

Sodium-Bearing Waste Treatment Technology Evaluation Report

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EXECUTIVE SUMMARY

A Settlement Agreement between the U.S. Department of Energy (DOE) and the State of Idaho mandates treatment of sodium-bearing waste (SBW) stored at the Idaho Nuclear Technology and Engineering Center located within the Idaho National Engineering and Environmental Laboratory (INEEL). One of the requirements of the Settlement Agreement is to complete treatment of SBW by December 31, 2012. Hence, SBW disposition is one of the Idaho Operation Office's (NE-ID) and State of Idaho's top priorities at the INEEL.

The INEEL has been working over the past several years to identify a treatment technology that meets NE-ID and regulatory treatment requirements, including consideration of stakeholder input. Many studies, including the High-Level Waste and Facilities Disposition Environmental Impact Statement, have resulted in the identification of five treatment alternatives that form a short list of perhaps the most appropriate technologies for the DOE to select from. The alternatives are (a) calcination with maximum achievable control technology (MACT) upgrade, (b) steam reforming, (c) cesium ion exchange (CsIX) with immobilization, (d) direct evaporation, and (e) vitrification. Each alternative has undergone some degree of applied technical development and preliminary process design over the past four years.

Applied technology development and preliminary process design activities have been required to provide the data necessary for informed decision making and evaluation of the treatment options. A technically defensible selection of a SBW treatment process has been a key driver for the collection of needed data. This document presents a summary of the data gathered in recent years and evaluates the technical maturity of each option by listing and discussing the identified higher-risk technical uncertainties. The SBW issue and the five alternatives are described, and their technical performance (throughputs, waste product descriptions and volumes, preliminary facility footprints, etc.) is summarized in the main body. Details of preliminary process design and applied development activities for three of the alternatives (steam reforming, CsIX with immobilization, and direct evaporation) are presented in three appendices; a recent feasibility study provides the details for calcination. There have been no recent activities performed with regard to vitrification; that section summarizes and references previous work.

This report only addresses technical issues that have been identified through examination of waste acceptance criteria (WAC), operability issues, and process design activities. It is assumed in this report that the SBW would be classified as a transuranic waste, suitable for disposal at the Waste Isolation Pilot Plant (WIPP), located in the State of New Mexico, after appropriate treatment to meet transportation requirements and WAC. This report does not address issues that are programmatic in nature. Examples of these include how the SBW will be classified with respect to the Nuclear Waste Policy Act, status of WIPP permits and waste storage availability, available funding for implementation, stakeholder issues, and meeting State of Idaho Settlement Agreement milestones. This report also does not present detailed cost and implementation schedule information for the treatment options.

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ACRONYMS

AAR	aluminum to alkali mole ratio
APS	Atmospheric Protection System
BBWI	Bechtel BWXT Idaho, LLC
BSG	borosilicate glass
CCIM	Cold Crucible Induction Melter
CEM	continuous emission monitor
CH	contact-handled
CMACT	Calciner/MACT
CPF	Calcine Packaging Facility
CsIX	cesium ion exchange
CST	crystalline silicotitanate
DBE	design basis element
DOE	Department of Energy
DWPF	Defense Waste Processing Facility
EDF	Engineering Design File
EIS	Environmental Impact Statement
EPA	Environmental Protection Agency
ETS	Evaporative Tank System
FY	fiscal year
GAC	granulated activated carbon
HEME	High Efficiency Mist Eliminator
HEPA	high efficiency particulate air (filter)
HLLWE	High Level Liquid Waste Evaporator
HLW	high-level waste
HVAC	heating, ventilation and air conditioning
HWC	Hazardous Waste Combustion
INEEL	Idaho National Engineering and Environmental Laboratory
INTEC	Idaho Nuclear Technology and Engineering Center
IRT	Independent Review Team
IWVF	Idaho Waste Vitrification Facility
LDR	Land Disposal Restrictions
LET&D	Liquid Effluent Treatment and Disposal
MACT	Maximum Achievable Control Technology
MCF	MACT Compliance Facility
NAR	nozzle-air-ratio
NE-ID	DOE Idaho Operations Office
NESHAP	National Emission Standards for Hazardous Air Pollutants
NGLW	newly generated liquid waste

