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EVALUATION OF AIR CLEANING SYSTEMS FOR FFTF CONTAINMENT MARGINS

Hanford Engineering Development Laboratory

APPLIED TECHNOLOGY

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A.K. Postma

R.K. Hilliard

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ABSTRACT

Alternative air cleaning concepts were evaluated for possible application to FFTF containment margins. For evaluation purposes, it was assumed that the air cleaning system must process 3.07 m³/s (6500 ACFM) of gas containing sodium compound aerosols (mainly NaOH) at temperatures up to 407°C (700°F) and pressures up to 0.184 MPa (26.4 psia) and accommodate 5450 kg (12,000 lb) of aerosol material. Three systems designed for 90% efficient removal (a venturi scrubber, a submerged gravel scrubber and a spray scrubber) were compared. The submerged gravel scrubber and the venturi scrubber were rated as prime candidates. Four systems designed for 99% removal efficiency (the two "optimum scrubbers" chosen for 90% removal efficiency fitted with fibrous elements, a sand and gravel filter and a HEPA filter bank) were compared. The two scrubbers were again rated as prime candidates. Both the sand and gravel filter and the HEPA filter bank were found to be excessively large and costly. Considerable experience supports the use of the "optimum" scrubber systems and it is concluded that their use is technically feasible for the FFTF containment margins application.

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CONTENTS

	<u>Page</u>
Abstract	iii
Acknowledgments	iv
Figures	vii
Tables	viii
I. SUMMARY AND CONCLUSIONS	1
A. SUMMARY	1
B. CONCLUSIONS	1
II. INTRODUCTION	3
III. AIR CLEANING REQUIREMENTS	5
A. BASIS	5
B. THERMAL CONDITIONS	5
C. CHEMICAL FORMS OF GASES AND AEROSOLS	7
D. AEROSOL PARTICLE SIZE DISTRIBUTION	8
E. GAS FLOW RATE	9
F. AEROSOL MASS COLLECTION	9
G. REQUIRED REMOVAL EFFICIENCY	10
H. COMPARISON OF DESIGN PARAMETERS	10
IV. PRELIMINARY SCREENING OF AIR CLEANING CONCEPTS	13
V. CRITERIA FOR RANKING ALTERNATIVE SYSTEMS	15
VI. EVALUATION RESULTS	21
A. DESCRIPTION OF SYSTEMS DESIGNED FOR 90% EFFICIENCY	21
1. Venturi Scrubber - System LE-1	21
2. Submerged Gravel Scrubber - System LE-2	23
3. Spray Chamber - System LE-3	27

CONTENTS (Cont'd)

	<u>Page</u>
B. DESCRIPTION OF SYSTEMS DESIGNED FOR 99% EFFICIENCY	27
1. Venturi Scrubber with Fibrous Backup - System HE-1	29
2. Submerged Gravel Scrubber with Fibrous Backup - System HE-2	32
3. Sand and Gravel Bed - System HE-3	34
4. HEPA Filters - System HE-4	36
C. COMPARISON OF ALTERNATIVE SYSTEMS	38
1. Ranking of 90% Efficient Candidates	38
2. Ranking of 99% Efficient Candidates	40
D. FEASIBILITY OF ASSESSMENT OF AIR CLEANING SYSTEMS FOR FFTF CONTAINMENT MARGIN APPLICATIONS	42
VII. REFERENCES	43
APPENDIX A NUMERICAL RANKING OF 90% EFFICIENT SYSTEMS	A-1
APPENDIX B NUMERICAL RANKING OF 99% EFFICIENT SYSTEMS	B-1

FIGURES

	<u>Page</u>
1 Maximum Temperature of Air Entering Air the Cleaning System	6
2 Maximum Gas Pressure in the Air Cleaning System	6
3 Composition of Inlet Gas	7
4 Particle Size Distribution	9
5 Gas Flow Rate	10
6 Flow Diagrams for 90% Efficient Candidates	22
7 Layout for Venturi Scrubber - System LE-1	24
8 Description of Submerged Gravel Scrubber Concept	25
9 Layout of a Submerged Gravel Scrubber - System LE-2	26
10 Layout of Spray Scrubber - System LE-3	28
11 Flow Diagrams for 99% Efficient Candidate Systems	30
12 Layout of Venturi Fibrous Scrubber - System HE-1	31
13 Layout of Submerged Gravel Scrubber with Fibrous Backup - System HE-2	33
14 Aggregate Used in Sand Bed Filter - System HE-3	35
15 Layout of Sand and Gravel Bed - System HE-3	35
16 Layout for HEPA Filter - System HE-4	37

TABLES

	<u>Page</u>
1 Comparison of Air Cleaning System Requirements	11
2 Preliminary Screening of Air Cleaning System Concepts	14
3 Air Cleaning Evaluation Criteria Groups	16
4 Evaluation Criteria for Air Cleaning Systems	17
5 Rating Factors for Air Cleaning Systems	19
6 Criteria with Mandatory Acceptable Ratings	19
7 Parameters for Venturi Scrubber - System LE-1	24
8 Parameters for Submerged Gravel Scrubber - System LE-2	26
9 Parameters for Spray Scrubber - System LE-3	28
10 Parameters for Venturi/Fibrous Scrubber - System HE-1	32
11 Parameters for Submerged Gravel Bed/Fibrous Scrubber - System HE-2	33
12 Parameters for Sand and Gravel Bed - System HE-3	36
13 Parameters for HEPA Filters - System HE-4	38
14 Numerical Ratings of 90% Efficient Systems	39
15 Numerical Ratings of 99% Efficient Systems	41
B-1 System Reliability Ratings	B-5
B-2 System Design Ratings	B-5
B-3 System Rating by Cost	B-9

EVALUATION OF AIR CLEANING SYSTEMS FOR
FFTF CONTAINMENT MARGINS (WAKVAA)

I. SUMMARY AND CONCLUSIONS

A. SUMMARY

An evaluation of alternative air cleaning systems was made to identify the most promising candidates for application to Fast Flux Test Facility (FFTF) containment margins. Seven candidate systems were selected for detailed comparison. The three systems capable of 90% aerosol removal efficiency were: 1) eductor venturi, 2) spray chamber scrubber and 3) submerged gravel bed. The four systems for 99% efficiency were: 1) eductor venturi/fibrous scrubber, 2) submerged gravel bed/fibrous scrubber, 3) sand and gravel bed and 4) HEPA filters.

A conceptual design was developed for each system to show size and major components, and to allow an approximate cost estimate. The systems within each efficiency class were then compared using a criteria list and candidate ratings were made. The rating process identified two prime candidates from each removal efficiency class. Final selection will be based on trade-off studies beyond the scope of this report.

B. CONCLUSIONS

Specific conclusions drawn from work completed are:

- For the 90% removal efficiency case, two scrubber systems (an eductor venturi and submerged gravel bed) were rated as prime candidates. The submerged gravel bed was superior to the eductor venturi in passivity and mechanical simplicity but it lacks an extensive use-history.
- For the 99% removal case, the eductor venturi and the submerged gravel bed scrubber systems were also prime candidates when upgraded by adding a packed bed back-up stage of polypropylene fibers.

- A spray chamber scrubber designed for 90% efficiency is larger and more costly to construct and to operate than the prime candidates; therefore, it was eliminated from further consideration.
- The sand and gravel bed (the 99% removal case) was found too large and costly to construct for use in the present application. The large aerosol mass load requires a sand bed with a planar area of more than 1 acre and a cost of tens of millions of dollars.
- A system using high efficiency particulate air (HEPA) filters, designed for the 99% removal case, was eliminated. The aerosol mass loading required a large number (9100) of filter units (0.61 m x 0.61 m x 0.3 m deep) enclosed in a pressure boundary, making this system too large and costly.
- Both prime candidates (the eductor venturi and the submerged gravel bed) would require a planar area of less than 150 m² (1600 ft²) and therefore, could be located adjacent to the containment vessel.
- A significant experience base exists for trapping sodium compound aerosols by aqueous scrubbers. The use of aqueous scrubbers is technically feasible for the FFTF containment margins application.

II. INTRODUCTION

Although extensive analyses of hypothetical core disruptive accident (HCDA) events in the FFTF show that the heat transport system would remain intact and the fuel coolable, further safety margins available for a postulated reactor vessel melt-through were assessed⁽¹⁾. In the assessment, it was assumed that the containment vessel would be vented to relieve overpressure and/or purged to prevent hydrogen buildup. Although the potential site boundary radiation exposures were within 10 CFR 100⁽²⁾ guideline values (even without the use of a filter system), a cleaning system capable of removing radioactive aerosol from a vented or purged containment atmosphere has some benefit in reducing the calculated radiological consequences⁽¹⁾. This report presents an analytical evaluation of various air cleaning systems for possible use in the FFTF containment margins.

