initial costs ranging from \$190K to \$418K for both the 91% and 99% collection efficiency units. Initial cost of the Vendor EE two-stage precipitator was less than half of the initial costs of the single-stage units.

TABLE F.2. Electrostatic Precipitator Costs

	Vendor K		Vendor EE		Vendor KK		Vendor CC		Vendor P	
	91%	99%	91%	99%	91%	99%	91%	99%	91%	99%
Precipitator System Cost, \$	120,000	240,000	84,068	168,136	314,800	384,800	209,400	418,800	190,000	350,000
Installation and Site Assembly, \$	--	--	--	--	20,000	20,000	80,000	157,000	150 hr	300 hr
Freight, \$	--	--	3,200	6,400	9,200	9,200	4,000	8,000	--	--

Cost of operating the precipitators is a function of electrical consumption and pressure drop. All the units have extremely low pressure drops ranging from 0.5 to 1.5 in. WG. The electrical requirements for the five systems range from 2.4 to 44 kW for particle charging for 99% collection efficiency. In addition, Vendor EE and Vendor P designs also require substantial power for insulator compartment heaters (see Table F.1).

COLLECTION EFFICIENCY

No collection efficiency data as a function of particle size were furnished by any of the precipitator manufacturers. All of the vendors replied that their units would collect 91% or 99% of the aerosol size distribution provided in the design specifications. All of the units appear to have been designed rather conservatively as shown by the large specific collection areas (SCA), which range from 244 to 344 ft² of collection electrode/1000 acfm for the 91% design to 487 to 648 ft²/1000 acfm for the 99% design. According to Beachler and Jahnke (1981), to achieve 99.5% collection efficiency the SCA should range from 350 to 400 ft²/1000 acfm.

The fractional efficiency for each precipitator size range was determined from a curve of theoretical collection efficiency as a function of particle size (Bethea 1978). Using the theoretical curve and the particle size distribution specified in the initial design, a collection efficiency of 99.1% was obtained. To determine the fractional efficiency for 91% total collection efficiency, a family of similar curves was drawn beneath the theoretical collection efficiency curve. The curve chosen produced a total collection efficiency of 91.7% for the specified size distribution.

Three particle size distributions of the firing range aerosol have been measured as shown in Tables 2 and 5 in the main text. The more conservative size distribution No. 3 data were finally used to evaluate the precipitators. Table F.3 presents the collection efficiencies for 91% and 99% total collection efficiency derived using both Size Distributions No. 1 and 3.

TABLE F.3. Electrostatic Precipitator Collection Efficiency as a Function of Particle Size

Particle Size Distribution	Total Collection Efficiency, %	Fractional Collection Efficiency, %						
		0.1 μm	0.32 μm	1.0 μm	3.2 μm	10.0 μm	32.0 μm	100 μm
No. 3	99	98.5	97.5	99.2	99.98	100	100	100
No. 3	91	86	81	90	99.4	100	100	100
No. 1	99	98	96.5	98.8	99.98	100	100	100
No. 1	91	78	73	86	98.8	99.99	100	100

COST ESTIMATING

Several of the important characteristics of the precipitators are summarized in Table F.4. The efficiency values listed are those calculated by FILTER for each precipitator and the finest challenge aerosol size distribution using the data of Table F.3. The specific collection area is the area of collection plates per 1000 acfm of airflow. The first column of power data is that electricity needed to operate the collection electrodes, purge air, and hopper heaters. The auxiliary equipment power is that needed for the air compressors or tumbling rappers that are used intermittently as estimated in the "Run Fraction" column.

Table F.5 shows a summary of the acquisition costs of the precipitator systems. The auxiliary equipment cost is for the required air compressor for the rapping systems. The installation cost is for installation of the precipitators beyond what is already accounted for under erection and ductwork. The cost used in most cases was that provided by Vendor KK. Vendor CC supplied their own erection cost, which accounts for a large amount of onsite fabrication. The erection cost was estimated as shown in Table F.6.

Estimates for precipitator maintenance are shown in Table F.7. The cost estimating methods are outlined in the main report (pp. 12-23). Equipment maintenance includes 16 man-hr/yr for miscellaneous maintenance; a one time insulator replacement of \$500, including labor; and a control board replacement (\$500 for parts, 4 man-hr labor). Where compressors are used, 16 man-hr/yr was included as a maintenance estimate.

Table F.8 shows various performance data and total costs for each combination of precipitator and disposable filter bank combination. The existing

TABLE F.4. Summary of Electrostatic Precipitator Characteristics

Maker	Device Type	Efficiency, %	Specific Collection Area, ft ² /1000, acfm	Power, kW	Pad Size, ft	Dust Collected Per Shot, g	Number of Insulators	Auxiliary Run Fraction, hr/hr
EE	1-field, 2-stage, tubular	91.4	324	18.8	22 x 30	4480	4	0.2
K	1-field, 2 stage	91.4		1.2	22 x 30	4480		0.2
KK	2-field, 1-stage	91.4	334	6.2	22 x 30	4480	6	0.2
CC	2-field, 1-stage	91.4	244	22.5	1600 sq ft	4480	4	0.3
EE	2-field, 2-stage, tubular	99.1	648	37.6	22 x 30	4854	8	0.2
K	2-field, 2-stage	99.1		1.2	22 x 30	4854		0.2
KK	3-field, 1-stage	99.1	500	8.8	22 x 30	4854	9	0.2
CC	4-field, 1 stage	99.1	487	44.5	1600 sq ft	4854	8	0.33

TABLE F.5. Summary of Electrostatic Precipitator First Costs

Maker	Unit, \$K	Auxiliary Equipment, \$K	Erection Pad, Duct etc., \$K	Freight, \$K	ESP Installation, \$K	Total, \$K
Vendor EE	84.1	9.9	60.1	3.2	20	177
Vendor K	120	9.9	60.1	1.2	20	211
Vendor KK	314.8	9.9	60.1	9.2	20	414
Vendor CC	209.4	0	63.8	4	80	357
Vendor EE	168.1	9.9	60.1	6.4	20	265
Vendor K	240	9.9	60.1	2.4	20	332
Vendor KK	367	9.9	60.1	9.2	20	466
Vendor CC	418.8	0	63.8	8	157	648

TABLE F.6. Erection Costs for Electrostatic Precipitators

Item	Vendor EE Vendor K Vendor KK	Vendor CC
Pad Size	22 x 30 ft	1600 ft ²
Pad Cost, \$	4,700	11,200
Compressor Shelter, \$	2,800	
Hopper shed, \$	5,300	5,300
Seven-gauge ducts and erection, \$	20,900	20,900
Electrical, \$	6,400	6,400
Pressure test, \$	1,900	1,900
Drum scale, \$	8,100	8,100
Flow controls, \$	10,000	10,000
Total	\$60,100	\$63,800

filters were assumed for the filter banks: first prefilter in bank 1, second prefilter in bank 2, and HEPA filters in bank 3. The filter replacement cost is the 20-year usage of disposable filters including new media, disposal, and all labor as estimated by FILTER. The total number of times a filter bank replacement may occur and the overall system efficiency were also estimated by FILTER and shown in the table. System pressure drop accounts for the building ductwork, the precipitator, and the maximum load on the filters. The precipitators have the lowest pressure drop of any of the devices investigated (about 0.5 to 1 in. WG). The cost of the larger capacity fan was listed as needed and

TABLE F.7. Electrostatic Precipitator Maintenance Estimates

Maker	Dust Disposal, \$K/6000 shots	Maintenance							Power					
		Repair Codes					Misc. Repairs, \$K	Housekeeping Inspection, day/yr	Start-up Shutdown, min/day	Operation Labor, \$K	Subtotal Maintenance, \$K	ESP Power, \$K	Auxiliary Power, \$K	Subtotal Power, \$K
		C	I	A	E	B								
EE	22.02	1	1	1	1	1	17.66	2	30	88	127	30.17	1.44	32
K	22.02	1		1	1		15.50	2	30	88	125	1.93	1.44	3
KK	22.02	1	1	1	1		15.75	2	30	88	125	9.95	1.44	11
CC	22.02		1	1	1		10.71	2	30	88	120	36.11	0.79	37
EE	23.86	1	1	1	1	1	17.82	2	30	88	129	60.34	1.44	62
K	23.86	1		1	1		15.50	2	30	88	127	1.93	1.44	3
KK	23.86	1	1	1	1		15.87	2	30	88	127	14.12	1.44	16
CC	23.86		1	1	1		10.87	2	30	88	122	71.41	0.79	72

Repair Code Key

C - Annual compressor maintenance

I - One time replacement of insulators

A - Annual miscellaneous maintenance

E - One time replacement of cleaning cycle control electronics

B - One time bearing and other repair of blower

A "1" under the repair code column indicates that the repair is applicable to the device and is accounted for in the cost estimate.

