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HIGH PERFORMANCE APCS CONCEPTUAL DESIGN AND EVALUATION SCOPING STUDY

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Published February 1998

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ABSTRACT

This Air Pollution Control System (APCS) Conceptual Design and Evaluation study was conducted to evaluate a high-performance (APC) system for minimizing air emissions from mixed waste thermal treatment systems. Seven variations of high-performance APCS designs were conceptualized using several design objectives. One of the system designs was selected for detailed process simulation using ASPEN PLUS to determine material and energy balances and evaluate performance. Installed system capital costs were also estimated. Sensitivity studies were conducted to evaluate the incremental cost and benefit of added carbon adsorber beds for mercury control, specific catalytic reduction for NO_x control, and offgas retention tanks for holding the offgas until sample analysis is conducted to verify that the offgas meets emission limits.

Results show that the high-performance dry-wet APCS can easily meet all expected emission limits except for possibly mercury. The capability to achieve high levels of mercury control (potentially necessary for thermally treating some DOE mixed streams) could not be validated using current performance data for mercury control technologies. If high mercury control cannot be achieved using existing or new technologies, then restrictive feed limits for mercury may become necessary for existing and new mixed waste thermal treatment facilities. Decontamination factors (ratio of the input pollutant mass flowrate and the mass flowrate of the pollutant in the cleaned offgas) for other pollutants were very high (1×10^9 to 4×10^9) because of the cumulative effectiveness of several different APCS components.

Installed APCS capital costs for two different cases ranged from \$27 million to \$46 million, depending on the offgas flowrate and system design. Offgas retention tanks could add hundreds of millions of dollars to the APCS capital costs and could significantly increase the generation of a secondary waste (condensed water). Because the high-performance APCS can generally control pollutant emissions to levels well below expected emission limits, the cost of retention tanks for holding offgas long enough to ensure that noncompliant offgas is not emitted cannot be technically justified.

Process simulation results also identified several issues in addition to mercury control that should be considered in future APCS design and evaluations for existing or new facilities. These include (a) incompatibility of reheat needed to prevent moisture condensation and maximum recommended carbon adsorber operating temperatures, (b) optimization of prefilter, high efficiency particulate-air (HEPA) filter, and carbon bed media replacement frequency, (c) offgas subcooling to minimize water usage, lower moisture dewpoint, and lower offgas temperature, (d) optimization of dioxin/furan control, (e) optimization of secondary waste volume and properties, (f) validation of assumptions for particulate matter size distribution and control, and (g) validation of metals partitioning and control.

The engineering approach and ASPEN PLUS modeling tool developed and used in this study identified APC equipment and system performance, size, cost, and other issues that are not yet resolved. These issues need to be addressed in feasibility studies and conceptual designs for new facilities or for determining how to modify existing facilities to meet expected emission limits. The ASPEN PLUS process simulation with current and refined input assumptions and calculations can be used to provide system performance information for decision-making, identifying best options, estimating costs, reducing the potential for emission violations, providing information needed for waste flow analysis, incorporating new APCS technologies in existing designs, evaluating vendor proposals, or performing facility design and permitting activities.

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ACRONYMS

ALARA	As Low As Reasonably Achievable
APC	air pollution control
APCS	air pollution control system
ARAR	applicable or relevant and appropriate requirement
BIF	Boilers and Industrial Furnaces
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
CIF	Consolidated Incineration Facility
CM	Construction Management
DF	decontamination factor
D/F	dioxins and furans
DOE	U.S. Department of Energy
DRE	Destruction and Removal Efficiency
DWPF	Defense Waste Processing Facility
EER	Energy and Environmental Research Corporation
EPA	U.S. Environmental Protection Agency
HEPA	high efficiency particulate-air
HVAC	heating, ventilation, and air conditioning
INTS	Integrated Nonthermal Treatment System
ITTS	Integrated Thermal Treatment System
IWPF	Idaho Waste Processing Facility
LMITCO	Lockheed Martin Idaho Technologies Company
LVM	low volatile metals
MACT	Maximum Achievable Control Technology
MEI	maximum exposed individual
M&O	maintenance and operations
MSE	Mountain States Energy
NESHAP	National Emission Standards for Hazardous Air Pollutants
PIC	Product of Incomplete Combustion
POHC	Principal Organic Hazardous Constituent
PM	particulate matter
RCRA	Resource Conservation and Recovery Act
SCC	secondary combustion chamber
SCR	selective catalytic reduction
SRS	Savannah River Site
SVM	semivolatile metals
TEQ	Toxicity Equivalent
THC	Total Hydrocarbons
TRU	transuranic
TSCA	Toxic Substances Control Act

SUMMARY

Thermal treatment processing of mixed waste is recognized as one of the most effective means for destroying hazardous organics, reducing waste volume, and immobilizing most hazardous metals and radionuclides. However, mixed waste thermal treatment can produce atmospheric pollutants, including particulates, radionuclides, toxic metals, dioxins and furans (D/F), and acid gases, that must be controlled to protect the public and the environment and to meet regulatory limits. New emission limits in the U.S. Environmental Protection Agency's (EPA's) proposed Maximum Achievable Control Technology (MACT) Rule are significantly more stringent than current emission limits. Current air pollution control system (APCS) configurations may require modifications to comply with the stricter proposed emission limits. Development and deployment of high-performance and reliable offgas systems are needed to improve pollutant control and address stakeholder concerns for emissions control. They may also enable less rigorous feed characterization and control, which may result in lower overall treatment costs.

This Air Pollution Control System Conceptual Design and Evaluation study was conducted to evaluate a high-performance (APC) system for minimizing air emissions from mixed waste thermal treatment systems.

S.1 TECHNICAL APPROACH

The technical approach included several separate activities. First, design objectives were identified for use in designing and evaluating alternative high-performance APCS configurations. APCS concepts were designed to meet these objectives. A representative baseline APCS was selected for detailed evaluations. The selected system included most of the key enhanced APCS features present in the other systems. Detailed evaluation of all seven alternatives was not within the scope of this study.

To focus on the emissions control functions of the APCS, the scope of the APCS designs was limited to equipment downstream of a hypothetical fully oxidizing primary thermal treatment unit (such as an incinerator) and secondary combustion chamber (SCC). Some thermal treatment approaches such as gasification produce a synthesis gas rather than a fully oxidized offgas, but only fully oxidized offgas was within the scope of this study. Therefore, the input gas to the air pollution control (APC) systems consisted of fully oxidized offgas with entrained and volatilized particulate matter (PM).

Flowrates and compositions of the offgas and PM (including entrained and volatilized metal species) entering the APCS were estimated based on a limited evaluation of SCC offgas that would be produced from treating DOE complex-wide mixed waste streams. This information was used in a process simulation model to evaluate the effectiveness of the selected APCS to achieve emission limits for selected pollutants and meet the other design objectives. The process simulation estimated the partitioning and control of PM and other pollutants and the offgas passed through each unit operation. The process simulation used equipment specifications from equipment vendors, empirical performance data, chemical reaction and phase equilibrium calculations, and engineering assumptions where necessary to perform mass and energy balances and determine the fate of offgas and pollutants. For further simplicity, the simulation did not specifically model the fate of radionuclides, although results indicate the expected fate of many volatile and nonvolatile radionuclide constituents that have properties similar to those metals that were modeled. In addition, the dioxins, furans, and other organic compounds were not specifically considered in this study. The conceptual design evaluated in this study was assumed to adequately control D/Fs because it complied with the D/F control specifications in the proposed MACT Rule. Other organic

compounds were considered to be adequately controlled in the upstream primary treatment unit and SCC, which were not included in the scope of this study.

Installed capital costs were estimated for two different cases. Sensitivity studies were also conducted to evaluate the incremental cost and benefit of added carbon adsorber beds for mercury control, specific catalytic reduction for NO_x control, and offgas retention tanks for holding the offgas until sample analysis is conducted to verify that the offgas meets emission limits. Operating costs were not included in the scope of this study.

S.2 APCS DESIGN OBJECTIVES

APCS design objectives for mixed waste thermal treatment and offgas systems have been identified in this study. The most important design objectives considered during the study included:

- Reduce emissions of gaseous organics, radionuclides, toxic metals, particulate, and acid gases to meet expected regulatory limits
- Avoid a nuclear criticality condition
- Have system capability to accept wide variations in offgas flowrate and composition entering the APCS without upsets or degradation of performance beyond acceptable limits
- Operate with minimal downtime
- Comply with As Low As Reasonably Achievable (ALARA) objectives
- Minimize secondary streams and maximize ease of secondary stream treatment and disposal
- Minimize total treatment facility life-cycle cost.

S.3 INPUT OFFGAS FLOWRATES AND COMPOSITIONS

An evaluation was conducted using available data to estimate representative thermal treatment offgas flowrates and compositions, including flowrates, particle size, and compositions of PM and metal species that enter the APCS from the primary thermal treatment unit and the SCC. This evaluation established minimum, normal, and maximum offgas flowrates and compositions, and PM/metals data for two separate thermal treatment cases. These cases included a relatively high offgas flowrate (high-flow) case resulting from assuming standard fuel-fired, air combustion thermal treatment (i.e., rotary kiln with a SCC) and a lower offgas flowrate (low-flow) case resulting from assuming a thermal treatment unit that uses electrical heat generation and oxygen combustion (i.e., plasma arc furnace with a SCC).

The maximum input offgas and PM flowrates and average compositions were generally used in this study. This provided a degree of conservatism, biasing the APCS size and cost estimates and estimates of secondary product streams conservatively high. For additional conservatism, maximum concentration values for ppm-level pollutant species (sulfur dioxide, nitrogen oxides, total chlorine) were used. The total PM was defined to include all of the metal species that can typically comprise fly ash or offgas solids entrained or volatilized in the offgas. Eleven metals were specifically modeled because they

are considered hazardous and are found in the waste based on available composition information. These metals were mercury, lead, cadmium, arsenic, beryllium, chromium, antimony, barium, selenium, silver, and tantalum. The bulk of the total PM includes other common metal and nonmetal species that were not specifically modeled, such as oxides of aluminum, iron, and silicon. The partitioning of specific radionuclides was not modeled at this time.

The flowrates and concentrations for the key metals in the input offgas stream were determined based on known or assumed maximum concentrations of the metals in the waste feed, waste feedrate to the primary treatment system, and chemical equilibrium calculations at thermal treatment operating conditions. Entrained particulate was assumed to be 10% of the total waste feedrate into the primary treatment system for both offgas cases. This level of PM entrainment was based on results of several different DOE-sponsored test programs and other estimates. Previous studies were also used to estimate the particle size distribution of the entrained particulate in the offgas entering the APCS. The entrained PM was assumed to be 40–60 weight % greater than 0.5 μm for the low-flow and high-flow cases. All of the PM formed in the APCS from condensed volatile matter was conservatively assumed to be less than 0.5 μm . The total PM in both cases, which includes entrained particulate and vapor-phase metal species at 2,200°F, was approximately 15% of the treatment system waste input feedrate. This total PM carryover value is conservatively high because measurements from past mixed waste demonstration tests have shown total carryover values of 1–10% of the waste input feedrate.

S.4 HIGH-PERFORMANCE OFFGAS SYSTEM DESIGNS

Seven high-performance offgas system designs were conceptualized for evaluation in this study. These systems all meet or exceed the APCS design objectives listed earlier by using redundant, oversized, or backup conventional control technologies, innovative systems such as no release, low-release, or delayed release systems, or various combinations of traditional and innovative designs. These systems are generally based on earlier Integrated Thermal Treatment Systems (ITTS) and Idaho Waste Processing Facility (IWPF) conceptual designs, but include various above-listed features that enhance control performance.

A baseline high-performance offgas system (R-1) was selected for process simulation in this study. This system is generally representative of the others. This system consists of evaporative water coolers, a dry baghouse, free-jet scrubber with two-stage phase separation, hot air reheater, prefilter, two-stage high efficiency particulate-air (HEPA) filters, sulfur-impregnated carbon adsorbers, selective catalytic reduction (SCR) for NO_x control, and optional offgas retention. This system is similar to the ITTS A-1 offgas system except for the placement of HEPAs and carbon filters and offgas retention. This dry-wet system design is a probable candidate for deployment in mixed waste treatment because, among other reasons, it includes standard APCS equipment and less technical uncertainty in system performance. Additional features that make this system “high performance” include (a) separation of PM upstream of the wet scrubber, minimizing PM-related maintenance and deposition issues in the wet scrubber, (b) indirect offgas reheat using preheated air, (c) multiple redundancy of PM, metals, and radionuclide removal, with different units based on different control principles, (d) sulfur-impregnated carbon absorption to remove Hg species and also trace organics including D/F, (e) an SCR for NO_x control, (f) a continuous emissions monitoring system (CEMS) compliant with the proposed MACT Rule, and (g) optional offgas retention tanks.

Operation of thermal and nonthermal treatment systems with “zero emissions” is not realistically possible because of effluent gases such as nitrogen and oxygen that cannot realistically be condensed. The

most technically feasible approach for “zero emissions” is to minimize the volumes of offgas to the extent possible and then prevent the release of the offgas until it has been demonstrated that the levels of any pollutants are within regulatory limits. Methods that can be used to achieve this include:

- Oxygen instead of air for combustion
- Electrical heat input for treating low-heating-value wastes rather than fossil fuel combustion
- Water spray evaporation for cooling rather than air dilution cooling
- Offgas retention until analyses are complete
- CO₂ absorption or removal via liquefaction or through photosynthesis.

All of these methods except CO₂ removal were considered in this study.

S.5 APCS SIMULATION USING ASPEN PLUS

Process simulation can be used to quickly evaluate the integrated APCS performance and quantitatively demonstrate if process objectives can be expected to be achieved for a given process design. ASPEN PLUS (hereafter referred to as ASPEN) is a process simulation code that was used to calculate mass and energy balances around each unit operation of the R-1 high-performance APCS using chemical reaction and equilibrium data specified by the user or retrieved from an extensive database.

Chemical reactions were calculated based on chemical equilibria at specified temperatures or by defining the extent of reaction. The composition of most constituents were calculated using chemical equilibria at the process temperature. In some cases, nonequilibrium conditions were expected when indicated by empirical data or kinetic or mass transfer limitations. Nonequilibrium conditions in the model were accounted for by specifying an extent of reaction less than 100% (i.e., 85% NO_x reduction in SCR unit, and 99% elemental Hg removal in carbon bed) or by specifying a reaction temperature different from the expected process temperature (i.e., calculating chemical equilibrium at 980°F for Hg-HgCl₂ equilibrium calculations, even though the offgas was cooled from 2,200°F to below 200°F).

Particulate removal from the offgas by the baghouse, prefilter, and HEPA filters were simulated in ASPEN, which allows the particulate removal efficiency to be specified by the user. All removal efficiencies were defined in terms of the ability to remove particles larger than and smaller than 0.5 μm. Particulate removal efficiency in the scrubber was based on vendor-provided design guides that specified the PM concentration in the scrubber offgas as a function of the atomizing air and scrubber liquid mass flowrates relative to the mass flowrate of the offgas being scrubbed. Particle formation resulting from the condensation of metal vapors was also simulated in the ASPEN model. Since the homogeneous condensation of vapors can yield submicron particles, all condensed metal vapor was conservatively assumed to form particles that were less than 0.5 μm in diameter. No heterogeneous condensation of vapors onto >0.5 μm particles, or growth of homogeneously condensed particles beyond 0.5 μm, was assumed. These assumptions challenged the capability of the APCS to capture submicron particles.

S.6 MODEL RESULTS AND APCS PROCESS EVALUATION

The ASPEN simulation model was used to calculate the material and energy balances associated with treating two different offgas cases, to evaluate the effect of changing process variables, and to identify potential process and design limitations in the APCS.

S.6.1 Material and Energy Balances

The design and operation of the dry-wet R-1 APCS results in several material/energy balance findings. While the offgas is efficiently cleaned of contaminants, the offgas mass flowrate at the stack increased by more than 100% over the APCS inlet offgas flowrate. Roughly half of the increase was from quench water evaporated into the offgas. The other half was from scrubber atomizing air and preheated air used to reheat the saturated scrubber outlet offgas.

The secondary waste streams generated in the baseline APCS models (not including the offgas retention option) consist primarily of the PM collected in the baghouse, and the scrub solution discharge containing dissolved salts and trace amounts of PM. Most of the PM was captured in the baghouse. The scrub solution discharge represents the largest volume secondary waste stream and the greatest disposal challenge. The scrub solution discharge was significantly greater in the low-flow case where the assumption of more hydrogen chloride in the offgas entering the APCS resulted in more dissolved salts. In this case, there was such a high level of dissolved salts that a large amount of scrub solution makeup water was necessary to dilute the dissolved salt concentration to the maximum acceptable limit of 10 wt%.

Other secondary wastes that were generated were spent baghouse bags, prefilters, HEPA filters, and carbon bed media. The replacement frequency for these materials depends on the operating conditions as well as total particulate and mercury concentrations in the offgas. HEPA filter and prefilter replacement frequency for the low-flow case was greater than for the high-flow case primarily because only 12 HEPA filters (instead of 24 filters for the air-combustion case) were used in parallel to process approximately the same particulate mass flowrate. While the HEPA filter replacement frequency was acceptably low at 340 to >4,000 operating hours, prefilter replacements were too frequent for both cases (13–31 operating hours). This high replacement frequency could be extended by using less conservative PM loading assumptions, higher efficiency baghouse filters, prefilters with lower removal efficiency and greater loading capacity, or cleanable prefilters. The prefilter efficiency should be optimized to maximize the operating time for the prefilters without causing undesirably high frequency HEPA filter replacements.

Carbon bed replacement frequency was determined based on the mass flowrate of mercury entering the carbon bed adsorbers and a conservative vendor-recommended mercury loading of 20 wt% on the carbon. The service life would increase if the maximum Hg feedrate was significantly decreased or more Hg was oxidized to water-soluble mercury chloride (which is assumed in this model to be removed with high efficiency in the upstream wet scrubber).

Energy balances were performed to calculate the amount of energy required to cool or heat a number of gas or liquid streams in the APCS. In the low-flow case, model simulations indicated an issue that needs to be resolved to prevent moisture condensation in HEPA filters while allowing reasonably low-temperature carbon bed operation. The moisture-saturated scrubber offgas temperature was only increased from 181°F (scrubber operating temperature) to 195°F (maximum allowable temperature for carbon beds). Moisture-saturated offgas is generally heated at least 40°F above the dewpoint to prevent moisture

condensation in downstream HEPA filters and carbon beds. The 14°F differential may be insufficient to prevent such condensation from occurring. A possible remedy to achieve sufficient offgas cooling before the reheater may be to introduce additional cold water in the full quench tower, and discharging the heated water from the full quench tower to waste water treatment or to a chiller that removes heat from the system and allows recycling of the quench water.

The greatest energy requirements occurred when the optional offgas retention was included. The offgas was cooled to a design temperature of 100°F upstream of the retention tanks to reduce the necessary capacity for the tanks and to reduce moisture condensation in the tanks. This requirement results in a large quantity of water condensate being removed from the gas. In both cases, water condensate is generated at a rate of approximately 25 gpm, which is at least 2.5 times higher than the scrub solution discharge rates for each case. The total heat removed was 19×10^6 BTU/hr and 17×10^6 BTU/hr for the high-flow and low-flow cases, respectively.

S.6.2 Metals, Total Particulate, and HCl Removal

Variations in the particle size distribution of offgas particulate within the limited ranges of this study had almost no effect on the total particulate mass captured in the baghouse. The presence of the baghouse upstream of the wet scrubber improves the performance of the entire offgas system by minimizing problems associated with particulate in the scrub solution such as sludge deposition, particle re-entrainment, and spray nozzle erosion. The primary purpose of the wet scrubber is the removal of acid gases and soluble salts. Additional particulate removal occurred in the scrubber although it was over 20 times less efficient than the baghouse.

The decontamination factors (DFs) for all metals except mercury were on the order of 10^9 . Such high DFs were attributed to the cumulative effects of the baghouse (DF = 100–217), the scrubber (DF = 1–340), the prefilter (3.88), and double HEPA filters (DF=1,000 for each filter). Calculated emission concentrations for particulate matter and volatile metals were 4–5 orders of magnitude lower than current or proposed limits. Predicted hydrogen chloride concentrations were approximately ½ of (or less than) proposed limits.

At a Hg feedrate of 10.74 lb/hr, the total Hg emission rates from the APCS for the high-flow and low-flow cases were 2,645 and 25 µg/dscm, respectively, compared to the proposed limit of 40 µg/dscm. The large difference, and failure to meet Hg emission limits for the high-flow case, was a function of the relative Cl:Hg ratios. The low-flow case also included maximum Cl input. The elevated Cl:Hg ratio in the offgas entering the APCS increased the oxidation of elemental Hg to the more water-soluble Hg(II) chloride. The water-soluble mercury was more easily captured in the wet scrubber than was elemental Hg. These results suggest that for moderate Cl:Hg ratios, the Hg-adsorbing efficiency of the carbon beds needs to be increased at least two orders of magnitude higher (99.99% instead of 99%) to ensure that Hg emission limits do not exceed the proposed limits. Such a high adsorption efficiency for carbon beds was not supported by vendor information. A more practical option may be to limit the maximum allowable mercury feed rate to around 0.1 lb/hr, while using carbon beds with removal efficiencies of 99%.

S.7 EQUIPMENT COST ESTIMATES

The installed capital costs for the offgas systems for the two cases were estimated using ASPEN model results, vendor-provided purchase costs, equipment estimates, and installation cost factors. The

installed APCS total capital cost for the high-flow case was \$46 million and the installed APCS cost for the low-flow case was \$27 million.

These costs do not include the cost for retention tanks and associated equipment that would be used to retain the offgas exiting the APCS for analysis. There were two variations of retention tanks that were considered—evacuated retention tanks that operate under slightly negative pressure when at full capacity, and retention tanks that are pressurized up to 100 psig when full. The addition of the evacuated retention tanks and associated equipment increased the cost of the APCS for the high-flow case to \$831 million. The total installed cost including evacuated retention tanks for the low-flow case increased to \$426 million. The total capital costs for the high-flow and low-flow cases using pressurized retention tanks were \$374 million and \$167 million, respectively.

Excluding the offgas retention tanks and associated equipment, the most expensive APC unit was the carbon adsorber bed, followed by the NO_x control unit and the HEPA filters.

S.8 CONCLUSIONS

This study has utilized a process simulation approach to evaluate a high-performance APCS design. The study included identification of several high performance APCS designs, selection of a design for process simulation, computations of APCS performance for controlling pollutants that could be emitted in offgas produced from DOE mixed waste thermal treatment, installed capital cost estimates, and identification of potential limitations and outstanding issues of the process simulation, assumptions, and APCS performance.

S.8.1 APCS Design and Emissions Control Performance

- The selected high-performance APCS design easily meets expected stringent emission limits for all pollutants, except possibly mercury.
- The offgas concentrations of PM and selected metals were reduced to 10^{-1} – 10^{-4} of current or proposed limits. This represents a significant safety factor below expected limits for these pollutants. HCl and Cl₂ concentrations were approximately ½ of or less than proposed limits.
- While the offgas concentration of Hg was around ⅓ of the expected limit for the low-flow case, it was over 60 times greater than the limit for the high-flow case. The lower Hg emissions in the low-flow case resulted from the removal of greater quantities of water-soluble HgCl₂ in the wet scrubber. Performance of Hg control technologies including sulfur-impregnated carbon absorption must be improved and validated to provide the level of Hg control (at least 99.99%) needed if some Hg-contaminated mixed wastes are thermally treated. If such high Hg control efficiencies are not possible, then the Hg content in waste fed to mixed waste incinerators may need to be significantly limited to meet expected emission limits.
- Decontamination factors (DFs) for all semivolatile and low volatile metals except mercury for both offgas cases were on the order of 10². Mercury DFs in the high-flow and low-flow cases were only 130 and 34,000, respectively. The higher Hg DF in the low-flow case was attributed to a higher HCl concentration in the offgas to form more water soluble HgCl₂ which was readily removed in the wet scrubber.

S.8.2 APCS Process Simulation Model

- ASPEN PLUS is a powerful process simulation tool that was used to evaluate the effectiveness of an integrated APCS to minimize pollutant emissions as a function of offgas flowrates, initial pollutant concentrations, and the APCS unit operations and their operating parameters.
- The process simulation helped to identify potential system design limitations such as limited Hg control efficiency, insufficient offgas cooling in the low-flow case to allow adequate offgas reheat, and high frequency HEPA prefilter replacements.
- Several simplifying steps and assumptions were used in this study. These included (a) exclusion of upfront thermal treatment steps including primary thermal treatment and secondary combustion, (b) the use of only fully oxidized input offgas from a hypothetical SCC, (c) exclusion of specific radionuclides, products of incomplete combustion, and D/F, (d) simplification and limited range of offgas and PM flowrate and composition, and PM size distributions, (e) exclusion of secondary waste treatment options and systems, (f) use of sometimes unproven vendor recommendations and assumptions for control equipment performance, (g) lack of optimization of some model results such as Hg control efficiency, secondary waste generation, offgas cooling, reheat, and carbon adsorber temperature limits, and (h) the use of cost factors for estimating installed capital costs.

S.8.3 Installed Capital Cost Estimates

- The installed capital costs of the APCS for the high-flow and low-flow cases were estimated to be \$46 million and \$27 million, respectively. These installed capital costs are 6 times higher than the major and other equipment purchase costs, largely because of large factors needed to account for costs associated with designing, constructing, and permitting DOE facilities (facility capital costs).
- The addition of retention tanks and associated equipment is prohibitively costly. The total estimated APCS costs for the high-flow and low-flow cases using pressurized retention tanks was \$374 million and \$160 million, respectively. The total estimated APCS costs for the high-flow and low-flow cases using evacuated retention tanks was \$831 million and \$426 million, respectively.
- Not including offgas retention tanks, the most costly control equipment was the carbon adsorbers followed by the NO_x control unit and HEPA filters.

S.9 RECOMMENDATIONS

Several recommendations result from this study. These include recommendations for future APCS design, uses of the APCS process simulation developed in this study, and validation or improved performance of specific control technologies.

S.9.1 APCS Design

- Future APCS design for new facilities or for modifying existing facilities should consider the features of the high-performance APCS modeled in this study to provide greatest assurance of adequate emissions control.

- Offgas retention tanks for holding offgas long enough to ensure that noncompliant offgas is not emitted are not recommended. Instead, efforts should emphasize proper APCS design, installation, and operation to achieve compliance goals without the use of offgas retention and delayed offgas release.
- Significant issues identified in this study that should be addressed in future APCS designs include (a) Hg control technology capabilities and limitations, (b) optimization of offgas cooling, reheat, and carbon adsorber temperature to prevent moisture condensation in HEPAs and downstream equipment while achieving desired Hg removal efficiency and minimizing secondary wastes, (c) optimization of prefilter, HEPA filter, and carbon bed media replacement frequency, (d) optimization of D/F control, (e) optimization of secondary waste volume and properties, (f) the impact that secondary waste treatment has on system alternatives, (g) validation of assumptions for PM size distribution and control, and (h) validation of metals partitioning and control.

S.9.2 Uses of the APCS Process Simulation

- The engineering analysis approach, including the process simulation model, established in this study should be used to evaluate additional high-performance APC systems proposed for new facilities or as modifications to existing facilities. This process simulation model can be used in feasibility studies, preconceptual and conceptual designs, technology development and validation programs, and to support higher-level waste flow analyses.
- Using this process simulation can help provide (a) better information for decisions about alternatives for existing mixed waste treatment facilities to comply with new regulations, (b) better identification and qualification of incomplete performance and cost information for new or existing technologies, (c) better public, regulatory, and stakeholder acceptance of thermal treatment and APC systems based on more definitive performance evaluations, (d) avoidance of costly and unnecessary features such as offgas retention, and (e) more rapid and less costly implementation of new facilities and needed modifications to existing treatment facilities.
- Parametric studies should be conducted to identify the impact of variations in offgas or waste feed conditions, new APCS equipment such as improved Hg control technologies, improved or validated control equipment performance data, and operating parameters on pollutant emissions and life-cycle costs for a given APCS. Parametric studies should also be conducted to optimize Hg control efficiency, secondary waste generation, offgas cooling, reheat, and carbon adsorber temperatures, and APCS costs.
- The process simulation should be upgraded to include (a) upstream thermal treatment steps such as primary thermal treatment and secondary combustion so the process simulation can determine species partitioning and offgas generation from the thermal treatment system as functions of the waste feed content and thermal treatment equipment design and operation, (b) modeling of specific radionuclides, products of incomplete combustion, and D/F, and (c) downstream secondary waste treatment and disposition options. Inclusion of upstream and downstream processes in the entire system would evolve this APCS simulation into a complete simulation of the entire treatment system. This would provide better identification of any issues that could impact different unit operations in the entire system, and enable optimization of the entire system to meet system objectives.

- A process simulation of candidate wet-dry high-performance APCS designs should be done to better identify and quantify advantages, disadvantages, and issues for wet-dry systems as compared to the dry-wet system modeled in this study.
- Cost estimates should be upgraded to focus on lifecycle costs which include capital costs and operating costs over some facility lifecycle.

S.9.3 Control Technology Improvement and Validation

- Existing and new Hg control technologies need to be improved and validated to provide assurance that mixed waste thermal treatment facilities can meet expected Hg emission limits while processing some Hg-containing mixed waste streams. If such validation is not possible, then restrictive Hg feed limits (and feed characterization for Hg, with the associated uncertainties and risks) will be required for existing and new thermal treatment facilities.
- Additional performance information should be obtained to validate model assumptions concerning (a) Hg removal efficiency in carbon beds, (b) PM and Hg removal in the wet scrubber, (c) possible D/F formation in the SCR reactor, and (d) cumulative impacts of multiple APC equipment connected in series.

HIGH PERFORMANCE APCS CONCEPTUAL DESIGN AND EVALUATION SCOPING STUDY

1. INTRODUCTION

Thermally treating organic and inorganic mixed waste materials can produce pollutants including particulates, radionuclides, toxic metals, dioxins and furans, and acid gases that must be controlled within prevailing regulatory and permit limits. New proposed limits for some pollutants are significantly more stringent than earlier acceptable emission limits. As a result, current air pollution control system (APCS) configurations may be inadequate in meeting the stricter proposed emission limits without severely restricting the content of potential pollutants or their precursors in the waste feed. The development and deployment of high-performance offgas systems designed with capabilities to meet stricter emission limits under expected and non-normal operating conditions would significantly address the most important stakeholder concerns and may also allow less rigorous feed characterization and control resulting in lower overall treatment costs.

This study was conducted to (a) identify various high-performance APCS configurations designed to meet stricter air emission limits from a mixed waste thermal treatment system, and (b) demonstrate a modeling tool for evaluating the effectiveness of an APCS in meeting those limits.

1.1 Background

Thermal treatment of organic and inorganic mixed waste materials can ultimately produce oxidation products such as carbon dioxide and water; entrained or volatilized particulate matter (PM), radionuclides, toxic metals; acid gases; dioxins and furans (D/F); and organic products of incomplete combustion (PICs). Pollutants, including PM, radionuclides, toxic metals, acid gases, and PICs, must be controlled within prevailing regulatory and permit limits. Pollutant emissions are one of the most important stakeholder issues for mixed waste treatment systems. Stakeholder concern is for emissions control not only during routine operation when all of the equipment is operating within design parameters, but also during non-normal conditions including process startup, shutdown, and atypical feed conditions. The U.S. Environmental Protection Agency (EPA) has proposed air pollutant emission standards for hazardous waste incinerators under the Hazardous Waste Combustor Maximum Achievable Control Technology (HWC MACT) Rule (EPA 1996, EPA 1997a). Pollutants expected to be regulated under this rule include mercury, total chlorine (hydrogen chloride and chlorine), semi-volatile metals (SVM) including lead and cadmium, low-volatility metals (LVM) including arsenic, beryllium, and chromium, PM, D/F, hydrocarbons (HC), and carbon monoxide. The proposed limits for some pollutants, such as for mercury and total chlorine, are significantly more stringent than earlier acceptable emission limits. As a result, a current APCS configuration that meets existing emission limits may be inadequate to meet restrictions imposed by the proposed MACT Rule.

The Waste Experimental Reduction Facility (WERF) controlled-air incinerator located at the Idaho National Engineering and Environmental Laboratory (INEEL) is an example of a currently acceptable dry APCS. The WERF incinerator processes beta/gamma-emitting low-level radioactive waste. The incinerator APCS consists of a dry particulate filtering system employing offgas dilution with ambient air for cooling the offgas, an air-cooled shell-and-tube heat exchanger for additional heat removal, and a baghouse and high-efficiency particulate air (HEPA) filters to remove particulate matter (Branter 1994).

The APCS is especially designed for efficient PM control, but it is not capable of effective acid gas or Hg control. To date, the Hg and Cl emissions have been controlled by limiting the Hg and Cl content of the waste feed.

The Consolidated Incineration Facility (CIF) utilizes a rotary kiln incinerator followed by a wet APCS. The APCS consists of a water spray quench, a free-jet scrubber, a cyclone separator and mist eliminator for liquid-gas separation, and a reheater prior to the downstream dry HEPA filters (Burns, 1997). The APCS is especially designed for efficient particulate and acid gas removal. Control of Hg by this APCS has not been adequately demonstrated and may be insufficient to meet expected emission limits without limiting the mercury content in the waste feed.