In the postulated melt-through event, a large quantity of sodium aerosol is assumed to be released along with the radioactive species. These sodium compound aerosols impose a higher aerosol mass loading on the present air cleaning system than on normal applications. Therefore, the results of a recent Liquid Metal Fast Breeder Reactor (LMFBR) air cleaning study⁽³⁾ are not directly applicable.

Objectives of this study are to identify the air cleaning concepts that enhance FFTF containment margins and judge the feasibility of these systems.

Guidelines that limit the scope of this study are:

- Numerous alternative candidates were eliminated by prescreening on the basis of an earlier study,⁽³⁾
- The application does not involve a design basis accident and the system is not required to meet all the requirements of an engineered safety system,
- In-containment cleanup devices were not considered, and
- Engineering trade-off studies necessary for final selection of systems were beyond the scope of this report.

III. AIR CLEANING REQUIREMENTS

A. BASIS

The design operating conditions used in the present evaluation are described in the following sections of this report. The conditions are arbitrarily specified, but are believed to represent bounding-case accident scenarios as described by Bankert, et al.⁽¹⁾

All conceptual designs developed in the present study are based on venting requirements alone. Because venting conditions are much more demanding than purging operations, a system designed for venting can easily handle purge cases. Only the purge fan and valving are different, and these differences are unimportant in the present evaluation.

B. THERMAL CONDITIONS

For vent mode operation, gas temperatures can vary from 21°C (70°F) to 371°C (700°F), depending on the energy released to the containment atmosphere. The purge mode involves temperatures in the range of 21°C (70°F) to 121°C (250°F). The upper-limit, temperature-time history shown in Figure 1 is used for thermal analyses in this study.

Because the flow control valve is downstream from the air cleaner, pressure in the air cleaning system is equal to that in the containment vessel after venting is initiated. The expected peak pressure is 0.184 MPa absolute (12 psig). The variation in maximum pressure with time is shown in Figure 2.

HEDL 7912-032.1

FIGURE 1. Maximum Temperature of Air Entering the Air Cleaning System.
Neg 8009286-10

HEDL 7912-032.12

FIGURE 2. Maximum Gas Pressure in the Air Cleaning System. Neg 8009286-9

C. CHEMICAL FORMS OF GASES AND AEROSOLS

In a hypothetical breach of containment accident, the initial air atmosphere in the containment vessel is altered by water released from heated concrete and by sodium combustion processes. The composition of gases entering the air cleaning system is shown in Figure 3 as a function of time.

FIGURE 3. Composition of Inlet Gas. Neg 8009286-8

Initially, sodium entering the containment reacts with O₂ to form Na₂O₂:

By the time the air cleaning system is in operation (30.5 h) appreciable water vapor is present and sodium peroxide is converted to NaOH with the liberation of O₂:

Excess H_2O vapor sorption by the NaOH particles depends on relative humidity:

Airborne particles are either dry, sticky or mist drops of NaOH solution, depending on the relative humidity.

Later, when O_2 is depleted, NaOH is formed directly by the reaction between Na and H_2O :

Based on the gaseous composition shown in Figure 3, the aerosol particles are composed primarily of NaOH with varying amounts of hydration.

To insure that solubility-based water requirements are not underestimated, 50% of the sodium aerosol is assumed to be present in the air cleaner as Na_2CO_3 . Sodium carbonate is formed if CO_2 is released with water from heated concrete,⁽⁴⁾ reacting with NaOH:

Fifty percent carbonate is probably a conservative value because of the low potential for CO_2 release in the FFTF, but scrubber water volumes designed on this basis will be adequate.

D. AEROSOL PARTICLE SIZE DISTRIBUTION

The particle size distribution of the aerosol entering the air cleaning system is assumed to be log normal, with an aerodynamic mass median diameter (AMMD) of $5.57 \mu\text{m}$ and a geometric standard deviation of 2.8. The particle size distribution is plotted on log-probability paper in Figure 4.

HEDL 8005-171

FIGURE 4. Particle Size Distribution. Neg 8009286-1

E. GAS FLOW RATE

Gas flow rate varies with time according to the pressure buildup rate in containment. The maximum flow rate of $3.07 \text{ m}^3/\text{s}$ (6500 ACFM) at 371°C (700°F) and 0.184 MPa (12 psig) occurs when venting begins. The flow rate versus time history used for the conceptual designs in this report is shown in Figure 5.

In actual use, the venting would probably be stopped periodically to maintain constant containment pressure. Therefore, Figure 5 should not be used as a basis for estimating total aerosol mass collection by the air cleaning system.

F. AEROSOL MASS COLLECTION

Based on code analyses of venting rates and aerosol concentrations, the maximum aerosol carried into the air cleaning system is projected to be 5440 kg (12,000 lb) anhydrous NaOH.

HEDL 7912-032.3

FIGURE 5. Gas Flow Rate.

G. REQUIRED REMOVAL EFFICIENCY

To provide information on the relative cost and complexity as a function of air cleaning system effectiveness, the study is performed for two classes of systems. For the first class, a 90% aerosol mass removal efficiency is specified; for the second class, a 99% efficiency is required.

H. COMPARISON OF DESIGN PARAMETERS

Air cleaning requirements for the FFTF containment margins application are found to resemble the "containment/confinement" system treated in a recent HEDL evaluation of air cleaning concepts.⁽³⁾ (See Table 1). However, the higher masses of aerosol and the higher temperatures required by the present study prevent direct utilization of the previous results.

TABLE 1
COMPARISON OF AIR CLEANING SYSTEM REQUIREMENTS

<u>Parameter</u>	<u>Previous Study(3)</u>	<u>FFTF Margins</u>
Aerosol Source	Head Release	Melt-Through and Sodium Boiloff
Maximum Gas Temperature (°C)	150	370
Flow Mode	Constant	Variable
Flow Rate (m ³ /s)	7.1	3.1 max 0 min
Aerosol Mass Collected as NaOH (kg)	1000	5450
Max Aerosol Concentration as NaOH at Inlet Conditions (g/m ³)	25	50
Aerosol Particle Properties:		
Mass Median Diameter (μm)	2.0	7.4
Geometric Std Deviation	2.0	2.8
Density, α_p (g/cm ³)	0.58	0.58
Aerodynamic Mass Median Diameter (μm)	1.5	5.57
Chemical Composition	NaOH	NaOH with Variable NaO _x , Na, Na ₂ CO ₃ , Partial Hydration
Start time (h) after HCDA	0	30.5*
Operational Duration (h)	24	720

* Reactor vessel melt-through assumed to occur 3 hours after HCDA initiation.

IV. PRELIMINARY SCREENING OF AIR CLEANING CONCEPTS

The large list of air cleaning concepts identified in an earlier study⁽³⁾ was screened to identify prime candidates for FFTF margins application. See Table 2. The following requirements eliminated many candidates:

- Aerosol mass loading is high (5450 kg).
- Concept technology must be at a state of development where hardware design can be started immediately.
- Only one of several apparently equivalent concepts was considered.
- Concepts involving in-containment cleaning were outside the scope of FFTF margins application and therefore were eliminated.
- Systems requiring gas recirculation were not considered.

Seven air cleaning systems were selected for evaluation. Four of these were designed to collect 99% or more of incident aerosol and three were designed to collect 90% or more.

The systems evaluated are:

Case I - 90% Efficient

LE-1 - Eductor Venturi
LE-2 - Spray Chamber
LE-3 - Submerged Gravel Bed

Case II- 99% Efficient

HE-1 - Spray Quench/Eductor Venturi/Fibrous Scrubber
HE-2 - Submerged Gravel Bed/Fibrous Scrubber
HE-3 - Sand and Gravel Bed
HE-4 - HEPA Filters

TABLE 2
PRELIMINARY SCREENING OF AIR CLEANING SYSTEM CONCEPTS

<u>Air Cleaning Concept</u>	<u>Reason Eliminated</u>
Filters:	
Industrial Prefilters	(b)
Deep Bed Graded Media	(a)
Bag Filters	(c)
Sand and Gravel Bed	
High Efficiency Particulate Air (HEPA)	
Cyclone Separator	(c)
Mechanical Separator	(c)
Dry Electrostatic Precipitator	(c)
Wet Electrostatic Precipitator	(c)
Wet Scrubbers:	
Spray Chamber	
Fibrous Packing (low efficiency type)	(d)
High Density Fiber Bed	
Packed Bed (e.g., gravel or Rashig rings)	
Venturi	
Centrifugal	(c)
Settling Chamber	(d)
Acoustic Agglomerator	(c)
Fluidized Bed	(b), (c)
Foam Dispersal	(a), (b), (c)
<hr/> (a) Low Mass Loading Capability (b) Low or Uncertain Efficiency (c) Uncertain Behavior for Margins Application (d) Overall Performance Similar to Other Systems Being Evaluated	

V. CRITERIA FOR RANKING ALTERNATIVE SYSTEMS

The criteria used in a previous air cleaning study⁽³⁾ were modified for application to FFTF containment margins. The six criteria groups are listed in Table 3. Each group contains several individual criteria listed in Table 4. Each criterion is assigned a weight factor to measure its relative importance. The total weight is adjusted to 100.