TABLE F.8. Twenty-Year Total Costs by Filter Bank Combination for Precipitators

Maker	Bank Combination	Filter Replacement, \$K	Number Bank Changes	System Efficiency, %	System ΔP, in. WG	Fan Cost, \$K	Total First Cost, \$K	Fan Power, \$K	Total Costs, \$K		
									Equipment and Maintenance	Power	Grand Total
EE 91%	1,2,3	574	264	99.99847	12.2	10	187	118	889	150	1038
	2,3	578	263	99.99847	11.2	0	177	108	883	140	1023
	3	1126	263	99.9903	11	0	177	106	1431	138	1569
	1,3	1117	264	99.9903	11	0	177	106	1422	138	1560
K 91%	1,2,3	574	264	99.99847	12.2	10	221	118	920	121	1042
	2,3	578	263	99.99847	11.2	0	211	108	914	112	1026
	3	1126	263	99.9903	11	0	211	106	1462	110	1572
	1,3	1117	264	99.9903	11	0	211	106	1453	110	1563
KK 91%	1,2,3	574	264	99.99847	12.2	10	424	118	1123	129	1253
	2,3	578	263	99.99847	11.2	0	414	108	1117	120	1237
	3	1126	263	99.9903	11	0	414	106	1665	118	1783
	1,3	1117	264	99.9903	11	0	414	106	1656	118	1774
C 91%	1,2,3	574	264	99.99847	12.2	10	367	118	1062	155	1216
	2,3	578	263	99.99847	11.2	0	357	108	1056	145	1201
	3	1126	263	99.9903	11	0	357	106	1604	143	1747
	1,3	1117	264	99.9903	11	0	357	106	1595	143	1738
EE 99%	1,2,3	63	29	99.99984	12.2	10	275	118	467	180	647
	2,3	63	29	99.99984	11.2	0	265	108	457	170	627
	3	123	29	99.9989	11	0	265	106	517	168	685
	1,3	123	29	99.9989	11	0	265	106	517	168	685
K 99%	1,2,3	63	29	99.99984	12.2	10	342	118	533	121	654
	2,3	63	29	99.99984	11.2	0	332	108	523	112	634
	3	123	29	99.9989	11	0	332	106	582	110	692
	1,3	123	29	99.9989	11	0	332	106	582	110	692
KK 99%	1,2,3	63	29	99.99984	12.2	10	476	118	667	134	800
	2,3	63	29	99.99984	11.2	0	466	108	657	124	781
	3	123	29	99.9989	11	0	466	106	717	122	839
	1,3	123	29	99.9989	11	0	466	106	717	122	839
CC 99%	1,2,3	63	29	99.99984	12.2	10	658	118	843	190	1033
	2,3	63	29	99.99984	11.2	0	648	108	833	181	1014
	3	123	29	99.9989	11	0	648	106	893	179	1072
	1,3	123	29	99.9989	11	0	648	106	893	179	1072

added to the first cost from Table F.5 to give an estimate of total initial investment. The 20-year fan power cost is listed and added to the power cost of the precipitator and auxiliaries. The total costs excluding and including power are shown.

REFERENCES

Beachler, D. S., and J. A. Jahnke. 1981. APTI Course 413 Control of Particulate Emissions Student Manual. EPA 450/2-80-066, Northrop Services, Inc., Research Triangle Park, North Carolina.

Bethea, R. M. 1978. Air Pollution Control Technology, An Engineering Analysis Point of View. Van Nostrand Reinhold Company, New York, New York.

APPENDIX G

CLEANABLE HIGH-EFFICIENCY FILTERS

APPENDIX G

CLEANABLE HIGH-EFFICIENCY FILTERS

Two types of cleanable filters were recommended by vendors for this firing range application. Both employ media pleated into a rectangular frame similar to those in the existing system. The two types are denoted cleanable high efficiency filters and pulsed panel filters.

The cleanable high-efficiency filters (CHEF) described here use panels of pleated media in a frame similar in appearance to the existing HEPA filters. Two cleaning techniques are used--vacuuming and reverse air pulses. These cleaning techniques have been applied to filters with varying collection efficiencies. Both the vacuumed and reverse pulse-cleaned systems use glass-fiber paper that has been coated to enhance the release of accumulated materials. Both systems use a similar housing as shown in Figure G.1. The reverse air pulse-cleaned system, represented at the top of Figure G.1, allows the material dislodged to fall by gravity into a hopper positioned under the filter units. This design would appear to suffer from the same problem that affects bag-type filters (reentrainment of the dislodged material in the airflow). The other system, represented at the left of Figure G.1, uses a vacuum nozzle passing beneath the filter to vacuum the accumulated material. The material vacuumed from the filter is removed by a combined cyclone and bag filter and is transmitted directly to the collection drum via a rotary valve. The vacuumed system also has provisions for a back-up cleanable HEPA filter.

A pulsed panel filter system, with a somewhat lower efficiency (ASHRAE 52-76 rating of 80%) (ASHRAE 52-76 1976) than the first two systems, is shown in Figure G.2. The filter panels are 2 ft x 3 ft x 3 in. of cotton fibers. The accumulated material is displaced by a reverse air pulse and falls by gravity into a hopper positioned under the filters. As with all such units, reentrainment in the airflow is a concern.

FIGURE G.1. Cleanable High-Efficiency Filter Showing Both Reverse Air (at top) and Vacuum Cleaning System Configurations (to left)

FIGURE G.2. Pulsed Panel

COLLECTION EFFICIENCY

Filter efficiency data for the pulsed panel device were obtained from the manufacturer. The HEPA filter data from Table B.1 were used for the other two units because no data were available from the vendors. Table G.1 lists the data used by the FILTER program.

TABLE G.1. Performance Input Data for Cleanable High-Efficiency Filters

Filters	Particle Diameter, μm							Max. Unit Pressure Drop, in. WG
	0.1	0.32	1.0	3.2	10.0	32.0	100.0	
Vendor S	0.998	0.99968	0.9999*	0.99999*	1.0*	1.0*	1.0*	11.0 Single Stage 13.0 Double Stage
Vendor D	0.998	0.99968	0.9999*	0.99999*	1.0*	1.0*	1.0*	15.0
Vendor Y	0.92*	0.93*	0.98	0.996	0.999	0.9999*	0.99999*	3.3

* Indicates extrapolation of data

COST ESTIMATING

Cost estimates were generated for the three cleanable filter devices. Pressure drops for each device were added to the 2.2 in. WG assumed for the structure and the maximum drops for the disposable filters. Cost estimates for the vacuumed CHEF included both the single and double-stage configurations. For the double-stage configuration, a disposable HEPA filter was assumed as the second stage rather than the more expensive cleanable filter. We assumed that additional filters downstream of the double-stage vacuumed CHEF would be superfluous. Key characteristics of these systems are listed in Table G.2.