Development and deployment of high-performance and more reliable offgas systems will significantly help the U.S. Department of Energy (DOE) address stakeholder and regulatory concerns for control of air pollutant emissions especially in light of more stringent proposed regulations. High-performance offgas systems can be designed with conservatively designed capabilities to meet stricter emission limits under expected and non-normal operating conditions. These offgas systems may allow less rigorous feed characterization and control by eliminating or loosening current restrictions on specific pollutants or their precursors in the waste feed. Rigorous feed characterization and control for most mixed wastes could be very expensive and difficult because of the physical and chemical heterogeneity of the wastes. The Integrated Thermal Treatment System (ITTS) (Feizollahi 1996) and the Integrated Nonthermal Treatment System (INTS) (Biagi 1997) studies estimated the life-cycle cost of the APCS for a mixed waste treatment system was 5% or less of the total estimated life-cycle cost. Estimated costs for upfront waste handling and characterization ranged up to 30% of the total costs. The ITTS and INTS studies included offgas system modeling, sizing, and cost estimating as a means of evaluating several different treatment system alternatives. However, the offgas system models and related assumptions used to calculate component partitioning were relatively simple. The detail of the models used in these studies was insufficient for quantitative emissions performance evaluations and mass/energy balances.

1.2 Technical Approach

This study used a detailed approach for determining component partitioning, which includes a description of the expected particle size distribution entering the APCS, additional particulate formed during offgas cooling, and partitioning based on chemical thermodynamic equilibria calculations. Additional performance information, such as filter efficiencies and particulate removal efficiencies in the wet scrubber as a function of operating conditions, were used. The study did not consider specifically the fate of radionuclides, although partitioning results for the volatile and nonvolatile toxic metals that were modeled can provide insight to the partitioning trends of volatile and nonvolatile radionuclide constituents. In addition, D/Fs and PICs are not specifically considered in this offgas system model. PICs were considered to be adequately controlled in the upstream primary treatment unit and SCC, which were not included in the scope of this study. The conceptual design evaluated in this study was assumed to adequately control D/Fs because it complied with the D/F control specifications in the proposed MACT Rule.

The technical approach included the following tasks:

Identify design objectives for high-performance APCS (Section 2). This task identified important design objectives in designing and evaluating high-performance APCS.

Identify baseline offgas flowrates and compositions from different thermal treatment systems for use in evaluation of high-performance APCS (Section 3). The offgas from mixed waste thermal treatment processes will vary in composition and flowrate, depending on (a) the input waste stream chemical and physical properties, flowrate, variability, and heterogeneity, and (b) treatment process design and operating conditions. Mass balance calculations have been done to establish offgas conditions at the outlet of a hypothetical secondary combustion chamber. These offgas conditions were used in this study.

Identify and conceptually design several alternative high-performance offgas systems (Section 4). These systems must meet or exceed the requirements and treat the offgas determined in Section 3 by using redundant, oversized, or backup conventional control technologies, or various combinations of traditional and innovative designs.

Evaluate selected APCS using ASPEN PLUS process simulator (Sections 5 and 6). ASPEN PLUS is a process simulation code used to calculate species partitioning within an APCS based on thermodynamic equilibrium calculations and particle size data. The process simulator was used to calculate mass and energy balances within an APCS and to demonstrate the effect of operating and process conditions in achieving pollutant emission limits.

Estimate costs of the selected base APCS and incremental costs of additional offgas equipment (Section 7). The total capital costs of the selected base APCS was estimated. In addition, the incremental costs associated with specific pollutant control and temporary offgas retention were estimated.

2. OFFGAS SYSTEM DESIGN OBJECTIVES

Offgas system design objectives for APCS associated with existing or proposed mixed waste thermal treatment systems have been reviewed as a part of this study (Soelberg 1996b, EER 1997, Soelberg 1997b). The most important and fundamental design objectives are listed in Table 2-1.

Current and proposed emissions regulations were considered for particulate, radionuclides, toxic metals, acid gases, and organic pollutants. Applicable emission limits that are relevant to offgas system design and operation downstream of the typical secondary combustion chamber (SCC) are shown in Table 2-2. This table lists current emission limits based on current regulations and expected permit conditions, and also emission limits as defined in the proposed Revised Standards for Hazardous Waste Combustors, also called the Maximum Achievable Control Technology (MACT) Rule (EPA 1996 and EPA 1997a). The MACT Rule is presently proposed and not yet promulgated, is subject to some modifications prior to promulgation, and may not apply to mixed waste treatment in its presently proposed form. To be conservative, however, compliance with the stricter of the current or proposed regulations was generally assumed. In some cases such as for HCl emissions, the simpler limit from the MACT Rule was assumed even if it may result in a slightly higher emission limit. Regulations that specify proper use and maintenance of offgas equipment were excluded from Table 2-2 and are summarized elsewhere (Soelberg 1997b).

Since the offgas system defined in this study is the equipment downstream of a SCC, regulations that apply to mixed waste treatment process equipment including and upstream of the SCC are not within the scope of this study. The assumption is made that the treatment equipment and the secondary combustion chamber will work as designed and the offgas emissions for such pollutants as total hydrocarbons (THC) will meet applicable regulations.

Both state and federal standards will apply to mixed waste treatment facilities. Current limits that are based on risk assessments also depend on facility location. For the purposes of this study, only federal standards were used because all potential facilities must comply with these standards. State regulations generally will be consistent with federal standards. State regulations that may impose additional or more stringent limits are listed in EER 1997, but are not considered in this study. Federal standards that govern mixed waste treatment are found in various sections of the Code of Federal Regulations (CFR):

- National Emission Standards for Hazardous Air Pollutants (40 CFR 61). While most of these standards are source-specific, three can apply for mixed waste treatment facilities based on waste materials treated in the process. There are some mixed waste streams that contain beryllium, so 40 CFR 61.32 is assumed to apply for beryllium emissions. There are some large mixed waste streams containing sludges produced from wastewater treatment, so 40 CFR 61.52 is assumed to apply for mercury emissions. Since radionuclides are present in mixed waste, 40 CFR 61.92 is assumed to apply.
- Standards for hazardous waste incineration [40 CFR 264, Subpart O (264.340–351)]. These have direct application because mixed waste includes hazardous waste as defined in 40 CFR 261 Appendix VIII, and is regulated under Resource Conservation and Recovery Act (RCRA). The applicability of the incineration rules is assumed for the purpose of system performance even if the primary treatment device is not classed as an “incinerator”, because of EPA’s Omnibus authority defined in Section 30005(c) of RCRA.

Table 2-1. Design objectives for mixed waste treatment offgas control systems.

Design objective	Comments
Control emissions of gaseous organics, radionuclides, toxic metals, particulate, and acid gases to meet expected regulatory limits.	Questions that must be defined include (a) which current or proposed emission limit values should be used, and (b) how far below selected limits should the offgas system control emissions? Targets of one-tenth of the expected limits have been assumed in Feizollahi 1996, for example.
Employ methods to ensure that a nuclear criticality condition will be avoided.	Design and operation must avoid any holdup of TRU-containing solid materials in amounts and concentrations that could approach criticality, especially in wet systems where the presence of water can increase the criticality potential.
Accept any likely offgas flowrate and composition variations from the primary treatment process without upsets or degradation of performance beyond acceptable limits.	This is important for enabling the treatment system to process widely varying feed materials with less rigorous characterization, sorting, significant turndown, or feed additives.
Operate reliably with minimal downtime and upsets.	The annual availability of a mixed waste treatment system for actual operation has been estimated at only 50% or less (4,400 hours or less) in several studies (Eddy 1996, Feizollahi 1996, and Soelberg 1994). Operating costs are the largest single component of a mixed waste treatment facility life cycle costs. Operating costs per unit of waste treated and time required to treat waste increase substantially when availability is decreased.
Comply with ALARA objectives by minimizing the exposure of workers, the public, and the environment to radiological hazards.	An ideal goal would be to operate remotely during normal, routine conditions, although some direct operator-performed maintenance should be expected during shutdowns or unusual conditions. This approach has been made in the preliminary designs reported in Eddy 1995, but existing systems such as the WERF incinerator, and the Savannah River Site CIF, and systems under construction such as the Pit-9 melter system do not have this approach and require hands-on operation while processing waste.
Minimize amounts of secondary streams and maximize ease of secondary stream final treatment and disposal.	Handling and disposal of offgas system secondary product streams can involve significant ALARA and waste form issues because of the potential for concentrated toxic metals and radioactive contamination in or on small particles, regardless of the treatment or offgas system design.

Table 2-1. Design objectives for mixed waste treatment offgas control systems (continued).

Design objective	Comments
Minimize total treatment facility life-cycle cost.	While some higher performance offgas systems that include more comprehensive monitoring may be more costly to purchase or operate, they may enable lower overall facility life cycle costs if less downtime is required or if less upfront feed characterization, sorting, or blending is required.
Comply with all other Applicable or Relevant and Appropriate Requirements (ARARs).	For CERCLA remediation facilities, there are a large number of ARARs that should be addressed. Potential sources of these ARARs depend on regulator, stakeholder, and operator discretion and precedence.
Minimize technology implementation risk.	This is important for any components or technologies that are not well demonstrated, proven, or accepted for the application in which they are specified.
Simplify equipment operation and maintenance by design.	Achieve reliable operation with minimal downtime and minimal total facility life cycle cost.
Interface adequately with the treatment process and secondary waste form handling process.	This is an important systems engineering design objective to ensure that the entire treatment facility operates as desired.

- Standards for Boilers and Industrial Furnaces [BIF rules, 40 CFR 266 Subpart H (266.100–112)]. Under EPA’s Omnibus authority, emission limits defined in the BIF rules can also apply even though a facility is neither a boiler or an industrial furnace.
- Standards from the Toxic Substance Control Act (TSCA, 40 CFR 761). Section 761 regulates the incineration of wastes that contain PCBs in concentrations greater than or equal to 50 ppmw. Some mixed waste streams are known or assumed to contain PCBs in concentrations greater than or equal to 50 ppmw.

In addition to EPA standards in the CFR, DOE Order 5280.2A regulates air emissions of radionuclides and hazardous materials by specifying compliance to National Emission Standards for Hazardous Air Pollutants (NESHAP) and RCRA standards, referring back to 40 CFR 61 and 264.343.

Table 2-2. Current and proposed emission limits.

Pollutant	Current Standard		Proposed MACT standard (EPA 1997a) (k)	Emission limit assumed for this study (k)
	Limit (k)	Reference		
Beryllium	10 g/24-hrs	40 CFR 61.32	—	—(j)
Mercury	3,200 g/24-hrs	40 CFR 61.52	40 µg/dscm	40 µg/dscm
Radionuclides	10 mrem/yr (a)	40 CFR 61.92	—	0.1 mrem/yr (b)
POHCs	99.99% DRE	40 CFR 264.343	—	—(j)
HCl	1.8 kg/hr or 1% of the uncontrolled HCl level	40 CFR 264.343	—	—
Total HCl and Cl ₂	(h)	40 CFR 266.107	75 ppm (c)	75 ppm
PM	180 mg/dscm	40 CFR 264.343	35 mg/dscm (d)	35 mg/dscm
CO	100 ppm (e)	40 CFR 266.104	100 ppm	100 ppm
THC	— (f)	40 CFR 266.104	10 ppm	10 ppm
D/F	(g)	40 CFR 266.104	0.2 ng TEQ/dscm	0.2 ng TEQ/dscm
PCBs	99.9999% DRE	40 CFR 761.70	—	—(j)
BIF metals	(h)	40 CFR 266.106	—	—(j)
SVM (Pb, Cd)	—	—	100 µg/dscm	100 µg/dscm
LVM (As, Be, Cr)	—	—	55 µg/dscm	55 µg/dscm
PICs	(i)	Draft PIC Guide	—	—(j)

BIF = Boilers and Industrial Furnaces

BIF metals = Sn, Ba, Pb, Hg, Ag, Tl, As, Cd, Cr, Be, Se, Ni

D/F = Dioxins and furans

DRE = Destruction and Removal Efficiency

LVM = Low Volatile Metals

PICs = Products of Incomplete Combustion

PM = Particulate Matter

POHC = Principal Organic Hazardous Constituent

SVM = Semivolatile Metals

TEQ = Toxicity Equivalent

a. Effective dose equivalent for any member of the public from total radionuclide emissions. This limit is typically far lower, such as 0.1 mrem/yr, for specific treatment systems that are located at a larger site, because the entire site limit is 10 mrem/yr.

b. A lower limit of 0.1 mrem/yr is assumed.

c. Unless otherwise noted, concentrations are on a volumetric, dry basis corrected to 7% excess oxygen (or representative oxygen level for treatment processes in which oxygen or oxygen-enriched air is used as an oxidant).

d. Unless otherwise noted, concentrations are on a dry basis corrected to 7% excess oxygen (or representative oxygen level for treatment processes in which oxygen or oxygen-enriched air is used as an oxidant).

e. The CO limit, if the CO level exceeds 100 ppm, may be established in a trial burn, providing that the THC level does not exceed 20 ppm.

f. Or, if the CO level exceeds 100 ppm, the THC limit is 20 ppm.

g. For facilities that have dry PM control in the 450–750°F temperature range, determine by stack emission measurements and risk assessment that emissions of D/F do not result in increased lifetime cancer risk to a hypothetical maximum exposed individual (MEI) exceeding 1:100,000 (base emission limit on the emission rate that would result in 1:100,000 risk of increased lifetime cancer to MEI).

h. Must comply with either Tier I feed limits, Tier II Emission screening limits, or Tier III emission dispersion limits.

i. Conduct a detailed exposure assessment, which includes measurements for the 12 BIF metals, many organic PICs, 20 largest peaks on a GC/MS scan, D/F, full PCB scan, highly toxic compounds in the waste, and nitrogenated organic compounds (EER 1997).

j. Permit writers may in fact specify compliance for these pollutants according to the existing NESHAP, RCRA, BIF, or Draft PIC Guide requirements. However, because these are (a) site-specific requirements for which a general limit is not available, (b) requirements of the primary treatment device and SCC, or (c) considered to be adequately covered by surrogates (such as THC) by the proposed MACT Rule, specific limits will not be used in this study for these pollutants.

k. Many of the limits are based on 1–10 hour rolling averages.

3. INPUT OFFGAS FLOWRATES AND COMPOSITIONS

The design and performance of any APCS depend on the properties of the offgas to be treated, which in turn depend on the properties and processing rate of the input waste as well as the design and operation of the thermal treatment system. An evaluation was conducted to determine reference offgas flowrates and compositions as well as the flowrate, particle size distribution, and composition of particulate matter (PM) being generated from a thermal treatment system. Using reference offgas input conditions for this study enables the comparison of performance, size, and cost on the same basis for different APC systems. The varieties and compositions of DOE mixed wastes were evaluated to estimate the minimum, normal, and maximum PM and offgas flowrates and compositions that would result from thermal treatment.

Two separate thermal treatment cases were considered which reasonably bracket the kinds of thermal treatment technologies presently available or being planned for mixed waste treatment. A relatively high offgas flowrate case (high-flow) resulted from the use of fossil-fired, air combustion thermal treatment represented by an air-fired rotary kiln with an air-fired SCC. A much lower offgas flowrate (low-flow) was produced when electrical heat generation and oxygen combustion was considered in the second case represented by the various plasma arc treatment technologies. The results of this evaluation are summarized in this section and are described in detail in Appendix A.

The mixed waste composition was based on earlier descriptions (Huebner 1994). While the DOE Interim Mixed Waste Inventory Report was also available (DOE 1993) and is often used as a standard for describing volumes of DOE site-wide mixed wastes, this report does not include waste masses or compositions that were needed in this evaluation. Waste feed flowrate and composition, offgas flowrates and compositions, and PM flowrates and compositions were based on those from the ITTS study (Feizollahi 1995) with some exceptions. These exceptions are noted in Appendix A and are based primarily on the use of improved assumptions or additional data that were not available at the time of the ITTS study. A reference waste feedrate of 2,149 lb/hr, which was the feedrate for the ITTS systems A-7 (slagging rotary kiln, air combustion) and C-2 (plasma furnace, O₂ combustion, CO₂ retention), was selected.

3.1 Input Offgas

The input offgas flowrates and compositions used in this study are shown in Table 3-1. These flowrates and compositions were based on the ASPEN PLUS simulation of the ITTS A-7 and C-2 systems with some relatively minor adjustments based on comparisons to actual offgas flowrates produced from treatment system demonstrations and actual operations under some similar process conditions. Only fully oxidized offgas, as typical for the outlet of a secondary combustion chamber, was considered as input gas.

The maximum SCC outlet offgas flowrates for the high-flow and low-flow cases from Appendix A were selected for input flowrates so that the offgas equipment was sized to accept the maximum flowrates. The average offgas compositions were generally used, however, for the offgas compositions, because the maximum composition levels for O₂, N₂, CO₂, and H₂O would not all occur at the same time—otherwise, the offgas composition values would sum to greater than 100%. Maximum concentration values for ppm-level species (CO, NO_x, HCl and Cl₂) were selected to be conservatively high for these pollutants. The concentrations of O₂, N₂, and H₂O were adjusted slightly so that the sum of the offgas constituents (not including volatilized PM) totaled 100%.

Table 3-1. Input offgas conditions at the outlet of the secondary combustion chamber.

Parameter	High-flow case	Low-flow case	Comments
Offgas temperature, °F	2,200	2,200	Design temperature for the SCC outlet
Offgas flowrate, scfm	6,715	3,429	(a)
Offgas composition, (by volume):			
Oxygen, %	7	14	(b)
Nitrogen, %	74	5	(b)
CO ₂ , %	8	30	(b)
H ₂ O, %	10	48	(b)
CO, ppm	10	10	(a)
NO _x , ppm	4,000	4,000	(a), (c)
HCl, ppm	2,500	25,000	(a)
Cl ₂ , ppm	5	100	(a)
SO ₂ , ppm	100	1,000	(a)
Total	100	100	Concentrations of oxygen, nitrogen, and H ₂ O are adjusted to enable sum to equal 100%

Note: The number of digits in a value does not indicate the number of significant figures.

a. Maximum value from Appendix A, Table A-4.

b. Normal value from Appendix A, Table A-4.

c. NO_x is assumed to be 100% NO.

3.2 Input Volatilized and Condensed Particulate Matter

The partitioning of 11 metals was specifically modeled because these metals are considered hazardous and are found in the waste based on composition information (Huebner 1994). These metals were Hg, Cd, Pb, As, Be, Cr, Sb, Ba, Se, Ag, and Ta. Total particulate matter (PM) was defined to include offgas solids (flyash), entrained vapor condensate, and volatilized metals. The bulk of the total particulate matter includes other common metal species which were assumed to be nonvolatile and chemically inert. The input concentrations of the 11 metals evaluated in this study are listed in Table 3-2.

Because filter efficiencies were usually defined in terms of particles approximately 0.5 μm in size, a particle size distribution was estimated for both thermal treatment systems in terms of particles greater and less than 0.5 μm . Two reports suggest that approximately 60% of particles exiting an air-combustion process are greater than 0.5 μm (EPA 1992 and Dalton 1992), so this value was used for the high-flow case (Table 3-2). Approximately 60% of particles exiting a low-flow thermal treatment process were less than 0.5 μm (Dalton 1992).

The total PM input composition and flowrate (Table 3-3) were determined based on the waste input feedrate to the primary treatment system, ranges for assumed and measured values for total PM carryover, and partitioning of the 11 key metals determined from chemical equilibrium modeling. The computer software *HSC Chemistry for Windows* was used to calculate chemical equilibria of each metal at 2,200°F (the design operating temperature for the SCC) with excess oxygen, water, and hydrogen chloride. *HSC Chemistry* utilizes an extensive thermodynamic database that contains data for over 7,600 chemical compounds. Chemical equilibrium calculations showed that three metals (Be, Ta, and Cr) would exist as solid oxides under the high-temperature conditions. Thus, it was assumed that only a small fraction of these metals (10% of Ta, Cr; 1% of Be) that may be present in the thermal treatment system become entrained as particulate carryover. The other eight metals could exist significantly in the vapor phase as either the element (in the case of Hg), the chloride (Ag, Ba, Cd, and Pb), or the oxide (As, Sb, and Se). Total carryover of 100% from the thermal treatment unit was conservatively assumed for these eight metals. The composition of the rest of the particulate matter was defined using the relative composition of the major components listed in Table A-3 in Appendix A.

Total particulate carryover used in the ITTS study was 20% of the input feed for the system A-7. After comparison with lower measured and estimated values for total carryover from several other studies, the total PM flowrate in the reference offgas for this study was 329 lb/hr, or approximately 15% of the treatment system waste input feedrate of 2,149 lb/hr. This total PM carryover value is conservatively high because most measurements from mixed waste demonstration tests have shown lower total carryover values of 1–10% of the waste input feedrate (Soelberg 1997a).

Radionuclides were not specifically modeled at this time. Key radionuclides such as Am-241, Pu-238 through Pu-241, U-232 through U-238, Ba-137, Co-60, Sr-90, Cs-137, Y-90, Zn-65, C-14, H-3, and I-129 may be added at a later time.

Table 3-2. Input volatilized and entrained metals at the outlet of the secondary combustion chamber.

Parameter	High-flow case				Low-flow case				Assumed %	
	Physical state at 2,200 F				Physical state at 2,200 F				carryover from	
	Aerosols	Aerosols	Vapor (b)	Total	Aerosols	Aerosols	Vapor (b)	Total	the primary	treatment
	<0.5 micron (a)	>0.5 micron (a)			<0.5 micron (a)	>0.5 micron (a)			unit (a)	Comments
Particle size distribution, wt%	40	60			60	40				From EPA 1992 and Dalton 1992

Flowrates of elemental metals from Appendix A, Table 5, lb/hr:**(Relatively low volatile)**

Be	3.10	4.64	---	7.74 (c)	4.64	3.10	---	7.74 (c)	1	Carryover of low volatile
Cr	1.72	2.58	---	4.30 (d)	2.58	1.72	---	4.30 (d)	10	metals due wholly to particle
Ta	0.09	0.13	---	0.22 (d)	0.01	0.01	---	0.02 (d)	10	entrainment, not volatilization

(Relatively volatile)

Ag	---	---	1.08	1.08 (d)	---	---	1.08	1.08 (d)	100	Carryover of relatively volatile metals due wholly to volatilization, not particle entrainment.
As	---	---	4.30	4.30 (d)	---	---	4.30	4.30 (d)	100	
Ba	---	---	5.37	5.37 (d)	---	---	5.37	5.37 (d)	100	
Cd	---	---	32.25	32.25 (d)	---	---	32.25	32.25 (d)	100	
Hg	---	---	10.74	10.74 (d)	---	---	10.74	10.74 (d)	100	
Pb	---	---	21.49	21.49 (d)	---	---	21.49	21.49 (d)	100	
Sb	---	---	3.22	3.22 (d)	---	---	3.22	3.22 (d)	100	
Se	---	---	2.15	2.15 (d)	---	---	2.15	2.15 (d)	100	

Note: the number of digits in a value does not indicate the number of significant figures.

- Aerosol-form metals and PM are listed in this column based on the estimated particle size distribution.
- These elements were found to be in vapor phase based on chemical equilibrium modeling conducted using HSC Chemistry at 2,200 F, with excess O₂, H₂O, and HCl.
- Calculated using 1% carryover for maximum Be value from Appendix A, Table 5. Only 1% carryover was assumed on the basis that Be metal, while a major component of some waste streams, is not present in most waste streams. When it is present, it is present as the relatively high boiling point metal (2,500 C boiling point).
- Maximum values from Appendix A, Table A-5.

Table 3-3. Flowrates and concentrations of the particulate matter at the outlet of the secondary combustion chamber.

Parameter	High-flow case (2,200 F)				Low-flow case (2,200 F)			
	Aerosols <0.5 micron (a)	Aerosols >0.5 micron (b)	Vapor (c)	Total	Aerosols <0.5 micron (b)	Aerosols >0.5 micron (a)	Vapor (c)	Total
Flowrate of PM, lb/hr (mass flowrates of species of above elements are renormalized based on molecular/atomic weights):								
AgCl			1.43	1.43			1.43	1.43
AsO			5.22	5.22			5.22	5.22
BaCl ₂			8.14	8.14			8.14	8.14
BeO	8.59	12.89		21.48	12.89	8.59		21.48
CdCl ₂			52.59	52.59			52.59	52.59
CrO ₂	2.78	4.17		6.95	4.17	2.78		6.95
Hg			10.74	10.74			10.74	10.74
PbCl ₂			28.84	28.84			28.84	28.84
SbO			3.64	3.64			3.64	3.64
SeO ₂			3.02	3.02			3.02	3.02
Ta ₂ O ₅	0.21	0.32		0.54	0.32	0.21		0.54
All Other	74.41	111.62		186.04	111.62	74.41		186.04
Total PM	86.00	129.00	113.64	328.64	129.00	86.00	113.64	328.64
Concentration of PM, mg/dscm:								
AgCl			63.38	63.38			214.83	214.83
AsO			230.50	230.50			781.24	781.24
BaCl ₂			359.66	359.66			1,219.02	1,219.02
BeO	379.53	569.30		948.84	1,929.57	1,286.38		3,215.95
CdCl ₂			2,323.17	2,323.17			7,874.04	7,874.04
CrO ₂	122.73	184.10		306.83	623.96	415.98		1,039.94
Hg			474.40	474.40			1,607.91	1,607.91
PbCl ₂			1,274.05	1,274.05			4,318.23	4,318.23
SbO			160.92	160.92			545.42	545.42
SeO ₂			133.45	133.45			452.33	452.33
Ta ₂ O ₅	9.49	14.24		23.73	48.26	32.17		80.43
All Other	3,286.97	4,930.46		8,217.43	16,711.10	11,140.73		27,851.84
Total PM	3,798.73	5,698.10	5,019.54	14,516.36	19,312.90	12,875.26	17,013.02	49,201.18

Note: the number of digits in a value does not indicate the number of significant figures.

- a. These species exist as solids at 2,200 F and are distributed according to the assumption that 40% will be less than 0.5 micron in size.
- b. These species exist as solids at 2,200 F and are distributed according to the assumption that 60% will be greater than 0.5 micron in size.
- c. Based on chemical equilibrium modeling conducted using HSC Chemistry at 2,200 F, with excess oxygen, water, and HCl.

4. HIGH-PERFORMANCE APCS DESIGNS

Several APC systems have been conceptualized, designed, or implemented for DOE-sponsored mixed waste treatment technology evaluations or demonstrations (Brown 1995, Dalton 1994, Eddy 1995, Feizollahi 1995, MSE 1994, O'Connor 1995). There are also many variations of offgas control systems installed and used worldwide in radioactive waste treatment processes (IAEA 1989). Various conceptual designs for offgas systems are described in Table 4-1. The first six are summaries of the main offgas systems that are included in the ITTS Phase 1 and Phase 2 studies, which are all dry-wet systems (partial cooling, dry particulate filtration, and then wet acid gas scrubbing). This table also includes a version of a wet-dry system (total quench and wet scrubbing for both particulate and acid gases) conceptualized at INEEL for the Idaho Waste Processing Facility (IWPF). This wet/dry system is similar to other wet/dry systems such as the offgas systems for the Savannah River Site Consolidated Incineration Facility and the INEEL Pit-9 melter offgas system.

High-performance offgas systems were conceptually designed to better tolerate system upsets and continue to meet pollutant emission limits through the use of various combinations of traditional and innovative designs. Potential high-performance offgas system conceptual designs are summarized in Table 4-2. These are designated R-1 through R-7. The flowsheets of these conceptual designs are listed in Appendix B. These systems are generally based on the ITTS and IWPF designs.

4.1 Dry-wet and Wet-dry APC Systems

Two main offgas system design categories have evolved to date from DOE-sponsored mixed waste treatment system development and demonstration efforts. These are termed the "dry-wet" and "wet-dry" systems. Either one of these can be well suited for controlling emissions from mixed-waste treatment processes. Both of these categories are represented in Tables 4-1 and 4-2. In the dry-wet system, particulate (including most of the toxic metals and radionuclides) is removed in a dry secondary stream that may be readily recycled to the melter or immobilized for final disposal. Acid gases are removed by wet scrubbing following the particulate removal. The dry-wet system may use lower temperature baghouses or high temperature filters for the initial particulate control, followed by wet acid gas scrubbing. In the wet-dry system, all contaminants, including particulate, radionuclides, toxic metals and acid gases, are wet scrubbed and produce a single secondary aqueous mixed waste with some suspended and dissolved particulate material. Both of these systems require cooling, reheating, and HEPA filtration. Because of the differences in particulate and acid gas control, each of the systems has distinct advantages and disadvantages which are summarized in Table 4-3.

4.2 Baseline High-performance APCS

The high-performance APCS R-1 was selected for process simulation. This selection was made because it is similar to the ITTS A-1 offgas system, except that it has several "high-performance" features that are representative of the other high-performance systems. While it is a dry-wet rather than wet-dry system, it includes the key components of the wet-dry systems, and also includes an upfront baghouse. A simplified schematic of this system is shown in Figure 4-1. This dry-wet system has many features that satisfy design objectives and make it a likely candidate for deployment in mixed waste treatment:

Table 4-1. APCS designs from the ITTS study and the IWPf project.

System	Functional Operations											
	Gas cooling	Particulate control	Gas cooling	Acid gas control	Gas reheating	CO ₂ absorption	Hg & trace organics control	HEPA filtration	NO _x control	Continuous monitoring	CO ₂ removal	Offgas retention
ITTS A-1, A-7, J-1 (dry-wet, air oxidation, free-jet scrubber, no CO ₂ /gas retention)	Evaporative water cooler, partial	Dry baghouse, followed by dual carbon filters and HEPA filters for Hg, trace organics, and particulate control	Water evaporative cooling	Pressure-atomized free-jet scrubber, phase separator, packed tower, mist eliminator	Electric or steam?	---	Following particulate control	Following particulate control	yes - probably NH ₃ -injected SCR	Not specified	---	---
ITTS C-2 (dry-wet, O ₂ oxidation, CO ₂ abs., gas retention)	Evaporative water cooler, partial	Dry baghouse, followed by dual carbon filters and HEPA filters for Hg, trace organics, and particulate control	---	Dry scrubber	Reheat to 650°C (electric?)	Fluidized bed CO ₂ adsorber with quicklime (CaO)	Following particulate control	Following particulate control, and also final HEPAs	---	Same as ITTS A-1	---	2 retention tanks prior to final HEPAs, and some offgas recycle for torch gas(?)
ITTS C-3 (reduced offgas)	Evaporative water cooler, partial	Dry baghouse, followed by dual carbon filters and HEPA filters for Hg, trace organics, and particulate control	Water evaporative cooling	Pressure-atomized free-jet scrubber, phase separator, packed tower, mist eliminator	Electric or steam?	---	Following particulate control	Following particulate control	yes - probably NH ₃ -injected SCR	Not specified	---	---
ITTS F-1 (Dry-wet)	Evaporative water cooler, partial	Dry baghouse	Full quench at scrubber inlet	Wet centrifugal scrubber	Electric or steam?	---	Activated carbon filters	Cleanable SS HEPAs	---	Same as ITTS A-1	---	---
ITTS G-1 (Dry-wet with cleaning of syngas, then final thermal oxid. or steam generation)	---	High temp filter followed by dual carbon filters and HEPA filters for Hg, trace organics, and particulate control (no indicated cooling)	Full quench at scrubber inlet	Wet scrubber	---	---	Following particulate control	Following particulate control	---	Same as ITTS A-1	---	---
ITTS H-1 (Dry-wet with hot cyclone and ceramic filter)	---	Hot cyclone and ceramic filters	Full quench at scrubber inlet	Venturi scrubber	Electric or steam?	---	Activated carbon filters	Cleanable SS HEPAs	---	Same as ITTS A-1	---	---
IWPf Wet-dry	water spray total quench	Free-jet scrubber with mist eliminator	---	Same free-jet scrubber	Steam or electric	---	Carbon filters with appr. media (S, Au, etc)	Prefilters upstream of carbon filters and HEPAs after	---	O ₂ , CO, THC, Hg, PM, beta/gamma, and alpha; Optional: SVMs, LVMs, HCl, and Cl ₂	---	---

Notes:

a. Thermal oxidation is considered to be a component of the primary treatment process. The offgas is assumed to be fully oxidized at the inlet of the first gas cooling stage.

b. Other robust system permutations include (a) additives to scrubber liquor for scrubbing mercury and D/F, (b) acidic rather than caustic scrubbers, (c) other types of high efficiency wet scrubbers, and (d) multiple HEPA filters or charcoal filters in series.

Table 4-2. High-performance APCS conceptual designs.