To rank the various systems, a scoring system was devised as shown in Table 5. A score of 0 to 4 is assigned to each air cleaning system on a criterion-by-criterion basis.

The rating definition is measured by the amount of development work required. However, the same rating factors are used to indicate the acceptability of intrinsic characteristics. For example, the efficiency of a spray chamber is, by the physical forces involved, very dependent on particle size; and no amount of development will change that dependence.

A system score is determined by summing individual criterion scores (the product of the criterion weight and the rating factor). The maximum possible system score is 400.

The following steps summarize the evaluation procedure:

- Definition of the system, including a preliminary conceptual design, utilizing the aerosol and containment atmosphere parameters listed in Section 3.
- The system is evaluated by the criteria listed in Table 4.
- The degree to which the system meets the criteria is quantified by assigning a rating factor ranging from 0 to 4 (to the nearest 0.1), based on criteria described in Table 5.

TABLE 3
AIR CLEANING EVALUATION CRITERIA GROUPS

<u>Group No.</u>	<u>Group Weight</u>	<u>Criterion Description</u>
1	17	<u>System Effectiveness</u> The system shall be effective in reducing the release of radioactive substances to the environment.
2	26	<u>System Reliability</u> The system shall have a high degree of reliability in startup and continuance of operation during the entire accident period.
3	9	<u>Containment Compatibility</u> The presence and operation of the system shall not degrade the normal effectiveness of the containment building.
4	22	<u>Technological Credibility</u> The effectiveness of the system shall be clearly demonstrable by experience, mathematical models and testing.
5	12	<u>System Characteristics and Flexibility</u> The system performance shall not be critically dependent on the accident environment conditions and shall accommodate possible future design changes.
6	14	<u>Fabrication Effort</u> The system shall be readily designed, fabricated and installed at reasonable cost and in a time frame consistent with plant construction.

TABLE 4
EVALUATION CRITERIA FOR AIR CLEANING SYSTEMS

<u>Criteria Description</u>	<u>Weight Factor</u>
1. <u>SYSTEM EFFECTIVENESS</u>	Total: <u>17</u>
*a. The design decontamination factor can be achieved using design parameters that fall within current state-of-the-art practice.	5
*d. The system can handle dry or sticky particles and particles of varying chemical composition.	5
*c. System effectiveness is not degraded by the radiation dose caused by the accident over the required operating period.	2
d. Characteristics inherently favor the system's ability to handle large masses of aerosol.	5
2. <u>SYSTEM RELIABILITY</u>	Total: <u>26</u>
*a. System shall have a high probability of startup after initiation of the accident.	9
*b. System does not degrade during non-use periods.	6
*c. System shall be capable of dependable operation over a 1000-hour accident period under accident conditions of temperature, humidity, aerosol loading and flow rate.	8
d. System requires simple components, control and conservative design stresses.	3
3. <u>CONTAINMENT SYSTEM COMPATIBILITY</u>	Total: <u>9</u>
*a. Inadvertent operation shall not harm the containment system or constitute a hazard to personnel.	4
b. Size shall be compatible with installation adjacent to the RCB, and not significantly impact the location of other ancillary plant systems.	5

*Denotes criteria with mandatory acceptable ratings.

TABLE 4 (Cont'd)

<u>Criteria Description</u>	<u>Weight Factor</u>
4. <u>TECHNOLOGICAL CREDIBILITY</u>	Total: <u>22</u>
a. Air cleaning concept is based on highly developed technology.	5
*b. System can be tested in-place for operability and efficiency.	6
c. System performance can be predicted by verified mathematical models.	5
d. System equipment scaleup from currently available sizes to LMFBF plant application is small.	3
e. System concept has been demonstrated with sodium aerosol or the extension of results to sodium aerosol can be made with confidence.	3
5. <u>SYSTEM CHARACTERISTICS AND FLEXIBILITY</u>	Total: <u>12</u>
a. System is effective for the entire particle size spectrum expected during the accident.	3
b. System performance is not highly sensitive to the atmospheric temperature or relative humidity.	3
c. System energy consumption is low.	3
d. Post-accident recovery is facilitated by the EACS.	3
6. <u>FABRICATION EFFORT</u>	Total: <u>14</u>
a. System costs, capital and maintenance, are low.	10
b. Materials and techniques used in construction are readily available and easily fabricated.	2
c. Components and equipment are readily available.	2
	<u>100</u> <u>100</u>

*Denotes criteria with mandatory acceptable ratings.

TABLE 5
RATING FACTORS FOR AIR CLEANING SYSTEMS

<u>Rating Factor</u>	<u>Rating Description</u>	
4	Clearly acceptable	Completely satisfies criterion.
3	Probably acceptable	Some development may be required. May not completely meet the criterion but is adequate.
2	Possibly acceptable	A large development effort may be required. Barely meets or falls short of the criterion.
1	Probably unacceptable	Low probability of meeting criterion.
0	Clearly unacceptable	Zero probability of meeting the criterion.

Because certain criteria were considered mandatory requirements, a score of 2.0 or better was required for the system to be considered feasible. Mandatory criteria are listed in Table 6.

TABLE 6
CRITERIA WITH MANDATORY ACCEPTABLE RATINGS*

<u>Criterion No.</u>	<u>Description</u>
1a	Removal efficiency is state-of-art
1b	Dry or sticky particles
1c	Radiation resistance
2a	Reliable startup
2b	Storage life
2c	Reliable long-term operation
3a	Inadvertent operation
4b	In-place testability

*Acceptable is defined as a minimum rating factor of 2.0, as described in Table 5.

- The system score for each individual criterion is obtained by multiplying the criterion weight factor (Table 4) by the assigned rating factor.
- The overall system rating is calculated by summing the scores of the individual criteria. The maximum possible score is 400.
- Systems having a low rating for any individual criterion are examined for possible design changes to improve their rating.
- The systems are ranked according to total score.
- Final ranking is made by considering both the numerical score and the probability of successful application. Because many of the criteria are only semi-quantifiable, the evaluation and rating necessarily entail considerable judgement.

VI. EVALUATION RESULTS

A rudimentary conceptual design was made for each of the seven systems selected in Section IV. Although the designs are not necessarily optimum, this is not expected to have a major influence in comparing systems except where two systems are closely equivalent.

The component and system designs in this study were based on information developed in an earlier study.⁽³⁾ Where available, equipment performance with sodium or sodium oxide aerosols was used. In the absence of operating performance data specific to LMFBF accident conditions, published information for standard air pollution control equipment was used. Modifications for LMFBF conditions were made according to the authors' judgment.

A cost estimate was made for each system based primarily on component costs developed in an earlier study.⁽³⁾ The costs include engineering, equipment, installation labor, instrumentation and the building needed to house the equipment. The cost estimates are presented as arbitrary units for comparison purposes.

A. DESCRIPTION OF SYSTEMS DESIGNED FOR 90% EFFICIENCY

Three air cleaning concepts were selected as candidates for 90% efficient systems. All three are aqueous scrubbers and are judged as the prime candidate systems available for application to FFTF margins. The candidate systems are shown schematically in Figure 6.

1. Venturi Scrubber - System LE-1

System LE-1 employs an eductor venturi scrubber to remove airborne particles. An eductor-type venturi was selected over a gas-atomized-type venturi because removal efficiency increases as gas flow rate decreases in an eductor unit. In this study the gas flow rate may vary from zero to the design maximum; therefore, use of a gas-atomized venturi would introduce

VENTURI SCRUBBER - SYSTEM LE-1

SUBMERGED GRAVEL SCRUBBER - SYSTEM LE-2

SPRAY CHAMBER SCRUBBER - SYSTEM LE-3

HEDL 7912-032.12

FIGURE 6. Flow Diagrams For 90% Efficient Candidates. Neg 7913162-12

design complexities that deal with the loss in removal efficiency when flow rate is decreased from the design value.

The main equipment components in this system are: 1) the venturi and separator, 2) the liquid recirculation spray pump and 3) the liquid storage tank. All three components must be designed to withstand an ambient pressure of 0.184 MPa (12 psig) because containment venting rate is controlled by a valve located downstream from the scrubber.