TABLE G.2. Summary of Characteristics of Cleanable High-Efficiency Filters

Device	Type	Solenoid Pulse Valves	Number Media Units	Media, ft ²	Compressed Media, cuff/set	Wall Thickness, in.	Grams to Hopper Per shot	Auxiliary Run Frac., hr/hr	Auxiliary Equipment, hp
Vendor S	Vacuumed CHEF		12		3		4900	0.2	28
Vendor S	Vacuumed 2-Stage CHEF		12		3		4900	0.2	28
Vendor O	Pulse Cleaned CHEF	12	12		3		4900	0.2	20
Vendor Y	Pulsed Panel	4	24	4800	4.8	0.1345	4713	0.2	3

The unit costs for the CHEF devices include walkways, hopper valves, basic unit, controls, and bag-out doors as available. The unit cost for the pulsed panel seems low (\$15K) and there is some question as to whether hoppers, hopper valves, and air compressor are included. Fan and compressor costs were selected from Appendix L as appropriate. Freight costs were not supplied by the vendors, but were values typical for similar equipment. The installation cost estimates were calculated from the estimates in Appendix L as shown in Table G.3. The two-stage vacuumed CHEF required a smaller pad than the others because the existing filter house is not part of the system. The pulsed panel is designed to be located outdoors, so only shelters for the compressor and hopper dumping station were judged absolutely necessary. A larger shed may be desirable.

TABLE G.3. Installation Costs For Cleanable High-efficiency Filters

Item	Vacuumed CHEF		Reverse	
	1 Stage	2 Stage	Pulse CHEF	Pulsed Panel
Additional Pad l x w ft	22 x 30	22 x 15	22 x 30	22 x 30
Cost, \$				
Pad	\$4,700	\$2,350	\$4,700	\$4,700
Hopper shed				5,300
Compressor shelter				2,800
Partial Shed				
Covering (484 ft ²)	\$16,940	\$16,940	\$16,940	
Drum Scale	8,100	8,100	8,100	8,100
Flow Controls	10,000	10,000	10,000	10,000
Pressure Test	1,900	1,900	1,900	1,900
Electrical	6,400	6,400	6,400	6,400
Seven-gauge SS Ducts plus Installation	20,900	20,900	20,900	20,900
Total	\$68,940	\$66,590	\$68,940	\$60,100

A large shed covering the both CHEF units is probably desirable because each filter element has an access door and because of the complexity of the dust removal system. The reverse pulsed CHEF system required an external blower as auxiliary equipment; the cost of a 20 hp compressor and air drier, \$14.8K, was included in the initial costs to approximate that expense. Table G.4 summarizes the initial procurement costs of these systems excluding increased fan capacities.

TABLE G.4. First Costs of Cleanable High-Efficiency Filters Excluding Fan

Device	Type	Unit, \$K	Auxiliary Equipment, \$K	Erection Pad, Duct etc., \$K	Freight, \$K	Subtotal, \$K
Vendor S	Vacuumed CHEF	88.6	0	68.9	2	160
Vendor S	Vacuumed 2-Stage CHEF	110	0	66.6	3	180
Vendor D	Pulse Cleaned CHEF	66.8	14.8	68.9	1.2	152
Vendor Y	Pulsed Panel	15	5.5	60.1	2	83

Table G.5 shows the estimated 20-year maintenance costs for these systems, excluding the usage of the downstream disposable filters. The general method is outlined in the main report (pp. 12-23). Miscellaneous repairs for those items checked under the repair codes were estimated. The total estimated labor costs and compressor or blower power costs were calculated.

Table G.6 summarizes the system performance data and total costs by each combination of device and downstream disposable filter bank. Banks 1, 2, and 3 consist of the existing filter types. All of these systems exceeded the filter performance criterion except the pulsed panel followed by filter banks 1 and 3 or bank 3 alone, which at 99.9947% efficiency, may be satisfactory considering the uncertainties of the method. The table shows the cost of using the disposable filter banks for 20 yrs and the total number of times a filter bank will be changed. The total system pressure drop, the cost of the fan sized for that pressure drop and the 20-year cost of operating that fan were computed and are shown in the table. The total first cost for the fan and the equipment procurement and installation is also shown. The total of acquisition and maintenance costs, with and without power, is the overall cost of each system for the 20-year expected life.

For the single-stage vacuumed CHEF, the systems including banks 1 and 3 or just bank 3 were the least expensive in total cost because of reduced fan power requirements. When considering only equipment and maintenance, all of the combinations costs were about equal. For this system we recommend the combination with banks 2 and 3 because of the reduced cost of disposable filters, higher efficiency, and the additional protection the bank 2 affords the HEPA filters. The low-efficiency prefilters would be superfluous and would only add to the pressure drop. The ability of the existing filter housing to withstand the maximum fan suction, 21 in. WG, must be investigated.

For the pulsed panel system we recommend the configuration with banks 2 and 3 as the after-filters because the equipment and maintenance cost is about the same as for the lowest cost combination, and when power cost is included, it is the lowest cost. The efficiency criterion is better met with bank 2 in the system before the HEPA's. Bank 1 adds essentially no improvement in efficiency

TABLE G.5. Maintenance Costs for Cleanable High-Efficiency Filters

Maker	Replacement	Media Replacement		Man-hr	Media	Media	Dust	Repair					Misc.	Housekeeping	Start-up	Operating	Subtotal	Auxiliary
	Media, sets/20 yr	\$/Unit	\$/20 yr	Per Media Change	Change Labor, K\$	Disposal, \$/20 yr	Disposal, \$/G000 shots	C	P	A	E	B	Repairs, \$/K	Inspection, day/yr	Shutdown, min/day	Labor, \$/K	Maintenance, \$/K	Power, hp
Vendor S	1	700	\$8.40	12	0.74	0.24	24.08	1	1	1			12.94	3	40	118.92	165	6.70
Vendor S	1	700	\$8.40	12	0.74	0.24	24.08	1	1	1			12.54	3	45	131.48	177	6.70
Vendor O	2	500	\$12.00	36	3.35	0.36	24.08	1	1	1	1		21.62	2.5	30	90.13	152	4.79
Vendor Y	19	81	\$36.94	6	3.72	3.64	23.16	1	1	1	1		18.86	3	30	92.61	179	0.72

Repair Code Key

C - Annual compressor maintenance

I - One time replacement of Insulators

A - Annual miscellaneous maintenance

E - One time replacement of cleaning cycle control electronics

B - One time bearing and other repair of blower

A "1" under the repair code column indicates that the repair is applicable to the device and is accounted for in the cost estimate.

TABLE G.6. Twenty-Year Total Costs by Filter Bank Combination for Cleanable High-efficiency Filters

Maker	Bank Combination	Filter Replacement, \$K	Number Bank Changes	System Efficiency, %	System AP, in. WG	Fan Cost, \$K	Total First Cost, \$K	Fan Power, \$K	Equipment and Maintenance, \$K	Power, \$K	Total, \$K
Vendor S Single Stage	1,2,3	5	3	99.99998	22.2	27	187	215	356	221	577
	2,3	5	3	99.99998	21.2	27	187	205	356	212	568
	3	9	3	99.99987	17.2	18	177	166	350	173	523
	1,3	9	3	99.99987	18.2	18	177	176	350	183	533
Vendor S Double Stage	N.A.	9	3	99.999937	15.2	18	197	147	383	154	537
Vendor O Single Stage	1,2,3	5	3	99.99998	26.2	35	187	253	343	258	601
	2,3	5	3	99.99998	25.2	35	187	244	343	248	592
	3	9	3	99.99987	21.2	27	179	205	339	210	549
	1,3	9	3	99.99987	22.2	27	179	215	339	219	559
Vendor Y Pulsed Panel	1,2,3	260	118	99.9991	14.5	18	100	140	539	141	680
	2,3	263	118	99.9991	13.5	18	100	131	542	131	673
	3	502	117	99.9947	11		83	106	764	107	871
	1,3	495	118	99.9947	11		83	106	757	107	864

because the coarse particles it is designed to remove are already filtered by the pulsed panel. In general, we found this to be the case for all the cleanable primary control devices.

REFERENCE

ASHRAE 52-76. 1976. Method of Testing Air Cleaning Devices Used in General Ventilation for Removing Particulate Matter, American Society of Heating, Ventilating, and Air Conditioning Engineers, New York.