System	Functional operations							
	Gas cooling	Particulate control	Gas cooling	Acid gas control	Gas reheating	CO ₂ absorption	Hg & trace organics control	HEPA filtration
R-1 (dry-wet w/ offgas retention)	Evaporative water cooler, partial	Dry baghouse	Water/scrubber liquor evaporative cooling to dewpoint	Pressure-atomized free-jet scrubber, 2-stage phase separator	Electric-heated hot air reheater	---	S-impregnated C beds in parallel following HEPA prefilters	2-stage HEPAs
R-2 (dry-wet w/ CO ₂ absorption, offgas retention)	Same as R-1	Same as R-1	Same as R-1	Same as R-1	Same as R-1	Fluidized bed adsorber following reheat to ~650°C	Same as R-1	Same as R-1
R-3 (dry-wet w/ CO ₂ liq., offgas retention)	Same as R-1	Same as R-1	Same as R-1	Same as R-1	Same as R-1	Same as R-1	Same as R-1	Same as R-1
R-4 (hot filtration and offgas retention)	Evap. water spray temp. control as needed	High temp. ceramic or metal cleanable	Same as R-1 but with a larger dT from around 1,700°F to dewpoint or less	Same as R-1	Same as R-1	Same as R-1	Same as R-1	Same as R-1
R-5 (wet-dry w/ offgas retention)	Full spray quench	Pressure-atomized free-jet scrubber, 2-stage phase separator	---	Same scrubber as used for particulate control	Same as R-1	---	Same as R-1	Same as R-1
R-6 (wet-dry w/ offgas retention and backup carbon & HEPA filters)	Same as R-5	Same as R-5	---	Same as R-5	Same as R-1	---	Same as R-1	Same as R-1
R-7 (wet-dry w/offgas retention and biological CO ₂ -O ₂ conversion)	Same as R-5	Same as R-5	---	Same as R-5	Same as R-1	---	Same as R-1	Same as R-1

Notes:

- a. Thermal oxidation is considered to be a component of the primary treatment process. The offgas is assumed to be fully oxidized at the inlet of the first gas cooling stage.
- b. Other possible robust system permutations include (a) additives to scrubber liquor for scrubbing mercury and D/F, (b) acidic rather than caustic scrubbers, (c) other types of high efficiency

NO _x control	Continuous monitoring	CO ₂ removal	Offgas retention	Other	Comments
NH ₃ -injected SCR w/ inlet & outlet NO _x CEMs and outlet NH ₃ CEM	Required: O ₂ , CO, THC, PM, beta/gamma, and alpha; Optional (included): CO ₂ , HCl	—	With and without: 3 tanks: 1 for filling, 1 for analysis hold, 1 for standby/emptying		Similar to ITTS A-1 except for placement of HEPAs and C filter, and offgas retention. Retained gas that cannot be released must be recycled or treated in separate gas treatment train (such as low-T Thermatrix, catalytic, or corona oxidizer, venturi/packed bed, reheater, treated charcoal, HEPAs, then back to retention tanks or at least to CEMs
Same as R-1	Same as R-1 with addition of CO ₂ monitor upstream of CO ₂ adsorber	Same as R-1	Same as R-1		Same as R-1 except added CO ₂ absorption per ITTS C-2, with 2 options: leave CaCO ₃ in solid form, or regenerate CaO following analysis and acceptance of CaCO ₃ in separate calciner, instrumentation, controls, stack.
Same as R-1	Same as R-2	Low-pressure CO ₂ liquefaction per Stull 1992	Same as R-1		Same as R-1 except add CO ₂ liquefaction (Stull 1992) followed by CO ₂ analysis, acceptance, and re-evaporation or solidification.
Same as R-1	Same as R-1	Same as R-1	Same as R-1		Same as R-1 except replace baghouse with high temperature ceramic or metal filter, and adjust offgas cooling demands accordingly.
Same as R-1	Same as R-1	—	Same as R-1		Wet/dry equivalent to R-1 with offgas retention
Same as R-1	Same as R-1	—	Same as R-1 w/o offgas retention	Carbon and HEPA filters	Wet/dry equivalent to R-1 without offgas retention and with backup carbon and HEPA filters
Same as R-1	Same as R-1	—	Same as R-1 w/o offgas retention	Biological CO ₂ to O ₂ conversion	Wet/dry equivalent to R-1 without offgas retention and with biological CO ₂ to O ₂ conversion (perhaps remove offgas retention and use the CO ₂ -O ₂ conversion chamber for offgas holdup due to residence time)

by wet scrubbers, and (d) multiple HEPA filters or charcoal filters in series.

Table 4-3. Comparison of dry-wet and wet-dry APC systems.

Offgas system	Advantages	Disadvantages
Dry-wet	<p>Separate dry particulate (radionuclide/hazardous metal) and aqueous salt solutions can simplify secondary handling and treatment for each of these streams. The dry particulate can be recycled to another thermal process or solidified in cement technologies such as polyethylene or sulfur polymer cement that do not allow water. The aqueous salt streams with essentially no radionuclides or solids can be treated or disposed of more easily without the radionuclides or toxic metals.</p> <p>Wet scrubber criticality is not a concern because, essentially, all fissile radionuclides are removed in the baghouse.</p> <p>Volume reduction of the dry and aqueous secondary wastes is easier. Recycling dry particulate can significantly reduce the volume of this waste. Evaporation of the scrubber effluent (made more easy by removal of most radionuclides and most particulate) can significantly reduce the volume of this waste.</p> <p>There is still barrier filtration in the event of a power failure.</p>	<p>Potential for dispersible fines in the baghouse catch and potential worker exposure and contamination control issues during baghouse/filter maintenance.</p> <p>Tighter process control is required in the partial quench step upstream of the baghouse/filter to prevent moisture condensation or moisture droplets, corrosion, or thermal damage to the bags/filters.</p> <p>The typical cooling temperature of ~300°F is not cool enough to prevent some D/F formation in the particulate filter according to some recent studies (Soelberg 1996). However, this potential is minimized by using high temperature filtration. Also, if carbon adsorption is used for trace pollutant control, the carbon should remove D/F formed.</p>
Wet-dry	<p>Simpler gas cleaning by rapidly cooling the gas to the dewpoint (or lower, condensing some water out of the offgas), and combining acid gas and particulate removal functions.</p> <p>No dispersible fines are produced, unless treatment of the scrubber effluent requires precipitation, filtration or drying.</p> <p>Minimizes D/F formation by rapidly quenching the offgas to under 200°F.</p> <p>Marginally better Hg control upstream of the charcoal filters because of the initial quench to a lower gas temperature.</p>	<p>Produces an aqueous mixed waste scrubber secondary stream that could contain fissile radionuclides, toxic metals, and halogen salts, producing more treatment challenges prior to disposal. This lessens the potential for recycling this waste stream to the primary treatment unit or evaporation to reduce secondary waste volume.</p> <p>The performance of the free-jet scrubber strongly depends on constant offgas flowrate, composition, temperature, and differential pressure, which may be difficult to control for different heterogeneous waste input streams.</p> <p>Increased potential for problems related to dissolved or suspended particulate in the scrub solution—nozzle erosion/plugging, sludge deposition, nuclear criticality, and residual submicron particulate in the gas remaining from evaporation of scrub solution droplets.</p> <p>A power failure or other upset that affects the scrubber spray can significantly reduce particulate removal capability.</p>

- It includes primarily standard, available, off-the-shelf equipment so it has less technical uncertainty.
- Since it uses dry particulate filtration followed by wet acid gas scrubbing, the dry particulate secondary waste is separate from the aqueous scrubber solution secondary waste. This simplifies secondary waste handling and treatment, reduces the risk of criticality in the wet scrubber by removing nearly all fissile radionuclides in baghouse, and contains barrier filtration that will still protect the HEPAs and prevent any additional PM, metals, and radionuclide emissions in the event of a power failure.
- The wet scrubber is a state-of-the-art, high-performance free-jet scrubber which has been used in several other mixed waste treatment designs and facilities. The combination of upfront particle

Figure 4-1. Schematic of the R-1 conceptual offgas system.

removal, offgas cooling below its dewpoint, and the use of an air-atomized rather than steam-atomized scrubber may improve scrubber performance and reduce some of the problems experienced with high offgas temperatures, moisture loading, and residual aerosols in the offgas at other DOE facilities.

- The offgas reheater downstream of the wet scrubber blends heated ambient air with the saturated offgas to raise the offgas temperature and also lower the dewpoint by dilution. This has the advantages of (a) maintaining the heating elements in a radioactively clean environment, facilitating easier maintenance, (b) preventing fouling of the heating elements from aerosols that may still be in the offgas in small amounts, and (c) enabling a lower net reheat temperature increase for the offgas by lowering the dewpoint somewhat. Some of the problems experienced with offgas reheating at the CIF incinerator may be avoided with this design.
- Following a prefilter and the first-stage HEPA, Hg and trace organics are removed using sulfur-impregnated carbon. While relatively new, several vendors provide commercial packed beds with commercially-produced carbon for this purpose.
- Two-stage HEPA filtration is a standard for mixed waste treatment. Each filter is designed for certification testing to enable the maximum credit for combined filtration efficiency.
- NO_x destruction using SCR technology is included as an option for removing NO_x in excess of allowable limits. The SCR technology is not expected to be needed unless a highly oxidizing plasma torch process that uses nitrogen as the torch gas is the primary treatment unit.
- Offgas retention tanks are included as an option to evaluate the costs and benefits of retaining the offgas long enough to complete detailed analyses that demonstrate that the offgas being delivered to each tank meets regulatory limits.

4.3 Offgas System Functional Description

To comply with emission regulations listed in Section 2, offgas systems need to include particulate control, acid gas control, Hg and trace organics removal, HEPA filtration, and in some cases NO_x removal. Many conditioning steps are required to prepare the offgas for the gas cleaning steps, enable the gas cleaning steps to operate effectively, and prevent damage to gas cleaning and other downstream equipment. Conditioning steps include initial offgas cooling of the hot (2,200°F) SCC outlet gas, secondary gas cooling (downstream of dry particulate removal if it is used), and offgas reheating to temperatures above the dewpoint or to reaction temperatures for such processes as NO_x control or CO₂ absorption. It may be desirable or necessary to use offgas retention tanks for preventing any offgas release to the atmosphere until it has been adequately analyzed and demonstrated to meet emission limits. Continuous emission monitoring for offgas flowrate, O₂, CO, CO₂, NO_x, THC, HCl, and PM is important to ensure that emission limits are being met or indicating when significant changes occur during non-normal or upset conditions.

4.3.1 Initial Offgas Cooling

The high temperature of the offgas exiting the SCC must be reduced to enable downstream control of particulates, metals, and acid gases, and to prevent thermal damage of the downstream equipment. Design objectives for offgas cooling include:

- Have sufficient control over the quench process to enable rapid response to temperature, flowrate, and composition variations of the offgas.
- Cool as rapidly as possible to reduce residence time in the temperature range in which D/F may be formed if D/F precursors are present. D/F precursors, if present in sufficient amounts, can cause unacceptable D/F emissions if allowed sufficient time to form in the temperature window of approximately 450–750°F, especially in the presence of significant catalyzing surface area presented by such equipment as heat exchangers, or simply on the PM entrained in the offgas.
- Minimize the potential for solid or liquid deposits that may impair offgas cooling or cause flow restrictions.
- Minimize total offgas flowrate through the remainder of the system to reduce equipment size and to have lower flowrates of offgas out the stack.

Heat recovery, though normally a good practice to increase energy efficiency and reduce operating costs, is a very low consideration compared to the above criteria. Heat exchangers such as heat recovery boilers to perform offgas cooling are not recommended because of the (a) potential for process upsets from fouling or corrosion of heat transfer surfaces, and (b) longer residence times in the D/F-forming temperature window.

The recommended choice for offgas cooling is water or scrubber solution spray and evaporation. While dilution with cooler air or recycled offgas is also acceptable, this method can increase the mass flowrate of the offgas mixture by 10 times or more depending on the dilution ratio. Depending on the downstream operations, the offgas may be cooled to a temperature well above its dewpoint (around 300°F for particulate control in a baghouse), at its dewpoint (typically resulting in a saturated gas temperature of around 170–180°F), or below its initial dewpoint. Cooling the offgas with a water or scrubber solution spray to a temperature below the initial dewpoint is possible if there is a separate scrubber liquor cooling system. This subcooling is sometimes desired to reduce corrosion, agglomerate condensed particles for more efficient removal, avoid D/F formation, reduce the offgas volumetric flowrate, and condense water vapor that may contain tritium out of the gas stream. Cooling of the scrubber solution avoids the need to discharge large amounts of warm scrubber solution to remove heat from the offgas. However, the cooling cost using chiller units can be high.

4.3.2 Particulate, Toxic Metals, and Radionuclide Control

Particulate, toxic metals, and radionuclide control are grouped together because, with a few exceptions, they are mostly in solid form at typical cooled offgas temperatures between 120–300°F, and can be removed with efficient particulate control equipment. This temperature range is sufficiently low that even the more volatile isotopes of Cs, Co, K, and Zn are mostly condensed into particulate form.

Exceptions include Hg and the isotopes C-14, H-3, and I-129, which can exist as gaseous species at temperatures between 120–300°F. Various radionuclides and their relative volatilities include:

<u>Isotope</u>	<u>Volatility</u>	<u>Comments</u>
Am-241	Non-volatile	Transuranic element
Pu-238 through Pu-241	Non-volatile	Transuranic element
U-232 through U-238	Non-volatile	Transuranic element
Ba-137	Low volatile	
Co-60	Low volatile	
Sr-90	Low volatile	
Cs-137	Semi-volatile	
Y-90	Semi-volatile	
Zn-65	Semi-volatile	
C-14	Volatile as CO ₂	
H-3	Volatile as H ₂ O	
I-129	Volatile as HI, I ₂	

These volatility indications are qualitative, since the actual volatility of any element will vary depending on the speciation of that element between its pure form and compounds such as oxides and chlorides.

Design objectives for particulate, toxic metals, and radionuclide control include:

- Meet expected emission limits
- Minimize the amounts of offgas secondary streams that are radioactive
- Minimize amounts of dispersible (dusty) secondary streams
- Optimize the handling and treatability of the secondary streams, including avoiding liquid mixed waste streams and maximizing recycle.

Only high efficiency technologies should be considered. The foremost dry technologies (when the offgas temperature is higher than the moisture saturation temperature) include pulse-jet baghouses that can operate at offgas temperatures up to around 500°F, and higher temperature ceramic and sintered metal filters that can operate up to around 1,700°F. A schematic of a pulse-jet baghouse is shown in Figure 4-2. Higher temperature filters have been and are being tested for DOE use (Christian 1978, EER 1992, and MSE 1995), and have been used in Germany, Austria, and Japan for low-level waste incineration using the Karlsruhe-type shaft incinerator (IAEA 1989, Soelberg 1996a, and Dirks 1996). High temperature filters need further development and demonstration testing to evaluate control efficiencies, operating lifetime, pressure drop, thermal tolerance, durability, and fouling potential.

Figure 4-2. Schematic of a pulse-jet baghouse (Wark 1981).

A leading wet scrubbing method is free-jet scrubbing. This technology has been specified, tested, or implemented in several DOE waste treatment testing and operating facilities including the Mountain States Energy (MSE) Plasma Arc Centrifugal Treatment furnace test facility (MSE 1994 and 1995), the Savannah River Site (SRS) Consolidated Incineration Facility (CIF), and the Defense Waste Processing Facility (DWPF). A schematic of a free-jet scrubber is shown in Figure 4-3. Other potential high efficiency wet scrubbing technologies include wet electrostatic precipitators. Venturi scrubbers and packed bed scrubbers, commonly used in nonradioactive thermal processes, are not recommended as stand-alone wet scrubbing devices because of their lower scrubbing efficiencies (unless the pressure drop for venturi scrubbers is very high, in excess of 60 in. water).

4.3.3 Acid Gas Control

Acid gases, including HCl and SO₂, will be produced from waste materials that contain chlorides and sulfates. Design objectives for acid gas control include:

- Meet expected control efficiency and emission limits
- Minimize the amounts of offgas secondary streams that are radioactive
- Optimize the treatability of the secondary streams, including avoiding liquid mixed waste streams
- Have minimal impact on system backpressure and flowrates.

If dry particulate filtration is used for particulate control upstream of the acid gas control, then such acid gas scrubbing technologies as packed bed scrubbers are acceptable. A total quench to the saturation temperature is necessary at the inlet to the scrubber. Assuming that the baghouse can efficiently filter particulate and radionuclides, the scrubber blowdown may be below regulatory limits for toxic metals and radionuclides, though it will contain high chloride levels from some waste streams. Analysis of the blowdown for toxic metals and radioactivity is expected to be required.

If wet scrubbing for particulate is used immediately following thermal oxidation and gas cooling for particulate control, then the acid gas control can occur in the same unit operation. Free-jet scrubber systems are very efficient for both particulate and acid gases. Other wet scrubbing technologies such as wet electrostatic precipitators may require combination in series with a unit such as a packed bed scrubber to provide adequate acid gas control and improve particulate control.

4.3.4 Mercury and Trace Organics Control

Along with any trace volatile and semivolatile organics present in the offgas, such as D/F, Hg may not be efficiently controlled upstream of the particulate capture and acid gas control steps. Carbon adsorption is specified in the proposed MACT Rule for both Hg and D/F control. Relevant issues regarding carbon adsorption include the optimum operating temperature for efficient adsorption, the form and type of carbon, adsorption-improving additives such as sulfur for mercury control, spent carbon disposal, and fire prevention. With reasonably efficient carbon adsorption for mercury and trace organics, a mixed waste treatment facility should readily meet emission limits for these pollutants.

Figure 4-3. Schematic of free-jet scrubber.

The type of Hg control depends on the amount of Hg and other elements in the waste feed. Because of the high volatility of elemental Hg and its compounds, all Hg fed to the primary thermal treatment system is generally assumed to volatilize as elemental Hg, HgCl_2 , and HgO . Upon cooling, some volatilized Hg species may condense if sufficient amounts are present to exceed vapor pressures at the quench temperatures. HgCl_2 is readily soluble in water and may be captured in an aqueous scrubber system such as the free-jet scrubber.

Even if only trace amounts of Hg are processed in the thermal treatment system, Hg removal processes are expected to be necessary for meeting strict Hg emission limits. A new technology uses amalgamation of mercury on gold supported by a substrate to remove mercury and mercury chloride vapors (Roberts 1995). This technology has not been as proven as sulfur-impregnated carbon adsorption, so only sulfur-impregnated carbon adsorption is included in this study.

The spent carbon will be a secondary waste. Spent carbon that does not contain significant amounts of Hg may be recycled to the primary treatment process, even if small amounts of D/F and other organics are present. However, large amounts of Hg may build up in the system if spent carbon containing large amounts of Hg are recycled. There is presently not an acceptable disposal alternative for spent carbon that contains Hg and radioactive contamination. The disposal issue is significant and must be resolved for the use of carbon adsorption in mixed waste treatment.

4.3.5 HEPA Filtration

Particulate control efficiencies for baghouses and for free-jet scrubbers can exceed 99.9%. Other offgas equipment including evaporative coolers, acid gas scrubbers, carbon adsorbers, and HEPA prefilters can also exhibit some particulate removal capability. The combined filtration capability of all equipment upstream of the HEPA filters will likely far exceed 99.9% efficiency. However, in a nuclear facility, final HEPA filtration is required to control any small remaining amounts of particulate for radionuclide and toxic metals control. Frequently, HEPA prefilters, HEPA filters, and carbon adsorption beds can be placed in a single housing with separate compartments for maintenance purposes. An example of this configuration is shown in Figure 4-4.

Spent HEPA filters will be a secondary waste, which may be recycled to the melter, processed in a low-temperature glass melter, or macroencapsulated. Recycle to a melter is possible as long as there is not a large buildup of Hg or difficult-to-control fines in the system. Because of the probable combined particulate removal efficiency of the offgas system upstream of the HEPA filters, the HEPAs for a well designed and operated offgas system should not require frequent replacement.

4.3.6 NO_x Control

Secondary abatement technologies used for controlling NO_x emissions can be described as dry or wet processes and catalytic or noncatalytic processes (Dalton 1992). Dry abatement processes convert NO_x to N_2 by reacting the NO_x with other gaseous reagents. Dry abatement technologies include selective catalytic and noncatalytic reduction as well as nonselective catalytic and noncatalytic reduction processes. The selective reduction processes react NO_x with ammonia or other nitrogen compounds. The catalytic process can achieve a destruction efficiency between 85 to 95% while operating at temperatures between 500–800°F.

Figure 4-4. Offgas containment housing consisting of HEPA prefilter, HEPA filters, and carbon beds with maintenance access doors.

Noncatalytic process achieves destruction efficiencies of up to 70–80% at temperatures between 1,600 and 2,200°F. In nonselective processes, a gaseous fuel is mixed with gas containing the NO_x and burned to convert NO_x to nitrogen and water or carbon dioxide. The fuel (hydrogen, methane, or other hydrocarbons) is not selective and will react with other constituents, primarily oxygen.

4.3.7 Continuous Monitoring

Continuous emissions monitoring is assumed based on the requirements of the proposed MACT Rule, with some assumed additions to meet expected permit requirements and for some specific process monitoring and control. Continuous emission monitors (CEMs) included in the high-performance systems are summarized in Table 4-4. Continuous monitoring for Hg, metals, and D/F is not included in any of the high-performance offgas systems because these monitors are still developmental, have not yet met EPA performance specifications for use as CEMs, and do not meet reliability requirements. While the draft proposed MACT Rule specifies the use of continuous monitoring for Hg, subsequent EPA documents report that Hg CEMs will not be required (EPA 1997b). The alternative of Hg feed limits and appropriate monitoring of carbon bed and other systems is recommended at this time instead of Hg monitoring.

Demonstrations of continuous multiple metals CEMs have also shown that they do not presently meet performance specifications. The alternative of metals feed limits and appropriate monitoring of scrubber, HEPA, and other systems is recommended instead of continuous metals monitoring. Continuous D/F monitors are even more developmental than Hg and metals CEMs. EPA may eventually identify a surrogate such as CO, THC, or a specific hydrocarbon species for D/F and other organic PICs rather than require continuous D/F monitoring.

4.3.8 Zero Emissions Approach

Operation of thermal and nonthermal treatment systems with “zero emissions” is not realistically possible because of the generation of effluent gas containing typically noncondensable gases such as N₂ and O₂. The most technically feasible approach for near “zero emissions” or zero uncontrollable emissions is to minimize the volume of offgas to the extent possible, and then prevent the release of the offgas to the atmosphere until adequate analysis is completed that demonstrates that pollutant emissions are within regulatory limits. Methods that can be used (and are included in various high-performance offgas system alternatives) to achieve this include using:

- Oxygen instead of air for combustion
- Electrical heat input for treating low-heating-value wastes rather than fossil fuel combustion
- Water spray evaporation for cooling rather than air dilution cooling
- Offgas retention until analyses are complete
- CO₂ absorption or removal via liquefaction or through photosynthesis.

These measures to approach a “zero emissions” philosophy have not been used significantly in DOE or non-DOE facilities, largely because of high additional costs that were not justified. The implementation of a “zero emissions” philosophy depends on stakeholder and operator requirements as well as cost/benefit evaluations.

Table 4-4. Continuous emissions monitoring for the high-performance offgas systems.

Parameter	Location	Comments
O ₂	Near SCC outlet	Continuously monitor excess oxygen in the SCC to show that the SCC outlet O ₂ stays above 3% (wet basis).
CO ₂	Upstrm of CO ₂ removal	Included only when the offgas system has CO ₂ absorption or other removal step, for process control of that operation and to determine removal efficiency.
NO _x	Upstrm of NO _x removal	Included only when the offgas system has a NO _x removal stage, for process control of that operation and to determine removal efficiency.
Offgas flowrate	Outlet duct/stack	Continuous offgas flowrate measurement is required to ensure adequate residence time in the SCC.
O ₂	"	For use in making oxygen correction calculations for pollutant measurements.
CO	"	Continuously monitor CO emissions.
THC	"	It is assumed that THC in addition to CO CEMs will be required either because they will be specified per the proposed MACT Rule, or as surrogates for emissions of D/F or other PICs (which will not be continuously monitored).
PM	"	Acceptable insitu laser-based PM monitor performance is expected to be shown in the FY97 joint DOE and EPA demonstration tests. They may be very reliable and sensitive down to even the <0.001 gr/dscf range expected at the outlet of HEPA filters.
CO ₂	"	The CO ₂ monitor is primarily for information only, and to verify combustion efficiency.
NO _x	"	NO _x monitoring is not required by the MACT Rule, but it is assumed that permit writers will require NO _x monitoring even if there is no NO _x control for the process.
HCl	"	The CEM option provided in the proposed MACT Rule may require that both HCl and Cl ₂ be monitored. HCl monitoring is included because they are commercially available and have been used for many years in the US. Cl ₂ monitors have not yet been accepted by EPA for compliance use in the US. The alternative of feedstream Cl limits and monitoring of scrubber and other systems is used instead of total HCl and Cl ₂ emissions monitoring. The use of HCl monitoring provides continuous process control data for the acid scrubber and assurance of acceptable total Cl emissions if Cl ₂ emissions are low compared to HCl emissions.

5. APCS PROCESS SIMULATION

System process simulations using a computational model allow quick comparisons of different design alternatives and evaluations of whether desired objectives can be achieved for a given design early in the design process. ASPEN PLUS (hereafter referred to as ASPEN) is a process simulation code that was used to model the selected APCS. ASPEN calculates mass and energy balances around each unit operation using thermodynamic equilibrium calculations based on chemical reaction and equilibrium data specified by the user or retrieved from an extensive database. ASPEN can also perform nonequilibrium calculations specified by the user, and model solids handling processes such as particulate filtration that are not based on thermodynamic equilibria. These features make ASPEN a powerful tool for evaluating APCS design.

5.1 APCS Unit Operations

The operating conditions, equipment specifications, and any performance data used to define them for each unit operation are presented below. More detailed information based on discussions with vendors is summarized in Appendix C.

5.1.1 Partial Quench

The purpose of the partial quench is to cool the offgas (using water spray evaporation) to an acceptable temperature before it enters the baghouse. The partial quench was operated adiabatically at near atmospheric pressure (12.5 psia at the elevation of the INEEL). Water was added at 60°F to the 2,200°F SCC outlet offgas. Water addition was limited to achieve an exit gas temperature of 300°F, still above the moisture saturation temperature. The temperature was still high enough to evaporate all water spray droplets and prevent water condensation in the baghouse that could blind the filter bags, increase corrosion, and cause agglomeration of ash collected in the baghouse.

5.1.2 Baghouse

The ASPEN block FABFL is specifically designed to model a baghouse. When used in the design mode, the block can calculate the total number of cells given the number of bags in a cell, the diameter and surface area of a bag, the average and maximum pressure drop across a bag, and a resistance coefficient indicative of the particle size filtration expected across the bag.

For design purposes, the bag diameter was specified to be 0.52 ft and the bag surface area was 19.6 ft² with 12 bags per cell. A resistance coefficient of 300,000 was assumed, reflecting the high efficiency for removing submicron particles. Minimum and maximum pressure drops across the bags are 4 and 4.5 in. water. Information from BHA Group stated that a particulate removal efficiency of 99.983% for 0.5 µm can be achieved for high efficiency bags. A more conservative removal efficiency of 99.9% for particles equal to or larger than 0.5 µm particles was assumed in the process simulation model. A removal efficiency of 99% was assumed for particles less than 0.5 µm.

5.1.3 Full Quench

The second and final quench was assumed to be operated adiabatically with no significant pressure drop. The rate of 60°F water addition was adjusted to ensure a saturated vapor leaving the unit

with no excess liquid water. The amount of water required and the final temperature of the offgas leaving the final quench depend on the water content of the offgas entering the unit.

5.1.4 Free-jet Scrubber

This high-efficiency, low-pressure drop scrubber can efficiently remove acid gases (represented by SO_2 and HCl) and particulate in the offgas using caustic scrubber solution that is air-atomized into the gas stream. A 1% excess NaOH was added in addition to the amount of NaOH needed to remove 99% of the SO_2 and 99.9% of the HCl . These removal efficiencies are readily achievable according to vendor information and empirical data. The added NaOH was sufficient to maintain pH between 8 and 10. Unreacted acid gases remained in the offgas. It was assumed that the scrubber can remove 99.9% of the HgCl_2 present in the offgas, but none of the elemental Hg vapor. This assumption has no supporting vendor information, but empirical data indicates that overall Hg removal efficiencies exceeding 99% are possible under some wet scrubber conditions (EPA 1997c).

In addition, the scrubber removes a portion of particulate that remains in the offgas following the baghouse. According to vendor specifications, the particulate concentration in the scrubber offgas is a function of the atomizing air mass flowrate (which controls the size of atomized solution droplets) and liquid mass flowrate relative to the mass flowrate of the offgas being scrubbed (liquid surface area to gas volume ratio). It was assumed that all particles greater than $0.5\ \mu\text{m}$ still in the offgas entering the free-jet scrubber were removed in the process. Particulate removal efficiency does not decrease at lower offgas flowrates. The scrubber was assumed to operate adiabatically with no significant pressure drop.

Scrub solution was recycled to maintain the liquid flowrate through the scrubber at 60 gpm in the high-flow case and 30 gpm in the low-flow case per vendor specifications. The recycled scrub solution was cooled to 60°F by a chiller to cool the offgas below its initial dewpoint and condense some moisture. The offgas was cooled approximately 10 to 15°F in the scrubber.

The maximum allowable dissolved salt concentration in the scrubber liquid was specified by the vendor at 10 wt%. Dissolved salts were maintained below this limit by discharging scrub solution in the blowdown. In the high-flow case, there was sufficient water condensate so that no makeup water was necessary to provide scrub solution blowdown. Additional makeup water was necessary for the low-flow case because more HCl was in the input offgas, so a higher blowdown rate was necessary.

5.1.5 Offgas Reheat

The offgas exiting the scrubber is saturated and must be heated above its dewpoint to prevent condensation within the filters. Also, the gas cannot exceed the temperature limit of 200°F for the carbon beds. Offgas reheat was achieved by mixing ambient air heated to $1,000^\circ\text{F}$ with the offgas. The process simulation considered the possible revolatilization of arsenic, mercury, or selenium in the solid particulate when the offgas is reheated. Volatilization of any other metals was not considered because of their typically low volatilities at temperatures below 200°F .

Using preheated air to blend with the saturated offgas is unique to this conceptual design, and has not been implemented in any existing DOE mixed waste treatment facilities. Advantages of the preheated air concept include (a) elimination of heater elements in contact with offgas, and (b) lowering of the blended offgas dewpoint. When the heating elements are not in contact with the saturated offgas,

several potential problems such as corrosion and fouling of the elements from aerosols impacted on the elements are eliminated. Also, any maintenance that is required for the heating elements can be done in an area of lesser contamination than expected for the offgas.

5.1.6 Prefilter

The prefilter was modeled using the FABFL block in simulation mode. In this mode, the block can remove particles according to size and removal efficiency specified by the user. Particulate removal efficiency for an Airpure Rigid Pak 95 from Flanders Filter was used to define the prefilter efficiency. The removal efficiency for this type of prefilter is a function of particle size:

<u>Particle size, μm</u>	<u>Efficiency, %</u>
>2	100
0.8	95
0.6	90
0.5	87

No information was available for particles below 0.5 μm . It was assumed that filter efficiency was worst for 0.3 μm particles at 70%, and for particles less than 0.1 μm removal efficiency was 87%. Although the particle size distribution was defined in terms of only two populations, this range of efficiencies defined average efficiency for particles in each group.

5.1.7 HEPA Filters

The HEPA filters were certified for 99.97% efficiency for removing 0.3 μm particles. However, a more conservative efficiency of 99.9% was assumed for both sets of HEPA filters in series. This more conservative assumption was made to be consistent for multiple filtration steps in series (Burchsted 1979) and to better account for nonidealities such as housing and frame warping, gas sneaking, occasional moisture, etc.

5.1.8 Carbon Bed for Mercury Adsorption

The sulfur-impregnated carbon beds were assumed to remove 99% of the total Hg still in the offgas at the carbon bed inlet. This efficiency is a rough estimate based on vendor information that suggests higher efficiencies at lower, more optimum temperatures of 158°F maximum. Since it was not reasonably possible to operate the carbon beds at such a low temperature, a maximum operating temperature of 200°F was assumed, with a more moderate removal efficiency. There is some potential that actual Hg removal efficiencies may not be as high as 99%.

No credit is taken for particulate removal. Sulfur-impregnated carbon designed for the removal of elemental Hg will have some potential for removing trace organics, but carbon vendors are uncertain about the organic removal efficiencies considering that some of the carbon active sites are occupied by

sulfur. Organic compounds most likely to be adsorbed on the carbon are those with high molecular weights and vapor pressures. At this time, THC removal is not included in the model.

5.1.9 NO_x Specific Catalytic Reactor

The offgas was reheated to the vendor-specified temperature of 400°F before the NO_x SCR to provide necessary heat for efficient NO_x-ammonia reaction. A stoichiometric quantity of ammonia was added and assumed to achieve 85% destruction. Ammonia was not allowed in the model to react with any other offgas constituents. The relatively moderate NO_x destruction efficiency of 85% was assumed because that level was assumed to be adequate for most mixed waste processes that require NO_x removal, and to provide confidence that ammonia (ammonia slip) would be limited to 10 ppm in the offgas.

5.1.10 Offgas Cooling and Condensation

The offgas was cooled to 100°F upstream of the retention tanks to reduce the volumetric flowrate and lower the dewpoint to a temperature nearer to ambient temperature to minimize moisture condensation in the tanks. Significant amounts of moisture were condensed from the offgas in this step. While the reduced offgas volume was desired to minimize volume and costs for the retention tanks, the lowering of the offgas temperature and dewpoint were considered necessary to prevent moisture condensation and corrosion in the tanks. There may be some more optimized or better designed retention tank scenarios that could avoid this cooling step, but it was included for conservativeness in this study.