Particle removal efficiency within the eductor was assessed by drop capture models and by comparison with experimental measurements reported for an eductor venturi scrubber studied at HEDL.⁽⁵⁾ The size of the venturi was based on a throat gas velocity of 16 m/s (52 ft/s) and the geometrical proportions used by several equipment manufacturers. The venturi unit, complete with entrainment separator, was estimated to be 5.8 m (19 ft) in height and 2.3 m (7.5 ft) in diameter.

The water storage tank holds 30.3 m³ (8,000 gal). The water volume is stipulated by solubility considerations for the collected aerosol material. An elevation view of equipment layout for the venturi scrubber system is shown in Figure 7. Important design parameters for System LE-1 are summarized in Table 7.

2. Submerged Gravel Scrubber - System LE-2

System LE-2 uses a submerged gravel bed to trap airborne particles. This system is novel because the air flow induces water circulation through the gravel bed and makes a separate water pumping system unnecessary. This concept is currently under development at HEDL and a patent application was filed.

In operation, inlet air is dispersed beneath a gravel bed by means of a submerged downcomer. Buoyant forces cause the air to pass upward through the gravel bed. Appreciable volumes of water are entrained with the air

HEDL 7912-032.8

FIGURE 7. Layout For Venturi Scrubber - System LE-1. Neg 8009286-7

TABLE 7

PARAMETERS FOR VENTURI SCRUBBER - SYSTEM LE-1

Water Flow Rate	1.70 m ³ /min (450 gal/min)
Water Pressure Drop	0.55 MPa (80 psid)
Throat Gas Velocity	16 m/s (52 ft/s)
Max Gas Flow Rate	3.07 m ³ /s (6500 ACFM)
Draft Generated	248 Pa (1 inch water)
Particle Removal Efficiency	90%
Relative Cost Units	0.80

flow. The circulating water keeps the bed clean of particulate debris and assures that water in the system is nearly isothermal. The submerged gravel bed concept is described in Figure 8.

Design of the submerged gravel bed was based on scale-up of results from engineering scale models tested at HEDL. The most important parameters, gas velocity and bed depth, were selected as 0.51 m/s (100 ft/min) and 0.61 m (2 ft), respectively. Particle removal efficiency was analyzed using an equation for packed beds⁽⁶⁾ and comparison with HEDL experiments.

HEDL 7912-032.14

Figure 8. Description of Submerged Gravel Scrubber Concept. Neg 8009286-3

An elevation view showing the layout of the submerged gravel bed is given in Figure 9. Important parameters that describe the design of the submerged gravel bed are summarized in Table 8.

HEDL 7912-032.7

Figure 9. Layout of a Submerged Gravel Scrubber - System LE-2. Neg 8009286-11

TABLE 8

PARAMETERS FOR SUBMERGED GRAVEL SCRUBBER - SYSTEM LE-2

Gravel Bed OD	3.05 m (10 ft)
Inlet Downcomer Diameter	0.61 m (2 ft)
Gravel Bed Depth	0.61 m (2 ft)
Superficial Gas Velocity in Gravel (maximum)	0.51 m/s (100 ft/min)
Size of Crushed Rock Packing	9.5 to 13 mm (3/8 to 1/2 in.)
Volume of Water	51.1 m ³ (13,500 gal)
Particle Removal Efficiency	90%
Relative Cost Units	0.45

3. Spray Chamber - System LE-3

The spray chamber scrubber is conceptually similar to the eductor venturi in that particle removal is dominated by water drop impaction. The water stream requires higher energy in the venturi but the venturi is smaller in size compared to a spray chamber.

The main component of the spray scrubber is the chamber where falling drops capture suspended particles, mainly by impaction. Due to large size, recirculating water inventory is accommodated within the chamber itself. A recirculating water pump is required to maintain spray flow.

Spray chamber size was determined by the spray rate required to remove 90% of airborne particles and by the maximum spray flux that will avoid significant drop coalescence. It was assumed that the gas phase within the spray chamber was well-mixed. The design approach used is supported by results obtained at HEDL on the removal of sodium compound aerosols within a spray quench chamber.⁽⁵⁾

An elevation view showing the size of the spray scrubber is given in Figure 10. The spray scrubber is appreciably larger than the other two candidates (Figures 8 and 9). Important parameters that describe the design of the spray scrubber are summarized in Table 9.

The significantly higher cost of the spray scrubber is mainly due to the larger size. The higher cost and larger size of the spray scrubber indicate that it will not be competitive with the two other scrubbers unless major off-setting advantages are identified in the detailed evaluation.

B. DESCRIPTION OF SYSTEMS DESIGNED FOR 99% EFFICIENCY

Four systems were selected as candidates for 99% efficiency removal - two aqueous scrubbers candidates from the 90% removal up-graded by adding a packed fiber bed to the outlet of the 90% scrubber; a sand and gravel bed and a bank

HEDL 7912-032.9

FIGURE 10. Layout of Spray Scrubber - System LE-3. Neg 8009286-6

TABLE 9

PARAMETERS FOR SPRAY SCRUBBER- SYSTEM LE-3

Diameter of Spray Chamber	10.4 m (34 ft)
Height of Spray Chamber	7.6 m (25 ft)
Spray Flow Rate	$1.70 \text{ m}^3/\text{min}$ (450 gal/min)
Nozzle Pressure Drop	0.28 MPa (40 psid)
Volume of Water	30.3 m^3 (8000 gal)
Effective Drop Diameter	$1200 \mu\text{m}$
Flow Rate Per Nozzle	$0.0473 \text{ m}^3/\text{min}$ (12.5 gal/min)
Particle Removal Efficiency	90%
Relative Cost Units	1.6

of HEPA filters. Flow diagrams for the candidate systems designed for 99% removal efficiency are shown in Figure 11.

1. Venturi Scrubber with Fibrous Backup - System HE-1

In this system, a packed bed of fibers is added to trap particles that penetrate the venturi. The combined system will yield removal efficiencies well in excess of 99%, as demonstrated in tests performed at HEDL⁽⁵⁾. The design of the venturi pre-scrubber was taken directly from System LE-1 (Figure 7).

The venturi/fibrous scrubber occupies a space envelope cylindrical in shape, 5.8 m high and 2.3 m in diameter. Other design parameters for the venturi scrubber are listed in Table 7.

The venturi/fibrous scrubber design used annular-shape packed beds of polypropylene fibers. The 72.6-mm (3-in.) thick annulus is 0.59 m (18 in.) inside diameter, 0.79 m (24 in.) outside diameter and 3.05 m (10 ft) in length. Four elements are required to handle the maximum gas flow rate of $1.75/\text{m}^3/\text{s}$ (3700 ACFM) exiting from the venturi scrubber. Fresh process water mist is applied to the upstream surface of the bed to assure that all soluble material is washed from the fibers. The spray mist flow rate was $20.8 \text{ cm}^3/\text{s}$ (0.33 gal/min). The venturi/fibrous scrubber elements were enclosed in a carbon steel tank.

This system requires a recirculation water tank appreciably larger than that used in the 90% design to accommodate the process water used to wet the fiber beds. Over an operating time of 720 hours, 54.5 m^3 (14,400 gal) of water would be added as spray mist to the 30.3 m^3 (8000 gal) of water required for

VENTURI SCRUBBER WITH FIBROUS BACKUP -
SYSTEM HE-1

SUBMERGED GRAVEL SCRUBBER WITH FIBROUS BACKUP -
SYSTEM HE-2

SAND AND GRAVEL FILTER - SYSTEM HE-3

HEPA FILTER BANK - SYSTEM HE-4

HEDL 7912-032.13

FIGURE 11. Flow Diagrams For 99% Efficient Candidate Systems. Neg 8009286-5

solubility for a total minimum liquid capacity of 84.8 m^3 (22,400 gal). A tank having a volume of 113.6 m^3 (30,000 gal) was specified to account for potential condensate accumulation and gas space margin requirements.

An alternative bed washing scheme using recycled water could in principle be used to minimize storage tank capacity. Such a scheme would require a filtration device to avoid plugging the spray nozzle. Only fresh water wash was considered.

An elevation view of the conceptual design for System HE-1 is given in Figure 12. Design parameters for the venturi/fibrous scrubber are summarized in Table 10.

The data of Table 10 show that a cost increment of 25% is added to the 90% efficient venturi scrubber system to increase the removal efficiency to 99%. Also, the spatial requirements are 50% greater. However, this system is less costly than the 90% spray scrubber. Unless a detrimental characteristic is borne out in the detailed ranking process, this 99% system is preferred compared to a lower efficiency, higher cost spray scrubber.