APPENDIX H

ROLLING FILTERS

APPENDIX H

ROLLING FILTERS

Most of the rolling filters are in the prefilter category and many were not recommended by the vendors for this application because of the size of the airborne material anticipated. The only roll-type filter which appears to have promise is the peeled-roll filter. The design differs from conventional rolling filters because the airflow passes radially inward through all the layers of media wound on the clean media roll and then out through the end of the roll's core as shown in Figure H.1. The initial roll contains some 44 layers of media and high filtration efficiencies are obtainable with six to ten layers remaining. The unit sized for this application consists of 24 such rolls in a sheet metal housing. When all but the last few layers of media are used, the media is then completely rolled onto the take-up roll so that cleaner media is on the outside of the roll. To remove the media, the top of the housing is removed, a person enters the housing to unlatch the rolls and the rolls are hoisted with a small winch and boom.

In a conventional rolling filter the media are oriented vertically rather than horizontally as was the case for the peeled-roll unit. Instead of air filtration occurring through the rolled media, filtration is performed by the media stretched between the reels for most rolling filters. Only one layer of media is used for filtering. The stretched media is supported by a grill or screen. Generally, the device is inserted between two sections of duct so that the stretched media traverses the duct and the reels are outside the duct. For radiotoxic aerosols, the reels must also be located in an air-tight housing or inside the ductwork.

The media from both types of rolling filters could be disposed of in the same way. The media is removed from the reel core by separating the innermost layer from the core and sliding the media off the end. This procedure would require special containment. Media compaction to 15% of the original volume was assumed. If compaction proved not to be practical, the rolls could be disposed of in special containers, but probably at higher cost because of the

FIGURE H.1. Peeled-Roll Filter Concept

greater volume. The next section gives the total cost estimates for the peeled-roll and a typical rolling prefilter.

COST ESTIMATING

Conventional Rolling Filter

The cost of using this type of rolling filter was estimated using FILTER. The filter contains two rolls with 650 ft^2 of media of which 620 ft^2 were assumed useable. The maximum load of ASHRAE 52-76 (1976) test dust was given as 60 g/ft^2 at 1 in. WG pressure drop. The life load was then assumed to be about $620 \text{ ft}^2 \times 60 \text{ g/ft}^2 = 37,200 \text{ g}$. The media cost was given as \$200/roll for a total of $2 \times \$200 = \400 per replacement. The labor and disposal costs were added as shown in Table H.1.

TABLE H.1. Rolling Filter Media Replacement Cost

Media, 2 rolls	\$400
Change-out, 4 man-hr	124
Compaction, 2 man-hr	62
Disposal cost = $0.15 \times$ $1 \text{ ft} \times 1 \text{ ft} \times 10 \text{ ft}$ $= 1.5 \text{ ft}^3$ at \$25/ft ³	38
Total	\$628

The filter efficiency data were obtained from a graph furnished by the manufacturer; however, the method of determination was unknown. The efficiencies are listed in Table H.2.

TABLE H.2. Rolling Filter Efficiency Data

Particle Diameter, μm	Collection Efficiency
0.1	0.0001*
0.32	0.0001*
1.0	0.18
3.2	0.57
10.0	0.88
32.0	0.999*
100.0	0.9999*

* Indicates an extrapolated value.

The results of the cost estimate for the conventional rolling filter are shown in Tables H.3 through H.6. The overall system efficiencies were about an order of magnitude lower than the performance criterion, but were the same as the existing system. The acquisition costs of the rolling filter were unavailable and were ignored; however, this device was not considered as a serious contender because the filter replacement costs were about the same as the existing system. If this ACS is to be considered, it would be used with all three of the existing filter banks downstream.

Peeled-Roll Filter

No fractional efficiency data were available for this device. Consequently, data from Table H.2 were used because the type of media is similar. The assumed minimum number of media layers was ten. Equation (H.1) shows how the efficiency was calculated. The method for one particle size was to calculate the fractional penetration by subtracting the efficiency from one. The penetration is then multiplied by itself for each layer of media. The result is subtracted from one to calculate an efficiency again. This process was repeated for each particle size bracket and the results are listed in Table H.7. These efficiency values served as input to FILTER to calculate the cost of the different combinations of disposable filters. The FILTER results

TABLE H.3. Characteristics of Rolling Filters

<u>Device Type</u>	<u>Number Media Units</u>	<u>Media, ft²</u>	<u>Compressed Media, ft³/set</u>	<u>Wall Thickness, in.</u>	<u>Grams to Hopper Per Shot</u>	<u>Auxiliary Run Fraction, hr/hr</u>	<u>Auxiliary Equipment, hp</u>
Peeled Roll	24	28,800	90	0.1046	0	0	0
Conventional Roll	2	50					

TABLE H.4. Rolling Filter Initial Costs

<u>Device Type</u>	<u>Unit, \$K</u>	<u>Auxiliary Equipment, \$K</u>	<u>Erection Pad, Duct etc., \$K</u>	<u>Subtotal \$K</u>
Peeled Roll	167	0	58.5	226
Conventional Roll	3		10	13

TABLE H.5. Peeled-Roll Filter Installation Costs

<u>Item</u>	<u>Cost, \$</u>
Pad, 22 x 30 ft	4,700
Airflow controls	10,000
Seven-gauge ducts plus installation	20,900
Pressure test	1,900
Electrical	6,400
Drum scale	8,100
Additional erection	6,500
Total	\$58,500

TABLE H.6. Maintenance Costs for Rolling Filter

Device Type	Replacement Media, Sets/20 yr	Replacement Media, \$/unit	Replacement Media, \$K/20 yr	Man-hr Per Media Change	Media Change Labor, \$K	Media Disposal, \$K/20yr	Dust Disposal, \$K/6000 shots	Repair Codes C P A E B	Misc. Repairs, \$K	Housekeeping Inspection, day/yr	Start-up Shutdown, min/day	Operating Labor, \$K	Subtotal Maintenance, \$K
Peel Roll	2	750	36.00	24	2.23	8.98	0.00	1	9.92	3	20	66.70	124
Conventional Roll								1	9.92	2.5	20	64.22	74

Repair Code Key

C - Annual compressor maintenance

P - Semi-annual pulse valve rebuilds

A - Annual miscellaneous maintenance

E - One time replacement of cleaning cycle control electronics

B - One time bearing and other repair of blower

A "1" under the repair code column indicates that the repair is applicable to the device and is accounted for in the cost estimate.

TABLE H.7. Peeled-Roll Filter Fractional Efficiency

<u>Particle Diameter,</u> <u>μm</u>	<u>Collection</u> <u>Efficiency</u>
0.1	0.001
0.32	0.001
1.0	0.863
3.2	0.99978
10.0	0.999999999
32.0	1.0
100.0	1.0

showed efficiencies an order of magnitude lower than the criterion, even if the coarser size distributions were used. The cost of the disposable filters used in 20 years was about 75% that of the existing system.

$$\text{Peeled-roll efficiency} = 1 - (1 - \text{Conventional roll efficiency})^{10} \quad (\text{H.1})$$

Table H.3 summarizes some of the characteristics of the two types of rolling filters. Table H.4 shows the initial cost of procuring the peeled-roll filter excluding the fan cost. The estimate for installation of the filter was calculated as shown in Table H.5 using estimates for the individual items from Appendix K. No extra auxiliary equipment was required to operate the system. Other than flow controls, no installation cost estimate was made for the conventional rolling filter because it was not considered as a serious option because of its low efficiency.

The peeled-roll filter is designed to operate at a high pressure drop, 10 in. WG, enabling the collection of large amounts of particles. For the dust loading expected at the range, the manufacturer estimated that media life is about 2000 shots, requiring two replacements in 20 years. The estimated media replacement, change labor, and disposal costs are shown in Table H.6. These cost items for the conventional rolling filter were included in the estimates generated by FILTER, so they are not included in Table H.6. No repairs were estimated for the rolling filters, only the 16 man-hr/yr for annual maintenance and the indicated operating labor.