5.2 Thermodynamic Chemical Equilibria Calculations

The capability of ASPEN to predict thermodynamic equilibria at conditions expected in the APCS was demonstrated by comparing results with those predicted using HSC Chemistry for Windows. The comparison showed that similar compounds, concentrations, and phases were predicted by both HSC and ASPEN for identical input conditions.

Calculations were done in each unit operation where phases changed or chemicals reacted to minimize the Gibbs free energy and achieve vapor-liquid-solid equilibrium, and thereby achieve thermodynamic equilibrium. These calculations were done using physical and chemical property data for all specified reactants and products, in all specified phases. Property data for reactants and products used in the calculations included the molecular weight, critical temperature, the standard free energy and enthalpy of formation for the ideal gas and solid at 25°C, the coefficients for the heat capacity equation for an ideal gas and solid, and the coefficients for the Antoine vapor pressure equation. Complete thermodynamic data for HgCl₂ and SeO₂ were not in the ASPEN database. The free energy, enthalpy, and heat capacity data for these species was extracted from the HSC Chemistry database and added to the ASPEN database, so these species could be included in ASPEN equilibrium calculations.

Some predicted equilibrium concentrations occasionally appeared inconsistent with measurements from actual systems. Reactions, especially at low temperatures, are often limited by kinetics or mass transfer from reaching thermodynamic equilibrium in the offgas system where residence time is measured in seconds or less. In these cases, the predictions were made to better reflect observed data by limiting the extent of reaction, or by specifying a reaction temperature at which to calculate the equilibrium composition.

An important example of how thermodynamic equilibria was adjusted to better reflect nonideal expectations is the calculation of Hg speciation in the offgas. At temperatures exceeding 980°F, elemental Hg is thermodynamically favored in typical offgas conditions. Hg speciation at the SCC outlet, where the temperature was 2,200°F, was predicted to be almost entirely elemental Hg. At temperatures below 980°F, HgCl_2 becomes thermodynamically favored. At temperatures between 800°F and 980°F, HgCl_2 formation from reaction of Hg and Cl is rapid and can be described by equilibrium calculations, but the reaction is kinetically limited at lower temperatures (Senior 1997). If the Hg- HgCl_2 reaction were allowed to reach equilibrium in the low temperature wet scrubber, then very little Hg would exist, and the process simulation would predict that the total Hg is readily scrubbed in the wet scrubber. However, this is not consistent with empirical data from many sources (Soelberg 1997c). As a result, the minimum equilibrium temperature for the Hg- HgCl_2 reaction in ASPEN calculations was specified at 980°F. The use of the higher temperature for Hg- HgCl_2 equilibrium calculations considers the rapid temperature quench and effectively “freezes” a significant portion of Hg as elemental Hg, even in excess Cl when HgCl_2 is thermodynamically favored at quench outlet temperatures.

The solubility of HgCl_2 in water and the conversion of HgCl_2 to $\text{Hg}_2\text{Cl}_2(\text{s})$ in the scrub solution was examined using HSC Chemistry. Approximately 20–30% of the mercury chlorides can be expected to precipitate out of solution depending on constituent concentrations and the scrub solution temperature. This provides a means for removing mercury from the scrubber solution via filtration or other means, so that the scrub solution can be recycled in the system. However, removal of precipitated Hg_2Cl_2 was not considered in this study. In reality, such a practice may be necessary to achieve appreciable Hg removal in wet scrubber systems that have high recycle:blowdown ratios, so that Hg is not re-entrained or re-evaporated into the offgas.

Equilibrium concentrations of SO_2 and SO_3 were specified in the partial quench at 1,400°F based on kinetic limitations at lower temperatures. Sulfur dioxide was not allowed to react in any subsequent unit operations until entering the free-jet scrubber where 99% was assumed to react with the sodium hydroxide solution. Also, only 85% NO_x removal was assumed in the catalytic reactor.

5.3 Particle Formation and Revolatilization

Particulate formation resulting from condensation of volatile metals was expected to occur when the offgas was cooled in the spray quench before the baghouse, the spray quench after the baghouse, and in the acid gas scrubber. The most conservative assumption assumes all particulate formation occurs by homogeneous condensation yielding submicron particulate with particle diameter less than 0.5 μm . The model also calculated the revolatilization of condensed mercury, arsenic, and selenium compounds when the offgas was reheated after the scrubber and upstream of the NO_x SCR unit. Some volatilization of trace particulate containing these compounds occurred when the scrubber offgas was heated to 200°F, and complete volatilization of particulate containing these compounds occurred when the offgas was heated to 400°F before the NO_x catalytic reactor.

6. APCS PROCESS EVALUATION

The process simulation computational model was used to evaluate the impacts of process conditions and assumptions on mass and energy balances, system and unit performance, and secondary waste streams to determine if process objectives can reasonably be achieved. Simulation results for the high-flow and low-flow cases are summarized in this section. A detailed description of the simulations is provided in Appendix D.

6.1 Mass and Energy Balances

Total and elemental mass balances and energy balances for each unit operation in the APCS were predicted for both high-flow and low-flow cases. Flowsheets for both cases that show stream flowrates, temperatures, and pressures are shown in Figures 6-1 and 6-2.

6.1.1 Overall Mass Balance

The calculated mass flowrates input and output APCS streams for both flow cases are summarized in Table 6-1. APCS input and output offgas flowrates for the high-flow case are approximately twice as great as for the low-flow case, primarily because of increased N_2 . Furthermore, the offgas flowrate in each case roughly doubled as it passed through the APCS. This increase is due to (a) roughly 50% increase from additional quench water that is evaporated but not subsequently condensed, and (b) roughly 50% more additional air used in atomizing the scrub solution and to reheat the saturated scrubber outlet offgas.

The total solution discharge from the scrubber system as blowdown was significantly greater in the low-flow system. The higher blowdown in this case was necessary to discharge larger amounts of dissolved salts to allow the scrub solution to stay below 10 wt% dissolved salts, because considerably more input HCl was assumed than in the high-flow case. The salt concentration in the scrub solution blowdown for the high-flow case was only 3.8 wt% and no make-up water was needed.

6.1.2 Elemental and Particulate Mass Balances

Elemental and total PM mass flowrates are summarized in Table 6-2. Decontamination factors (DFs) for all metals except mercury were on the order of 10^9 . Such high DFs were attributed to the cumulative effects of the baghouse (DF=100–217), the scrubber (DF=1–340), the prefilter (DF=3.88), and double HEPA filters (DF=1,000 for each filter). These DF values for the HEPA filters were comparable to the recommended DF design values of 500 and 1,000 for the first and second HEPA filters to use when considering an accident scenario (Burchsted 1979) when the filters do not perform at the certified efficiency. Thus, the efficiencies for non-Hg elements and total PM in this process simulation are conservative. The decontamination factor for Hg was on the order of 10^2 – 10^4 , depending on the amount of $HgCl_2$ in the offgas that can be removed in the free-jet scrubber.

One of the design features of the R-1 APCS that contributes to such high metals and PM removal effectiveness is the use of multiple control devices in series. The baghouse, prefilter, and HEPA filters are based on filtration of the entire offgas stream and will be effective even in the event of a process upset that could affect the wet scrubber performance, such as a failure of the atomizing air system, the scrub solution nozzles, or scrub solution pumps. The filtration equipment will continue to filter any offgas that

Figure 6-1. APCS process simulation flowsheet for the high-flow case.

Table 6-1. Mass balance in the APCS of the high-flow and low-flow cases.

Stream	Stream Description	High-flow case Mass flowrate (lb/hr)	Low-flow case Mass flowrate (lb/hr)
Feedstreams:			
SCCGAS	Thermal treatment offgas	30,678	15,845
H2O-SQ	Partial quench water	14,464	9,138
H2O-Q	Full quench water	1,499	767
SCRUBAIR	Scrubber atomizing air	16,406	5,569
NAOH	Sodium hydroxide	113	568
H2O-MKP	Make-up water	----	4,471
AIR	Air to reheat offgas	3,813	650
NH3	Ammonia	72	36
	TOTAL:	67,045	37,044
Product streams:			
EXITGAS	Offgas exiting APCS	63,835	30,443
BLOWDOWN	Scrubber blowdown	2,883	6,284
BAGSOLID	Collected baghouse solids	318	317
PREFSOL	Collected prefilter solids	0.33	0.40
HEPASOL1	Collected HEPA(1) solids	0.11	0.14
HGACC	Captured mercury vapor	7.75	0.042
HEPASOL2	Collected HEPA(2) solids	1.1×10^{-4}	1.3×10^{-4}
	TOTAL:	67,044	37,045

Table 6-2. Decontamination factors for elemental metals and total PM.

Element	Mass flowrate at outlet of:					Decontamination factors:				
	SCC	Baghouse	Scrubber	HEPA 1	HEPA 2	Baghouse	Scrubber	HEPA 1	HEPA 2	Total
High-flow case:										
Ag	1.08	1.08E-02	2.48E-03	6.39E-07	6.39E-10	100	4.35	3,883	1,000	1.69E+09
As	4.30	4.30E-02	9.78E-03	2.52E-06	2.52E-09	100	4.40	3,883	1,000	1.71E+09
Ba	5.37	5.37E-02	1.23E-02	3.18E-06	3.18E-09	100	4.35	3,883	1,000	1.69E+09
Be	7.74	3.56E-02	7.14E-03	1.84E-06	1.84E-09	217	4.99	3,883	1,000	4.21E+09
Cd	32.25	3.22E-01	7.41E-02	1.91E-05	1.91E-08	100	4.35	3,883	1,000	1.69E+09
Cr	4.30	1.98E-02	3.96E-03	1.02E-06	1.02E-09	217	4.99	3,883	1,000	4.21E+09
Hg	10.74	10.74	7.82	7.82	7.82E-02	1.00	1.37	1.00	100	1.37E+02
Pb	21.49	0.21	4.94E-02	1.27E-05	1.27E-08	100	4.35	3,883	1,000	1.69E+09
Sb	3.22	3.22E-02	7.32E-03	1.89E-06	1.89E-09	100	4.40	3,883	1,000	1.71E+09
Se	2.15	2.15E-02	4.88E-03	1.26E-06	1.26E-09	100	4.40	3,883	1,000	1.71E+09
Ta	0.22	1.01E-03	2.07E-04	5.32E-08	5.32E-11	217	4.89	3,883	1,000	4.13E+09
All other PM	186.31	0.86	0.17	4.42E-05	4.42E-08	217	4.99	3883.50	1,000	4.21E+09
Total PM	279.17	12.35	8.16	7.82	7.82E-02	22.6	1.51	1.04	100	3.57E+03
Low-flow case:										
Ag	1.08	1.08E-02	2.41E-03	6.20E-07	6.20E-10	100	4.47	3,883	1,000	1.74E+09
As	4.30	4.29E-02	9.60E-03	2.47E-06	2.47E-09	100	4.47	3,883	1,000	1.74E+09
Ba	5.37	5.37E-02	1.20E-02	3.09E-06	3.09E-09	100	4.47	3,883	1,000	1.74E+09
Be	7.74	4.95E-02	1.04E-02	2.67E-06	2.67E-09	156	4.77	3,883	1,000	2.90E+09
Cd	32.28	3.23E-01	7.22E-02	1.86E-05	1.86E-08	100	4.47	3,883	1,000	1.74E+09
Cr	4.30	2.75E-02	5.77E-03	1.48E-06	1.48E-09	156	4.77	3,883	1,000	2.90E+09
Hg	10.74	10.74	3.16E-02	3.16E-02	3.16E-04	1	340	1	100	3.40E+04
Pb	21.46	0.21	4.80E-02	1.23E-05	1.23E-08	100	4.47	3,883	1,000	1.74E+09
Sb	3.22	3.22E-02	7.20E-03	1.85E-06	1.85E-09	100	4.47	3,883	1,000	1.74E+09
Se	2.15	2.15E-02	4.81E-03	1.24E-06	1.24E-09	100	4.47	3,883	1,000	1.74E+09
Ta	0.22	1.40E-03	2.94E-04	7.58E-08	7.58E-11	156	4.77	3,883	1,000	2.90E+09
All other PM	186.31	1.19	2.50E-01	6.43E-05	6.43E-08	156	5	3883	1,000	2.90E+09
Total PM	279.16	12.70	0.45	3.17E-02	3.16E-04	22	28	14.32	100	8.84E+05

Notes: 1. Decontamination Factor = inlet elemental mass flowrate in the offgas/outlet elemental mass flowrate in the offgas.

2. The carbon bed provides a decontamination factor of 100 for mercury.

3. HCl is removed only by the scrubber, DF = 1,000. SO₂ is removed only by the scrubber, DF = 100. NO_x is removed only in the SCR system, DF = 6.7.

4. HEPA1 = Prefilter and first bank of HEPA filters.

5. HEPA2 = Carbon bed and second bank of HEPA filters

passes through them as long as the filter media is not physically or thermally damaged or compromised by excessive moisture condensation. The potential of damaging or compromising all four filtration devices in series (baghouse, prefilter, and 2 HEPA filter stages) is remote because the baghouse is preceded by an offgas cooling stage that is separate from the full quench and wet scrubber that precedes the prefilter and HEPA's.

In addition to the four filter stages in series, the wet scrubber is also highly efficient for PM and metals control. Based on vendor information, the PM concentration in the offgas exiting the scrubber depends on the flowrates of the atomizing air and the scrub solution compared to the offgas flowrate, and is relatively independent of the input PM concentration. In its present configuration downstream of the baghouse, the scrubber DFs for PM and metals DFs are very marginal. However, in the event of a failure of the upstream baghouse, the concentrations of the PM and metals at the outlet of the scrubber would not appreciably increase.

The extent of HCl and NO_x removal was limited to the efficiency of one unit operation within the APCS. Therefore, much smaller (but still highly acceptable) decontamination factors result for these species.

Treated offgas concentrations of metals and PM modeled in this study are compared to expected emission limits in Table 6-3. The calculated metals emissions, excluding mercury, were 4–5 orders of magnitude lower than expected limits. Total PM concentrations range from less than 10% to less than 0.1% of the allowable limit. The low treated concentrations for the non-Hg metals and PM provide considerable safety factors for routine process inefficiencies and upsets.

The calculated Hg concentration exiting the high-flow APCS was over 60 times greater than the limit, while the Hg concentration exiting the low-flow APCS was about 2/3 of the limit. The initial HCl offgas concentration entering the low-flow APCS was significantly greater (by a factor of 5) than for the high-flow APCS which resulted in the generation of a significant amount of water-soluble HgCl₂ that was captured in the wet scrubber. This situation highlights how sensitive Hg control and emissions can be, even for a high-performance system designed for efficient Hg control. To meet the Hg emission limits for the high-flow case, the assumptions of Hg speciation and control efficiency must be changed, or else the maximum allowable Hg concentration in the feed must be limited to 2 orders of magnitude less than the feedrate used in the model calculations. This would reduce the maximum Hg feedrate to approximately 0.1 lb/hr, which corresponds to a relatively low Hg concentration of <50 ppm for waste fed to the upstream waste treatment system.

6.1.3 Energy Balances

Energy balances were performed to calculate the amount of energy required to (a) cool the recycled scrubber solution, (b) reheat the scrubber outlet (HEPA filter inlet) offgas, (c) heat the offgas at the SCR inlet, and (d) cool the offgas upstream of the retention tanks.

A chiller unit was used to cool the liquid recycle from the scrubber outlet temperature to 60°F. In the high-flow case where the higher gas flowrate required a 60 gpm scrub solution flowrate, 3.1×10^6 BTU/hr was removed by the chiller. In the low-flow case where the scrub solution flowrate was 30 gpm, 1.3×10^6 BTU/hr was removed.

Table 6-3. Comparison of estimated emission concentrations to emission limits.

Pollutant	High-flow case	Low-flow case	Emission limits ^a
Beryllium	2×10^{-5} g/24-hrs	1.6×10^{-5} g/24-hrs	10 g/24-hrs
Mercury $\mu\text{g/dscm}^b$	2,645	25	40
Total HCl, ppmv ^b	1.4	11	75
Total particulate matter, mg/dscm ^b (including PM, metals, and Hg)	2.6	0.025	35
SVM ^c (Pb, Cd), $\mu\text{g/dscm}^b$	8×10^{-4}	2×10^{-3}	100
LVM ^d (As, Be, Cr), $\mu\text{g/dscm}^b$	2×10^{-4}	5×10^{-4}	55

a. Strictest of current or proposed emission limits listed in Table 2-2.

b. Concentrations are corrected to 7% excess oxygen on a volumetric, dry basis.

c. Semivolatile metals.

d. Low volatile metals.

The energy requirement to reheat the cooled scrubber offgas was calculated to be 0.91×10^6 BTU/hr and 0.16×10^6 BTU/hr for the high-flow and low-flow cases, respectively. The reheat energy for the low-flow case was significantly less because of the smaller total gas flow and the smaller temperature increase. The scrubber offgas for the high-flow case was heated 40°F from 157°F to 197°F. The scrubber offgas for the low-flow case was only heated 14°F from 181°F to 195°F. The offgas temperature could not exceed 200°F to prevent degradation of the carbon beds. A reheat temperature that is at least 40°F above the gas dewpoint is usually desired to prevent moisture condensation in the filters. Dilution of the offgas with the heated air only decreases its dewpoint temperature by 1 to 2°F because of the low volume of added air relative to offgas.

Optimization of the low-flow case to provide more assurance that moisture is not condensed in the HEPAs, while maintaining a maximum reheated gas temperature of 200°F, would require additional cooling of the offgas before entering the free-jet scrubber, or else undesirably high air dilution. Additional gas cooling could possibly be achieved by using a chiller or feeding excess water in the second quench. However, this would cause considerable moisture condensation, and would increase capital and operating costs for the APCS. This is an example of issues that are not often well known when waste treatment options such as electrical heating and oxygen combustion are considered to reduce offgas flowrates.

The energy requirements of the reheater upstream of the SCR unit were 3.6×10^6 BTU/hr and 1.9×10^6 BTU/hr for the high-flow and low-flow cases, respectively, and were proportional to the total gas flowrate through the process. When the offgas was cooled to a design temperature of 100°F upstream of the retention tanks to reduce the required capacity of retention tanks and reduce condensation in the tanks, the total heat removed was 19×10^6 BTU/hr and 17×10^6 BTU/hr for the high-flow and low-flow cases, respectively. A large quantity of water condensate was generated during this process. In both cases, the water condensate effluent rate was approximately 25 gpm (12,000 lb/hr).

6.1.4 Secondary Waste Streams

The secondary waste streams include the (a) PM collected in the baghouse, (b) scrub solution discharge containing dissolved salts, salt precipitate, and trace amounts of particulate matter, and (c) prefilters and HEPA filters, (d) spent carbon containing mercury and trace contaminants, and (e) water condensate produced from cooling the offgas upstream of the retention tanks. Excluding the retention tank cooler condensate, the liquid waste from the scrubber represents the largest stream and the greatest challenge in disposal. The largest mass of PM is captured from the baghouse. All other filters collected significantly less particulate matter.

Used baghouse bags are secondary wastes that will be infrequently generated. The frequency for replacement of these materials depends on the operating conditions as well as total particulate and mercury concentrations in the offgas.

The replacement frequency and amounts of filters and carbon adsorbing media are estimated in Tables 6-4 and 6-5. Because of the efficiency of particulate removal upstream of the HEPAs, the replacement frequency of the HEPAs is acceptably low at 800 operating hours for the high-flow case. If the facility is operated continuously 24 hours per day, this equates to once every 33 days. Campaign-type operation of 10 or more 24-hr days each are assumed or used in many scenarios such as the current INEEL WERF incinerator operation. Such a low HEPA filter replacement frequency could provide reasonable assurance that HEPA replacements can be performed when the facility is not operating, barring upset conditions that may rapidly load the filters over a short time.

The HEPA filter replacement frequency for the low-flow case was shorter because only 12 instead of 24 HEPA filters are used in parallel, but the mass flowrate of particulate from the primary treatment unit was assumed to be the same as in the high-flow APCS. Still, the HEPA filter replacement frequency of 340 hrs (14 days) is long enough so that the filters would last through an operating campaign of up to two weeks without a replacement. Also, the total particulate loading in the low-flow case should be considered very conservative. The calculated input total particulate matter concentration in this case was 49,000 mg/dscm (21 gr/dscf). This concentration is over twice as high as most measurements from incinerators and from arc melter demonstration tests. The level of total particulate was conservatively estimated in Section 3 as about 15% of the feed mass to the upfront primary treatment unit. This results in a conservatively high total PM concentration in the SCC offgas for both the high-flow and low-flow cases, and relatively large amounts of particulate in the secondary wastes. Actual primary treatment units may produce from 2–10 times less total PM.

The prefilter replacement frequency is more significant at undesirably high frequencies of only 31 and 13 hours for the high-flow and low-flow cases. This model highlights the importance of very efficient upstream PM filtration for satisfactory prefilter and HEPA filter operation. The prefilter replacement frequency could be reduced by using higher efficiency baghouse filters, and by optimizing the prefilter efficiency to match the prefilter and HEPA filter replacement frequency. Prefilter and HEPA filter replacement frequency can also be adjusted by using more prefilters and HEPA filters in a larger matrix, so the gas flow through each filter is smaller and the PM loading rate on each filter is less.

The carbon bed replacement frequency for typical sulfur-impregnated carbon bed adsorbers was determined based on a mercury removal efficiency of 99%. Mercury was considered to be the limiting element and loading of trace organics was not included in the calculations of carbon bed capacity. The total mass of carbon was calculated using the Hg mass flowrate in the offgas, Hg loading capacity of the

Table 6-4. Masses and volumes of secondary wastes generated (high-flow case).

Secondary waste	Replacement frequency (operating hours)	Mass rate (lb/hr) (a)	Volume rate (ft ³ /hr)
Baghouse bags	4,000 (b)	0.465	24
Prefilters	31 (c)	NK	NK
HEPA filters (front 24 filters)	800 (d)	0.12 (e)	5×10^{-3}
HEPA filters (back 24 filters)	4,000 (f)	0.025 (e)	1×10^{-3}
Carbon media	1,820 (g)	46.5	1.3

NK = Not known

a. Including mass of contaminants (dust and Hg).

b. It is assumed that each bag will require replacement every 4,000 operating hours.

c. Prefilters are assumed to load up to 0.44 lb of dust before replacement (Burchsted 1979).

d. HEPA filters are assumed to load up to 4 lb of dust before replacement (Burchsted 1979).

e. Assumed weight of dirty HEPA filter to be 99 lb (Burchsted 1979).

f. The calculated frequency is very low based on a loading of 4 lb dust (Burchsted 1979), so it is simply assumed that replacement will occur once every 4,000 operating hours (roughly once per year of operation, if the entire facility is operated about 4,000 hours per year).

g. Adsorptive capacity of carbon assumed to be 0.2 lb Hg/ lb C.

h. Assumes volume of Hg-contaminated carbon media is equal to volume of new carbon media. Carbon density of 30 lb/ft³.

Table 6-5. Masses and volumes of secondary wastes generated (low-flow case).

Secondary waste	Replacement frequency (operating hours)	Mass rate (lb/hr) (a)	Volume rate (ft ³ /hr)
Baghouse bags	4,000 (b)	0.27	14
Prefilters	13 (c)	NK	NK
HEPA filters (front 12 filters)	340 (d)	0.29 (e)	1.2×10^{-2}
HEPA filters (back 12 filters))	4,000 (f)	0.025 (e)	1×10^{-3}
Carbon media	167,700 (g)	0.25	0.08

NK = Not known

a. Including mass of contaminants (dust and Hg).

b. It is assumed that each bag will require replacement every 4,000 operating hours.

c. Prefilters are assumed to load up to 0.44 lb of dust before replacement (Burchsted 1979).

d. HEPA filters are assumed to load up to 4 lb of dust before replacement (Burchsted 1979).

e. Assumed weight of dirty HEPA filter to be 99 lb (Burchsted 1979).

f. The calculated frequency is very low based on a loading of 4 lb dust (Burchsted 1979), so it is simply assumed that replacement will occur once every 4,000 operating hours (roughly once per year of operation, if the entire facility is operated about 4,000 hours per year).

g. Adsorptive capacity of carbon assumed to be 0.2 lb Hg/lb C.

h. Assumes volume of Hg-contaminated carbon media is equal to volume of new carbon media. Carbon density of 30 lb/ft³.

carbon adsorbers, and the density of the carbon granules (Appendix C). Calculations showed that 81,000 lb of carbon media would last for approximately 1,800 hours for the high-flow case with the high Hg mass flowrate in the offgas entering the carbon bed. In the low-flow case, more of the total Hg was removed in the wet scrubber. This extended the lifetime of the sulfur-impregnated carbon, so that 40,500 lb of carbon would last nearly 168,000 operating hours.

6.2 APCS Equipment Evaluations

Results and discussion of the process simulation with respect to specific APCS equipment is discussed in the following sections.

6.2.1 Partial and Total Quench Towers

The purpose of the first partial quench tower using water spray evaporation is to rapidly cool the SCC offgas from 2,200°F to 300°F to reduce D/F formation and to protect baghouse material from excessively high temperatures. The effect of varying the SCC outlet temperature on process operation and APCS performance has not been evaluated in this study. An SCC temperature of 2,200°F is only required if the system is designed to treat PCB-contaminated wastes. If a lower SCC temperature such as 1,800°F is used, then less water evaporation is needed to cool the offgas. Also, the offgas dewpoint (and temperature) following the full quench will be lower. This would enable a wider reheat temperature difference, reduce the volumetric offgas flowrate, reduce energy requirements, reduce moisture condensation and potential corrosion problems, and improve sulfur-impregnated carbon bed performance.

The water fed into each quench unit was assumed to be utility water available at 60°F. Recycling scrubber solution blowdown to the quench towers was not investigated in this study. Recycle of these wastewater streams as means of reducing the total secondary waste stream should be investigated. However, if the scrubber solution blowdown is not treated to remove dissolved and suspended solids (especially Hg species) then these contaminants can be re-entrained as very small (submicron) particles when the water droplets evaporate. These small particles are especially difficult to capture in the scrubber. The greatest potential for untreated scrub solution recycle is to inject it into the partial quench tower, where much of the small particles formed from evaporation can be captured in the baghouse.

6.2.2 Baghouse

Variations in the particle size distribution of offgas particulate investigated in this study had almost no effect on the removal of particulate by the baghouse. Given the conservative assumption of 99% removal for $<0.5 \mu\text{m}$ PM and 99.9% removal for $>0.5 \mu\text{m}$ PM, the particulate mass removed in the baghouse was nearly identical for the two cases. The presence of the baghouse upstream of the wet scrubber is a viable feature for improving the performance of the entire offgas system, since problems associated with particulate in the scrub solution such as sludge deposition, nozzle erosion, and particle re-entrainment loading are significantly reduced.

6.2.3 Wet Scrubber

The atomization of the liquid within the free-jet scrubber creates submicron droplets with high surface area, upon which particulate matter can accumulate. The resulting total available liquid surface area is generally so great that the outlet particulate concentration approaches a limiting value and is practically independent of the particulate load in the gas entering the scrubber. Only about 2 lb/hr

particulate is removed in the scrubber, because the baghouse removes over 99% of the total PM. Most of the difference in particulate size distribution attributed to feed composition is eliminated at the scrubber where the outlet particulate concentration in the scrubber offgas is a function of the atomizing air fed into the scrubber.

It was assumed that 99.9% of the oxidized mercury, in the form of HgCl_2 , is removed in the wet scrubber. Approximately 20–30% of the mercury chlorides can be expected to precipitate out of solution depending on constituent concentrations and scrubber solution temperature. This provides a means for removing mercury from the scrubber blowdown via filtration or other separation methods, while still potentially recycling the blowdown liquid elsewhere in the process such as in the partial quench process upstream of the baghouse. Treatment and handling of scrubber solution was not included in this study.

6.2.4 Offgas Reheat

The fully quenched offgas dewpoint is a critical design and operating parameter for all wet systems that include offgas reheating, HEPA filtration, and carbon bed adsorption. This is because offgas reheating should be great enough to raise the gas temperature at least 40°F above the dewpoint but not exceed maximum operating temperatures for downstream equipment such as the sulfur-impregnated carbon beds. A feature of the R-1 APCS modeled in this study that helps to address this situation is the "heated air" reheater. This method of offgas reheating lowers the dewpoint through the addition of dry hot air, although the decrease in dewpoint temperature is only 1–2°F in the current models because of the low reheat air flowrate relative to the offgas flowrate.

6.2.5 Offgas Retention Tanks

The volume of offgas holding tanks was calculated based on anticipated operating conditions. The tanks were designed to hold the treated offgas until it can be analyzed and determined to be sufficiently clean to be released into the environment. The total hold time before tank evacuation is initiated was defined by the total time required to collect and analyze gas samples from the tank and report the results. After determining that the tank contents can be released, the gas is released. The time required to fill a tank should exceed the time required to collect and analyze tank gas samples and to evacuate the tank contents.

Several design specifications were assumed. The offgas was cooled to reduce the moisture content, lower the gas volumetric flowrate, and reduce the required storage volume. In addition, the tanks were designed to hold 10% more than expected in this worst case. Total tank fill time was assumed to be two hours greater than the total hold and evacuation time. Total sample collection, analysis, and reporting time is assumed to be 12 hours. Only 70% of tank contents are removed during a given evacuation period.

If the gas in the holding tanks cannot be released directly into the environment, it must be recycled through the treatment system and subsequently the offgas treatment system to remove the undesirable constituents. To stay within the gas-carrying capacity of the total system, waste feeding may have to be reduced or stopped until the tank contents have been recycled. During tank evacuation, only 70% of the tank contents can be expected to be removed. Thus, the remaining tank contents may contaminate the next batch of gas, requiring additional gas recycle.

7. EQUIPMENT SIZE AND COST ESTIMATES

The installed capital costs for the offgas systems for the high-flow and low-flow cases were estimated using vendor-provided purchase costs, equipment and system and footprint estimates, and installation cost factors. The estimated costs are expected to be representative but not exact, since many design and operating details were not included at this point, and cannot be included without a more specific treatment system scenario. Facility capital costs such as building, design, inspection, electrical, instrumentation, and management cost factors are generally consistent with those used in cost estimates for the ITTS study (Feizollahi 1996).

The capital cost estimates of the APCS alternatives for the high-flow and low-flow cases are shown in Table 7-1. The estimates are organized to separately show the major cost components, which are the (a) purchase costs of major equipment, (b) other equipment and installation costs, (c) building costs, (d) indirect costs, and (e) other facility capital costs. The costs of installation and other equipment and indirect costs are determined using cost factors. Consistent with most DOE facilities total capital cost estimates, the actual major equipment purchase cost is the smallest of all these cost components.

The largest single cost component is the "other facility capital costs" category. This cost category includes five key subcomponents, namely design, inspection, project management, and construction management. The design subcomponent includes both Title 1 (preliminary design) and Title 2 (detailed design) and is estimated at 25% of the facility construction cost for an alpha facility. The inspection subcomponent includes Title 3, or engineering support during construction, and is estimated at 7% of the facility construction cost. The project management subcomponent is estimated at 10% of the facility construction cost and includes project management costs incurred both by DOE and the site management and operations (M&O) contractor. Construction management (CM) is estimated at 17% of the construction costs, which is the sum of the equipment, building, and indirect costs. Construction management includes material and services procurement and control activities, which are typically handled by the site CM contractor. Allowances for project scope change or management reserve is estimated at 10% of construction costs.

Facility construction costs include the rest of the installed costs and include the purchase cost of equipment, installation costs, building costs, and indirect costs as defined below:

- *Major equipment purchase cost.* Cost estimates for the individual pieces of equipment that comprise the air pollution control system were primarily determined by soliciting budgetary costs from suppliers and vendors. Where this was not a practical option, engineering estimation methods were used and costs were scaled for time and capacity.
- *Other equipment and installation costs.* For systems which involve processing equipment, the allowance for electrical is 15%, mechanical support is 30%, and instrumentation is 30% of the equipment costs. Factors for installation costs and costs for connecting ductwork were also included in the equipment subtotal at 30% and 10% of the purchase cost, respectively.
- *Building and structures.* Building and structure costs are estimated by multiplying building unit costs by the space square footage allocated to each process unit. Assumed unit rates are applied to several categories of buildings. The category chosen for this study was that of an alpha waste processing area rated at \$1,700 per square foot for triple-confinement alpha cells. Building unit

Table 7-1. Capital costs (\$1,000) for conceptual APCS alternatives.