HEDL 7912-032.10

FIGURE 12. Layout of Venturi/Fibrous Scrubber - System HE-1. Neg 8009286-2

TABLE 10
PARAMETERS FOR VENTURI/FIBROUS SCRUBBER - SYSTEM HE-1

Venturi Scrubber Flow Rate	1.70 m ³ /min (450 gal/min)
Venturi Water Pressure Drop	0.55 MPa (80 psid)
Venturi Throat Gas Velocity	16 m/s (52 ft/s)
Draft Generated By Venturi	248 Pa (1 in. water)
Length of Fibrous Bed Elements	3.05 m (10 ft)
Diameter of Fibrous Bed Elements	0.79-m (24-in.) OD by 0.59-m (18-in.) ID
Number of Fibrous Elements	Four
Fiber Material	Polypropylene
Fibrous Element Spray Flow Rate	20.8 cm ³ /s (0.33 gal/min)
Overall Particle Removal Efficiency	99%
Volume of Recycle Water Tank	113.6 m ³ (30,000 gal)
Relative Cost Units	1.0

2. Submerged Gravel Scrubber with Fibrous Backup - System HE-2

This system combines the submerged gravel scrubber design of System LE-3 with the polypropylene fiber beds described for System HE-1. The combined system is shown conceptually in Figure 13.

The gravel bed size used in this system is identical to that described for the 90% efficient System LE-3 (Table 8). The diameter of water tank and the water depth are the same as specified for System LE-3. The primary difference is the tank height required to accommodate the fibrous scrubber elements. Design parameters for the submerged gravel scrubber with fibrous back-up are listed in Table 11.

The submerged gravel bed with a fibrous backup is low in cost (0.7 relative units) in comparison with the other candidate scrubbers. When combined with passive features, e.g., no liquid pumping system requirement, this system appears to be a strong candidate. One off-setting aspect of this system is lack of a broad use-history.

HEDL 7912-032.4

FIGURE 13. Layout of Submerged Gravel Scrubber with Fibrous Backup - System HE-2. Neg 8009286-4

TABLE 11

PARAMETERS FOR SUBMERGED GRAVEL BED/FIBROUS SCRUBBER - SYSTEM HE-2

Scrubber Tank Overall Size	7.9-m (26-ft) dia x 3.7-m (12-ft) height
Gravel Bed Outside Diameter	3.05 m (10 ft)
Inlet Downcomer Diameter	0.61 m (2 ft)
Gravel Bed Depth	0.61 m (2 ft)
Superficial Gas Velocity in Gravel (max)	0.51 m/s (100 ft/min)
Crushed Rock Packing Size	9.5 to 13 mm (3/8 to 1/2 in.)
Volume of Water	51.1 m ³ (13,500 gal)
Fibrous Bed Elements Length	1.22 m (4 ft)
Fibrous Bed Elements Number	Ten
Fibrous Bed Elements Diameter	0.79-m (24-in.) OD x 0.59-m (18-in.) ID
Fiber Material	Polypropylene
Overall Particle Removal Efficiency	>99%
Relative Cost Units	0.70

3. Sand and Gravel Bed - System HE-3

Sand and gravel bed filters rated high in a previous study⁽³⁾ because they are passive and can withstand high temperatures and corrosive atmospheres. A major drawback to sand filters is the low mass loading capability.

The sand bed design employed was based on an installation at the Savannah River Laboratory⁽⁷⁾ and loading capacity measurements made at HEDL for sodium compound aerosols. The holding capacity of a sand filter is tentatively estimated to be 1.0 kg/m^2 irrespective of air velocity. The superficial flow area required for the present application is

$$5455 \text{ kg} \times \frac{1 \text{ m}^2}{\text{kg}} = 5455 \text{ m}^2 \quad .$$

If square, this unit would be 74 m (242 ft) on a side. This large bed would be difficult to locate close to the FFTF containment building.

A cross-sectional view of the sand and gravel layers is given in Figure 14. As indicated 0.91 m (3 ft) of fine sand is supported by 0.46 m (1.5 ft) of coarser sand and 0.91 m (3 ft) of gravel, yielding a whole bed depth of 2.3 m (7.5 ft). An elevation view of the sand bed filter is presented in Figure 15.

Costs for the sand bed were taken from actual costs incurred at Savannah River Laboratory in 1973. The cost per unit area was increased to account for inflation and design change requirements to meet the 0.184 MPa (12 psig) pressure rating. Parameters that describe the conceptual design of the sand filter are listed in Table 12.

The sand bed is much larger and much more costly than Systems HE-1 and HE-2. These considerations alone would appear to preclude the use of a sand bed filter for FFTF Margins.

HEDL 7912-032.11

FIGURE 14. Aggregate Used in Sand Bed Filter - System HE-3 Neg 7913162-11

HEDL 7912-032.5

FIGURE 15. Layout of Sand and Gravel Bed - System HE-3. Neg 7913162-5

TABLE 12
PARAMETERS FOR SAND AND GRAVEL BED - SYSTEM HE-3

Overall Bed Depth	2.3 m (7.5 ft)
Overall Height of Structure	4.6 m (15 ft)
Bed Planar Area	5455 m ² (58,691 ft ²)
Aerosol Mass Captured (NaOH)	5455 kg (12,000 lb)
Number of Layers of Aggregate	Six
Largest Aggregate	31.8-mm to 75.4-mm (1-1/2-in. to 3-in.) Gravel
Finest Aggregate	No. 50 to No. 30 Sand
Basis For Aggregate Layer Design	SRL facility (Reference 7)
Basis For Mass Loading Capacity	HEDL Data
Removal Efficiency	>99%
Relative Cost	16.0

4. HEPA Filters - System HE-4

HEPA filters rated for high temperature service would be installed in banks located inside a pressure building. The size and cost of this system relate directly to the number of individual filter units required.

Loading capacity of HEPA filters for sodium compound aerosols was studied by McCormack, et al.⁽⁸⁾ It was found that the mass of aerosol required to plug a filter was a function of humidity. The minimum loading capacity was found to be 0.6 kg per standard HEPA unit. The number of HEPA units required is calculated:

$$5455 \text{ kg} \times \frac{1 \text{ unit}}{0.6 \text{ kg}} = 9092 \text{ units.}$$

This number is very large, and if built, would represent the worlds largest HEPA filter installation. Therefore, no existing commercial HEPA filter banks could be used to cost and size this system.

A conceptual design for this system was developed on the basis of the following premises:

- HEPA filters were used without prefilters.
- The filter units were arranged on horizontal plenums.
- A pressure building was used to house the filter banks.

The layout of the conceptual design is shown in Figure 16. As indicated, the required pressure building is large, approximating a truncated section of the reactor containment building itself. Parameters for this system are summarized in Table 13.

The most notable data of Table 13 are the large size and high cost of the system. Compared to alternatives, this system would appear to be non-competitive because of these two factors.

HEDL 7912-032.6

Figure 16. Layout for HEPA Filters - System HE-4. Neg 7913162-6

TABLE 13
PARAMETERS FOR HEPA FILTERS - SYSTEM HE-4

Number of HEPA Filter Units Required	9090
Aerosol Mass Collected Per HEPA	0.6 kg
HEPA Filter size	0.61 m x 0.61 m x 0.31 m
HEPA Filter Temperature Rating	399 ⁰ C (750 ⁰ F)
HEPA Filter Media Composition	Fiber Glass
No. of HEPA Units Per Tier	1818
No. of Tiers In Pressure Building	5
Diameter of Enclosure Building	41.5 m (136 ft)
Height of Enclosure Building	16 m (52.5 ft)
Particle Removal Efficiency	>99%
Relative Cost Units	110

C. COMPARISON OF ALTERNATIVE SYSTEMS

Candidate systems are ranked in terms of criteria described in Section V. The 90% efficient systems are ranked separately from the 99% efficient systems. Choice between the two classes of systems is left to the user who must determine whether the extra cost and complexity of the high efficiency system are justified by the incremental removal efficiency obtained.

1. Ranking of 90% Efficient Candidates

Numerical ranking of the three 90% efficient candidate systems is listed in Table 14. The rationale for assigning the individual scores is described in Appendix A.