Table H.8 shows various performance data and total costs for each combination of rolling filter and disposable filter bank combination. The existing filters were assumed for the filter banks; thus, banks 1, 2, and 3 consisted of first prefilter, second prefilter, and HEPA filters, respectively. The disposable filter replacement cost is the 20-year cost of new filters and disposal of used filters as estimated by FILTER. For the conventional rolling filter, the disposable filter cost also includes the costs of the roll media and its disposal. The total number of times a filter bank replacement may occur and the overall system filtration efficiency were also estimated by FILTER and are listed in Table H.8. System pressure drop accounts for the building ductwork, the rolling filter, and the maximum load on the disposable filters. The fan cost selection was based on the pressure drops listed. Total maintenance and acquisition costs for each combination are the sum of maintenance from Table H.3, first cost from Table H.2, disposable filter usage, and fan costs from Table H.4. Power costs are calculated and added to the equipment and maintenance cost.

The overall efficiencies shown in the table were not substantially better than the existing system and do not meet the performance criterion stated in Table 1 (~99.9984%). The overall 20-year operating cost for the peeled-roll system was estimated to be about 75% of that of the existing system, which is a small improvement when compared to the systems with cleanable media. The estimated cost of using the conventional rolling filter was intermediate between the peeled-roll and the existing system. If the peeled-roll approach were implemented, all of the current disposable filters except bank 1 should also be used because that combination resulted in lowest cost for the system. All three of the disposable filter banks should be used downstream of the conventional roll. The rolling filters are not highly recommended because of their high cost and low efficiency relative to other devices.

TABLE H.8. Twenty-Year Cost of Rolling Filter

Maker	Bank Combination	Disposable Filter Replacement, \$K	Number Bank Changes	System Efficiency, %	System ΔP , in. W.G.	Fan Cost, \$K	Total First Cost, \$K	Fan Power, \$K	Total Cost, \$K		
									Equipment and Maintenance	Power	Grand Total
Vendor G, Peeled Roll	1,2,3	3243	1440	99.989	21	27	253	203	3619	203	3822
	2,3	3244	1440	99.989	20	27	253	193	3620	193	3814
	3	6169	1438	99.933	16	17.5	243	155	6536	155	6691
	1,3	6168	1438	99.933	17	17.5	243	164	6535	164	6699
Vendor A, Conventional Roll	1,2,3	4362	2511	99.989	12.2	18	31	118	4467	118	4585
	2,3	4804	2391	99.989	11.2		13	108	4891	108	4999
	3	9396	2389	99.932	11.2		13	108	9483	108	9591
	1,3	8299	2510	99.932	11.2		13	108	8386	108	8494

APPENDIX I

VANED INERTIAL SEPARATOR

APPENDIX I

VANED INERTIAL SEPARATOR

I.1 DESCRIPTION

The vaned inertial separator is rated at 80% efficiency (ASHRAE 52-76). Ninety percent of the airflow is sharply turned through vanes while 10% of the airflow proceeds in a straight line. Because large particles cannot follow the rapid change in direction through the vanes, they follow the 10% airflow in a straight line. The 10% airflow, now more heavily laden with particles, passes through a pulsed-panel unit that removes 80% to 90% of the particles. The 90% airflow from the vaned inertial separator and the exhaust from the pulsed panel are combined and passed through a second pulsed panel. The airflow through the vaned inertial separator/pulsed-panel combination is diagrammed in Figure I.1. A section of a vaned inertial separator is shown in Figure I.2. The vaned inertial separator would be enclosed in a sheet metal housing.

FIGURE I.1. Vaned Inertial Separator Equipment Arrangement

FIGURE I.2. Vaned Inertial Separator

I.2 COLLECTION EFFICIENCY

To calculate the usage of the disposable filters, overall efficiency data for the combined vaned inertial separator--pulsed-panel system were required. Efficiency data for the vaned inertial separator were obtained from the manufacturer and are listed in Table I.1. The pulsed-panel efficiency data are listed in Table G.2.

Figure I.1 illustrated how the vaned inertial separator and pulsed-panel are combined. The dirty air from the vaned inertial separator passes through pulsed-panel No. 1, where particles are removed, and then to pulsed-panel No. 2 for further particle removal. The clean air from the vaned inertial separator goes directly to pulsed-panel No. 2 for particle removal. The size distribution from pulsed-panel No. 2 is needed to calculate the usage of the disposable filters. The dirty airflow from the vaned inertial separator is about 10% of the inlet airflow; thus, pulsed-panel No. 1 was sized for only 2400 acfm.

TABLE I.1. Fractional Filter Efficiency Data for Vaned Inertial Separator

<u>Particle Diameter, μm</u>	<u>Collection Efficiency</u>
0.1	0.18*
0.32	0.18*
1.0	0.30*
3.2	0.67
10.0	0.985
32.0	0.999*
100.0	0.9999*

* Indicates an extrapolated value

Table I.2 shows the calculation of the combined efficiency for the system shown in Figure I.1. The initial distribution of aerosol mass is that of Size Distribution No. 3 from Table 5. The mass of particles in each size bracket passed to pulsed-panel No. 1 was calculated by multiplying the initial mass distribution column by the vaned inertial separator efficiency column and the balance of the particles go on to pulsed-panel No. 2. The mass collected in pulsed-panel No. 1 was obtained by multiplying the quantity from the vaned inertial separator by the pulsed-panel efficiency values, and the uncollected fractions are passed as additional input to pulsed-panel No. 2. The combined inputs to pulsed-panel No. 2 are multiplied by the pulsed-panel efficiency values to compute the amounts collected from which the overall fractional efficiencies for the combined system were computed. The total efficiency for the original aerosol was estimated to be about 97%, which was only slightly better than the efficiency of a single pulsed-panel alone (96%). The overall fractional efficiencies for these combined devices was used as an input to FILTER to compute the usage of the combinations of disposable after-filters. Thus, for such a fine aerosol size distribution, the vaned inertial separator accomplishes little; however, it would serve as a good barrier to particles in the size range where cyclones are also effective, but with a lower pressure drop than the cyclones.

TABLE I.2. Calculation of Combined Vaned Inertial Separator
and Pulsed-Panel Efficiency

<u>Size Bracket</u>	<u>Inlet Mass Dis- tribution, g</u>	<u>Vaned Inertial Separator Efficiency, %</u>	<u>Grams to Pulsed- Panel No. 1</u>	<u>Grams to Pulsed- Panel No. 2</u>	<u>Pulsed- Panel Efficiency, %</u>
1	1519	0.18	2.73E+02	1.25E+03	0.92
2	686	0.18	1.23E+02	5.63E+02	0.93
3	735	0.3	2.21E+02	5.15E+02	0.98
4	637	0.67	4.27E+02	2.10E+02	0.996
5	539	0.985	5.31E+02	8.09E+00	0.999
6	343	0.999	3.43E+02	3.43E-01	0.9999
7	441	0.9999	4.41E+02	4.41E-02	0.99999
Total	4900		2.36E+03	2.54E+03	

<u>Size Bracket</u>	<u>Pulsed-Panel No. 1</u>		<u>Pulsed-Panel No. 2</u>		<u>Grams To Disposable Filters</u>	<u>Combined System Efficiency, %</u>
	<u>Grams Collected</u>	<u>Grams Penetrated</u>	<u>Total Grams In</u>	<u>Grams Collected</u>		
1	2.52E+02	2.19E+01	1.27E+03	1.17E+03	1.01E+02	0.933248
2	1.15E+02	8.64E+00	5.71E+02	5.31E+02	4.00E+01	0.941718
3	2.16E+02	4.41E+00	5.19E+02	5.09E+02	1.04E+01	0.98588
4	4.25E+02	1.71E+00	2.12E+02	2.11E+02	8.48E-01	0.99866928
5	5.30E+02	5.31E-01	8.62E+00	8.61E+00	8.62E-03	0.99998401
6	3.43E+02	3.43E-02	3.77E-01	3.77E-01	3.77E-05	0.99999989
7	4.41E+02	4.41E-03	4.85E-02	4.85E-02	4.85E-07	0.99999999
Total	2.32E+03	3.72E+01	2.58E+03	2.43E+03	1.53E+02	0.96885464

COST ESTIMATING

Table I.3 contains a descriptive summary of the characteristics of the vaned inertial separator/pulsed-panel system. Table I.4 shows the initial acquisition costs. To estimate the acquisition cost for the vaned inertial separator system we assumed that the installation cost was about the same as for the pulsed-panel alone (Table G.4). Table I.5 shows the estimate for 20-year maintenance of the system excluding the cost of downstream disposable filters. The estimating method is described in the main report (pp. 12-23). The pulsed-panel media life was assumed to be 1 year, and the total number of filter units would be 28 for both units No. 1 and 2 together. Media compaction was the same as for the pulsed-panel alone. The repair items considered were compressor maintenance, pulse valve rebuilds, miscellaneous annual maintenance, and the replacement of filters.