Case:	1	2
Major equipment purchase cost:		
Partial quench spray tower	251	186
Baghouse (2) (one in operation, one as backup)	324	182
Full quench spray tower	44	32
Free-jet scrubber	160	117
Scrubber water chiller	125	90
Air heater	30	30
2-HEPA filtration systems (includes prefilters) (one in operation, one as backup)	377	189
Carbon adsorbers	1,404	520
Reheater	196	196
NO _x control	500	400
Retention tanks (3)/Vacuum pumps (2)		
Pressure vessels (3)/Compressors (2)		
CEMs	166	166
Subtotal of major equipment purchase costs	3,577	2,108
Other equipment and installation costs:		
Electrical, 15% of equipment cost	537	316
Mechanical support, 30% of equipment cost	1,073	632
Instrumentation, 30% of equipment cost	1,073	632
Installation costs, 30% of purchase cost	1,073	632
Connecting ductwork, 10% of purchase cost	358	211
Subtotal of other equipment and installation costs:	4,114	2,424
Building cost (at \$1,700/ft² for alpha containment):		
Area of building housing APCS, ft ²	5,400	3,090
APCS building cost, \$1,700/ft ² for alpha containment		
Area of building housing retention tanks or pressure vessels, ft ²		
Retention tanks/pressure vessel building cost, \$420/ft ² for packaged waste handling areas		
Building cost:	9,180	5,253
Subtotal of installed equipment and building:	16,871	9,785
Indirect costs, 29% of total of building, structure, and equipment costs	4,892	2,838
Total facility construction costs:	21,763	12,623
Other facility capital costs:		
Design, 25% of facility construction costs	5,441	3,156
Inspection, 7% of facility construction costs	1,523	884
Project management, 10% of facility construction costs	2,176	1,262
Construction management, 17% of construction costs	3,700	2,146
Allowance for proj. scope change or mgmt reserve, 10% of const. costs	2,176	1,262
Subtotal of other facility capital costs:	15,017	8,710
Subtotal of installed facility capital costs:	36,780	21,333
Contingency, 25% of total installed capital costs	9,195	5,333
Total installed capital cost:	45,975	26,666

Notes:

Case 1: High-flow case with the baseline APCS.

Case 4: Low-flow case with baseline APCS using tanks and vacuum pumps.

Case 7: High-flow case with baseline APCS excluding NO_x control system.

Case 10: Low-flow case with baseline APCS excluding carbon adsorption.

Case 2: Low-flow case with the baseline APCS.

Case 5: High-flow case with baseline APCS using

Case 8: Low-flow case with baseline APCS exclu

3	4	5	6	7	8	9	10
251	186	251	186	251	186	251	186
337	189	337	189	337	189	337	189
44	32	44	32	44	32	44	32
160	117	160	117	160	117	160	117
125	90	125	90	125	90	125	90
30	30	30	30	30	30	30	30
377	189	377	189	377	189	189	94
1,404	520	1,404	520	1,404	520		
196	196	196	196	196	196	196	196
500	400	500	400			500	400
62,100	31,500						
		26,225	10,775				
166	166	166	166	166	166	166	166
65,690	33,615	29,815	12,890	3,090	1,715	1,998	1,500
9,853	5,042	4,472	1,933	463	257	300	225
19,707	10,084	8,944	3,867	927	514	599	450
19,707	10,084	8,944	3,867	927	514	599	450
19,707	10,084	8,944	3,867	927	514	599	450
6,569	3,361	2,981	1,289	309	171	200	150
75,543	38,657	34,287	14,823	3,553	1,972	2,297	1,725
5,400	3,090	5,400	3,090	5,400	3,090	5,400	3,090
9,180	5,253	9,180	5,253				
367,500	187,500	152,000	67,500				
154,350	78,750	63,840	28,350				
163,530	84,003	73,020	33,603	9,180	5,253	9,180	5,253
304,763	156,275	137,122	61,316	15,823	8,940	13,475	8,479
88,381	45,320	39,765	17,782	4,589	2,593	3,908	2,459
393,144	201,595	176,887	79,098	20,412	11,533	17,383	10,938
98,286	50,399	44,222	19,775	5,103	2,883	4,346	2,734
27,520	14,112	12,382	5,537	1,429	807	1,217	766
39,314	20,159	17,689	7,910	2,041	1,153	1,738	1,094
66,835	34,271	30,071	13,447	3,470	1,961	2,955	1,859
39,314	20,159	17,689	7,910	2,041	1,153	1,738	1,094
271,270	139,101	122,052	54,578	14,084	7,958	11,994	7,547
664,414	340,695	298,939	133,676	34,496	19,490	29,377	18,485
166,104	85,174	74,735	33,419	8,624	4,873	7,344	4,621
830,518	425,869	373,674	167,095	43,120	24,363	36,721	23,106

essure vessels/compressors.
g NO_x control system.

Case 3: High-flow case with baseline APCs using retention tanks and vacuum pumps.

Case 6: Low-flow case with baseline APCS using pressure vessels and compressors.

Case 9: High-flow case with baseline APCS excluding any form of carbon adsorption.

rates incorporate all material and labor needed for constructing the building shell including utilities, lighting, heating, ventilation, and air conditioning (HVAC), and site development costs.

- *Indirect costs.* Indirect costs, including subcontractor overhead and fee, are estimated at 29% of the total of equipment, building, and structure costs.

Because the costs are a planning-level estimate, a 25% contingency is also included. The contingency is applied to the total of all components in the production facility construction cost.

7.1 Equipment Sizing

The major components of the air pollution control system contributing to the size of the housing required to contain the system were the baghouse, the spray quench towers, the HEPA filters, and the carbon adsorbers. All of the other process units were considered to be small factors in determining the total equipment footprint needed to estimate a building size in square feet. The footprint for the baghouse for the high-flow case was calculated in ASPEN to be roughly 900 ft². The baghouse footprint for the low-flow case was determined to be about 500 ft².

The estimated footprint for the Flanders HEPA filter system, including prefilters and two banks of HEPAs, was 320 ft² for the high-flow case and 160 ft² for the low-flow case. The carbon adsorption system using fixed beds in parallel was sized based on vendor information. For the high-flow case, calculations showed that six beds would be required in parallel to handle the gas flowrate with each bed being 10 ft in diameter and 15 ft long, a footprint of 150 ft² per bed and a total footprint of 900 ft². The low-flow case only required three parallel beds of the same size for a total footprint of 450 ft².

The partial spray quench tower was 100 ft² for the high-flow case and 50 ft² for the low-flow case. The estimated footprint for the full quench tower was 30 ft² for the high-flow case and 25 ft² for the low-flow case.

The total footprint for the other pieces of equipment were assumed to occupy roughly 450 ft² for the high-flow case and 360 ft² for the low-flow case. This area includes the SCR at 150 ft²; free-jet scrubber at 100 ft² for high-flow and 60 ft² for low-flow; scrubber water chiller at 100 ft² for high-flow and 50 ft² for low-flow; and heater and reheater at 100 ft² together.

The total equipment footprint was multiplied by a factor of two, to account for such space as the areas needed between each major equipment component, access around the equipment, and filter and adsorbent replacement space. Consideration was not given to how some equipment items may be physically located on decks or structures above other equipment, which may in fact be desirable not only to reduce footprint but also to avoid long or tortuous runs of interconnecting ducting. Costs for non-alpha containment building space for control rooms, storage, laboratories, maintenance, and other activities are also not specifically itemized, but should be considered to be within the factor of two safety factor for the alpha-containment space. The total area of the alpha-containment building for the APCS is estimated at 5,400 ft² for the high-flow case and 3,090 ft² for the low-flow case.

7.2 Capital Cost Estimate

The purchase costs for major pieces of equipment were based on data supplied by vendors. These costs are itemized below for each major component in the offgas systems:

<u>Item</u>	<u>High-flow case</u>	<u>Low-flow case</u>
Partial quench tower	251,000	186,000
Baghouse	168,000	94,000
Full quench tower	44,000	32,000
Free-jet Scrubber	160,000	117,000
Scrubber water chiller	125,000	90,000
Air heater	30,000	30,000
Prefilter/HEPA filters	189,000	94,000
Fixed bed carbon adsorbers	1,404,000	520,000
Reheater	196,000	196,000
SCR for NO _x Control	500,000	400,000
Retention tanks (3)	60,000,000	30,000,000
Vacuum pump (1 and 1 backup)	2,100,000	1,500,000
Pressure vessels (3)	23,000,000	10,000,000
Compressors (1 and 1 backup)	2,800,000	850,000
CEMS	166,000	166,000
O ₂ monitors (1 paramagnetic, 1 fuel cell): \$7,000		
CO ₂ monitor: \$5,000		
CO monitor: \$6,000		
NO _x monitor (2): \$20,000		
THC monitor: \$12,000		
Gas conditioner and pump: \$20,000		
DAS: \$10,000		
Heated sample line: \$20,000		
Flow splitter: \$10,000		
Stripchart recorder: \$5,000		
Regulators, fittings, etc.: \$5,000		
Instrument racks: \$5,000		
Offgas flowmeter: \$1,000		
Pressure transducer: \$2,000		
In-situ particulate matter monitor: \$25,000		
Misc. fittings, valves, tubing, gauges: \$13,000		

Figure 7-1 shows how each major component contributed to the total purchased equipment cost. The carbon adsorber beds, NO_x control unit, and HEPA filtration system are the largest contributors to the purchased equipment cost. For the carbon beds, the high-flow case was calculated to need 6 beds in parallel that are 10 ft in diameter, 15 ft long, with a carbon bed depth of 3 ft. The ASPEN model assumed the carbon beds had a removal efficiency of 99%. Thus, it was calculated that there would be 7.75 lb of mercury captured in the beds per hour. At this capture rate and an assumed carbon adsorptive capacity of 20 wt%, the carbon beds were calculated to have a lifetime of 1,800 hours of operation before saturation. The cost of the carbon needed to achieve this removal would be on the order of \$404,000. This cost is rather high because of the need to use sulfur-impregnated carbon because of the expected high percentage of elemental mercury as opposed to oxidized species of mercury. It was assumed that 99.6% of the mercury going to the carbon beds was elemental. The cost of impregnated carbon is about \$5/lb compared to plain activated carbon which costs between \$0.50–\$1/lb.

The low-flow case, at half the offgas flowrate of the high-flow case, only needed 3 beds of carbon of the same dimensions stated previously. The same assumptions of removal efficiency and adsorptive capacity were made as in the high-flow case. For this case only 0.042 lb of mercury would be captured in the carbon beds per hour. At this capture rate, the carbon beds would have a lifetime of 168,000 hours of operation. Assuming 4,032 hrs per year as in the life-cycle costs, the carbon beds would have a lifetime of 42 operational years. The cost of the carbon to achieve this removal would be about \$20,000. This cost is much lower than that of the high-flow case because much of the Hg was removed in the low-flow case in the scrubber upstream of the carbon beds and because the mercury was assumed to be 100% HgCl₂ because of the high HCl levels. Therefore, plain activated carbon can be used instead of impregnated carbons at a cost of about \$0.50/lb.

The estimated installed APCS total capital cost for the high-flow case was about \$46 million, and the installed APCS cost for the low-flow case was about \$27 million. These costs do not include the cost for three retention tanks and associated equipment that would be used to retain the offgas exiting the SCR NO_x control process until analysis could be completed to show that the offgas meets regulatory limits.

Figure 7-2 shows the components of the total capital cost for the two systems modeled in this study. The largest cost component is the “facility capital costs” which includes design, inspection, project management, construction management, and an allowance for project scope change or management reserve. Contingency and building costs are similar in magnitude and are the second and third largest cost components. The remaining three factors, indirect costs, equipment installation costs, and equipment purchase costs, are also roughly equivalent, although the actual purchase cost of major equipment is the smallest of all cost components.

7.3 Capital Cost Sensitivity Studies

A number of cost variations were evaluated for the baseline system. These variations were:

- Inclusion of evacuated retention tanks and associated equipment
- Inclusion of pressurized retention tanks and associated equipment
- Deletion of the SCR for NO_x control
- Deletion of the carbon beds for Hg control.

Figure 7-1. Breakdown of purchased equipment cost by major process units of the APCs.

- 1-Contingency
- 2-Facility capital costs including design, inspection, management, and allowance
- 3-Indirect costs
- 4-Building cost
- 5-Installation cost w/electrical, mechanical, instrumentation, and connecting ductwork
- 6-Equipment purchase cost

Figure 7-2. Breakdown of factors that determine total capital cost.

7.3.1 Retention Tanks

Two variations of retention tanks were considered. The first variation was the use of evacuated retention tanks that operated over a pressure range from 0.2 to 0.9 atm (-10 to -1.3 psig), and the second variation used retention tanks that can be pressurized up to 100 psig. For both concepts, a retention time of 12 hours was assumed for each of three tanks. Twelve hours was considered sufficient time for any necessary sample analysis to be completed, including metals and organic analyses. Three tanks were needed so that in operation, the sequence could be as follows: One tank is being filled, while the second tank is sitting full with sample analyses in progress, and the third tank has analyses complete and is being emptied. This approach assumes that a full tank that has analyses complete can be emptied within the time required to fill a tank, regardless of whether the contents of the full tank pass air emissions limits or not. Also, any added facility costs for expediting sample analysis or performing sample analysis on-site are not included in this estimate.

The evacuated retention tank concept has the inherent safety of always operating under negative pressure, like the rest of the APCS. Also, since the offgas is vented into an evacuated area, there is less potential for moisture condensation and the gas temperature will actually decrease under assumed adiabatic conditions. However, the evacuated tank concept requires (a) much larger tank capacity, (b) cooling of the offgas to reduce the offgas volume (otherwise the tank capacity requirement would be even larger) and resultant energy costs and heat exchange equipment, (c) discharge of significant amounts of condensed (although relatively clean) water condensed from the gas upon cooling, and relatively large vacuum pumps for emptying the tanks.

The pressurized tank concept enables much smaller tank capacity because of the elevated pressure, but (a) may not be considered acceptable because of the pressurized gas, (b) may result in moisture condensation in the tanks caused by compression, (c) will cause gas temperatures to increase upon compression, and (d) requires relatively large gas compressors.

The estimated installed capital costs, including the evacuated retention tanks, are shown in Figure 7-3. The addition of the evacuated retention tanks and associated equipment (not including any additional handling equipment for the increased water condensate discharge) increases the cost of the APCS for the high-flow case by 18 times to \$831 million. The APCS cost for the low-flow case increases by 16 times to \$426 million. These are huge increases in the APCS cost.

Using pressurized rather than evacuated retention tanks can significantly reduce the total capital costs as shown in Figure 7-4 and in Table 7-1, Cases 5 and 6. The total capital costs for the high-flow and low-flow cases (including pressurized retention tanks) are reduced to \$374 million and \$167 million, respectively. However, even these lower costs increase the costs of the baseline high-performance APCS by hundreds of millions of dollars.

Stakeholders and operators of planned mixed waste treatment facilities should seriously consider such large costs and determine if the added assurance that no unanalyzed, non-compliant emissions are released is worth the added cost. In the case of evacuated retention tanks, the added benefit is probably not worth the added costs. This is especially true for the high-performance APCS conceptualized in this report. A reasonable alternative to spending hundreds of millions of dollars extra for the retention tanks would be to spend a few million dollars more and install backup gas cleaning equipment such as added carbon and HEPA filters (which are included in alternative high-performance APCS designs in

Figure 7-3. Increased capital cost due to use of retention tanks.

Figure 7-4. Comparison of the cost of evacuated and pressurized retention tanks.

Appendix B). Other alternatives (R-2 and R-3) shown in Appendix B, but not presently modeled in this study, incorporate O_2 combustion and CO_2 removal to further reduce the offgas volumetric flowrate. This would decrease the costs associated with the use of the retention tanks, but the cost of the CO_2 removal system would have to be added to the total system. It is not likely that the chance of unanalyzed, noncompliant emissions can be prevented without adding at least \$100 million to the capital cost of the APCS. Increases in operating and lifecycle costs would need to be considered in addition to capital costs to assess how much impact this would have on total costs for the entire treatment system.

7.3.2 Selective Catalytic Reduction NO_x Control

Many primary waste treatment processes do not produce large amounts of NO_x , even for waste streams that contain some nitrates that can be a source of NO_x . Existing and proposed federal regulations for waste treatment do not include emission limits for NO_x , although state and local regulations can limit NO_x emissions. If NO_x emissions from the treatment process are not regulated or are within applicable emission limits, then the SCR reactor for NO_x control can be eliminated. The SCR is one of the largest single cost components for the APCS capital costs. Elimination of the SCR will decrease the APCS capital costs by 6–9% as shown in Figure 7-5. The capital cost for the high-flow case will decrease from \$46 million to about \$43 million, and the capital cost for the low-flow case will decrease from \$27 million to \$24 million, as shown in Table 7-1, Cases 7 and 8.

7.3.3 Carbon Bed Adsorbers for Mercury Removal

Sensitivity studies were conducted to evaluate the cost savings that would be realized without the carbon bed adsorbers. This savings is shown in Figure 7-5, and was calculated to be \$9.3 million (20% of the total cost) for the high-flow case and \$3.6 million (13% of the total cost) for the O_2 combustion case. The capital cost estimates for the air and O_2 cases minus the carbon bed adsorbers are shown in Table 7-1, Cases 9 and 10, respectively.

7.4 Comparison of APCS Costs to ITTS Study

The estimated APCS capital cost for the high-flow case is \$46 million. This value is somewhat higher than the estimate of \$38 million for the APCS for air-fired rotary kiln incinerator from the ITTS study (Feizollahi 1996). The APCS from the ITTS included a larger baghouse, developmental backflushable stainless steel HEPAs, a packed bed scrubber in addition to the free-jet scrubber, and additional floorspace. Considering the component differences, the two estimates, are relatively similar.

Figure 7-5. Comparison of the cost for the complete APCS to the cost without NO_x control and without carbon adsorbers.

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

This study has utilized a process simulation approach to evaluate a high-performance APCS design. The study included identification of several high performance APCS designs, selection of a design for process simulation, computations of APCS performance for controlling pollutants that could be emitted in offgas produced from DOE mixed waste thermal treatment, installed capital cost estimates, and identification of potential limitations and outstanding issues of the process simulation, assumptions, and APCS performance.

8.1.1 APCS Design and Emissions Control Performance

- The selected high-performance APCS design easily meets expected stringent emission limits for all pollutants, except possibly mercury.
- The offgas concentrations of PM and selected metals were reduced to 10^{-1} – 10^{-4} of current or proposed limits. This represents a significant safety factor below expected limits for these pollutants. HCl and Cl_2 concentrations were approximately $\frac{1}{2}$ of or less than proposed limits.
- While the offgas concentration of Hg was around $\frac{2}{3}$ of the expected limit for the low-flow case, it was over 60 times greater than the limit for the high-flow case. The lower Hg emissions in the low-flow case resulted from the removal of greater quantities of water-soluble HgCl_2 in the wet scrubber. Performance of Hg control technologies including sulfur-impregnated carbon absorption must be improved and validated to provide the level of Hg control (at least 99.99%) needed if some Hg-contaminated mixed wastes are thermally treated. If such high Hg control efficiencies are not possible, then the Hg content in waste fed to mixed waste incinerators may need to be significantly limited to meet expected emission limits.
- Decontamination factors (DFs) for all semivolatile and low volatile metals except mercury for both offgas cases were on the order of 10^9 . Mercury DFs in the high-flow and low-flow cases were only 130 and 34,000, respectively. The higher Hg DF in the low-flow case was attributed to a higher HCl concentration in the offgas to form more water soluble HgCl_2 which was readily removed in the wet scrubber.

8.1.2 APCS Process Simulation Model

- ASPEN PLUS is a powerful process simulation tool that was used to evaluate the effectiveness of an integrated APCS to minimize pollutant emissions as a function of offgas flowrates, initial pollutant concentrations, and the APCS unit operations and their operating parameters.
- The process simulation helped to identify potential system design limitations such as limited Hg control efficiency, insufficient offgas cooling in the low-flow case to allow adequate offgas reheat, and high frequency HEPA prefilter replacements.
- Several simplifying steps and assumptions were used in this study. These included (a) exclusion of upfront thermal treatment steps including primary thermal treatment and secondary combustion,

(b) the use of only fully oxidized input offgas from a hypothetical SCC, (c) exclusion of specific radionuclides, products of incomplete combustion, and D/F, (d) simplification and limited range of offgas and PM flowrate and composition, and PM size distributions, (e) exclusion of secondary waste treatment options and systems, (f) use of sometimes unproven vendor recommendations and assumptions for control equipment performance, (g) lack of optimization of some model results such as Hg control efficiency, secondary waste generation, offgas cooling, reheat, and carbon adsorber temperature limits, and (h) the use of cost factors for estimating installed capital costs.

8.1.3 Installed Capital Cost Estimates

- The installed capital costs of the APCS for the high-flow and low-flow cases were estimated to be \$46 million and \$27 million, respectively. These installed capital costs are 6 times higher than the major and other equipment purchase costs, largely because of large factors needed to account for costs associated with designing, constructing, and permitting DOE facilities (facility capital costs).
- The addition of retention tanks and associated equipment is prohibitively costly. The total estimated APCS costs for the high-flow and low-flow cases using pressurized retention tanks was \$374 million and \$160 million, respectively. The total estimated APCS costs for the high-flow and low-flow cases using evacuated retention tanks was \$831 million and \$426 million, respectively.
- Not including offgas retention tanks, the most costly control equipment was the carbon adsorbers followed by the NO_x control unit and HEPA filters.

8.2 Recommendations

Several recommendations result from this study. These include recommendations for future APCS design, uses of the APCS process simulation developed in this study, and validation or improved performance of specific control technologies.

8.2.1 APCS Design

- Future APCS design for new facilities or for modifying existing facilities should consider the features of the high-performance APCS modeled in this study to provide greatest assurance of adequate emissions control.
- Offgas retention tanks for holding offgas long enough to ensure that noncompliant offgas is not emitted are not recommended. Instead, efforts should emphasize proper APCS design, installation, and operation to achieve compliance goals without the use of offgas retention and delayed offgas release.
- Significant issues identified in this study that should be addressed in future APCS designs include (a) Hg control technology capabilities and limitations, (b) optimization of offgas cooling, reheat, and carbon adsorber temperature to prevent moisture condensation in HEPAs and downstream equipment while achieving desired Hg removal efficiency and minimizing secondary wastes, (c) optimization of prefilter, HEPA filter, and carbon bed media replacement frequency, (d) optimization of D/F control, (e) optimization of secondary waste volume and properties, (f) the impact that secondary waste treatment has on system alternatives, (g) validation of assumptions for PM size distribution and control, and (h) validation of metals partitioning and control.

8.2.2 Uses of the APCS Process Simulation

- The engineering analysis approach, including the process simulation model, established in this study should be used to evaluate additional high-performance APC systems proposed for new facilities or as modifications to existing facilities. This process simulation model can be used in feasibility studies, preconceptual and conceptual designs, technology development and validation programs, and to support higher-level waste flow analyses.
- Using this process simulation can help provide (a) better information for decisions about alternatives for existing mixed waste treatment facilities to comply with new regulations, (b) better identification and qualification of incomplete performance and cost information for new or existing technologies, (c) better public, regulatory, and stakeholder acceptance of thermal treatment and APC systems based on more definitive performance evaluations, (d) avoidance of costly and unnecessary features such as offgas retention, and (e) more rapid and less costly implementation of new facilities and needed modifications to existing treatment facilities.
- Parametric studies should be conducted to identify the impact of variations in offgas or waste feed conditions, new APCS equipment such as improved Hg control technologies, improved or validated control equipment performance data, and operating parameters on pollutant emissions and life-cycle costs for a given APCS. Parametric studies should also be conducted to optimize Hg control efficiency, secondary waste generation, offgas cooling, reheat, and carbon adsorber temperatures, and APCS costs.
- The process simulation should be upgraded to include (a) upstream thermal treatment steps such as primary thermal treatment and secondary combustion so the process simulation can determine species partitioning and offgas generation from the thermal treatment system as functions of the waste feed content and thermal treatment equipment design and operation, (b) modeling of specific radionuclides, products of incomplete combustion, and D/F, and (c) downstream secondary waste treatment and disposition options. Inclusion of upstream and downstream processes in the entire system would evolve this APCS simulation into a complete simulation of the entire treatment system. This would provide better identification of any issues that could impact different unit operations in the entire system, and enable optimization of the entire system to meet system objectives.
- A process simulation of candidate wet-dry high-performance APCS designs should be done to better identify and quantify advantages, disadvantages, and issues for wet-dry systems as compared to the dry-wet system modeled in this study.
- Cost estimates should be upgraded to focus on lifecycle costs which include capital costs and operating costs over some facility lifecycle.

8.2.3 Control Technology Improvement and Validation

- Existing and new Hg control technologies need to be improved and validated to provide assurance that mixed waste thermal treatment facilities can meet expected Hg emission limits while processing some Hg-containing mixed waste streams. If such validation is not possible, then

restrictive Hg feed limits (and feed characterization for Hg, with the associated uncertainties and risks) will be required for existing and new thermal treatment facilities.

- Additional performance information should be obtained to validate model assumptions concerning (a) Hg removal efficiency in carbon beds, (b) PM and Hg removal in the wet scrubber, (c) possible D/F formation in the SCR reactor, and (d) cumulative impacts of multiple APC equipment connected in series.

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APPENDIX A.

Offgas Flowrates and Compositions for the Offgas System Conceptual Design and Evaluation Project

OFFGAS FLOWRATES AND COMPOSITIONS FOR THE OFFGAS SYSTEM CONCEPTUAL DESIGN AND EVALUATION PROJECT

September 20, 1996

Nick Soelberg

The Offgas System Conceptual Design and Evaluation Project is being conducted to identify and evaluate various traditional and innovative offgas management systems that are most promising for reliably and efficiently controlling air emissions from mixed waste thermal treatment systems. The scope of the study includes:

- Conceptualizing several different offgas management systems for controlling all of the expected pollutants in the offgas from mixed waste thermal treatment systems, such as included in the Integrated Thermal Treatment Systems study (Feizollahi, F. and W. J. Quapp, Integrated Thermal Treatment System Study - Phase 2 Results, INEL-95/0129, Revision 1, February 1996).
- Evaluating the conceptualized systems in terms of performance data and estimates, operating and maintenance information, implementation risk (potential for successful development and implementation), mass and energy balances, and characteristics and disposal of secondary waste streams. The most promising systems will be identified based on their technical merit. Equipment size estimates and cost estimates will be conducted for those with the most technical merit.

Potential Variations in Input Offgas Flowrates and Compositions

The design and performance of any offgas system depends on the properties of the offgas to be treated. The properties of the offgas depend on the properties and processing rate of the input waste, any additives, and the design and operation of the primary treatment system. There are 19 different treatment systems included in the ITTS evaluations. These are listed from Feizollahi 1996 in Table A-1 of Appendix A. This table shows the input feedrates for the systems. The baseline waste inputs to the main thermal treatment or thermal desorption systems range from 1,949 to 2,617 lb/hr. The breakdown of the waste materials is shown in Table A-2 of Appendix A, and compositions of each of these waste streams are provided in Feizollahi 1996.

The flowrates of offgas into each offgas system for the main thermal treatment system range from 399 to 28,241 lb/hr. This variation is because of the differences in amounts and kinds of waste feed to the main thermal treatment system, use of oxygen or air for oxidizing organics, operation in a pyrolysis mode or an oxidizing mode, use of added water spray evaporation for temperature control where needed, use of electrical energy input or auxiliary fossil fuels where needed, and use of offgas recycling.

Systems G-1 and H-1 produce a synthesis gas that requires treatment in an offgas system prior to full oxidation. The synthesis gas composition for these two systems is much different from the oxidized offgas produced in the other systems. Offgas systems from fully oxidizing waste treatment systems (the more likely DOE approach) will be considered first in the Offgas System Conceptual Design and Evaluation Project, so gas compositions and flowrates for systems G-1 and H-1 are not included in this document. The offgases produced from the K-1 and L-1 thermal desorber systems are also not included in this document, because of the differences in offgas composition and handling methods.

Input feed rates

Table A-1. Input feed rates for nineteen systems (lb/hr) (from Feizollahi 1996).

	Rotary kiln, air	Rotary kiln, oxygen	Rotary kiln, air, wet APC	Rotary kiln, oxygen, CO2 retention	Rotary kiln, air, polymer stabilization	Rotary kiln, air, max. recycling	Slagging rotary kiln	Indirectly heated pyrolyzer	Plasma furnace	Plasma furnace, CO2 retention	Plasma gasification	Fixed hearth pyrolyzer, CO2 retention	Rotary kiln, air, thermal desorption	Molten salt oxidation	Molten Metal Waste Destruction	Steam gasification	Joule-heated Vitrification	Thermal desorption and MEO	Thermal desorption and SWO
Subsystem	A-1	A-2	A-3	A-4	A-5	A-6	A-7	B-1	C-1	C-2	C-3	D-1	E-1	F-1	G-1	H-1	J-1	K-1	L-1
Administration (a)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Receiving & Preparation	2,927	2,927	2,927	2,927	2,927	2,927	2,927	2,927	2,927	2,927	2,927	2,927	2,927	2,927	2,927	2,927	2,927	2,927	2,927
Sorting	1,500	1,500	1,500	1,500	1,500	1,500	1,190	2,927	1,500	1,190	1,190	2,927	2,080	2,070		2,120	1,540	2,250	2,250
Metal decontamination	468	468	468	468	468	468	468	468	468	468	468	468	468	468		468	468	468	468
Metal melting	149	149	149	149	149	149		149				149	149	149		149	149	149	149
Lead recovery	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26	26
Main thermal treatment (Waste feedrate)	2,000	2,000	2,000	2,000	2,000	2,000	2,149	2,000	2,149	2,149	2,149	2,000	660	2,000	2,617	2,000	2,000		
Thermal desorption													1340						
Air pollution control (SCC outlet gas flowrate)	21,420	8,448	21,452	28,241	21,589	21,423	27,561	2,397	7,339	3,039	1,159	6,196	21,531	6,653	1,467	957	4,239	399	399
Aqueous waste treatment (b)	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	64	64
Organic liquid waste treatment																		67	67
Primary stabilization	1,518	1,518	1,132	1,518		1,508						1,519	184	1,523		1,516			
Secondary stabilization (c,d)	595	595	1,981	460	1,673	30.24	595	595	595	259	595	245	492	282	120	595	595	334	119
Grout Stabilization	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	1,051	0.3	0.3	0.3	0.3	1,550	1,550
Special Waste	153	153	153	153	153	153	153	153	153	153	153	153	153	153	153	153	153	153	153
Mercury amalgamation	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
Certification & shipping	2,546	2,546	2,714	3,180	3,183	2,310	2,584	2,546	2,513	2,745	2,515	2,751	4,319	2,629	2,425	2,544	2,521	5,699	5,635

- The input feed rate is not applicable to the administration subsystem.
- The aqueous waste feed rate shown above only accounts for primary feed stream from receiving and shipping and does not account for secondary aqueous waste streams and recycle streams which varies on a system by system basis.
- The feed to secondary stabilization is comprised of concentrated sludge from aqueous waste treatment, trace metals, and spent lime from APC, sludge containing surface metal grit from metal decontamination and sulfate salts from receiving and shipping liquids from SCWO, and solids from MEO.
- The sludge waste input to secondary stabilization from aqueous waste treatment is 20% salts and solids by weight. In the case of system A-4, C-2, and D-1 10% of the used lime is routed to polymer stabilization.

Table A-2. Breakdown of mixed wastes processed in each system.

Waste Material	Feedrate, lb/hr
Combustible waste	660
Noncombustible waste	1,340
Combustible and noncombustible waste subtotal (feed to most of the main thermal treatment systems - A-1 to A-6, B-1, D-1, F-1, H-1, and J-1)	2,000
Metal waste with entrained contamination (included in some main thermal treatment systems - A-7, C-1 to C-3, and G-1)	149
Metal waste that is decontaminable (included only in the G-1 main thermal treatment system)	468
Lead waste (not included in any of the main thermal treatment systems)	26
Aqueous waste (not included in any of the main thermal treatment systems, but partly included in the thermal desorption systems)	80
Special waste (not included in any of the main thermal treatment systems)	153
Mercury waste (not included in any of the main thermal treatment systems)	50
Grout stabilization waste (not included in any of the main thermal treatment systems)	0.3
Total waste processed in main thermal treatment and other subsystems	2,927

Recommended Offgas Flowrates and Compositions

The range of systems that fully oxidize the offgas is generally well represented by systems A-7 (Slagging rotary kiln, air combustion) and C-2 (Plasma furnace, oxygen combustion and CO₂ retention). The offgas compositions and flowrates for these two systems are shown in Tables A-3 and A-4. Table A-3 also shows the particulate flowrate and composition determined from ASPEN mass and energy balances for the A-7 and C-2 systems. These particulate compositions are estimated using some simplifying assumptions as inputs to the ASPEN program, and actual particulate will likely include many species not included here such as chlorides, sulfur species, possibly some carbonates and some unburned carbon, some fluorides, and many other elements including Mg, Mn, P, Ti, and Zn. Table A-4 also includes offgas flowrate and composition information from other similar studies for comparison. Most of the values are similar or within reasonable ranges, except for the high levels of total particulate estimated in the ITTS study. These levels resulted from a somewhat arbitrary calculation of total particulate in the offgas as 20% of the inorganic material processed in the primary treatment unit (kiln, melter, etc). This approach may overestimate the likely amounts of total particulate.

The bolded columns in Table A-4 show recommended flowrates and compositions for use in this study. These two sets of flowrate and composition data are based on whether oxygen or air is used for

Mass flowrates

Table A-3. Flowrate at the secondary combustion chamber outlet from Feizollahi 1996 (a).