From the total scores shown in Table 14, the candidates rank in the following order:

Submerged Gravel Scrubber	(341 points)
Venturi Scrubber	(331.5 points)
Spray Chamber	(309 points)

TABLE 14
NUMERICAL RATINGS OF 90% EFFICIENT SYSTEMS

<u>Criterion</u>	<u>Weight Factor</u>	<u>LE-1 Venturi Scrubber</u>		<u>LE-2 Submerged Gravel</u>		<u>LE-3 Spray Chamber</u>	
		<u>Rating</u>	<u>Score</u>	<u>Rating</u>	<u>Score</u>	<u>Rating</u>	<u>Score</u>
1a*	5	3.5	17.5	3.8	19.0	3.0	15.0
1b*	5	4.0	20.0	4.0	20.0	4.0	20.0
1c*	2	4.0	8.0	4.0	8.0	4.0	8.0
1d	5	4.0	20.0	4.0	20.0	4.0	20.0
2a*	9	3.5	31.5	4.0	36.0	3.5	31.5
2b*	6	3.5	21.0	3.5	21.0	3.5	21.0
2c*	8	3.0	24.0	3.5	28.0	3.0	24.0
2d	3	3.5	10.5	3.5	10.5	3.5	10.5
3a*	4	4.0	16.0	4.0	16.0	4.0	16.0
3b	5	3.0	15.0	3.0	15.0	3.0	15.0
4a	5	4.0	16.0	2.0	10.0	3.0	15.0
4b*	6	2.5	15.0	3.0	18.0	2.5	15.0
4c	5	3.0	15.0	3.0	15.0	3.0	15.0
4d	3	4.0	12.0	2.0	6.0	4.0	12.0
4e	3	4.0	12.0	4.0	12.0	4.0	12.0
5a	3	2.5	7.5	3.0	9.0	2.0	6.0
5b	3	3.5	10.5	3.5	10.5	3.5	10.5
5c	3	2.0	6.0	3.0	9.0	2.5	7.5
5d	3	3.0	9.0	3.0	9.0	3.0	9.0
6a	10	2.5	25.0	3.5	35.0	1.0	10.0
6b	2	4.0	8.0	3.0	6.0	4.0	8.0
6c	<u>2</u>	4.0	<u>8.0</u>	4.0	<u>8.0</u>	4.0	<u>8.0</u>
Total	100		331.5		341.0		309.0

*Mandatory criterion: A rating of 2.0 or better is required to prevent automatic exclusion of concept.

The submerged gravel bed ranks highest due to the favorable rating in reliability (Group 2) and ease of fabrication (Group 6). The weakest aspect of this system is technological credibility (Group 4). While there is little doubt that the system works as designed, lack of a use-history for the submerged gravel scrubber makes it less credible than the other two candidates. The performance of large scale tests on this system could enhance the credibility rating and make it even more desirable than the other candidates.

The venturi scrubber ranked second because the liquid recirculation system (pump & piping) requirement resulted in lower ratings in reliability and cost (Groups 2 and 6, respectively). The broad industrial use-history resulted in the highest rating in technological credibility (Group 4).

The spray chamber ranked last. It is quite similar in many respects to the venturi scrubber, but the large size and attendant high cost make it less desirable. No factors were uncovered that override the low numerical score for the spray chamber and it was eliminated from the viable candidate list.

The two prime candidates had numerically similar scores. Also, it is evident that both system designs are feasible for the FFTF containment margins application. Therefore, a final selection between the submerged gravel scrubber and the venturi scrubber should be based on trade-off studies beyond the scope of this report.

2. Ranking of 99% Efficient Candidates

The numerical ranking of the four 99% efficient systems is listed in Table 15. The rationale for assigning the individual scores is described in Appendix B. From the total scores shown in Table 15, the candidates rank in the following order:

Submerged Gravel/Fibrous Scrubber	(338.1 points)
Venturi/Fibrous Scrubber	(335.9 points)
Sand and Gravel Bed	(282.9 points)
HEPA Filter Bank	(257.7 points)

TABLE 15
NUMERICAL RATINGS OF 99% EFFICIENT SYSTEMS

Criterion	Weight Factor	HE-1 Venturi-Fibrous		HE-2 SGS-Fibrous		HE-3 Sandbed		HE-4 HEPA Filters	
		Rating	Score	Rating	Score	Rating	Score	Rating	Score
1a*	5	4.0	20.0	4.0	20.0	3.0	15.0	4.0	16.0
1b*	5	3.5	17.5	3.5	17.0	3.0	15.0	2.5	12.0
1c*	2	3.0	6.0	3.3	6.6	4.0	8.0	3.6	7.2
1d	5	4.0	20.0	4.0	20.0	2.0	10.0	2.0	10.0
2a*	9	3.0	27.0	3.5	31.5	4.0	36.0	4.0	36.0
2b*	6	3.5	21.0	3.5	21.0	4.0	24.0	4.0	24.0
2c*	8	3.0	24.0	3.5	28.0	3.8	30.4	2.0	16.0
2d	3	3.5	10.5	3.4	10.2	2.0	6.0	1.0	3.0
3a*	4	3.6	14.4	3.8	15.2	4.0	16.0	4.0	16.0
3b	5	3.0	15.0	3.0	15.0	0.0	0.0	0.0	0.0
4a	5	4.0	20.0	2.0	10.0	3.0	15.0	3.8	19.0
4b*	6	3.0	18.0	3.1	18.6	4.0	24.0	4.0	24.0
4c	5	3.0	15.0	3.0	15.0	2.0	10.0	2.0	10.0
4d	3	4.0	12.0	2.0	6.0	3.5	10.5	3.0	9.0
4e	3	4.0	12.0	3.0	9.0	2.5	7.5	3.5	10.5
5a	3	4.0	12.0	4.0	12.0	3.0	9.0	4.0	12.0
5b	3	3.5	10.5	3.5	10.5	3.0	9.0	2.0	6.0
5c	3	2.0	6.0	3.0	9.0	3.5	10.5	3.5	10.5
5d	3	3.0	9.0	3.0	9.0	2.0	6.0	0.0	0.0
6a	10	3.0	30.0	4.0	40.0	1.0	10.0	0.0	0.0
6b	2	4.0	8.0	3.0	6.0	3.5	7.0	4.0	8.0
6c	2	4.0	8.0	4.0	8.0	2.0	4.0	4.0	8.0
Total	100		335.9		338.1		282.9		257.7

*Mandatory criterion: A rating of 2.0 or better is required to prevent automatic exclusion of concept.

The low ratings of the sand and gravel bed and HEPA filter systems, as well as their very high costs and large sizes, eliminated these two systems from further consideration.

The two scrubber systems have comparable scores. The submerged gravel/-fibrous scrubber was rated low in technological credibility (Group 4) because it lacks an extensive use-history. In all other categories the submerged gravel scrubber rated superior to the venturi system.

In selecting between the two scrubber systems, the main trade-off is an element of risk in scale-up of the submerged gravel unit versus greater cost and mechanical complexity of the venturi system. Final selection should be made by the system designer following conceptual design studies.

D. ASSESSMENT OF FEASIBILITY OF AIR CLEANING SYSTEMS FOR FFTF CONTAINMENT MARGINS APPLICATIONS

A review of available information concludes that air cleaning based on aqueous scrubbers is feasible for the FFTF Containment Margins application. Wet systems (scrubbers) are preferred compared to dry systems because the high aerosol mass loading requirements result in very large and costly systems for all dry systems considered.

Extensive testing of scrubber systems at large scale and under realistic aerosol stream conditions has demonstrated the efficient and reliable operation of the candidates. While the design efficiency of the two stage systems was stated as 99% in this study, more detailed analyses⁽⁹⁾ and experiments⁽⁵⁾ have shown the removal efficiencies to exceed 99.9%.

VII. REFERENCES

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A P P E N D I X A

NUMERICAL RANKING OF 90% EFFICIENT SYSTEMS

Three candidates (an eductor venturi, a spray chamber and a submerged gravel bed) are compared on a criterion-by-criterion basis. As noted in Section V, the numerical scores varied from 0 to 4.0. A rating of 4.0 denotes totally acceptable conformance and a rating of 0.0 denotes totally unacceptable conformance.

Criterion 1a. "The design decontamination factor shall be achieved using design parameters that fall within current state-of-the-art practice."

For this criterion scores were assigned on the basis of the inherent removal efficiency. The submerged gravel scrubber was rated 3.8. Average removal efficiencies exceeded 99% for a bed design comparable to that developed in this study. This indicates a design removal efficiency of 90% could be met without difficulty.

The venturi scrubber rated 3.5 because Containment Systems Test Facility (CSTF) tests on a 1000 cfm prototype showed that removal efficiencies exceeding 90% could be obtained routinely.⁽⁵⁾

The spray chamber rated 3.0. Calculations and experiments in CSTF show efficiencies of 90% can be obtained, but carefully defined operating parameters must be adhered to. The spray chamber is inherently less efficient than the other two scrubbers but is satisfactory for the present application.

Criterion 1b. "The system shall handle dry or sticky particles and particles of varying chemical composition."

All three systems rate 4.0 because the physical and chemical composition of the aerosol does not adversely affect performance.

Criterion 1c. "System effectiveness shall not be degraded by the radiation dose caused by the accident over the required operating period."