Table I.6 shows various performance data and total costs for the vaned inertial separator system and each disposable filter bank combination. The existing filters were assumed for the filter banks; thus, banks 1, 2, and 3 consisted of the first prefilter, second prefilter, and high-efficiency particulate air (HEPA) filters, respectively. The disposable filter replacement cost is the 20-year cost of new filters and disposal of used filters as estimated by FILTER. The total number of times a filter bank replacement may occur and the overall system filtration efficiency was also estimated by FILTER and listed in the table. System pressure drop accounts for the building duct work, the vaned inertial separator system, and the maximum load on the disposable filters. However, the use of pulsed panel No. 1 requires a booster fan between it and pulsed panel No. 2. The pressure drops across the vaned inertial separator and pulsed panel No. 2 were taken as 1.1 and 3.3, respectively, for a total of 4.4 in. WG. This was added to the total for the building, duct work, and after filters to determine the price of the main fan. The booster fan would also see a pressure drop of about 4.4 in. WG and \$8K was the assumed price of the booster fan. The pressure drops listed in the table were estimated for the overall system with 4.4 in. WG added so that power costs would be estimated for both fans. Total maintenance and acquisition costs for each

TABLE I.3. Vaned Inertial Separator Descriptive Summary

Media Access	Solenoid Pulse Valves	Number Media Units	Media, ft ²	Compressed Media, ft ³ /set	Wall Thickness, in.	Grams to Hopper Per Shot	Auxiliary Run Fraction, hr/hr	Auxiliary Equipment, hp
Hopper Hatch	5	28	5600	5.6	0.1196	4747	0.2	3

TABLE I.4. Vaned Inertial Separator Initial Costs, Excluding Fan

Unit, \$K	Auxiliary Equipment, \$K	Erection Pad, Duct, etc., \$K	Freight, \$K	Subtotal, \$K
25	5.5	60.1	3	94

TABLE I.5. Vaned Inertial Separator Twenty-Year Maintenance

Replacement media, sets/20 yr	Media Replacement \$/unit	Media Replacement \$K/20 yr	Media Change, man-hr	Media Change, Labor \$K	Media Disposal, \$K/20 yr	Dust Disposal, \$K/6000 shots	Repair Codes C P A E R	Miscellaneous Repairs, \$K	Housekeeping Inspection, day/yr	Start-up Shutdown, min/day	Operating Labor, \$K	Subtotal Maintenance, \$K	Auxiliary Power, \$K
19	81	\$43.09	9	5.58	4.25	23.33	1 1 1 1	19.21	3.5	30	95.09	191	0.72

Repair Code Key

- C - Annual compressor maintenance
- P - Semi-annual pulse valve rebuilds
- A - Annual miscellaneous maintenance
- E - One time replacement of cleaning cycle control electronics
- R - One time bearing and other repair of blower

A "1" under the repair code column indicates that the repair is applicable to the device and is accounted for in the cost estimate.

TABLE I.6. Twenty-Year Total Costs by Filter Bank Combination for Vaned Inertial Separator and Pulsed-Panel System

Bank Combination	Disposable Filter Replacement, \$K	Number Bank Changes	System Efficiency, %	System AP, in. WG	Fan Cost, \$K	Total First, Cost \$K	Fan Power, \$K	Equipment and Maintenance, \$K	Power, \$K	Total, \$K
1,2,3	214	96	99.9993	19.6	26	119	190	524	190	714
2,3	215	96	99.9993	18.6	26	119	180	525	181	705
3	409	96	99.9956	14.6	10	104	141	703	142	845
1,3	407	96	99.9956	15.6	18	112	151	709	152	861

combination are the sum of maintenance from Table I.5, first cost from Table I.4, disposable filter usage, and fan costs from Table I.6. Power costs are calculated and added to the equipment and maintenance cost.

The equipment and maintenance costs for using this system were slightly lower than for the pulsed panel alone; however, when power consumption is included, the vaned inertial separator system was slightly more expensive than the pulsed-panel alone. If this approach were to be implemented, the after-filters should include the second prefilter and the HEPA banks because this combination yielded the lowest cost.

APPENDIX J

CHARGED WATER MIST

APPENDIX J

CHARGED WATER MIST

A local-dust-control unit was uncovered during this study. The unit supposedly generates a fine charged mist that evaporates, leaving charged particles in the air. These particles attract and agglomerate with airborne material producing larger particles that deposit locally by gravity. Such a unit(s) could be positioned in the target bay in a shielded position. Once the initial blast effects have passed, the units could be started and may enhance the rapid settling of the airborne material locally. Because the efficacy of the device is uncertain and a pilot study is needed, it has not been considered further in this report.

APPENDIX K

INSTALLATION COST ESTIMATES

APPENDIX K

INSTALLATION COST ESTIMATES

A few of the air cleaning equipment vendors contacted were willing to supply budget estimates for the turnkey installation of their equipment and adaptation to the existing ductwork and filter house; however, most vendors were unable to do so, either because of the time involved or the fact that they did not do turnkey work. To put the 20-year life cost estimates for the different devices on a common footing, it was decided to obtain authoritative installation estimates from an outside licensed engineering firm. Kaiser Engineers Hanford Company, Richland, Washington, was requested to supply estimates for concrete pads; air compressors; fans; airflow controls; electrical service; pressure testing; freight to jobsite; fabrication and installation of ductwork; erection of new air cleaning equipment; relocation of the existing filter house; sheds to cover compressors, hopper dumping stations, or the entire pad; and drum-handling equipment (e.g., dollies and scales). Labor and material costs were based on Mossman's (1982) cost index for Baltimore. Table K.1 summarizes the totals for each item.

The concrete pad estimates included labor and material for excavating, backfilling, forming, concrete, finishing, rebar (100 lb/yd^3), form stripping, and curing. The estimates for the air compressors included receiver tank, auto trap on tank, air-cooled compressor, low-oil-level switch, enclosed motor, dual controls, heavy duty filter, dryer, piping, heat tracing, and insulation.