	Flowrate at the secondary combustion chamber outlet			
	System A-7, slagging rotary kiln, air combustion,		System C-2, Plasma Furnace, O2 combustion, CO2 retention	
	lb/hr	scfm	lb/hr	scfm
Gas flowrate	27,138.46	6,222.92	2,951.73	666.93
O2	1,473.00	295.37	546.00	109.48
CO2	3,401.00	495.98	1,352.00	197.17
CO	0.35	0.08	0.01	0.00
NOx	33.40	7.14	0.15	0.03
THC	0.00	0.0000	0.00	0.0000
HCl	69.80	12.27	69.76	12.26
Cl2	0.01	0.0007	0.06	0.0058
SO2	3.05	0.31	2.94	0.29
H2O	2,628.00	936.83	971.00	346.14
F2	0.11	0.02	1.03	0.17
As (b)	0.06	0.01	0.06	0.01
Cd (b)	3.50	0.20	3.50	0.20
Hg (b)	0.15	0.0048	0.15	0.0048
Se (b)	0.03	0.0024	0.03	0.0024
N2 (b)	19,526.00	4,474.71	5.04	1.16
Particulate matter flowrate	423.31		88.36	
SiO2	213.00		42.30	
Al2O3	147.00		30.50	
Fe3O4	5.80		11.80	
Fe	37.00			
Ba	0.31		0.07	
Cr	1.60		0.34	
Pb	0.04		0.01	
Ag	0.01		0.00	
MgO	3.24		0.58	
Na2O	1.83		0.33	
K2O	3.38		0.61	
CaO	10.10		1.82	
Total gas and particulate flowrate	27,561.77		3,040.09	

- a. Unpublished documentation for Feizollahi, F. and W. J. Quapp, Integrated Thermal Treatment System Study - Phase 2 Results, INEL-95/0129, Revision 1, February 1996.
- b. 100% of all input amounts of these species was assumed to volatilize to a gas in the primary treatment process in the ITTS study. These should be included in total particulate values.

Table A-4. Offgas flowrates and compositions for selected ITTS and other systems.

	Flowrate and composition at the secondary combustion chamber outlet						Flowrates and compositions recommended for the Offgas System Conceptual Design and Evaluation Project (c)						Stack gas emission levels (dry, @ 7% O ₂ Max.			Necessary total control efficiencies, %, to meet target emission levels			
	System A-7, slagging rotary kiln, air combustion (a)	System C-2, Plasma Furnace, O ₂ combustion (a)	Graphite electrode melters (b)	Rotary Kilns (b)	Plasma torch Melters (b)		Air combustion (d)			O ₂ combustion (e)			Normal (target)	(regulatory limit) (f)		Air combustion		O ₂ combustion	
							Normal	Min	Max	Normal	Min.	Max.				Normal	Max.	Normal	Max.
Gas flowrate, lb/hr	27,138	2,952	2,900-20,700				27,000	18,000	30,000	5,000	3,000	20,000							
Gas flowrate, kg/hr	12,336	1,342	1,300-9,400				12,273	8,182	13,636	2,273	1,364	9,091							
Gas flowrate, scfm (@ 68 F, 1 atm)	6,223	667	470-3,100				6,044	4,029	6,715	857	514	3,429							
Gas flowrate, dscm @ 7 % O ₂	150	9					154	108	152	6	6	19							
Gas temperature, degrees F	2,500	2,200					2,200	1,800	2,400	2,200	1,800	2,400							
Gas Composition (wet volumetric basis)																			
O ₂ , %	5	16	7				7	4	8	14	10	16							
CO ₂ , %	8	30	2.3-41				8	5	10	30	20	40							
CO, ppm	13	3	10	50	40		5	1	10	5	1	10	40	100		0.0	0.0	0.0	0.0
NO _x , ppm	1,148	48	50-500	50-500	1,000-10,000		1,000	400	4,000	1,000	400	4,000							
THC, ppm	0	0	10	10	5		2	1	5	1	0.5	5	0.1	12		95.5	98.2	97.5	99.5
HCl, ppm	1,972	18,388	72-34,000	4,900	250		2,000	500	2,500	20,000	5,000	25,000							
Cl ₂ , ppm	0	9	0-170				2	0.5	5	10	10	100							
Total HCl and Cl ₂ , ppm							2,002	501	2,505	20,010	5,010	25,100	30	67		98.7	98.8	99.96	99.97
SO ₂ , ppm	49	442	0-1,200	40	20		50	10	100	500	100	1,000							
H ₂ O, %	15	52	5.8-76				10	5	20	50	20	60							
N ₂ , %	72	0					75	60	80	4	2	10							
Total, %	100	100					100			100									
Gas molecular weight							28.7			37.4									
Total particulate matter, lb/hr (g)	427	92	10-50				107	21	215	43	21	215							
Total particulate matter, kg/hr	194	42	4.5-23				49	10	98	20	10	98							
Total particulate conc., mg/dscm	21,591	43,445	500-2,500	11,000	200		5,283	1,501	10,698	53,629	27,932	83,795	2	69		99.962	99.981	99.996	99.998

a. Feizollahi, F. and W. J. Quapp, Integrated Thermal Treatment System Study - Phase 2 Results, INEL-95/0129, Revision 1, February 1996.

b. Soelberg, N, G. Anderson, and B. Raivo, Offgas System Equipment and Design for Mixed Waste Treatment, unpublished draft report, Idaho National Engineering Laboratory, July 1996. The flowrates from Soelberg 1996 are for a waste feedrate of 1,000 kg/hr, slightly larger than the waste feedrate of 2,000 lb/hr of Feizollahi 1996. Also, the waste compositions used in Soelberg 1996 are slightly different than used in Feizollahi 1996, and oxygen was used for combustion rather than air. Other notes regarding the Soelberg 1996 data are shown in Soelberg 1996.

c. This composition and flowrate is meant to generally encompass the compositions and flowrates from the ITTS systems. Some specific systems may have somewhat different values. The pyrolysing systems that result in a synthesis gas that is processed in an offgas system and then oxidized are excluded, due to the different flowrates and compositions.

d. The air-fired minimum gas flowrate values are 60% of the maximum value, a typical allowable turndown for offgas equipment.

e. The O₂-fired minimum gas flowrates were determined by mass/energy balance based on the offgas generated from different potential waste feed extremes. The gas flowrates vary so widely because of the potential need for added air, inert gas, water/steam, or offgas recycle to control peak temperatures. Since these minimum values are lower than a typical 60% of the maximum values, added air, inert gas, or offgas recycle may be required for adequate offgas equipment performance.

f. From EPA, The Revised Standards for Hazardous Waste Incinerators, March 1996, Proposed MACT Standards for New Incinerators.

g. The recommended particulate levels range from 5% (normal), 1% (minimum), and 10% (maximum) of the design ITTS feedrate of 2,149 lb/hr waste feed input for the baseline ITTS systems.

combustion, and include estimated normal, minimum, and maximum concentration and flowrate levels. These estimates should be used in conceptual design and evaluation of innovative offgas systems for thermal treatment processes that fully oxidize the offgas produced from treating approximately 2,000 lb/hr of wastes similar to the wastes used in the ITTS study.

Using these recommended values enables offgas systems to be evaluated based on how well they control the range of specified offgas flowrates, temperatures, and compositions, without being associated to any of the specific primary treatment systems. This will enable evaluation of different offgas systems on their own merit for two different general offgas conditions (from air combustion and fossil-fired heat generation and from oxygen combustion and electrical heat generation) rather than on how well they perform for a given treatment system. The mass flowrate and most of the concentration values are order-of-magnitude values that are similar to the values shown for the A-7 or C-2 systems, with some exceptions. These exceptions are:

- Volumetric gas flowrate: The recommended offgas volumetric flowrates were calculated using the mass flowrates and the molecular weights determined from the gas compositions.
- THC: Total hydrocarbons (THC) were not included in the ITTS Phase 2 mass balances. A THC level of 0 is not realistic, so reasonably achievable ranges of 0.5-5 ppm were used in the recommended compositions.
- N₂: While no N₂ is estimated in the C-2 system, such a low value is not realistic considering potential air inleakage, feeder purge air or N₂, and air or N₂ in interstitial spaces in the waste itself. The N₂ concentration for both recommended compositions was determined by difference from 100% of the sum of the other gas species.
- Total particulate: The recommended values are based on order-of-magnitude estimates of carryover as a percent of the total feed input, ranging 1, 5, and 10% of the feed input for the minimum, normal, and maximum carryover for air-fired systems, and 1, 2, and 10% for O₂-fired systems. Carryover for the normal condition for the O₂-fired case was assumed to be less than for the normal air-fired case to be consistent with the significantly lower gas flowrates (and potentially lower entrainment).

Table A-4 also shows expected stack gas emission levels based on reasonable capabilities of the proposed offgas systems, and the proposed MACT Rule. While the ITTS Phase 1 and Phase 2 studies arbitrarily set a safety factor for routine operation that was 10 times lower than most of the expected emission limits, the difference between the normal and regulatory emission levels in this document were based more on the expected performance capability of the offgas systems. The normal target levels ranged from under ½ of the limit (for CO and total HCl and Cl₂) to 120 times lower (for THC). Table A-4 also shows the necessary control efficiencies to enable the normal and maximum SCC levels to be reduced to the normal stack gas levels. This way, there is still a safety factor of from around 2-120 in meeting the expected emission limits even for the maximum SCC outlet concentrations.

The recommended metals emission levels are calculated on Table A-5. Concentrations and mass emission rates in the offgas were calculated using the (a) estimated amounts of the metals in the DOE mixed low-level waste inventory, (b) average and maximum reasonable expected concentrations in

Table A-5. Recommended metals and particulate flowrates and concentrations.

Table 12-3. Recommended metals and particulate flow rates and concentrations																			
Metals content in DOE mixed low-level wastes (a)										Stack gas emission levels, microgram/dscm									
Effluent	Mass, kg	Avg Conc., ppmw	Maximum concentration based on stream variations, ppmw	Stream with maximum concentrations	Elemental boiling point, C	% carryover to APCS (b)		Est. mass flow rates, lb/hr, 2,149 lb/hr feedrate		Estimated SCC outlet concentration, concentration, mg/dscm @ 7% O ₂ (c)				Necessary total control efficiencies, %, to meet target emission levels					
						From Feizollahi 1996 (c)	Estimate for this study (d)	Avg	Max	Air combustion		O ₂ combustion		Normal (target)	Maximum (regulatory limit) (f)	Air combustion		O ₂ combustion	
										Avg	Max	Avg	Max			Avg	Max	Avg	Max
Total wastes	156,292,790																		
Mercury (g)	41,912	268	16,436	Bulk mercury	357	100	100	---	---	---	---	---	---						
Mercury (h)	22,722	145	5,000	Abs. inorganics	357	100	100	0.31	10.74	15	534	389	4,185	25	50	99.84	99.9953	99.9936	99.9994
Semivolatile metals								5.98	53.74	294	2,672	7,457	20,929	31	62	99.99	99.9988	99.9996	99.9999
Cadmium	244,823	1,566	15,006	Abs. inorganics	765	100	100	3.37	32.25	165	1,603	4,195	12,559						
Lead (i)	10,773,124	68,929	100,000	Arbitrary value	1,740	5	100	---	---	---	---	---	---						
Lead (j)	190,370	1,218	10,000	Arbitrary value	1,740	5	100	2.62	21.49	129	1,068	3,262	8,369						
Low Volatile Metals								2.06	89	101	4,438	2,572	34,761	31	60	99.97	99.9993	99.9988	99.9999
Arsenic	9,094	58	2,001	Abs. inorganics	221	100	100	0.13	4.30	6	214	156	1,674						
Beryllium	753,726	4,823	360,320	Beryllium	2,970	not included	10	1.04	77.43	51	3,850	1,292	30,157						
Chromium	422,110	2,701	20,008	Abs. inorganics	2,672	5	10	0.58	4.30	29	214	723	1,675						
Antimony	Not reported	300	3,000	metal debris (k)	1,750	not included	50	0.32	3.22	16	160	402	1,255						
Other metals																			
Barium	98,749	632	5,000	organic sludge	1,640	5	50	0.68	5.37	33	264	846	2,092						
Selenium	4,545	29	1,001	Abs. inorganics	685	100	100	0.06	2.15	3	106	78	837						
Silver	4,548	29	1,001	Abs. inorganics	2,212	5	50	0.03	1.08	2	53	39	419						
Tantalum	23,100	148	1,000	Arbitrary value	2,996	not included	25	0.08	0.54	4	26	99	209						
Total of above metals										444	7,908	11,265	61,967						
Total particulate from Table 4, for comparison										5,283	10,698	53,629	83,795						

a. Huebner, T. L., J. M. Wilson, A. H. Ruhter, and S. J. Bonney, *Quantities and Characteristics of the Contact-Handled Low-Level Mixed Waste Streams for the DOE Complex*, EGG-MS-11303, August 1994.

The values shown here are directly from Huebner 1994 spreadsheets. The implied number of significant figures is a function of the spreadsheet calculations, and not indicative of the actual accuracy of the mass or concentration values. These estimated values should generally be considered very conservative.

b. Carryover includes all potential mechanisms including volatilization, feed dust entrainment, and melt ejection.

c. Unpublished documentation for Feizollahi, F. and W. J. Quapp, *Integrated Thermal Treatment System Study - Phase 2 Results*, INEL-95/0129, Revision 1, February 1996.

d. These estimates are qualitative estimates, presumably conservative, without considering speciation or how different primary treatment systems may have somewhat different total carryover values.

e. Calculated using the recommended normal, and minimum, and maximum offgas flowrates and particulate concentrations from Table 4.

f. From EPA, *The Revised Standards for Hazardous Waste Incinerators*, March 1996, Proposed MACT Standards for New Incinerators.

g. This level includes "bulk mercury", that probably will be excluded from thermal treatment, as is done in Feizollahi 1996. The value for mercury in the "bulk mercury" stream has been reduced from that reported in Huebner to 19,191 kg in subsequent ITTS and INTS studies.

h. This level excludes "bulk mercury".

i. Includes "lead shielding" that may be excluded from thermal treatment.

j. Excludes "lead shielding" that may be excluded from thermal treatment.

k. Antimony was not included in the ITTS mass balances. Analyses from Soelberg 1994 show 300 ppm antimony in a surrogate mixture of metal debris and 60% soil.

waste that will possibly be thermally treated, calculated from the waste inventories, (c) assumed % carryover of each metal to the offgas system, considering relative volatilities and without considering how some treatment systems and operating conditions may be able to minimize carryover of some metals, and (d) the normal and maximum offgas flowrates from Table A-4. As in Table A-4, the stack gas levels, estimated emission limits, and necessary control efficiencies were also calculated. Normal (target) stack gas concentrations of mercury, semivolatile metals, and low-volatile metals were set at only $\frac{1}{2}$ of the expected emission limits, rather than $\frac{1}{10}$ of the limits as was done in the ITTS study. Even so, metals control efficiencies must range from 99.9 to 99.9999%, higher than typical in most industrial and incineration processes.

APPENDIX B

APCS Conceptual Flowsheets

Figure B-1. Schematic of the R-1 conceptual offgas system.

B-2

Figure B-2. Schematic of the R-2 conceptual offgas system.

Figure B-3. Schematic of the R-3 conceptual offgas system.

Figure B-4. Schematic of the R-4 conceptual offgas system.

Figure B-5. Schematic of the R-5 conceptual offgas system.

B-6

Figure B-6. Schematic of the R-6 conceptual offgas system.

Figure B-7. Schematic of the R-7 conceptual offgas system.

APPENDIX C

Vendor Data and Calculations

Baghouse

Information from Andy Miller of BHA Group in Kansas City, August 7, 1997:

In designing a baghouse, one of the important parameters one needs to determine is the square feet of cloth needed to clean the expected gas volume (the air-to-cloth ratio). The air-to-cloth ratio is directly related to the face velocity of the gas going into the bags such that an air-to-cloth ratio of 3:1 is equivalent to a face velocity of 3 ft/min. Standard diameters for bags are 6 1/4" or 4 5/8" (there are also 5 3/4" bags as well as many other sizes). Generally, the larger the diameter, the fewer elements are required in the baghouse. Standard lengths range from 10 ft long to 14 ft long with a typical length being 12 ft. To determine how many bags are needed, determine the cfm of gas and divide it by the desired air-to-cloth ratio (which is usually determined based on experience, type of process, and size of particulate expected). This determines how many total square feet of cloth are needed in the baghouse to clean the expected gas volume. Then based on the diameter and length of the bags chosen, it is possible to figure out the total number of bags that will be required.

The pressure drop over a brand new baghouse with all clean bags inside running clean air through it with no particulate loading will typically be less than half an inch of water column pressure drop. When the baghouse is in operation, treating a particulate laden gas stream, the pressure drop will typically range from 3 to 5 inches of water. Generally, it is not desirable to operate at pressure drops higher than that. When setting up a bag cleaning schedule, it is possible to set it up to clean according to pressure drop. For example, if the normal pressure drop for efficient operation is 4 1/2" water, then cleaning can be set up to pulse the bags clean when the bags reach a pressure drop of 4 1/2". The bags can then be cleaned down to a pressure drop of 4" to keep some particulate cake buildup present on the bags at all times since the particulate cake assists in the filtering process. It is desirable to keep the pressure drop cleaning window rather tight in order to keep a consistent dustcake on the bags at all times.

It is important to remember that the baghouse operates at varying pressure losses depending on the particulate buildup on the baghouse and the cleaning schedule, etc. There is typically a damper on the fan that helps adjust for variations in pressure drop across the system. For example, if the fan was designed to account for as high as 10" water pressure drop across the baghouse, when the bags are pulsed clean the baghouse is really operating at 4" water and the damper has to take up the slack in the fan to insure that there is the proper draft potential available for the treatment process.

During cleaning, it is good practice to stagger the rows of bags to be cleaned. For example, first pulse row 1, then row 4, then row 7, and so on. If staggering is not performed, then it is possible that row 1 will be pulsed clean and then when row 2 is pulsed clean next, the particulate that is pulsed off of row 2 will end up being immediately collected on the newly cleaned row 1. Staggering prevents this from happening. It is important to be careful to watch the header pressure before pulsing the next row and allow it to come back up to the set point before pulsing the next row. It is also important to pulse at as low a pressure as possible. In designing the baghouse, one should find the lowest pressure that will clean the bag properly and efficiently and use that for pulsing the bags.

The can velocity is the velocity of the gas going up between the bags at the bottom of the bags. This value is calculated by determining the total air volume and dividing it by the open area of the baghouse, which is the area of the baghouse housing minus the cross-sectional area of the bags. The can velocity is the average velocity in the upwards direction. A general guideline for the maximum can velocity is 250 ft/min, however, there are baghouses that operate at 300 ft/min with no problems.

The dust resistance coefficient is not an important design parameter and is primarily a function of the resistance of the dust buildup on the bags and is calculated using the porosity of the dustcake and several other complex variables.

With baghouses, the higher the inlet loading, the greater the efficiency achieved. Efficiency equals the inlet loading minus the emissions divided by the inlet loading. Typical efficiencies for a baghouse are 99.9% and greater for particles 0.5 μm and greater. For smaller particles, it is possible to use membrane filtration on the bags in which case efficiencies of 99.99% and greater for particles 0.3 μm and greater would be achieved.

The type of fabric chosen is dependent on the temperature, expected chemicals in the gas stream, and the application. In general, soil remediation work that generates soil-type particulate will require the use of a felt fabric. If clays are expected, it would likely be desirable to use a membrane filtration system; if some oil carryover is expected, some other type of bag would be used. It is all dependent on experience and what's expected in the gas stream.

The floor space required by the system will be approximately 1-3/4 to 2 times the length of the bags for determining the height of the baghouse. This will account for the hopper and clean air plenum area depending on the requirements, available space, and operational needs. The normal distance between bags is generally 1 to 1 1/2 inches. To determine a rough estimate of the length and width of the baghouse housing, take the diameter of the bags and add an inch or so, then multiply by the number of bags in a row, then add a foot or two for a conservative estimate. For example, if there are 6 1/4" diameter bags, with 14 bags per row, and 1,000 bags total, the baghouse is going to be roughly 10 ft wide by 45 ft long.

Fourteen bags per row is about the maximum desired in a row due to air requirements for cleaning and so forth. Twelve bags per row is a typical standard, giving the baghouse housing about a 10 ft width.

For costs, a general Rule of thumb is \$5-8 per cubic foot of air. So if the process is 50,000 acfm, it will cost about \$250,000 for the baghouse and associated accessories, including fans, etc. Operating costs are primarily dependent on the fan requirements and the compressed air used for pulsing the bags clean. Maintenance costs are fairly minimal. Bags typically last anywhere from 1 to 3 years. It is generally assumed to cost about \$25 per bag and cage assembly per year.

Calculations:

Air combustion case:

Gas flow into baghouse = 21,050 acfm

Choose a typical air-to-cloth ratio for the process and conditions of 3:1 (which is equivalent to a face velocity of 3 ft/min).

The square feet of cloth needed = $(21,050 \text{ acfm}) / (3 \text{ ft/min}) = 7017 \text{ ft}^2$.

Choose a standard bag size of 6.25" diameter and 12' long.

Surface area of bag = $\pi(6.25")(144") = 2,827 \text{ in}^2 = 19.6 \text{ ft}^2$.

Number of bags needed = $(7017 \text{ ft}^2) / (19.6 \text{ ft}^2/\text{bag}) = 357 \text{ bags}$.

Typically have no more than 12 bags per row.

Number of rows needed = $(357 \text{ bags}) / (12 \text{ bags/row}) = 30 \text{ rows (cells)}$.

Add one extra row to be offline for cleaning = 31 rows (cells).

Cross-sectional area of bags = $\pi(6.25'')^2 / 4 = 30.7 \text{ in}^2$.

$372 \text{ bags} * 30.7 \text{ in}^2 = 11,413 \text{ in}^2 = 79.3 \text{ ft}^2$.

Area of baghouse housing = $(6.25'' + 1.5'' \text{ spacing}) * 12 \text{ bags/row} = 7.75' = 10'$ (conservative).

$(6.25'' + 1.5'' \text{ spacing}) * 31 \text{ rows of bags} = 20' = 22'$ (conservative).

$10 \text{ ft} * 22 \text{ ft} = 220 \text{ ft}^2$.

Open area = $220 \text{ ft}^2 - 79.3 \text{ ft}^2 = 141 \text{ ft}^2$.

Can velocity = $(21,050 \text{ acfm}) / (141 \text{ ft}^2) = 149.6 \text{ ft/min}$.

Typical Rule-of-thumb costs are \$5-8 per cubic foot of air. Conservative cost estimates are, therefore, \$8 * $21,050 \text{ acfm} = \$168,400$.

O₂-combustion case:

Gas flow into baghouse = 11,800 acfm

Choose a typical air-to-cloth ratio for the process and conditions of 3:1 (which is equivalent to a face velocity of 3 ft/min).

The square feet of cloth needed = $(11,800 \text{ acfm}) / (3 \text{ ft/min}) = 3933 \text{ ft}^2$.

Choose a standard bag size of 6.25" diameter and 12' long.

Surface area of bag = $\pi(6.25'')(144'') = 2,827 \text{ in}^2 = 19.6 \text{ ft}^2$.

Number of bags needed = $(3933 \text{ ft}^2) / (19.6 \text{ ft}^2/\text{bag}) = 200 \text{ bags}$.

Typically have no more than 12 bags per row.

Number of rows needed = $(200 \text{ bags}) / (12 \text{ bags/row}) = 17 \text{ rows (cells)}$.

Add one extra row to be offline for cleaning = 18 rows (cells).

Cross-sectional area of bags = $\pi(6.25'')^2 / 4 = 30.7 \text{ in}^2$.

$216 \text{ bags} * 30.7 \text{ in}^2 = 6,627 \text{ in}^2 = 46 \text{ ft}^2$.

Area of baghouse housing = $(6.25'' + 1.5'' \text{ spacing}) * 12 \text{ bags/row} = 7.75' = 10'$ (conservative).

$(6.25'' + 1.5'' \text{ spacing}) * 18 \text{ rows of bags} = 12' = 15'$ (conservative).

$10 \text{ ft} * 15 \text{ ft} = 150 \text{ ft}^2$.

Open area = $150 \text{ ft}^2 - 46 \text{ ft}^2 = 104 \text{ ft}^2$.

Can velocity = $(11,800 \text{ acfm}) / (104 \text{ ft}^2) = 113.5 \text{ ft/min}$.

Typical Rule-of-thumb costs are \$5-8 per cubic foot of air. Conservative cost estimates are, therefore, \$8 * $11,800 \text{ acfm} = \$94,400$.

Free-jet Scrubber

Information from O. L. Holland of Hydro-Sonic Systems in Linden, Texas, August 13, 1997:

The ratio of scrubbing water to gas to be scrubbed is typically about 0.5 lb H₂O / lb gas. Savannah River has used all the way up to 1 lb H₂O / lb gas to get cleaning all the way down to 0.0001. There is a point of diminishing returns after going any higher than 1 lb H₂O/lb gas. The ratio of atomizing steam to gas is typically in the range of 0.15 to 0.25 lb steam / lb gas (at 50 psi). Atomizing air is generally double the

ratio of atomizing steam because of the density difference (also at 50 psi). Typical values are 0.3 lb air/lb gas or 0.15-0.20 lb steam/lb gas. The difference between air and steam is 1.65 lb air:1 lb steam. The advantage of steam over air is that it immediately condenses and doesn't add to the fan burden.

After the system has been designed to handle a typical gas flow, the inlet particulate loading has little effect on the particulate removal efficiency desired. The system achieves the efficiency that is desired simply by adjusting the amount of atomizing steam or air to achieve the desired outlet particulate concentration. Increasing the flowrate of the atomizing gas increases the particulate removal efficiency of the process by increasing the available surface area of the atomized liquid. Particulate matter agglomerates onto the surface of the liquid droplets and are removed from the offgas. The water droplet size should be no more than 10 times bigger than the particle size that it is desired to capture. If the droplets are more than about 10 times bigger, the particles are likely to just go right around them because of the surface tension. If the process has a vast number of very small particles, say 90% $<0.05 \mu\text{m}$ at 1000 lb/min, it is going to require significantly more power to achieve good efficiencies in order to atomize the water droplets to that fine of a level. Particle removal overall efficiencies are as high as 99+% depending on the particulate particle size. Wettability of the particle also influences the energy required. It is more desirable to deal in grains per standard cubic feet emission requirements as it is an absolute number. An example is tests conducted on a Hazardous Waste Incinerator where the inlet grain loading was varied from 2 grains to 10 grains. The outlet emissions were the same, around 0.005 gr/scf in both cases but from an efficiency standpoint the tests with 10 grains inlet was much higher than that with 2 gr/scf.

Removal of 95% on particles as small as $0.05 \mu\text{m}$ has been catalogued. For acid gas removal, if the system uses NaOH and the pH is kept at about 7, virtually all acid gases will be removed. It is possible to achieve 99.99% removal for SO_2 and nearly complete HCl removal can be obtained. The SO_2 reaction with NaOH/water solution is a liquid phase reaction. SO_2 gas is absorbed by the solution to form liquid containing Na_2SO_3 and/or NaHSO_3 depending on the bottoms pH. The liquid is separated in a liquid/gas separator so there is no carryover with the scrubbed gas.

There are virtually no temperature limits on the scrubber system. Hydro-Sonic Systems have designed and operated scrubbers that function up to about $2,200^\circ\text{F}$, in which case they would build the unit out of Hastelloy, all the way to systems that operate below 200°F , in which case they can use a fiberglass material.

The gas velocity entering the mixing tube should be below 200 ft/s. For a steam driven system, the velocity can be anywhere from 0 to 200 ft/s. The system is fairly insensitive to turndown and there is no effect on the system operation at lower gas velocities. It is common practice to size a system to 120% of what is required and because of the infinite turndown it has no problem operating at levels lower than the design values.

For the steam driven system, there is usually a pressure rise instead of a pressure drop. If it is undesirable for the system to go positive, the system can be sized differently to use the damper on the fan to hold the pressure at neutral at the exit of the scrubber. It is possible to use the fan to keep the pressure between -0.5" and 0" H_2O and avoid going positive in the system.

The cost of equipment for 4 cases were considered.

Case 1: Rotary kiln incinerator using air combustion with offgas at 7000 scfm cleaning to 0.03 gr/dscf will require a Hydro-Sonic Model 1250 Air Hydro Scrubber.

Case 2: Melter using oxygen combustion with offgas at 3500 scfm cleaning to 0.03 gr/dscf will require a Model 600.

Because of the large amount of compressed air that must be added to decrease the outlet emissions to 0.0009 gr/dscf, a larger unit size is needed to handle the gas plus the added compressed air.

Case 3: Rotary kiln incinerator using air combustion with offgas at 7000 scfm cleaning to 0.0009 gr/dscf will require a Model 1500.

Case 4: Melter using oxygen combustion with offgas at 3500 scfm cleaning to 0.0009 gr/dscf will require a Model 800.

The scrubber unit will consist of the following components:

1	FRP	Ejector mounting section
1	C276	Air injector/water injector assembly
1	FRP	Plenum/Mixing tube assembly
1	FRP	Cyclone separator assembly
1	lot	nuts, bolts, water nozzles, and other miscellaneous parts
3	copies	Assembly, process flow, and instrumentation drawings
3	copies	Operations, installation, and maintenance manual.

The high-flow case will have a particle size distribution of 40% $<0.5 \mu\text{m}$, 60% $>0.5 \mu\text{m}$. The Low-flow case will have a particle size distribution of 60% $<0.5 \mu\text{m}$, 40% $>0.5 \mu\text{m}$.

For the high-flow case, there will be 48,200 lb/hr of gas entering the scrubber. For the Low-flow case, there will be 25,800 lb/hr of gas entering the scrubber. That gas stream contains approximately 58 mass % water.

The budget price for case 1 is \$145,000; case 2 is \$105,000; case 3 is \$160,000; and case 4 is \$117,000. Prices are FOB point of manufacture.

The Steam/Air Hydro is a wet scrubbing system in which the energy for cleaning and pumping of polluted gases is provided by the flow of a compressible fluid from a supersonic ejector nozzle. Steam or compressed air at 30 psig (minimum) is commonly used as the driving fluid. It is estimated that at least 0.2 lb of 100 psig air per pound of gas is required to scrub to 0.03 gr/dscf and about 0.68 pounds of compressed air per pound of gas is required to scrub to 0.0009 gr/dscf. That is the reason for the increase in model size for the higher scrubbing efficiency. The water or scrub liquid requirement is 60 gpm for case 1 and 3 and 30 gpm for case 2 and 4, at a pressure of 30 psig at the scrubber manifold.

There will need to be a downstream fan to pull about 4" water negative pressure on the cyclone outlet in order to keep the total system under negative pressure. There must be a damper control valve between the scrubber and the furnace to regulate the furnace draft.

If an Air Ejector drive is used the unit would be sized with the added gas taken into consideration. The gas flowrate will increase very little.

A high scrubbing efficiency can be maintained with a pH as low as 6.5. As the pH drops lower than this, efficiency will fall off somewhat. Other acid gases such as HCl are more easily scrubbed as the pH increases above 7.

The operation and performance of the scrubber will be designed with turndown if required. The ejector scrubbers aren't sensitive to turndown but due to having a fixed orifice throat, the Fan drives will require either a recycle duct from the exhaust stack to the scrubber inlet or a variable nozzle unit could be built to maintain a constant delta P across the scrubber.

In a brochure provided by Hydro-Sonic Systems there is a page showing various graphs and one of these plots emissions (gr/scf) versus lbs steam/lb gas cleaned. On this graph the slopes of the lines for the various processes are all very similar except for the hazardous waste incineration process. The absolute outlet emission is almost independent of inlet dust load because the atomizing gas can be adjusted to achieve a specific result. The only time that it becomes dependent upon inlet dust load is when the inlet dust load is very low (say <5 times the outlet allowable). When this happens, the curve begins to flatten out, which is what happened in this case. Normally all processes have the same emission/energy slope, including hazardous waste processes. The modeling takes low dust load cases into account when predicting energy requirements.

SO₂ removal efficiency is dependent almost totally upon the ratio of SO₂ to reagent addition. The scrubber scrubs SO₂ to almost 100% theoretical stoichiometric values, for both the sulfite and bisulfite reactions. Air and steam give essentially the same efficiency based on equivalent molecular weights of each input. That is, it takes M_{air}/M_{steam} more air than steam to scrub to the same level. The only notable difference is that much of the steam condenses out, while the air does not, and that is the reason for recommending larger units for higher efficiency.

Prefilter

Information from Wilford W. Stagg of Midgley-Huber, a representative of Flanders Filter, on August 20, 1997.

For the prefilter, it is preferred to use the Airpure Rigid Pak 95 in a 24" x 24" x 6" size.

Generally, Flanders see 25-30% or 60-65% ASHRAE filters used as prefilters. The filter specified above has 90-95% efficiency with 99% average arrestance and 29 ft² of media area.

HEPA

Information from Wilford W. Stagg of Midgley-Huber, a representative of Flanders Filter, on August 20, 1997.

We are modeling a system where the gas flow will be about 22,500 acfm when it enters the HEPA train so we will need two 4x3 units in parallel to handle the gas flow.

If HNO₃ is expected to be present in the airstream, the filters should be treated for resistance to HNO₃. However, depending on the concentration, the airstream may need to be treated or diluted before it contacts the HEPA filters.

It is possible to replace the first test outlet and the second test inlet with a test combination, model TSC-4H3W-GG-304-D1. In doing so, individual filter testing capability of at least one bank is eliminated. It is recommended that the test combination be located between the carbon banks to allow for overall testing of each HEPA bank and each carbon bank.

By definition, HEPA filters must be at least 99.97% efficient on 0.3 μm size particles. All HEPA filters are factory tested to ensure this efficiency and factory test reports are available and should be requested. A clean HEPA filter which exhibits 99.97% efficiency will only become more efficient as it loads with particulate. Certainly the second HEPA filter will see significantly less particulate, but it is still a HEPA filter and therefore must be at least 99.97% efficient.