All three systems are rated 4.0 because they use materials and components that could be constructed to easily withstand the radiation exposures encountered.

Criterion 1d. "System characteristics shall inherently favor the systems with ability to handle large masses of aerosol".

The three systems are equally efficient in handling large masses of sodium compound aerosols. Each was assigned a score of 4.0.

Criterion 2a. "The air cleaning system shall have a high probability of startup after initiation of the accident".

All three systems are equally dependent on a supply of water and on the operation of valves in the vent line. The submerged gravel bed has no active liquid pumping system and was rated 4.0 because it employs no pumps. The other two scrubbers were rated 3.5 because they employ pumps.

Criterion 2b. "The system shall not degrade during periods of non-use".

Because all three systems are expected to be "dry" in standby, little degradation would occur during non-use. If rusting of steel does occur, it will affect the venturi and spray chamber because they employ small openings in spray nozzles. On the other hand, biological growths in the gravel bed represent a possible mode of degradation not present in the other two systems. Overall, the systems appear to be equivalent and were assigned a 3.5 rating.

Criterion 2c. "The system shall be capable of dependable operation over the 1000-hour accident period under the accident conditions of temperature, humidity, aerosol loading and flow rate."

For this criterion, scores were assigned on the basis of passivity and the ability to handle changing thermal and flow conditions. All three systems

will require a water source to replace evaporative losses, A system requiring no service during an accident would be more reliable. Because the venturi and spray scrubbers require electrical energy and operation of water pumps, they were assigned scores of 3.0. The submerged gravel scrubber does not employ a liquid pumping system and was rated 3.5.

Criterion 2d. "The system shall require simple components and control and conservative design stresses.

The gravel bed is probably the most complex component of the three candidate systems. However, the spray and venturi systems require control systems for liquid pumping. None of the three systems imposes design stress problems. Therefore, the advantages and disadvantages are off-setting and all three systems were assigned scores of 3.5.

Criterion 3a. "Inadvertent operation of the system shall not harm the containment system (containment vessel and purge system) or constitute a hazard to personnel.

All three candidate systems are external to the containment vessel and involve no hazard to personnel. No detrimental impacts from inadvertent operation of the system could be identified and all systems were assigned a score of 4.0.

Criterion 3b. "The size of the system shall be compatible with installation adjacent to the Reactor Containment Building (RCB), and not significantly impact the location of other ancillary plant systems."

Foot print sizes for the three candidates are comparable and small enough to be located adjacent to the RCB. All systems were rated 3.0 recognizing that an even smaller system would be more desirable.

Criterion 4a. "The air cleaning concept is based on highly developed technology."

The eductor venturi scrubber system is widely used in industry and was rated 4.0. The spray chamber was rated 3.0 because spray air washers are widely used but not typically designed for efficiencies as high as this application requires. The submerged gravel scrubber was rated 2.0 because, although many studies of particle capture in a massive packing bed are published, a self-cleaning bed is novel and not yet supported by industrial practice.

Criterion 4b. "The air cleaning system shall be testable in-place for operability and efficiency."

Periodic testing of the aqueous systems involve the following:

1. Fill tank with water
2. Start pumps (venturi and spray)
3. Start fans
4. Inject test particles
5. Collect aerosol samples
6. Measure liquid and gas flow rates
7. Shut down fans and pumps
8. Drain water from system

Because this procedure is more complex than the required procedure for a dry filter system the simpler system (the submerged gravel scrubber) was assigned a score of 3.0. The venturi and spray scrubbers were rated at 2.5 because additional effort is required to operate the liquid pumps and put them into standby condition.

Criterion 4c. "The system performance shall be predictable by verified mathematical models."

Models for predicting particle removal exist for all three candidates. Reasonable agreement between theory and experiment is evident in available comparisons, and a rating of 3.0 was assigned to all candidates.

Criterion 4d. "The equipment scale-up from currently available sizes to FFTF plant application shall be small."

Both the venturi and spray scrubbers are used industrially in sizes larger than required for the application; therefore, no scale-up is required and a score of 4.0 is assigned.

The submerged gravel scrubber would require a scale-up in diameter by a factor of three as compared to engineering scale units operating to date. A rating of 2.0 is assigned because of the scale-up.

Criterion 4e. "The air cleaning concept shall be demonstrated with sodium aerosol or the extension of results to sodium aerosol can be made with confidence."

All three system concepts have been extensively tested at HEDL with sodium compound aerosols and a 4.0 score is assigned.

Criterion 5a. "The air cleaning concept shall be effective for the entire particle size spectrum during the accident."

All three systems are expected to show moderate to low efficiencies for submicron particles. Ranking was based on the measured sodium compound particle efficiency of each system. The submerged gravel scrubber rated 3.0, the venturi 2.5 and the spray scrubber 2.0.

Criterion 5b. "The system performance shall not be highly sensitive to the atmospheric temperature or relative humidity."

All three systems process gas at any temperature within design limits and operation is independent of the relative humidity of inlet gas. Since water would have to be added to compensate for evaporation, all systems were rated 3.5.

Criterion 5c. "The system energy consumption shall be low."

Energy requirements for the three candidates are modest. Scores were assigned on the basis of horsepower requirements for the conceptual designs, allowing for a possible purge fan operation. Because the gravel scrubber

has no water pump, it was rated 3.0. The spray chamber was rated 2.5 and the venturi scrubber 2.0.

Criterion 5d. "Post-accident recovery shall be facilitated by the air cleaning system."

Contaminants removed from the air stream would be dissolved or entrained in the water of all three systems. After an accident, this water could be processed to put the contaminants into the desired form. This ability is considered satisfactory and a score of 3.0 is assigned to all three systems.

Criterion 6a. "System costs, capital and maintenance, shall be low."

Scores were assigned on the basis of capital costs estimated from the conceptual designs developed. The relative costs and ratings are as follows:

<u>System</u>	<u>Relative Cost Units</u>	<u>Score</u>
Eductor Venturi	0.80	2.5
Submerged Gravel	0.45	3.5
Spray Chamber	1.6	1.0

Criterion 6b. "Materials and techniques used in construction shall be readily available."

All three systems use standard construction materials. The venturi and spray chamber scrubbers use standard construction techniques and were rated 4.0. Since the submerged gravel bed represents a small departure from usual construction techniques, it was given a score of 3.0.

Criterion 6c. "Components and equipment shall be readily available."

All three systems use standard, readily available components and were assigned a score of 4.0.

A P P E N D I X B

NUMERICAL RANKING OF 99% EFFICIENT SYSTEMS

The four candidates (an eductor venturi with fibrous scrubber, a submerged gravel bed with fibrous scrubber, sand and gravel bed and a HEPA filter system) are compared on a criterion-by-criterion basis. As noted in Section V, the numerical scores varied from 0.0 to 4.0. A rating of 4.0 denotes acceptable conformance and a rating of 0.0 denotes totally unacceptable conformance.

Criterion 1a. "The design decontamination factor shall be achieved using design parameters that fall within current state-of-the-art practice."

While all four candidates exhibit efficiencies that exceed the 99% design level, the two scrubber systems and the HEPA filter system are appreciably more efficient than the sand filter. Therefore, the two scrubber systems and the HEPA filter system were assigned scores of 4.0 and the sand and gravel filter was assigned a score of 3.0.

Criterion 1b. "The system shall handle dry or sticky particles and particles of varying chemical composition."

The two scrubber candidates are minimally affected by particle chemical composition because solubility considerations dictate minimum water volumes and the dissolution of aerosol trapped in the fibrous elements. A score of 3.5 was assigned to both scrubbers.

The physical characteristics of particles (sticky or dry) appreciably affect the mass loading capability of the sand bed and HEPA filter systems because fiberglass is susceptible to corrosion by moist sodium hydroxide. The sand bed was given a rating of 3.0. The HEPA filter system was rated 2.5.

Criterion 1c. "System effectiveness shall not be degraded by the radiation dose caused by the accident over the required operating period."

All four candidates can be designed to accommodate the modest radiation exposures expected. Due to the difference in inherent resistance to radiation

doses, the sandbed filter was rated 4.0, the HEPA filter system 3.6, the submerged gravel scrubber 3.3 and the venturi scrubber 3.0. The submerged gravel scrubber uses polypropylene fibers that are susceptible to radiation damage, although the radiation doses expected for this application do not cause material failures. In addition to the use of polypropylene, the venturi uses pumps and motors not present in the other systems.

Criterion 1d. "System characteristics shall inherently favor systems with ability to handle large masses of aerosol".

Because scrubber candidates are able to capture large masses of aerosol without difficulty, they were rated 4.0. Both the sand bed and HEPA systems are inherently inefficient in trapping large aerosol masses. The two dry systems were rated 2.0.