The estimates for sheds (Table K.1, items 8 and 9) included metal walls, lights, heat, ventilation, electrical service, insulation, windows, side doors, overhead doors, water, and sewer. The basic cost estimate was $\$35/\text{ft}^2$ of floor space and for a wall height up to 12 ft. For wall heights over 12 ft, $\$8.50$ was added for each additional foot in wall height per foot of building perimeter. The hopper dump shed was based on an area of 150 ft^2 . This shed could be employed where a total system building was not used and could be built around the bottom of an ESP, baghouse, or other device with sufficient

TABLE K.1. Cost Estimate Summary for Installation,
Fans and Auxiliary Equipment

Item	Description	Estimated Cost, \$
1.	Concrete pad, 22 x 30 ft	4,700
2.	Concrete pad, 16 x 100 ft	11,200
3.	Air compressor, 8.5 scfm @ 100 psig, 3 hp	5,500
4.	Air compressor, 15.3 scfm @ 100 psig, 5 hp	5,600
5.	Air compressor, 32 scfm @ 100 psig, 7 hp	9,900
6.	Air compressor, 39 scfm @ 100 psig, 10 hp	10,000
7.	Air compressor, 77.7 scfm @ 100 psig, 20 hp	14,800
8.	Hopper dump shed	5,300
9.	Shed cover for pad	19,400
10.	Shed for air compressor	2,800
11.	Drum dollies, each	40
12.	Drum scale, low ramp, digital	8,100
13.	Drum scale, warehouse platform	4,100
14.	Single inlet Fan, 23 in. WG vac., 110 hp	27,000
15.	Single inlet Fan, 17 in. WG vac., 100 hp	17,500
16.	Single inlet Fan, 13 in. WG vac., 75 hp	17,000
17.	Upgrade existing Fan To 13 in. WG vac. 75 hp	10,000
18.	Same fan cap. as #14. in existing housing	19,200
19.	New fan housing for existing fan	6,000
20.	Fan motor speed and airflow controller, 75 hp	12,800
21.	Fan motor speed and airflow controller, 100 hp	15,100
22.	Fan motor speed and airflow controller, 125 hp	17,900
23.	Fan motor speed and airflow controller, 150 hp	20,800
24.	Install new system, 16 gauge galvanized ducts	11,400
25.	Install new system, 7 gauge carbon steel ducts	20,900
26.	Install new system, 7 gauge stainless steel ducts	26,900
27.	Pressure test ductwork to filter house	1,900
28.	Move electrical services, hookups	6,400
29.	Freight rates (sample, 50,000 lb, Chicago to Aberdeen)	1,200
30.	Vortex dampers, electrical airflow controls	10,000

clearance. The shed would permit dumping of the hopper and changing and filling of the drum under all weather conditions. The estimate for a metal shed totally enclosing the air system was an example for an enclosure 20 x 20 x 20 ft high. The air compressor housing was estimated in the same way using a floor space of 80 ft²; however, the insulation would not be needed and a separate concrete pad would be used. The drum dollies would facilitate movement of the drums and have a capacity of 800 to 1400 lb. The digital low-ramp scale allows the drum plus dolly to easily be rolled onto the scale, and its capacity is 2000 lb. The warehouse platform scale had a capacity of 4000 lb

and a 4- x 3-ft platform. A ramp would have to be fabricated separately or the drums hoisted onto the platform. Generous allowances were made for shipping and other overheads.

The estimates for new fans were supplied by a major vendor. These estimates included variable inlet vanes (vortex dampers) and belt or direct drives. These fans would be mounted externally to the existing filter house permitting some maintenance and inspection without breaking the vacuum seal of the housing. The estimate to upgrade the existing fan to its maximum 13 in. WG suction capacity was based on specifications furnished by the manufacturer; estimates for the motor, vortex damper, and drive were obtained locally. An example of installing a new larger vacuum capacity fan of the same configuration (double width, double inlet) in the existing housing was given as item 18. If it were desirable to build a larger separate fan housing for a double-width double-inlet fan, a cost estimate is provided as item 19. The construction of this housing would be with a 12-gauge inner wall, angle iron bracing, and 18-gauge outer wall. For this study, we recommend using the new single-width, single-inlet fan outside the filter house for capacities over 13 in. WG. For a capacity between 11 and 13 in. WG, the upgrade for the existing fan was used as the cost estimate. For capacities below 11 in. WG, it was assumed that the existing fan would be used and vortex dampers and flow controls added so the fan would continue to operate at 11 in. WG.

Two types of flow rate controls were estimated, motor speed control and vortex damper control (items 20 through 23, and 30). The motor speed controls use a velocity transducer and solid state motor speed control in a feedback control loop. Manual speed/flow setting was also included. The other system uses an averaging pitot tube and electronic pressure transducer, controller, and motor to drive vortex dampers. The transducer, controller, and dampers were included in the estimate to allow the upgrading of the existing fan. This estimate was used for this study; however, the motor speed control would allow easy reduction of airflow for special conditions such as maintaining a low airflow while cleaning shock attenuators, changing filter media, or other maintenance.

The installation and ductwork estimate included several tasks: shop fabrication of ducts from the shock attenuators to the new filter device and to the existing filter house, a new outlet duct/stack from the existing filter house, labor to install and paint ducts and supports, labor to set new device in place, crane time, and labor to move the existing filter house to a new pad. Eighty man-hours each were budgeted for relocating the filter house and erecting the new device. Some new devices would require additional erection time. This was estimated by the vendors and added to the individual estimates as appropriate.

The leak test estimate included 32 man-hr of labor and the fabrication of plugs to seal the system. The electrical service estimate allowed for disconnecting the existing fan, reconnecting to the new fan and new controls. The example freight estimate assumed the use of a flat bed trailer. The individual cost estimates were used as explained in the appropriate appendix covering each filtration device. The cost estimates were current as of November 1983.

REFERENCE

Mossman, M. J., (ed). 1982. Mechanical and Electrical Cost Data. 1983. 6th Edition, Robert Snow Means Company, Inc., Kingston, Massachusetts.

APPENDIX L

COST ANALYSIS SUMMARY METHOD

APPENDIX L

COST ANALYSIS SUMMARY METHOD

The cost analysis summary table discussed in the main report (pp. 24-29) was derived from the data tabulated in Appendices B through J and from the FILTER outputs described in Appendices B and C. In most cases, the values shown in the report did not come directly from the other tabulations, but had to be derived from their data because of the different formats of the tables. This appendix describes the derivation of the summary values for the configurations recommended for each type of air cleaning device. Table L.1 shows how the labor, disposal volume, and replacement filter costs were calculated separately for the disposable filters of the type used in the existing filter banks that may be used downstream of any new device. FILTER lumped all these costs into a single output value, but they must be broken out to develop the summary table. The first part of the table shows the number of man-hours, compacted filter volume, and new filter cost associated with the change of a filter bank. The second part of the table shows the calculations for each device in their recommended configurations. The first three columns of data are the number of times each filter bank would be changed during exposure to 6000 shots with 4900 g of aerosol generated per shot, as estimated by FILTER. The man-hours, filter cost, and compacted volume for each bank were multiplied by the number of respective bank changes. The estimated quantity of dust collected from each shot was also listed. Calculated values could be scaled to allow for changes in the assumptions characterizing the shots. The total cost of using disposable filters was calculated as a check against FILTER. A disposal cost of \$24.26/ft³ (the value used in FILTER) was assumed for the check; however, \$25/ft³ was used for the rest of the cost estimates described below.

The first two columns of Table L.2 list the recommended configuration for each device. The next two columns list the initial investment and the overall system filtration efficiency of each system (rounded to nine digits, values of one are not real). The labor for changing the disposable filters was taken

TABLE L.1. Breakdown of Disposable Filter Usage Costs

Device	Filter Changes per 6000 shots			Changeout Labor, man-hr	New Media, \$	Media Disposal, ft ³	Disposal Labor, man-hr	Dust Collected by Cleanable Device /shot, g	Dust Per Shot Scaled, g	Total, \$K
	Bank 1	Bank 2	Bank 3							
Electrostatic Baghouse	0.00	4.90	0.98	25.41	10981	64.81	12.73	4900	4900	14
Baghouse, Pulse-jet, Std. Felt	0.00	25.83	0.06	52.70	42046	219.76	51.85	4900	4900	51
Baghouse, Pulse-jet, Coated Bag	0.00	1.36	0.01	2.80	2222	11.63	2.74	4900	4900	3
Baghouse, Shaker, Std. Sateen	0.00	0.49	0.00	1.05	813	4.27	1.00	4900	4900	1
Cartridge, Standard	0.00	37.23	7.33	191.71	83180	490.41	96.45	4900	4900	104
Cartridge, Coated Media	0.00	0.44	0.08	2.08	947	5.52	1.10	4900	4900	1
Cleanable High-Efficiency Filter, 1-stage	0.00	1.75	0.33	8.80	3875	22.76	4.50	4900	4900	5
Cleanable High-Efficiency Filter, 2-stage	0.00	0.00	2.08	33.31	6496	49.97	6.25	4900	4900	9
Vaned Inertial and Pulsed-Panel	0.00	83.02	12.34	363.43	172988	997.46	203.06	4747	4747	215
Electrostatic Precipitator	0.00	25.60	3.11	100.91	51169	290.85	60.52	4854	4854	63
Pulsed-Panel	0.00	102.27	14.81	441.48	211878	1219.37	248.96	4713	4713	263
Existing System	1641.60	1720.20	192.85	9809.14	3631364	20920.37	5660.54	0	0	4618
Conventional Rolling Filter	401.09	1683.96	192.78	7254.62	3388860	19282.85	4347.36	0	0	4216
Extended Surface at Bank 2	1641.60	755.651	495.79	14238.39	3639634	33063.67	4640.25	0	0	5027
Peeled-Roll Filter	0.00	1252.02	187.42	5502.74	2613016	15075.10	3066.29	0	0	3244
Single Cyclone	92.40	1496.63	189.83	6215.42	3030501	17298.62	3655.17	2098	2098	3756