In ASME N509-1989, decontamination factor is defined as "the ratio of the concentration of a contaminant in the uncleaned (untreated) air to its concentration in the clean (treated) air". The decontamination factor can be obtained by calculating the reciprocal of the filter's penetration expressed as a fraction. For example, a 99.97% efficient HEPA filter has a penetration of 0.03%, therefore, $1/0.0003 = 3,333$ decontamination factor.

The standard equipment offered by Flanders/CSC is constructed of T-304 stainless steel. This type of stainless was chosen as the base material because it is readily available, reasonably priced, and will satisfy most project requirements. There are lower and higher grades of material that may be used as dictated by the project requirements.

A faceguard is a wire mesh protective screen attached to the HEPA filter element's upstream and/or downstream face. To meet MIL-F-51068, a 24"x24" HEPA filter is required to have faceguards on both the upstream and downstream faces.

Filter life can not be determined based on the given information. Typically, differential pressure indicators are installed across the filter banks. When the differential pressure reaches a predetermined point, it is time for filter replacement. The Rule of thumb is that clean standard capacity HEPA filters are rated at 1" water gage pressure drop at 1,000 cfm air flow. Typically, HEPA filters are designed to withstand a maximum pressure drop of 10" water gage before failure but it is recommended they not be used to that extent. Usually filters are changed when they reach 3" to 5" water gage pressure drop.

Specific process upsets would have to be specified. The filter unit can withstand, to some extent, air flow or pressure surges.

Carbon bed for mercury adsorption

Information from Wilford W. Stagg of Midgley-Huber, a representative of Flanders Filter, on August 20, 1997.

Mercury removal with charcoal requires a specially impregnated carbon and a very long air to carbon bed contact time. Carbon adsorbers should not be used for particulate removal. The system should be configured to protect carbon adsorbers from particulate by incorporating a prefilter and/or HEPA filter upstream. Mercury is difficult to remove and requires a sulfur-impregnated carbon for removal. Several vendors suggested that the carbon media would have a 20 wt% loading capacity for mercury.

Information from Calgon Carbon Corporation indicated that temperatures in the carbon beds should not exceed 158°F. At temperatures higher than this, the impregnate may volatilize and be driven into the offgas, possibly requiring the use of a scrubber or other acid gas removal device downstream of the carbon beds. At temperatures close to 200°F, approximately 1 lb of sulfur will be removed from the carbon bed per day, resulting in a decrease in the carbon impregnation of about 4.8 wt% over a period of one year. Because of this phenomenon, the removal efficiency of mercury on the carbon beds will be decreased at temperatures higher than 158°F. The sulfur-impregnated carbon will have some potential for removal of organics. Organic compounds most likely to be adsorbed on the carbon are those with high molecular weights and vapor pressures. These compounds will likely see a 99% removal. For weaker adsorbing organic compounds such as methane and propylene, the removal will be in the range of 25-99%. Iodine impregnates will likely behave in a similar manner.

This and other vendors have suggested that spent impregnated carbon from a bed system can be thermally generated using the same type of equipment used in a retort-condenser process. There are not any commercial facilities to regenerate radioactively contaminated carbon, although one vendor suggested the regeneration equipment could be bought and the regeneration performed at the offgas facility.

Impregnated carbons will have little or no effect on removing dioxins and furans (D/F). However, plain activated carbon has been demonstrated to effectively remove D/F from a gas stream with various efficiencies being reported throughout the literature. Most vendors recommend using a separate bed of virgin activated carbon for removal of dioxins before a second bed designed for mercury removal. Other options include preparing a single bed with a mixture of impregnated and virgin carbons whose capture cross sections will be adequate for both gases.

Final HEPA

Information from Wilford W. Stagg of Midgley-Huber, a representative of Flanders Filter, on August 20, 1997.

New model numbers are as follows:

-HEPA filter:	T-010-W-03-05-NU-51-23-GG-FU5
-Adsorber:	AF-GG16-62-NS
-Pre/test inlet hsg:	TSI-4H3W-6GG-304-D1
-HEPA hsg:	BF1-4H3W-GGF-304-D1 (both stages)
-Test outlet hsg:	TSO-4H3W-GG-304-D1 (both stages)
-Carbon hsg:	BF1-4H3W-GG16-304-D1 (both stages)
-Test inlet hsg:	TSI-4H3W-GG-304-D1

The sequence of equipment shown will work fine for in-place testing of the HEPA filters. It allows for in-place leak testing of each individual HEPA filter in each bank. In other words, a single leaking filter in either bank of twelve filters can be easily located. In the absence of the test sections, a single leaking filter could not be located without first removing all filters from the filter housing and individually testing them outside the housing.

To make the system even more in-place testable, it is recommended to change both test inlet housings (located downstream of first HEPA and upstream of second HEPA) to test combinations AND add a test combination between the carbon banks. This arrangement will allow in-place testing of each individual HEPA filter and each individual carbon adsorber. The current arrangement requires that both carbon banks be tested together at one time, thus they must be considered one bank.

Require 2 nominal 12,000 cfm bag-in/bag-out filter system including:

- Model TSI-4H3W-6GG-304-D1 prefilter/inlet test section
- Model BF1-4H3W-GGF-304-D1 HEPA housing
- Model BF1-4H3W-GG16-304-D1 carbon housing
- Model BF1-4H3W-GG16-304-D1 carbon housing
- Model TSC-4H3W-GG-304-D1 combination test section
- Model BF1-4H3W-GG16-304-D1 carbon housing
- Model BF1-4H3W-GGF-304-D1 carbon housing
- Model BF1-4H3W-GGF-304-D1 HEPA housing
- Model TSO-4H3W-GG-304-D1 outlet test section
- Welding in series
- 6" system base
- Static pressure taps
- (4) installed Magnehelic gages
- Test ports
- Weathercaps
- Lifting lugs
- Swivel access door latches
- (12) 95% ASHRAE prefilters
- (24) 99.97% mil-spec HEPA filters
- (48) Model AF-GG16-62-*S(SP) carbon adsorbers for mercury removal

Unit price of \$286,400. Total price of \$572,800. There is sufficient moneys in this estimate for some seismic bracing and documentation in case it is required. This price includes an initial set of filters.

NO_x Control

Information from Gary Bernstein of Babcock & Wilcox in Portland, September 15, 1997:

SCR equipment used by the boiler industry typically operates at temperatures of 350-450°F. SCRs can often reduce NO_x levels to 9 ppm to meet some stringent limits. For removal efficiencies, a gas turbine typically puts out 300-400 ppm NO_x and it is possible to reduce it down to 9 ppm (roughly 98% removal).

As far as excess ammonia is concerned, ammonia slip is not that big of a problem and in general it is not necessary to have any scrubbers or other collection equipment downstream of the SCR in order to catch excess ammonia.

The catalyst is purchased from Hitachi. It is a plate-type catalyst where the catalyst is baked onto the plates. The catalyst is titanium based. The catalyst has a fairly long life and if processing clean gas only it will likely last 5 or more years. Catalyst replacement will depend primarily on the gas stream constituents and potential poisons of which the primary ones are excessive moisture and certain heavy metals.

Temperature is of course an issue too on the catalyst life but if the temperature remains within the design constraints of the system it should not be a problem.

For a gas flow of 78,250 lb/h, the capital costs will run approximately \$500,000 and will include the SCR system, the catalyst, the flue work, and the ammonia injection skid. For a gas flow of 39,125 lb/hr, the capital costs will be roughly \$400,000. The operating costs will consist primarily of the purchase of ammonia.

Information from CSM Environmental Systems, Inc. from NWCF study: The NO_x removal step requires the upstream injection of ammonia into the offgas followed by intimate mixing before introduction into the SCR bed. The amount of ammonia added exceeds the stoichiometric amount by a safety factor based upon experience to insure the complete (about 99%) conversion of NO_x to N_2 . Typically about 1.1 to 1.2 moles of ammonia are added per mole of NO_x to be converted. The temperature into the SCR bed is very critical and is controlled at about 750°F via an upstream burner.

The fuel costs for operation of catalyst systems is much less than for direct fired combustion processes. Since the offgas treatment system will be located downstream of existing HEPA filters the main source of catalyst poisoning, which is particulates, will be reduced. The formation of ammonium sulfite in the SCR could be a source of catalyst poisoning for both catalyst beds.

Quench Towers

Information from Ralph Koenig of Merlin Co./Boulder, Inc., September 25, 1997.

The materials of construction for the units quoted are carbon steel with an internal lining of tough, acid-resistant, baked-on polymer. This method of construction is very strong and is appropriate for an evaporative cooler, which runs dry, and for the full quencher, which in this case has a cool offgas inlet temperature. Also at the rather mild full-quench inlet conditions, a jet-ejector type of saturator can be specified which is much less expensive than a wetted-wall quencher. If it was necessary to cool to saturation in the first unit following the SCC, it would be recommended to use Hastelloy C-22 or C-276 which is much more expensive. The top section of the evaporative cooler is refractory-lined.

Budget costs for the partial and full quench tower for the high-flow case are \$251,000 $\pm 25\%$ and \$44,000 $\pm 25\%$, respectively. For the Low-flow case, costs for the partial and full quench tower are \$186,000 $\pm 25\%$ and \$32,000 $\pm 25\%$, respectively.

The vessels are welded inside and out. The price includes refractory installation, interior coating, exterior painting, gaskets and fasteners, spray nozzles (regular and emergency), spray manifolds, thermocouples, control valves, and other controls specific to proper function. The price does not include support structures or external insulation (required at the base of the evaporative cooler).

Retention Tanks

Figure 14-56 from Peters and Timmerhaus provided costs for mixing, storage, and pressure tanks. Using this graph, the January 1990 cost of a 100,000 gal 30-psig carbon steel spherical tank was estimated to be \$190,000. The January 1990 Marshall & Swift Process-industry cost index was 924 as found in Peters and Timmerhaus, Table 3 on p. 163. From the August 1997 edition of *Chemical Engineering*, p. 166, the

Marshall & Swift Process-industry average cost index for the second quarter of 1997 was listed as 1066.8. Using a formula found in Peters and Timmerhaus p. 164, the present cost of a 100,000 gal carbon steel spherical tank was calculated to be \$219,364. Next, a capacity-ratio exponent formula from Perry's, p. 25-65 was used to scale the cost for a 132,086,026 gal tank. This method, using data for pressure vessels, gave the cost of one tank as \$18,884,083. For three such tanks, the cost will be \$56,652,249. The cost for the tank needed in the Low-flow case was calculated the same way as previously described resulting in the cost for one tank as \$8,951,815, and for three tanks, a total cost of \$26,855,445. A vacuum pump capable of evacuating the tanks for the high-flow case will require roughly 800 hp at 18,000 cfm. The Low-flow case will require a 250 hp vacuum pump to evacuate the tank at 5,500 cfm. Using similar cost scaling factors for size, capacity, and time, the pumps for the high-flow case were calculated to be in the range of \$500,000 to \$1,050,000. For the Low-flow case, the range was determined to be \$300,000 to \$750,000. These numbers were derived by assuming that the type of pump to be used would be reciprocating pumps. One pump is all that would be needed for evacuating the tanks, however, in the capital cost estimate, the cost of two pumps was factored in to include a spare pump as a backup in case the first pump failed.

A range of costs was calculated for the retention tanks to include the uncertainty of engineering and design of such massive structures. It is uncertain whether the tanks would need to be housed inside of a structure. If the tanks were to simply sit outside on a concrete pad, there may be need to provide special weatherization to protect against changes in temperature from one season to another. There may also be need to provide heating of the tanks to prevent condensation of the offgas from occurring. If housing for the tanks is needed, a cost factor of \$420/ft² was used. It is not known what level of containment would be necessary, if any, for the retention tanks.

Such a large tank system would be an engineering feat to design and build. It would need to be spherical in shape to prevent it from collapsing in on itself during evacuation. The structural supports and bracing that would be required would require much time and money. Since the costs for the tanks alone far exceeds the cost of the entire air pollution control system, it seems ludicrous to pursue such an option.

The retention tank option that was modeled for this study represents the worst case based on the assumption that the entire offgas volume would need to be retained. Other options available include removing the carbon dioxide from the offgas prior to retention, which would decrease the volume of the offgas by as much as 40%. The water present in the offgas could also be condensed out of the stream reducing the offgas volume even more. It is possible that using a variety of options, the offgas volume could be reduced by as much as a factor of ten which would decrease the size of the retention tanks needed to retain the offgas and thereby reduce the associated costs.

Process Instrumentation and Automatic Waste Feed Cutoff System

Technical details regarding equipment for process control, monitoring, and instrumentation was not investigated for this study. Estimation factors for instrumentation were used in the calculation of the total capital cost. This factor was rated at 30% of the purchased equipment cost and it is assumed that this factor will adequately cover any costs incurred for instrumentation, monitoring, and process control equipment.

Pressure Vessels and Compressors

From Figure 14-48 in Peters and Timmerhaus, p. 530 (Peters 1991), costs for a compressor are given. A sensitivity study was conducted to determine if replacing the retention tanks with pressure vessels would provide a cost savings since the gas volume would be compressed. A pressure of 112.5 psi was used for the calculations and a compressor was chosen for moving the gas. Calculations found that a 4,000 hp compressor would be needed for the high-flow case and 1,100 hp for the O₂-case. A centrifugal motor compressor was chosen and for the air and Low-flow cases, the costs were calculated to be \$1,386,000 and \$416,000, respectively. These are the costs for one compressor. In calculating the capital costs of the entire system, two compressors were costed assuming that a backup would be needed in case of failure or other unforeseen need. Due to the compression of the gas, it was determined that a 125,000 m³ vessel would be needed to contain the gas from the high-flow case and a 35,000 m³ vessel for the O₂-case. Using design equations for spherical shell pressure vessels from Tables 4 and 6 of Peters and Timmerhaus (Peters 1991) and adjusting to 1997 costs, the cost for a pressure vessel for the high-flow case were calculated to be in the range of \$6.3-8.7 million. For the Low-flow case, the pressure vessel cost was calculated to be in the range of \$2.6-3.9 million. Three such pressure vessels were costed in the computation of the capital costs. Use of pressure vessels rather than retention tanks will offer a significant cost savings.

APPENDIX D

ASPEN PLUS: Process Simulation Code

ASPEN PLUS (hereafter referred to as ASPEN) is the process simulation code that was used to model the selected high-performance offgas system. ASPEN calculates mass and energy balances around each unit operation using chemical reaction and equilibrium data specified by the user or retrieved from an extensive database. ASPEN also possesses the capability of modeling solids handling processes such as particulate filtration. These features make ASPEN a powerful tool for evaluating APCS design.

An ASPEN simulation flowsheet consists of blocks and streams. Material streams enter and exit blocks. Each feedstream must have its stream conditions and composition specified by the user. Stream conditions are specified by two of the following variables - temperature, pressure, and vapor fraction. Feed composition can be specified by total stream flowrate and component fractions or by the individual component flowrates. Most blocks represent unit operations where physical or chemical processes cause the chemical species in the feedstream(s) to react, mix, or separate. Each block representing a unit operation must have its operating conditions and performance specified, or it can identify operating conditions and performance based on such factors as feedstream conditions and compositions and any heat input/loss. A brief description of the block types used in the model are listed in Table D-1. The block types used to model each APCS component are described in Table D-2.

In addition to specifying the blocks and streams in a process flowsheet, the user must specify the components in the process and the physical property databanks to be used. Selecting the correct physical property package is critical for obtaining valid simulation results. If physical property parameters do not exist in ASPEN for a component, the user can add those properties or otherwise supplement ASPEN so that the missing physical properties can be estimated.

The ASPEN-generated flowsheet of the offgas system described in Section 4 is shown in Figure D-1. This figure is more complex than the simplified block diagram for the baseline system shown in Figures 6-1 and 6-2 because additional ASPEN blocks were often needed to model offgas equipment. Feed streams enter the APCS, product streams exit the APCS, and intermediate streams pass between different unit operations in the APCS. The streams used in the model are summarized in Table D-3.

Simulation results for the high-flow and low-flow cases are listed in Tables D-4 and D-5. The substream label MIXED describes streams that contain materials in gas and vapor phases. All other substream labels apply to particulate substreams.

Table D-1. ASPEN block types used in APCS model.

Block type	Description
RGIBBS	Reactor model that computes simultaneous phase and chemical equilibrium by Gibbs free energy minimization with phase splitting. Reaction stoichiometry is not needed. To restrict equilibrium, specify the extent of reaction or fraction of component that does not react. Also computes the chemical equilibria between any number of conventional solid components and the fluid phases.
RSTOIC	Reactor model that simulates reactor when reaction kinetics are unknown or unimportant but the stoichiometry is known.
FABFL	Gas-solid separator model used to separate an inlet gas stream containing solids into a solids stream and a gas stream carrying residual solids. Can be used to design baghouse unit. Also used to specify particulate removal by particle size.
HEATER	Block used to determine thermal and phase conditions of a mixture of one or more inlet streams, given specifications from among temperature, pressure, heat duty, or vapor fraction. Applications include heaters, coolers, valves, pumps, and compressors.
FLASH2	Block used to determine the thermal and phase conditions of a mixture of one or more inlet streams, given specifications from among temperature, pressure, heat duty, or vapor fraction. Performs vapor-liquid and vapor-liquid-liquid equilibrium calculations. Applications include flashes, evaporators, and most single-stage separators.
COMPR	Block used to calculate power requirement of polytropic or isentropic compressors to change fluid pressure.
SEP	Combine streams and separates the result into two or more streams according to splits specified for each component. Can be used in place of a rigorous separation model to save computation time when details of separation are unknown or unimportant but splits for each component are known.
FSPLIT	Combines streams and divides the resulting stream into two or more streams. All outlets have the same composition and properties as the mixed inlet.
MIXER	Combines streams into one stream.
CLCHNG	Changes stream class. It is used between blocks for which different stream classes are used. This block does not perform a real unit operation.
MULT	Multiplies component flowrates and total flowrates of a stream by a factor supplied by user. It is useful when possible roundoff to zero of stream value may result due to value being less than minimum cutoff.

Table D-2. ASPEN PLUS model for the R-1 offgas system.

Block name (ASPEN block type)	Unit operation	Other ASPEN blocks used	Inlet streams	Outlet streams	Description and assumptions
SPRAQNCH (RGIBBS)	Spray quench	SEP (SEPA, SEPHG) CLCHNG (CH1,CH2, CHG1, CHG2) RSTOIC (RS-A, RS-HG) MIXER (MIXA, MIXHG) RGIBBS (RGHG)	SCCGAS0 H2O-SQ	SPRAYOUT	Adiabatic evaporative water spray quench to cool secondary combustion chamber (SCC) offgas to 300°F before entering baghouse. The input offgas composition and temperature is specified. Clean water is fed into process at 60°F, and is fully evaporated to cool the outlet gas stream to 300°F. The reaction temperature for Hg and HCl is fixed at 980°F, to reflect kinetic limitation of reaction. Blocks denoted by HG allow remaining Hg to react completely with Cl ₂ in system and calculate thermal properties at 300°F.
BAGHOUSE (FABFL)	Baghouse		BHIN	BGASSOL BAGSOLID	Performs particulate removal from the input gas stream. Also used to determine number of filter bags, filtration surface area, number of cells, and baghouse footprint. The pressure drop across filter and filter efficiency as a function of particle size were specified. Removal efficiencies of 99.9% and 99% for particles greater than and less than 0.5 µm, respectively, were assumed.
QUENCH (RGIBBS)	Quench cooler	SEP (SEPB) CLCHNG (CH3,CH4) RSTOIC (RS-B) HEATER (HTRB)	BAGGAS0 H2O-Q	QGASSOL	Adiabatic evaporative water spray quench cooler designed to cool gas to saturation conditions before entering the acid gas scrubber. Clean water is fed into process at 60°F.
SCRUBBER (RGIBBS)	Acid gas wet scrubber	SEP (SEPC, SEPD, SEPE, SEPR) CLCHNG(CH5, CH6, CH7) RSTOIC (RS-C, RS-D) MIXER (MIXC, MIXE, MIXR) HEATER(HTRD,HTRF) FLASH2 (FLSHD) FABFL (FILTE) FSPLIT (SPLTD, SPLTE) MULT (M1,M2)	QNCHGAS SCRUBAIR NAOH SCRUBLIQ	SCRUBOUT	Assumed that acid gas scrubber removes 99% SO ₂ and 99.9% HCl in gas. A 1% excess of NaOH is added to ensure liquid pH greater than 7. The liquid stream exiting process is recycled to maintain liquid flowrate (30 or 60 gpm). Excess liquid from condensed or makeup water exits the process as discharge along with solids and acid gases removed by scrubber. The particulate concentration in scrubber outlet offgas depends on the atomizing air flowrate to scrubber (SCRUBAIR) and mass ratio of the scrubber liquid and the offgas. FABFL is used to specify pressure drop across scrubber. 100% removal of particles greater than 0.5 µm is assumed, based on vendor information. The FSPLIT block (SPLTE) is adjusted to achieve solid concentration in exit gas for a given value of SCRUBAIR.

Table D-2. ASPEN PLUS model for the R-1 offgas system (continued).

Block name (ASPEN block type)	Unit operation	Other ASPEN blocks used	Inlet streams	Outlet streams	Description and assumptions
CHILLER (HEATER)	Chiller		CHILLIN	CHILLOUT	Removes heat from the system by cooling the hot scrubber liquid recycle from the scrubber outlet temperature to 60°F.
HEATER (HEATER)	Gas reheater	SEP (SEPG) CLCHNG (CH8, CH9) MIXER (MIXG) RSTOIC (RS-G, RS-H) MULT (M3, M5)	AIR	HOTAIR	Reheats the saturated offgas exiting the scrubber to avoid water droplets or moisture condensation in the downstream equipment. Clean ambient air is heated and added to the gas stream entering prefilter to raise the gas temperature and ensure that moisture does not condense. Air is heated to 1,000°F. The air flowrate is adjusted so when mixed with scrubber offgas it will increase offgas temperature at least 40°F above the dewpoint of the air and offgas mixture. Because the air is relatively dry, it also lowers the dewpoint of the offgas.
PREFILTR (FABFL)	Prefilter	MULT (M7)	REHOUT	HEPA1IN PREFSOL	This is a coarse filter to protect the HEPAs. FABFL used to specify pressure drop across prefilter and particulate removal efficiency as function of particle size. Based on data from Flanders Filter, particulate removal efficiencies were assumed to be 87% for 0.5 µm particles, 70% for 0.3 µm, and 87% for particles less than 0.1 µm.
HEPA1 (FABFL)	HEPA filter	MULT (M8)	HEPA1IN	HEPAGAS1 HEPASOL1	FABFL is used to specify pressure drop across the filter and particulate removal efficiency as function of particle size. As certified HEPAs, a removal efficiency of 99.97% for 0.3 µm particles was used for these filters.
HGCBED (SEP)	Mercury adsorption carbon bed	MULT (M9)	HEPAGAS1	HEPA2IN HGACC	The S-impregnated carbon beds are designed to remove mercury vapor in gas stream. Mercury accumulates in bed but is represented in ASPEN as an exit stream from block. A total Hg removal efficiency of 99% is assumed. No pressure drop nor additional particulate removal is assumed.
HEPA2 (FABFL)	HEPA filter	MULT (M10)	HEPA2IN	HEPAGAS2 HEPASOL2	FABFL used to specify pressure drop across filter and particulate removal efficiency as function of particle size. Even though these are certified HEPAs, a removal efficiency of only was used 99.9% for all particles less than 0.5 µm.

Table D-2. ASPEN PLUS model for the R-1 offgas system (continued).

Block name (ASPEN block type)	Unit operation	Other ASPEN blocks used	Inlet streams	Outlet streams	Description and assumptions
REH-NOX (RGIBBS)	Reheater, Catalytic reactor	SEP (REHSEP) CLCHNG (CHA,CHB) MIXER (REHMIX) MULT (M4, M11)	NOXIN NH3	NOXOUT	The offgas is reheated and treated to reduce NO _x levels. An RGIBBS block is used to represent the heating the offgas and NH ₃ to 400°F before entering a catalytic reactor. A NO _x removal efficiency of 85% is assumed.
ZFLASH (FLASH2)	Condenser		EXITGAS	ZLIQ ZVAP	Exit gas is cooled to condense and remove water and reduce the gas volumetric flowrate.
COMP (COMPR)	Compressor		ZVAP	COMPV	Compressor for pressurizing the gas into retention tanks.

Figure D-1. ASPEN-generated flowsheet of the baseline high-performance APCS.

Table D-3. Streams in ASPEN PLUS model.

Stream name	Stream type	Exits block type (block name)	Enters block type (block name)	Stream temp. (°F)	Stream pres. (psia)	Description
SCCGAS	FEED	--	SEP (SEPA)	2,200	12.5	Offgas exiting secondary combustion chamber
H2O-SQ	FEED	--	RGIBBS (SPRAQNCH)	60	12.5	Clean water for quench
SCCGAS0	INTERMEDIATE	CLCHNG (CH1)	RGIBBS (SPRAQNCH)			Vapor from stream SCCGAS
SCCSOL	INTERMEDIATE	SEP (SEPA)	MIXER (MIXA)			Solids from stream SCCGAS
SPRAYOUT	INTERMEDIATE	RGIBBS (SPRAQNCH)	CLCHNG (CH2)			Gas and new solids from SPRAQNCH
BAGHIN	INTERMEDIATE	MIXER (MIXA)	SEP (SEPHG)			Total gas/solids after SPRAQNCH block
BHIN	INTERMEDIATE	MIXER (MIXHG)	FABFL (BAGHOUSE)			Total gas/solids entering BAGHOUSE
RGHGIN	INTERMEDIATE	CLCHNG (CHG1)	RGIBBS (RGHG)			Gas/vapor from stream BAGHIN
BGASSOL	INTERMEDIATE	FABFL (BAGHOUSE)	SEP (SEPB)			Gas/solids in offgas
BAGSOLID	PRODUCT	FABFL (BAGHOUSE)	--			Collected solids from BAGHOUSE
BAGSOL	INTERMEDIATE	SEP (SEPB)	HEATER (HTRB)			Solids from stream BGASSOL
BAGGAS0	INTERMEDIATE	CLCHNG (CH3)	RGIBBS (QUENCH)			Gas/vapor from stream BGASSOL
H2O-Q	FEED	--	RGIBBS (QUENCH)	60	12.5	Clean water for quench
QGASSOL	INTERMEDIATE	RGIBBS (QUENCH)	CLCHNG (CH4)			Gas and new solids from QUENCH
QNCHOUT	INTERMEDIATE	HEATER (HTRB)	SEP (SEPC)			Total gas/solids after total quench
QNCHSOL	INTERMEDIATE	SEP (SEPC)	MIXER (MIXC)			Solids from stream QNCHOUT
QNCHGAS	INTERMEDIATE	CLCHNG (CH5)	RGIBBS (SCRUBBER)			Gas/vapor from stream QNCHOUT
NAOH	FEED	--	RGIBBS (SCRUBBER)	77	12.5	Added to neutralize acid gases
SCRUBAIR	FEED	--	RGIBBS (SCRUBBER)	100	65	Atomizing air
H2O-MKP	FEED	--	MIXER (MIXQ)	60	12.5	Make-up water (used in O2-combustion only)

Table D-3. Streams in ASPEN PLUS model (continued).

Stream name	Stream type	Exits block type (block name)	Enters block type (block name)	Stream temp. (°F)	Stream pres. (psia)	Description
LIQRECYC	INTERMEDIATE	SEP (SEPR)	CLCHNG (CH7)			Liquid flow recycle to scrubber
SCRUBLIQ	INTERMEDIATE	MIXER (MIXQ)	RGIBBS (SCRUBBER)			Complete liquid flow to scrubber (LIQRECYC+H2O-MKP)
SCRUBOUT	INTERMEDIATE	RGIBBS (SCRUBBER)	CLCHNG (CH6)			Gas/solids/salt from SCRUBBER
SEPROUT	INTERMEDIATE	SEP (SEPR)	MIXER (MIXR)			Recycled solids
SEPDIN	INTERMEDIATE	MIXER (MIXR)	SEP (SEPD)			All phases from scrubber
SOLIDS	INTERMEDIATE	SEP (SEPD)	RSTOIC (RS-D)			Solids from stream SEPDIN
LIQVAPMX	INTERMEDIATE	SEP (SEPD)	FLASH2 (FLSHD)			Gas/liquid/salt from SEPDIN
SCRBGAS	INTERMEDIATE	FLASH2 (FLSHD)	MIXER (MIXC)			Saturated gas exiting scrubber
SCRBLIQ	INTERMEDIATE	FLASH2 (FLSHD)	HEATER (HTRD)			Liquid exiting scrubber
LIQREC	INTERMEDIATE	HEATER (HTRD)	FSPLIT (SPLTD)			Total recycled liquid/solid from scrubber
CHILLIN	INTERMEDIATE	FSPLIT (SPLTD)	HEATER (CHILLER)			Recycled liquid entering chiller
CHILLOUT	INTERMEDIATE	HEATER (CHILLER)	SEP (SEPR)			Recycled liquid exiting chiller
SCGASSOL	INTERMEDIATE	MIXER (MIXC)	FABFL (FILTE)			Combined gas/solids streams
BLOWSOL1	INTERMEDIATE	FABFL (FILTE)	MIXER (MIXE)			All particles > 0.5 µm removed by scrubber
FGASSOL	INTERMEDIATE	FABFL (FILTE)	SEP (SEPE)			SCGASSOL gas/solids < 0.5 µm
BLOWSOL2	INTERMEDIATE	SEP (SEPE)	FSPLIT (SPLTE)			FGASSOL solids < 0.5 µm
GASSCRUB	INTERMEDIATE	SEP (SEPE)	HEATER (HTRF)			Gas/vapor exiting SCRUBBER
BLOWSOL3	INTERMEDIATE	FSPLIT (SPLTE)	MIXER (MIXE)			Small particles removed by scrubber
BLOWSOL	INTERMEDIATE	MULT (M2)	MIXER (MIXD)			Particles removed by scrubber
BLOWDOWN	PRODUCT	FSPLIT (SPLTD)	—			Blowdown from scrubber
SCRUBGAS	INTERMEDIATE	HEATER (HTRF)	MULT (M1)			Gas/particles exiting scrubber
REHGAS	INTERMEDIATE	RSTOIC (RS-G)	RGIBBS (GASMIX)			Gas/vapor from stream REHIN

Table D-3. Streams in ASPEN PLUS model (continued).

Stream name	Stream type	Exits block type (block name)	Enters block type (block name)	Stream temp. (°F)	Stream pres. (psia)	Description
REHSOL	INTERMEDIATE	SEP (SEPG)	MIXER (MIXG)			Particulate in stream REHIN
AIR	FEED	--	HEATER (HEATER)	77	12.5	Humid ambient air
HOTAIR	INTERMEDIATE	HEATER (HEATER)	MULT (M3)	1,000	12.5	Heated stream AIR
REHOUT	INTERMEDIATE	MULT (M5)	FABFL (PREFILTR)			Heated gas/solids entering prefilter
PREFSOL	PRODUCT	MULT (M7)	--			Solids removed by prefilter
HEPA1IN	INTERMEDIATE	FABFL (PREFILTR)	FABFL (HEPA1)			Gas/solids entering first HEPA filter
HEPASOL1	PRODUCT	MULT (M8)	--			Solids removed by first HEPA filter
HEPAGAS1	INTERMEDIATE	FABFL (HEPA1)	MULT (M6)			Gas/solids entering carbon bed
HGACC	PRODUCT	MULT (M9)	--			Mercury removed by carbon bed
HEPA2IN	INTERMEDIATE	SEP (HGCBED)	FABFL (HEPA2)			Gas/solids entering second HEPA filter
HEPASOL2	PRODUCT	MULT (M10)	--			Solids removed by second HEPA filter
HEPAGAS2	INTERMEDIATE	FABFL (HEPA2)	SEP (REHSEP)			Gas/solids entering NO _x reactor
NH3	FEED	--	MULT (M4)	77	12.5	Ammonia
NOXIN	INTERMEDIATE	CLCHNG (CHA)	RGIBBS (REH- NOX)			Gas/vapor from stream HEPAGAS2
NOXSOL	INTERMEDIATE	SEP (REHSEP)	MIXER (REHMIX)			Solids from stream HEPAGAS2
NOXOUT	INTERMEDIATE	RGIBBS (REH- NOX)	CLCHNG (CHB)	400		Gas/vapor exiting REH- NOX
EXITGAS	PRODUCT	MULT (M11)	--			Gas/solids exiting APCS
ZLIQ	PRODUCT	FLASH2 (ZFLASH)	--	100		Water condensate from condenser
ZVAP	INTERMEDIATE	FLASH2 (ZFLASH)	COMPR (COMP)	100		Saturated vapor from condenser
COMPV	PRODUCT	COMPR (COMP)	--			Compressed gas to storage tank

Table D-4. Multiplication factors used in ASPEN PLUS process simulation model.