Criterion 2a. "The system shall have a high probability of start-up after initiation of the accident."

The two dry scrubbers are rated 4.0 because there are no active components for venting and because no water pools are maintained during the systems shelf life.

The two scrubbers (venturi and submerged gravel bed) require water and introduce a failure mode not present in the dry systems. The venturi scrubber also requires liquid pump start-up. Therefore, the submerged gravel and venturi scrubbers were rated at 3.5 and 3.0 respectively.

Criterion 2b. "The system shall not degrade during periods of non-use."

Both dry systems were rated 4.0 because no credible degradation mode could be identified during periods of non-use. The scrubbers were rated 3.5 because of possible corrosion in the water storage tank.

Criterion 2c. "The system shall be capable of dependable operation over the 1000-hour accident period under the accident conditions of temperature, humidity, aerosol loading and flow rate."

Scores were assigned to reflect inherent aspects of reliability in each system. The factors and scores are summarized as follows:

TABLE B-1
SYSTEM RELIABILITY RATINGS

<u>System</u>	<u>Score</u>	<u>Judgment Factors</u>
Sand Bed (HE-3)	3.8	No water required, no pumps
Submerged Gravel (HE-2)	3.5	No pump required
Venturi/Fibrous (HE-1)	3.0	Pump required
HEPA Filters (HE-4)	2.0	Possible corrosion of media by NaOH

Criterion 2d. "The system shall require simple components and control and conservative design stresses."

All four candidate systems incorporate simple components but differ in overall design. System scores and judgment factors are summarized as follows:

TABLE B-2
SYSTEM DESIGN RATINGS

<u>System</u>	<u>Score</u>	<u>Judgment Factors</u>
Venturi/Fibrous (HE-1)	3.5	Standard design, modest size
Submerged Gravel (HE-2)	3.4	Modest size, novel gravel bed
Sand bed (HE-3)	2.0	Very large bed, under pressure
HEPA Filter (HE-4)	1.0	Largest pressurized HEPA installation in the world

Criterion 3a. "Inadvertent operation of the air cleaning system shall not harm the containment system or constitute a hazard to personnel."

Because all four candidate systems are external to the containment vessel and could not harm personnel, no major short-comings for any of the systems are envisioned. Both dry systems were rated 4.0. Because effort is required to drain tanks and lines, the submerged gravel and venturi scrubbers were rated 3.8 and 3.6, respectively.

Criterion 3b. "The size of the air cleaning system shall be compatible with installation adjacent to the RCB, and not significantly impact the location of other ancillary plant systems."

The two scrubbers are of similar size and appear to fit within available free regions close to the containment vessel. They were given a rating of 3.0. Because dry systems are very large, cannot be located adjacent to the containment vessel and would grossly impact the location of ancillary plant systems, they were assigned scores of 0.0.

Criterion 4a. "The air cleaning concept shall be based on highly developed technology."

The venturi/fibrous system uses components that have broad industrial application. The combined system was tested extensively at HEDL with sodium compound aerosols typical of those postulated for margins application.⁽⁵⁾ Therefore, this system was rated 4.0.

The HEPA filter system was rated 3.8. Although HEPA filters have very broad industrial application, questionable use with NaOH aerosol and the large installation size detracted from the score. The sand bed rated 3.0 because few sand bed filters are used in industry. The submerged gravel scrubber was rated 2.0 because the system was not demonstrated at full scale.

Criterion 4b. "The air cleaning system shall be testable in-place for operability and efficiency."

All systems are external to the containment building and could be tested without significantly impacting other plant operations. However, the scrubber systems would require more effort to operate and put into standby condition. Both the HEPA and sand bed filter systems were assigned scores of 4.0 because the testing procedure would involve only the operation of valves, fans and aerosol testing instruments. The venturi/fibrous scrubber was rated 3.0. The submerged gravel scrubber was rated slightly higher at 3.1 because it has no liquid pumping system to operate.

Criterion 4c. "The system's performance shall be predictable by verified mathematical models."

For the scrubbers, particle capture, heat transfer and mass loading capacity can be predicted by available models. Although the models are probably satisfactory, additional verification work would increase confidence. Therefore the scrubbers were rated 3.0.

Dry systems performance, particularly the mass loading capacity, lacks extensive modeling. Off-setting lack of modeling is the availability of empirical information that can be used to design the dry systems. A score of 2.0 was assigned to both the sand bed and HEPA filter systems.

Criterion 4d. "The scale-up of air cleaning equipment from currently available sizes to FFTF margins application shall be small."

The venturi/fibrous scrubber was rated 4.0 because no scale-up in size is involved. The sand bed rated 3.5 because, although the required unit would be larger than any presently in existence, there appear to be no technical issues involved in enlarging the planar area. The HEPA filter installation was rated 3.0. While there is no scale-up of the individual filter units, the assembled system would be larger than any existing installation. The submerged gravel/fibrous scrubber was rated 2.0 because a large system was not tested and requires scale-up.

Criterion 4e. "The system concept shall have been demonstrated with sodium compound aerosol or the extension of results to sodium aerosol can be made with confidence."

All four candidates were tested with sodium compound aerosols at HEDL and at other laboratories. The venturi/fibrous scrubber rated 4.0. Extensive tests at HEDL have demonstrated the efficiency of this system. The HEPA filter system rated 3.5. Significant experience on trapping sodium compound aerosols was accrued in HEDL test programs. The submerged gravel/fibrous scrubber rated 3.0 because the equipment used in HEDL tests was of a modest size. The sand bed filter rated 2.5 because less information is available on this candidate than for the other candidates.

Criterion 5a. "The air cleaning system shall be effective for the entire particle size spectrum during the accident."

The two scrubber systems and the HEPA filter system trap all particles sizes efficiently and rate 4.0. HEDL experiments show that a measurable fraction of fine particles can penetrate a sand bed filter, and this candidate was rated 3.0.

Criterion 5b. "The system performance shall not be highly sensitive to the atmospheric temperature or relative humidity."

The two scrubber systems rated 3.5 because their performance is independent of relative humidity and affected by temperature only under extreme conditions when water temperatures approach the safe limit for polypropylene fibers. The sand bed filter was rated 3.0 because loading capacity is dependent on particle stickiness, which in turn depends on relative humidity. The HEPA filter system was rated 2.0 because its loading capacity is dependent on relative humidity and the fiber glass medium is susceptible to corrosion by moist NaOH.

Criterion 5c. "The system energy consumption shall be low."

The sand and HEPA filter systems rated 3.5 because they would exhibit low pressure drop and have no water pumping requirements. The submerged gravel/fibrous scrubber rated 3.0 because pressure drop is higher than that of the dry systems. The venturi/fibrous scrubber rated 2.0 because it also requires a liquid pumping system.

Criterion 5d. "Post-accident recovery shall be facilitated by the design of the air cleaning system."

All systems are external to the containment building and have similar characteristics regarding re-entry to containment, but differ in trapped contaminant disposal. In the scrubber systems most of the contaminants would be suspended in the water and could be processed for permanent storage. The scrubbers were assigned scores of 3.0. The sand bed filter was also rated 3.0. It was assumed that the contaminants would be left in place. The HEPA filter system was rated 0.0 because removal and disposal of the large number of HEPA units would involve large expenditure of cost and manpower.

Criterion 6a. "System costs, capital and maintenance, shall be low."

Maintenance costs are expected to be low for all candidates. However capital costs vary widely and ratings for this criterion were based on capital cost estimates listed in Tables 7 through 11. Results are tabulated below.

TABLE B-3
SYSTEM RATING BY COST

<u>System</u>	<u>Cost Units</u>	<u>Assigned Score</u>
Submerged gravel (HE-2)	0.7	4.0
Venturi/fibrous (HE-1)	1.1	3.0
Sand bed (HE-3)	16.0	1.0
HEPA filters (HE-4)	110	0.0

Criterion 6b. "Materials and techniques used in construction shall be readily available."

The venturi/fibrous scrubber and the HEPA filter system use standard readily available materials and construction techniques and were assigned scores of 4.0. The sand bed rated 3.5. While construction materials are readily available, only a few large sand bed filters have been constructed. Therefore, construction techniques may require more planning than the "optimum" system. The submerged gravel/fibrous scrubber was rated 3.0. No substantial difficulties in construction techniques are expected, but the design lacks a use-history.

Criterion 6c. "Components and equipment shall be readily available."

Components and equipment required for all systems, except the sand bed are readily available. The two scrubber systems and the HEPA filter are rated 4.0. The fine sand layer used in the sand bed would probably have to be shipped in from the Midwest; therefore a rating of 2.0 was assigned.

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