TABLE L.2. Breakdown of Initial Investment and Maintenance Costs

Device	Filter Bank	Initial Investment, \$K	System Filtration Efficiency, %	Labor, man-hr				Total Labor, man-hr	Labor Cost, \$K	Total Parts, \$K	Total Maintenance, \$K
				Media Change		Repairs	Operation				
				Cleanable	Disposable						
Electrostatic Baghouse	2,3	167	0.99999937	550	25	548	3823	4946	153.34	3.25	156.59
Baghouse, Pulse-jet, Std. Felt	2,3	157	0.999999998	1320	53	548	2827	4748	147.18	7.72	154.90
Baghouse, Pulse-jet, Coated Bag	2,3	157	0.999999999	1056	3	548	2827	4434	137.45	7.72	145.17
Baghouse, Shaker, Std. Sateen	2,3	134	0.999999999	2880	1	324	2987	6192	191.96	0.50	192.45
Cartridge, Standard	2,3	129	0.999995	165	192	548	2827	3732	115.68	7.72	123.41
Cartridge, Coated Media	2,3	129	0.99999995	165	2	548	2827	3542	109.80	7.72	117.53
Cleanable High-Efficiency Filter, 1-stage	2,3	187	0.9999998	66	9	444	3365	3884	120.40	3.32	123.71
Cleanable High-Efficiency Filter, 2-stage		197	0.99999937	24	33	340	4241	4638	143.79	2.00	145.79
Vaned Inertial and Pulsed Panel	2,3	119	0.999993	180	363	548	3067	4158	128.91	2.22	131.13
Electrostatic Precipitator	2,3	466	0.9999984		101	487	2839	3427	106.23	0.80	107.03
Pulsed-Panel	2,3	100	0.999991	120	441	548	2987	4096	126.99	1.88	128.87
Existing System	1,2,3	20	0.99989		9809	320	1912	12041	373.28		373.28
Conventional Rolling Filter	1,2,3	31	0.99989	934	725	324	2072	10585	328.12	0.50	328.62
Extended Surface at Bank 2	1,2,3	10	0.99975		14238	320	1912	16470	510.58		510.58
Peeled-Roll Filter	2,3	253	0.99989	72	5503	320	2152	8047	249.45	0.50	249.95
Single Cyclone	1,2,3	112	0.99989		6215	320	1912	8447	261.87		261.87

from Table L.1. The labor for changing the cleanable filter media and for operating the system was taken from the tabulations in Appendices B through J. The labor and parts costs for performing various repairs were calculated using the methods outlined in the main report (p. 18-22), and assuming \$31/man-hr. The table shows the total number of man-hours and its associated cost and the total 20-year maintenance cost for each system.

Table L.3 shows the calculation of power, replacement filter media, and waste disposal costs for each candidate system. The power cost, from the tabulations in Appendices B through J, was divided by \$0.04/kWh to estimate the megawatt hours that would be consumed in 20 years. The disposable media costs were from Table L.1 and the cleanable media replacement costs from the tabulations in Appendices B through J. The total cost for filter media replacement was then calculated. The labor required to dispose the cleanable media was calculated as suggested in Equation (2). The labor required to dispose of the disposable filters was taken from Table L.1. The labor to dispose of the dust collected from the hoppers into drums was calculated as suggested by Equation (4). The labor hours were summed and multiplied by \$31/man-hr to calculate the labor cost. The compacted volume of cleanable filter media was taken from the estimates of Appendices B through J and the volume of disposable filters from Table L.1. The amount of dust collected per shot, from Table L.1, was multiplied by 6000 shots and divided by 3×10^5 g per drum to estimate the number of drums the dust would fill; this in turn, was multiplied by 7.35 ft^3 , the volume of a 55-gal drum. The volume of compacted filters and dust was summed and multiplied by $\$25/\text{ft}^3$ to estimate the disposal cost without labor. The sum of the disposal cost and labor cost equals the total waste disposal cost. Tables L.1 to L.3 served as the basis for the summary table on pp. 27-29 of the main report. These cost estimates were compared against those generated in Appendices B through J and any differences were reconciled. The only remaining difference occurred because a disposal cost of $\$24.26/\text{ft}^3$ was used in FILTER and $\$25/\text{ft}^3$ was used in this Appendix and elsewhere. This resulted in only a small difference (less than 1%) in those systems where the usage of disposable filters was very high, so cost ranking was unaffected.

TABLE L.3. Breakdown of Power, Replacement Media, and Waste Disposal Costs

Device	Power		New Media, \$K			Labor, man-hr			Total, man-hr	Labor Cost, \$K	Volume, ft ³			Nonlabor Disposal Cost, \$K	Waste Disposal Total, \$K
	\$K	MW/hr	Cleanable	Disposable	Total	Cleanable Media	Disposable Media	Dust			Cleanable Filters	Disposable Filters	Dust		
Electrostatic Baghouse	160	4000	8.91	10.98	19.89	5	13	196	214	6.63	290	65	720	26.88	33.50
Baghouse, Pulse-Jet, Std. Felt	160	4000	17.52	42.05	59.57	11	52	196	259	8.02	460	220	720	35.00	43.03
Baghouse, Pulse-Jet, Coated Bag	160	4000	91.38	2.22	93.60	9	3	196	208	6.44	368	12	720	27.50	33.94
Baghouse, Shaker, Std. Sateen	118	2950	47.86	0.81	48.67	24	1	196	221	6.85	522	4	720	31.16	38.02
Cartridge, Standard	139	3475	38.61	83.18	121.79	55	96	196	347	10.77	317	490	720	38.19	48.96
Cartridge, Coated Media	139	3475	38.61	0.95	39.56	55	1	196	252	7.82	317	6	720	26.07	33.89
Cleanable High-Efficiency Filter, 1-stage	230	5750	10.2	3.87	14.07	3	5	196	204	6.31	6	23	720	18.73	25.04
Cleanable High-Efficiency Filter, 2-stage	154	3850	8.4	6.50	14.90	3	6	196	205	6.36	6	50	720	19.41	25.77
Vaned Inertial/Pulsed-Panel	181	4525	43.09	172.99	51.17	47	203	190	440	13.64	112	997	698	45.18	58.82
Electrostatic Precipitator	124	3100		51.17	51.17		61	194	255	7.90		291	714	25.11	33.00
Pulsed-Panel	131	3275	36.94	211.88	248.82	40	249	189	477	14.80	96	1219	693	50.20	65.01
Existing System	128	3200		3631.36	3631.36		5661	0	5661	175.48		20920	0	523.01	698.49
Conventional Rolling Filter	118	2950	93.4	3388.86	3482.26	467	4347	0	4814	149.25	350	19283	0	490.82	640.07
Extended Surface at Bank 2	108	2700		3639.63	3639.63		4640	0	4640	143.85		33064	0	826.59	970.44
Peeled-Roll Filter	193	6575	36	2613.02	2649.02	72	3066	0	3138	97.29	270	15075	0	383.63	480.91
Single Cyclone	263	6575		3030.50	3030.50		3655	84	3739	115.91		17299	308	440.18	556.09

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