Label	Multiplication Factor
M1	1×10^4
M2	1×10^{-4}
M3	1×10^4
M4	1×10^{12}
M5	1×10^4
M6	1×10^4
M7	1×10^{-8}
M8	1×10^{-8}
M9	1×10^{-12}
M10	1×10^{-12}
M11	1×10^{-12}

D.1 Model Property Sets and Component Databases

Two property option sets were used to estimate thermodynamic properties in the unit operations where the offgas temperature varies. In the quench towers and heaters, the SOLIDS option set is used to handle the condensation and volatilization of the metal compounds. The ideal gas equation of state is used to describe the vapor phase. In the scrubber where the major component is the recirculated water, the NRTL (non-random two-liquid) option set is used. The NRTL option set uses a Renon activity coefficient model for the liquid phase, an ideal gas equation of state for the vapor phase, the Rackett model for liquid molar volume, and Henry's law for supercritical components. For many simulations, all required binary parameter values are in the ASPEN databanks.

Complete thermodynamic data for some compounds are not in the ASPEN database. By adding property parameters from other sources to the ASPEN database, the equilibrium concentration of these compounds can be estimated. The property parameters required may be molecular weight, critical temperature, the standard free energy and enthalpy of formation for the ideal gas and solid at 25°C, the coefficients for the heat capacity equation for an ideal gas and solid, coefficients for the Watson heat of vaporization equation, and the coefficients for the Antoine vapor pressure equation.

Equilibrium concentrations predicted by ASPEN PLUS occasionally appeared inconsistent with measurements from actual systems. Reactions, especially at low temperatures, are often limited by kinetics or mass transfer from reaching thermodynamic equilibrium in the offgas system where residence time is measured in seconds or less. In these cases, the predictions can be made to better reflect observed data by

limiting the extent of reaction or by specifying a reaction temperature at which to calculate the equilibrium composition. Examples of how the model handled nonequilibrium conditions are described below.

D.2 Particulate Formation in ASPEN PLUS Model

Particulate formation resulting from condensation of volatile metals is expected to occur when the offgas temperature is reduced in the spray quench before the baghouse, the quench unit after the baghouse, and the acid gas scrubber. These chemical reaction phase changes are done in ASPEN using the RGIBBS block. However, the RGIBBS block cannot have particulate-laden gas streams for inputs. So, for each of these unit operations, the following protocol is used in the model:

- The particulate-containing gas stream entering the process is separated into a solids stream and a gas stream.
- The stream class of the gas stream is changed to a RGIBBS-compatible stream class before entering a RGIBBS block.
- After thermodynamic equilibrium is calculated at process conditions, the stream class of the exiting stream is converted back to the global stream class.
- The exiting stream is passed through an RSTOIC block to assign newly formed solids to a new substream with a specific particle size distribution. In all cases, any condensed volatile materials are assumed to form particles via homogeneous condensation with a diameter less than 0.5 μm . This assumes negligible heterogeneous condensation of volatile materials onto existing particles, although particle growth of new and existing particles up to 0.5 μm is allowed. This approach is consistent with findings from studies of metals volatilization, entrainment, condensation, and particle growth where particle sizes down to less than 0.1 μm have been evaluated (Sarofim 1997).
- Combine the stream from RSTOIC block with earlier solids stream.

The model also calculated the revolatilization of condensed mercury, arsenic, and selenium compounds when the offgas was heated after the scrubber. Some volatilization of trace particulate containing these compounds occurs when the scrubber offgas is heated to 200°F, and all particulate containing these compounds is volatilized when the offgas is heated to 400°F before the NO_x catalytic reactor.

Table D-5. Simulation results for primary steams in the high-flow case.

Temp	F	SCCGAS	BHIN	BAGSOLID	QNCHOUT	SCRUBGAS	BLOWDOWN	REHOUT	PREFSOL
Pres	PSI	2200.000000	300.000000	0.000000	184.000000	157.200000	157.300000	197.300000	0.000000
Substream:MIXED	PSI	12.500000	12.500000	12.337000	12.337000	12.264000	12.340000	12.264000	12.192000
CompFlow	LB/HR								
O2		2351.000000	2359.000000	0.000000	2359.000000	6116.000000	0.205600	6.978000E+11	0.000000
N2		22150.000000	22150.000000	0.000000	22150.000000	34590.000000	0.905800	3.742000E+12	0.000000
H2		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
H2O		1899.000000	16360.000000	0.000000	17860.000000	15410.000000	2710.000000	1.553000E+12	0.000000
CO2		3711.000000	3712.000000	0.000000	3712.000000	3712.000000	0.343400	3.712000E+11	0.000000
HCL		96.050000	95.400000	0.000000	95.400000	0.094870	4.319000E-05	9.487000E+06	0.000000
CL2		0.373700	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SO2		6.753000	6.450000	0.000000	6.450000	0.064380	9.751000E-06	6.438000E+06	0.000000
SO3		0.000000	0.379700	0.000000	0.379700	0.009295	0.030660	9.295000E+05	0.000000
CO		0.295300	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NO		126.500000	126.500000	0.000000	126.500000	126.500000	5.239000E-05	1.265000E+10	0.000000
NH3		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AL2O3		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SiO2		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CAO		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
K2O		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
FE3O4		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
MGO		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NA2SO4		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NAOH-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NaCL-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
HG		10.740000	7.782000	0.000000	7.782000	7.782000	0.000000	0.000000	0.000000
HGCL2		0.000000	4.006000	0.000000	4.006000	0.000000	0.000000	7.782000E+08	0.000000
HGCL2-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	4.726000E+06	0.000000
CD		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CD-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CDCL2		52.590000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CDCL2-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
PBCL2		28.850000	9.945000E-09	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
PBCL2-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
BEO-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
TA2O5		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CR02		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AG		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AG-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AGCL		1.435000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AGCL-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
ASO		5.223000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AS2O5		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SBO		3.645000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SB2O5		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
BACL2		8.144000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

Table D-5. Simulation results for primary streams in the high-flow case.

Substream:CIPSD CompFlow	LB/HR										
		SCCGAS	BHIN	BAGSOLID	QNCOUT	SCRUBGAS	BLOWDOWN	REHOUT	PREFSOL		
BACL2-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
SE02		3.018000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
SE02-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
Substream:CIPSD											
O2		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
N2		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
H2		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
H2O		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
CO2		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
HCL		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
CL2		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
SO2		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
SO3		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
CO		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
NO		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
NH3		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
Al2O3		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
SiO2		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
CAO		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
K2O		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
FE3O4		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
MGO		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
NA2SO4		0.000000	0.000000	0.000000	0.000000	0.000000	14.550000	0.000000	0.000000		
NAOH-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.080380	0.000000	0.000000		
NACL-S		0.000000	0.000000	0.000000	0.000000	0.000000	151.400000	0.000000	0.000000		
HG		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
HGCL2		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
HGCL2-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
CD		0.000000	0.000000	0.000000	0.000000	0.000000	3.908000	0.000000	0.000000		
CD-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
CDCL2		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
CDCL2-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
PBCL2		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
PBCL2-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
BEO-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
TA2O5		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
CR02		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
AG		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
AG-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
AGCL		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
AGCL-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
ASO		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
AS2O5		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
SBO		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		
SB2O5		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000		

Table D-5. Simulation results for primary steams in the high-flow case.

BACL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
BACL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SEO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SEO2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	SCCGAS	BHIN	BAGSOLID	QNCHOUT	SCRUBGAS	BLOWDOWN	REHOUT	PREFSOL
Substream:CIASH								
CompFlow	LB/HR							
O2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
N2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
H2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
H2O	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
HCL	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SO3	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NH3	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AL2O3	93.710000	93.710000	93.280000	0.431100	0.086420	0.339500	8.642000E+06	0.064170
SIO2	65.600000	65.600000	65.300000	0.301800	0.060490	0.237700	6.049000E+06	0.044920
CAO	4.498000	4.498000	4.478000	0.020690	0.004147	0.016290	4.147000E+05	0.003079
K2O	1.874000	1.874000	1.866000	0.008622	0.001740	0.006836	1.740000E+05	0.001292
FE3O4	18.740000	18.740000	18.660000	0.086220	0.017280	0.067890	1.728000E+06	0.012830
MGO	1.874000	1.874000	1.866000	0.008622	0.001708	0.006709	1.708000E+05	0.001268
NA2SO4	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NAOH-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NACL-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
HG	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
HGCL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
HGCL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CD	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CD-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CDCL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CDCL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
PBCL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
PBCL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
BEO-S	21.480000	21.480000	21.380000	0.098810	0.019810	0.077830	1.981000E+06	0.014710
TA2O5	0.268000	0.268000	0.266800	0.001233	2.522000E-04	9.909000E-04	25220.000000	1.873000E-04
CR02	6.946000	6.946000	6.914000	0.031950	0.006404	0.025160	6.404000E+05	0.004755
AG	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AG-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AGCL	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AGCL-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
ASO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

Table D-5. Simulation results for primary streams in the high-flow case.

	SCCGAS	BHIN	BAGSOLID	QNCHOUT	SCRUBGAS	BLOWDOWN	REHOUT	PREFSOL
AS205	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SBO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SB205	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
BACL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
BACL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SE02	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SE02-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Substream:CI-1								
CompFlow	LB/HR							
O2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
N2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
H2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
H2O	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
HCL	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SO3	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NH3	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AL2O3	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SiO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CAO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
K2O	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
FE3O4	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
MGO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NA2SO4	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NAOH-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NACL-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
HG	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
HGCL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
HGCL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CD	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CD-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CDCL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CDCL2-S	0.000000	52.590000	52.060000	0.525900	0.120900	0.398800	1.209000E+07	0.089780
PBCL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
PBCL2-S	0.000000	28.850000	28.560000	0.288500	0.066320	0.218800	6.632000E+06	0.049250
BEO-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
TA2O5	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CRO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AG	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AG-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

Table D-5. Simulation results for primary steams in the high-flow case.

		HEPA1IN	HEPASOL1	HEPAGAS1	HEPA2IN	HEPASOL2	HEPAGAS2	EXITGAS
Temp	F	197.300000	0.000000	197.300000	197.300000	0.000000	197.300000	400.000000
Pres	PS	12.192000	12.119000	12.119000	12.119000	12.047000	12.047000	12.047000
Substream:MIXED								
CompFlow	LB/HR							
O2		6.978000E+11	0.000000	6.978000E+11	6.978000E+15	0.000000	6.978000E+15	6935.000000
N2		3.742000E+12	0.000000	3.742000E+12	3.742000E+16	0.000000	3.742000E+16	37530.000000
H2		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	5.205000E-21
H2O		1.553000E+12	0.000000	1.553000E+12	1.553000E+16	0.000000	1.553000E+16	15640.000000
CO2		3.712000E+11	0.000000	3.712000E+11	3.712000E+15	0.000000	3.712000E+15	3712.000000
HCL		9.487000E+06	0.000000	9.487000E+06	9.487000E+10	0.000000	9.487000E+10	0.094870
CL2		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SO2		6.438000E+06	0.000000	6.438000E+06	6.438000E+10	0.000000	6.438000E+10	0.064380
SO3		9.295000E+05	0.000000	9.295000E+05	9.295000E+09	0.000000	9.295000E+09	0.009295
CO		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	3.440000E-23
NO		1.265000E+10	0.000000	1.265000E+10	1.265000E+14	0.000000	1.265000E+14	18.980000
NH3		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.718100
AL2O3		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SiO2		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CAO		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
K2O		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
FE3O4		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
MGO		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NA2SO4		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NAOH-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NACL-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
HG		7.782000E+08	0.000000	7.782000E+08	7.782000E+10	0.000000	7.782000E+10	0.077820
HGCL2		4.726000E+06	0.000000	4.726000E+06	4.726000E+08	0.000000	4.726000E+08	4.726000E-04
HGCL2-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CD		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CD-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CDCL2		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CDCL2-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
PBCL2		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
PBCL2-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
BEO-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
TA2O5		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CRO2		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AG		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AG-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AGCL		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AGCL-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
ASO		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AS2O5		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SBO		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SB2O5		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
BACL2		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

Table D-5. Simulation results for primary steams in the high-flow case.

BACL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SE02	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SE02-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
HEPALIN						
HEPASOL1						
HEPAGAS1						
HEPAZIN						
HEPASOL2						
HEPAGAS2						
EXITGAS						
<div>Substream:CIPSD</div>						
CompFlow	LB/HR	O2	N2	H2	H2O	CO2
O2		0.000000	0.000000	0.000000	0.000000	0.000000
N2		0.000000	0.000000	0.000000	0.000000	0.000000
H2		0.000000	0.000000	0.000000	0.000000	0.000000
H2O		0.000000	0.000000	0.000000	0.000000	0.000000
CO2		0.000000	0.000000	0.000000	0.000000	0.000000
HCL		0.000000	0.000000	0.000000	0.000000	0.000000
CL2		0.000000	0.000000	0.000000	0.000000	0.000000
SO2		0.000000	0.000000	0.000000	0.000000	0.000000
SO3		0.000000	0.000000	0.000000	0.000000	0.000000
CO		0.000000	0.000000	0.000000	0.000000	0.000000
NO		0.000000	0.000000	0.000000	0.000000	0.000000
NH3		0.000000	0.000000	0.000000	0.000000	0.000000
AL2O3		0.000000	0.000000	0.000000	0.000000	0.000000
SIO2		0.000000	0.000000	0.000000	0.000000	0.000000
CAO		0.000000	0.000000	0.000000	0.000000	0.000000
K2O		0.000000	0.000000	0.000000	0.000000	0.000000
FE3O4		0.000000	0.000000	0.000000	0.000000	0.000000
MGO		0.000000	0.000000	0.000000	0.000000	0.000000
NA2SO4		0.000000	0.000000	0.000000	0.000000	0.000000
NAOH-S		0.000000	0.000000	0.000000	0.000000	0.000000
NACL-S		0.000000	0.000000	0.000000	0.000000	0.000000
HG		0.000000	0.000000	0.000000	0.000000	0.000000
HGCL2		0.000000	0.000000	0.000000	0.000000	0.000000
HGCL2-S		0.000000	0.000000	0.000000	0.000000	0.000000
CD		0.000000	0.000000	0.000000	0.000000	0.000000
CD-S		0.000000	0.000000	0.000000	0.000000	0.000000
CDCIL2		0.000000	0.000000	0.000000	0.000000	0.000000
CDCIL2-S		0.000000	0.000000	0.000000	0.000000	0.000000
PBCL2		0.000000	0.000000	0.000000	0.000000	0.000000
PBCL2-S		0.000000	0.000000	0.000000	0.000000	0.000000
BEO-S		0.000000	0.000000	0.000000	0.000000	0.000000
TA2O5		0.000000	0.000000	0.000000	0.000000	0.000000
CRO2		0.000000	0.000000	0.000000	0.000000	0.000000
AG		0.000000	0.000000	0.000000	0.000000	0.000000
AG-S		0.000000	0.000000	0.000000	0.000000	0.000000
AGCL		0.000000	0.000000	0.000000	0.000000	0.000000
AGCL-S		0.000000	0.000000	0.000000	0.000000	0.000000
ASO		0.000000	0.000000	0.000000	0.000000	0.000000
AS2O5		0.000000	0.000000	0.000000	0.000000	0.000000
SBO		0.000000	0.000000	0.000000	0.000000	0.

Table D-5. Simulation results for primary steams in the high-flow case.

		HEPALIN		HEPASOL1		HEPAGAS1		HEPA2IN		HEPASOL2		HEPAGAS2		EXITGAS	
Substream:CIASH															
CompFlow	LB/HR														
O2		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
N2		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
H2		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
H2O		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CO2		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
HCL		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CL2		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SO2		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SO3		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CO		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NO		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NH3		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Al2O3	2.225000E+06	0.022230	0.022230	2225.000000	2.225000E+07	2.223000E-05	22250.000000	2.225000E+07	2.223000E-05	22250.000000	2.225000E-08	2.225000E-08	2.225000E-08	2.225000E-08	2.225000E-08
SiO2	1.558000E+06	0.015560	0.015560	1558.000000	1.558000E+07	1.556000E-05	15580.000000	1.558000E+07	1.556000E-05	15580.000000	1.558000E-08	1.558000E-08	1.558000E-08	1.558000E-08	1.558000E-08
Cao	1.068000E+05	0.001067	0.001067	106.800000	1.068000E+06	1.067000E-06	1068.000000	1.068000E+06	1.067000E-06	1068.000000	1.068000E-09	1.068000E-09	1.068000E-09	1.068000E-09	1.068000E-09
K2O	44800.000000	4.476000E-04	44.800000	44.800000	4.480000E+05	4.476000E-07	448.000000	4.480000E+05	4.476000E-07	448.000000	4.480000E-10	4.480000E-10	4.480000E-10	4.480000E-10	4.480000E-10
FE3O4	4.449000E+05	0.004445	0.004445	444.900000	4.449000E+06	4.445000E-06	4449.000000	4.449000E+06	4.445000E-06	4449.000000	4.449000E-09	4.449000E-09	4.449000E-09	4.449000E-09	4.449000E-09
MGO	43970.000000	4.393000E-04	43.970000	43.970000	4.397000E+05	4.393000E-07	439.700000	4.397000E+05	4.393000E-07	439.700000	4.397000E-10	4.397000E-10	4.397000E-10	4.397000E-10	4.397000E-10
NA2SO4	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NAOH-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NaCl-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Hg	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
HGCL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
HGCL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CD	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CD-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CDCL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CDCL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
PBCL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
PBCL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
BE0-S	5.101000E+05	0.005096	0.005096	510.100000	5.101000E+06	5.096000E-06	5101.000000	5.101000E+06	5.096000E-06	5101.000000	5.101000E-09	5.101000E-09	5.101000E-09	5.101000E-09	5.101000E-09
TA2O5	6494.000000	6.488000E-05	6.488000E-05	6.494000	64940.000000	6.488000E-08	64940.000000	64940.000000	6.488000E-08	64.940000	6.494000E-11	6.494000E-11	6.494000E-11	6.494000E-11	6.494000E-11
CRO2	1.649000E+05	0.001647	0.001647	164.900000	1.649000E+06	1.647000E-06	1649.000000	1.649000E+06	1.647000E-06	1649.000000	1.649000E-09	1.649000E-09	1.649000E-09	1.649000E-09	1.649000E-09
AG	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AG-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AGCL	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AGCL-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
ASO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

Table D-5. Simulation results for primary steams in the high-flow case.

[illegible]

Table D-5. Simulation results for primary steams in the high-flow case.

AGCL	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AGCL-S	84940.000000	8.486000E-04	84.940000	8.494000E+05	8.486000E-07	849.400000	8.494000E-10
ASO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AS205	3.865000E+05	0.003861	386.500000	3.865000E+06	3.861000E-06	3865.000000	3.865000E-09
SBO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SB205	2.506000E+05	0.002503	250.600000	2.506000E+06	2.503000E-06	2506.000000	2.506000E-09
BACL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
BACL2-S	4.821000E+05	0.004816	482.100000	4.821000E+06	4.816000E-06	4821.000000	4.821000E-09
SEO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SEO2-S	1.767000E+05	0.001765	176.700000	1.767000E+06	1.765000E-06	1767.000000	1.767000E-09

	HEPA1IN	HEPASOL1	HEPAGAS1	HEPA2IN	HEPASOL2	HEPAGAS2	EXITGAS
Substream:CI-2							
CompFlow	LB/HR						
O2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
N2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
H2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
H2O	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
HCL	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SO3	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NH3	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AL2O3	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SiO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CAO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
K2O	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
FE3O4	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
MGO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NA2SO4	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NAOH-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NaCl-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
HG	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
HGCL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
HGCL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CD	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CD-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CDCL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CDCL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
PBCL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
PBCL2-S	0.058870	5.881000E-10	5.887000E-05	0.588700	5.881000E-13	5.887000E-04	5.887000E-16
BEO-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
TA205	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

Table D-5. Simulation results for primary steams in the high-flow case.

CRO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AG	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AG-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AGCL	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AGCL-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
ASO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AS2O5	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SBO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SB2O5	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
BACL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
BACL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SEO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SEO2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
TOTAL FLOW	LB	6.377000E+12	0.113000	6.377000E+12	6.376000E+16	1.130000E-04	6.376000E+16	63830.000000	
MassFlow									

Table D-6. Simulation results for primary streams in low-flow case.

		SCCGAS	BHIN	BAGSOLID	QNCHOUT	SCRUBGAS	BLOWDOWN	REHOUT	PREFSOL
Temp	F	2200.000000	300.000000	0.000000	202.500000	181.500000	181.500000	195.000000	0.000000
Pres	PSI	12.500000	12.500000	12.337000	12.337000	12.257000	12.330000	12.257000	12.184000
Substream:MIXED									
CompFlow	LB/HR								
O2		2523.000000	2520.000000	0.000000	2520.000000	3789.000000	0.442900	3.936000E+11	0.000000
N2		736.400000	736.400000	0.000000	736.400000	4961.000000	0.462700	5.444000E+11	0.000000
H2		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
H2O		4736.000000	13870.000000	0.000000	14640.000000	14000.000000	5423.000000	1.402000E+12	0.000000
CO2		6941.000000	6941.000000	0.000000	6941.000000	6939.000000	2.052000	6.939000E+11	0.000000
HCL		479.200000	477.300000	0.000000	477.300000	0.475400	6.563000E-04	4.754000E+07	0.000000
CL2		3.728000	1.753000	0.000000	1.753000	0.000000	0.000000	0.000000	0.000000
SO2		33.680000	31.580000	0.000000	31.580000	0.315400	1.417000E-04	3.154000E+07	0.000000
SO3		0.000000	2.625000	0.000000	2.625000	0.000000	0.000000	0.000000	0.000000
CO		0.147300	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NO		63.100000	63.100000	0.000000	63.100000	63.100000	8.859000E-05	6.310000E+09	0.000000
NH3		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AL2O3		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SiO2		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CAO		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
K2O		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
FE3O4		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
MGO		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NA2SO4		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NAOH-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NaCL-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
HG		10.740000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
HGCL2		0.000000	14.530000	0.000000	8.901000	0.000000	0.000000	4.270000E+06	0.000000
HGCL2-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CD		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CD-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CDCL2		52.650000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CDCL2-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
PBCL2		28.800000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
PBCL2-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
BEO-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
TA2O5		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CRO2		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AG		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AG-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AGCL		1.432000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AGCL-S		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
ASO		5.210000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AS2O5		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SBO		3.643000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SB2O5		0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
BACL2		8.145000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

Table D-6. Stimulation results for primary streams in low-flow case.

BACL2-S	0.000000	0.000000	 
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Table D-6. Simulation results for primary streams in low-flow case.

BACL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
BACL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SEO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SEO2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	SCCGAS	BHIN	BAGSOLID	QNCHOUT	SCRUBGAS	BLOWDOWN	REHOUT	PREFSOL
Substream:CIASH								
CompFlow	LB/HR							
O2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
N2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
H2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
H2O	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
HCL	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SO3	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NH3	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AL2O3	93.710000	93.710000	93.110000	0.599800	0.128900	0.470900	1.289000E+07	0.095690
SIO2	65.600000	65.600000	65.180000	0.419800	0.090210	0.329600	9.021000E+06	0.066980
CAO	4.498000	4.498000	4.470000	0.028790	0.006186	0.022600	6.186000E+05	0.004593
K2O	1.874000	1.874000	1.862000	0.012000	0.002578	0.009417	2.578000E+05	0.001914
FE3O4	18.740000	18.740000	18.620000	0.120000	0.025780	0.094170	2.578000E+06	0.019140
MGO	1.874000	1.874000	1.862000	0.012000	0.002578	0.009417	2.578000E+05	0.001914
NA2SO4	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NAOH-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NACL-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
HG	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
HGCL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
HGCL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CD	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CD-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CDCL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CDCL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
PBCL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
PBCL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
BEO-S	21.480000	21.480000	21.340000	0.137500	0.029540	0.107900	2.954000E+06	0.021930
TA2O5	0.268000	0.268000	0.266300	0.001715	3.686000E-04	0.001347	36860.000000	2.737000E-04
CRO2	6.946000	6.946000	6.902000	0.044460	0.009552	0.034900	9.552000E+05	0.007093
AG	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AG-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AGCL	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AGCL-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
ASO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

Table D-6. Simulation results for primary streams in low-flow case.

Substream:CI-2 CompFlow	SCGAS	BHIN	BAGSOLID	QNCHOUT	SCRUBGAS	BLOWDOWN	REHOUT	PREFSOL
AGCL	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AGCL-S	0.000000	1.432000	1.417000	0.014320	0.003282	0.011030	3.282000E+05	0.002437
ASO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AS205	0.000000	6.585000	6.520000	0.065850	0.015100	0.050750	1.510000E+06	0.011210
SBO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SB205	0.000000	4.277000	4.235000	0.042770	0.009805	0.032970	9.805000E+05	0.007280
BACL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
BACL2-S	0.000000	8.145000	8.063000	0.081450	0.018670	0.062770	1.867000E+06	0.013860
SE02	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SE02-S	0.000000	3.022000	2.992000	0.030220	0.006927	0.023290	6.927000E+05	0.005143
O2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
N2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
H2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
H2O	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
HCL	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SO3	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NH3	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AL2O3	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SiO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CAO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
K2O	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
FE3O4	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
MGO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NA2SO4	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NAOH-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
NaCl-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
HG	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
HGCL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
HGCL2-S	0.000000	0.000000	0.000000	5.630000	0.000000	0.000000	0.000000	0.000000
CD	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CD-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CDCL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
CDCL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
PBCL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
PBCL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
BEQ-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
TA205	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

Table D-6. Simulation results for primary streams in low-flow case.

CRO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AG	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AG-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AGCL	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AGCL-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
ASO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AS205	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SBO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SB205	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
BACL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
BACL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SEO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SEO2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
TOTAL FLOW										
MassFlow	15850.000000	24980.000000	317.500000	25430.000000	29760.000000	6285.000000	3.041000E+12	0.398100		

Table D-6. Simulation results for primary streams in low-flow case.

HEPA1IN		HEPASOL1	HEPAGAS1	HEPA2IN	HEPASOL2	HEPAGAS2	EXITGAS
195.000000	Temp	F	0.000000	195.000000	0.000000	195.000000	400.000000
12.184000	Pres	PS	12.112000	12.112000	12.039000	12.039000	12.039000
Substream:MIXED							
CompFlow		LB/HR					
3.936000E+11	O2	0.000000	3.936000E+11	3.936000E+15	0.000000	3.936000E+15	3915.000000
5.444000E+11	N2	0.000000	5.444000E+11	5.444000E+15	0.000000	5.444000E+15	5498.000000
0.000000	H2	0.000000	0.000000	0.000000	0.000000	0.000000	4.417000E-21
1.402000E+12	H2O	0.000000	1.402000E+12	1.402000E+16	0.000000	1.402000E+16	14080.000000
6.939000E+11	CO2	0.000000	6.939000E+11	6.939000E+15	0.000000	6.939000E+15	6939.000000
4.754000E+07	HCL	0.000000	4.754000E+07	4.754000E+11	0.000000	4.754000E+11	0.475400
0.000000	CL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
3.154000E+07	SO2	0.000000	3.154000E+07	3.154000E+11	0.000000	3.154000E+11	0.315400
0.000000	SO3	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	CO	0.000000	0.000000	0.000000	0.000000	0.000000	6.064000E-23
6.310000E+09	NO	0.000000	6.310000E+09	6.310000E+13	0.000000	6.310000E+13	9.465000
0.000000	NH3	0.000000	0.000000	0.000000	0.000000	0.000000	0.358100
0.000000	AL2O3	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	SIO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	CAO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	K2O	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	FE3O4	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	MGO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	NA2SO4	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	NAOH-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	NACL-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	HG	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
4.270000E+06	HGCL2	0.000000	4.270000E+06	4.270000E+08	0.000000	4.270000E+08	4.270000E-04
0.000000	HGCL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	CD	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	CD-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	CDCL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	CDCL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	PBCL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	PBCL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	BEO-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	TA2O5	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	CRO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	AG	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	AG-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	AGCL	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	AGCL-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	ASO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	AS2O5	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	SBO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	SB2O5	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	BACL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

Table D-6. Simulation results for primary streams in low-flow case.

HEPA1IN	Substream:CIPSD							HEPASOL1	HEPAGAS1	HEPA2IN	HEPASOL2	HEPAGAS2	EXITGAS
	CompFlow		LB/HR										
	O2	N2											
				H2	H2O	CO2	HCL						
0.000000	BACL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	SE02	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	SE02-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	H2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	CO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	HCL	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	CL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	SO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	SO3	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	CO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	NO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	NH3	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	AL2O3	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	SiO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	CAO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	K2O	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	FE3O4	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	MGO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	NA2SO4	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	NAOH-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	NaCl-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	HG	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	HGCL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	HGCL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	CD	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	CD-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	CDCL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	CDCL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	PBCL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	PBCL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	BEO-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	TA2O5	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	CRO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	AG	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	AG-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	AGCL	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	AGCL-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	ASO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	AS2O5	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	SBO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	SB2O5	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

Table D-6. Simulation results for primary streams in low-flow case.

0.000000	BACL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	BACL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	SEO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	SEO2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
HEPA1IN		HEPASOL1	HEPAGAS1	HEPA2IN	HEPASOL2	HEPAGAS2	EXITGAS
Substream:CIASH							
CompFlow	LB/HR						
0.000000	O2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	N2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	H2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	H2O	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	CO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	HCL	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	CL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	SO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	SO3	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	CO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	NO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	NH3	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
3.319000E+06	AL2O3	0.033150	3319.000000	3.319000E+07	3.315000E-05	33190.000000	3.319000E-08
2.323000E+06	SiO2	0.023210	2323.000000	2.323000E+07	2.321000E-05	23230.000000	2.323000E-08
1.593000E+05	CAO	0.001591	159.300000	1.593000E+06	1.591000E-06	1593.000000	1.593000E-09
66370.000000	K2O	6.631000E-04	66.370000	6.637000E+05	6.631000E-07	663.700000	6.637000E-10
6.637000E+05	FE3O4	0.006631	663.700000	6.637000E+06	6.631000E-06	6637.000000	6.637000E-09
66370.000000	MGO	6.631000E-04	66.370000	6.637000E+05	6.631000E-07	663.700000	6.637000E-10
0.000000	NA2SO4	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	NAOH-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	NACL-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	HG	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	HGCL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	HGCL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	CD	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	CD-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	CDCL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	CDCL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	PBCL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	PBCL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
7.607000E+05	BEO-S	0.007599	760.700000	7.607000E+06	7.599000E-06	7607.000000	7.607000E-09
9491.000000	TA2O5	9.481000E-05	9.491000	94910.000000	9.481000E-08	94.910000	9.491000E-11
2.460000E+05	CRO2	0.002457	246.000000	2.460000E+06	2.457000E-06	2460.000000	2.460000E-09
0.000000	AG	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	AG-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	AGCL	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	AGCL-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	ASO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

Table D-6. Simulation results for primary streams in low-flow case.

0.000000	AS205	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	SB0	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	SB205	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	BACL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	BACL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	SEO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	SEO2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
HEPA1IN		HEPASOL1	HEPAGAS1	HEPA2IN	HEPASOL2	HEPAGAS2	EXITGAS
Substream:CI-1							
CompFlow	LB/HR						
0.000000	O2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	N2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	H2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	H2O	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	CO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	HCL	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	CL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	SO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	SO3	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	CO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	NO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	NH3	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	AL2O3	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	SiO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	CAO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	K2O	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	FE3O4	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	MGO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	NA2SO4	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	NAOH-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	NACL-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	HG	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	HGCL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	HGCL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	CD	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	CD-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	CDCL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
3.108000E+06	CDCL2-S	0.031050	3108.000000	3.108000E+07	3.105000E-05	31080.000000	3.108000E-08
0.000000	PBCL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
1.700000E+06	PBCL2-S	0.016980	1700.000000	1.700000E+07	1.698000E-05	17000.000000	1.700000E-08
0.000000	BEO-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	TA205	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	CRO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	AG	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	AG-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

D-6. Simulation results for primary streams in low-flow case.

	HEPALIN	HEPASOL1	HEPAGAS1	HEPA2IN	HEPASOL2	HEPAGAS2	EXITGAS
	AGCL	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	AGCL-S	8.442000E-04	84.500000	8.450000E+05	8.442000E-07	845.000000	8.450000E-10
	ASO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	AS205	0.003883	388.700000	3.887000E+06	3.883000E-06	3887.000000	3.887000E-09
	SBO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	SB205	0.002522	252.500000	2.525000E+06	2.522000E-06	2525.000000	2.525000E-09
	BACL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	BACL2-S	0.004803	480.800000	4.808000E+06	4.803000E-06	4808.000000	4.808000E-09
	SEO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	SEO2-S	0.001782	178.400000	1.784000E+06	1.782000E-06	1784.000000	1.784000E-09
	Substream:CI-2						
	CompFlow	LB/HR					
	O2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	N2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	H2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	H2O	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	CO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	HCL	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	CL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	SO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	SO3	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	CO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	NO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	NH3	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	AL2O3	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	SiO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	CaO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	K2O	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	FE3O4	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	MGO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	NA2SO4	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	NAOH-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	NACL-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	HG	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	HGCL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	HGCL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	CD	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	CD-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	CDCL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	CDCL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	PBCL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	PBCL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	BEO-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
	TA205	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

Table D-6. Simulation results for primary streams in low-flow case.

0.000000	CRO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	AG	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	AG-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	AGCL	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	AGCL-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	ASO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	AS205	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	SBO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	SB205	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	BACL2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	BACL2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	SEO2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.000000	SEO2-S	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
TOTAL FLOW							
3.041000E+12	MassFlow LB	0.137900	3.041000E+12	3.041000E+16	1.379000E-04	3.041000E+16	30440.000000