NO _x	gas containing both NO and NO ₂
NRC	Nuclear Regulatory Commission
NWCF	New Waste Calcining Facility
NWPA	Nuclear Waste Policy Act
PUREX	plutonium-uranium extraction
RAM	reliability, availability, and maintainability
RCRA	Resource Conservation and Recovery Act
RH	remote-handled
SAIC	Science Application International Corporation
SBW	sodium-bearing waste
S-GAC	sulfur-impregnated, granulated activated carbon
SRS	Savannah River Site
T&FR	Technical and Functional Requirements
TFF	Tank Farm Facility
THOR	Thermal Organic Reduction
THOREX	thorium extraction
TRU	transuranic (waste)
TTT	THOR sm Treatment Technologies
TWR	ThermoChem Waste Remediation
WAC	Waste Acceptance Criteria
WCF	Waste Calcining Facility
WFQP	Waste Form Qualification Plan
WIPP	Waste Isolation Pilot Plant
WVDP	West Valley Demonstration Project

Sodium-Bearing Waste Treatment Technology Evaluation Report

1. INTRODUCTION

Sodium-bearing waste (SBW) disposition is one of the U.S. Department of Energy (DOE) Idaho Operation Office's (NE-ID) and State of Idaho's top priorities at the Idaho National Engineering and Environmental Laboratory (INEEL). The INEEL has been working over the past several years to identify a treatment technology that meets NE-ID and regulatory treatment requirements, including consideration of stakeholder input. Many studies, including the *High-Level Waste and Facilities Disposition Environmental Impact Statement* (EIS), have resulted in the identification of five treatment alternatives that form a short list of perhaps the most appropriate technologies for the DOE to select from. The alternatives are (a) calcination with maximum achievable control technology (MACT) upgrade, (b) steam reforming, (c) cesium ion exchange (CsIX) with immobilization, (d) direct evaporation, and (e) vitrification. Each alternative has undergone some degree of applied technical development and preliminary process design over the past four years.

This report presents a summary of the applied technology and process design activities performed through February 2004. The SBW issue and the five alternatives are described in Sections 2 and 3, respectively. Details of preliminary process design activities for three of the alternatives (steam reforming, CsIX, and direct evaporation) are presented in three appendices. A recent feasibility study provides the details for calcination. There have been no recent activities performed with regard to vitrification; that section summarizes and references previous work.

1.1 Purpose and Objectives

The purpose of this document is to summarize technical information that is available to enable the DOE to make an informed decision regarding the selection of a treatment technology for a SWB Treatment Facility. This report does not address issues that are programmatic in nature. Examples of these include how the SBW will be classified with respect to the Nuclear Waste Policy Act (NWPA), status of Waste Isolation Pilot Plant (WIPP) permits and waste storage availability, available funding for implementation, stakeholder issues, and meeting State of Idaho Settlement Agreement milestones. This report also does not present detailed cost and implementation schedule information for the treatment options.

This report only addresses technical issues that have been identified through examination of waste acceptance criteria (WAC), operability issues, and process design activities. It is assumed in this report that the SBW would be classified as a transuranic (TRU) waste, suitable for disposal at WIPP, located in the State of New Mexico, after appropriate treatment to meet transportation requirements and WAC.

Descriptions of anticipated treatment processes, preliminary facility sizes and throughputs, waste product descriptions and volumes, and higher risk technical uncertainties and their potential impacts are presented.

1.2 Independent Reviews

To ensure the proper emphasis and staging of decision activities, independent reviews have been conducted of the preliminary process design and applied development activities by a standing ad hoc team of DOE Complex technical experts referred to as the Independent Review Team (IRT). The following

were identified during a February 2003 review and recommended as areas to accelerate or emphasize, thereby reducing technical risk to the project:

- Identify level of risk associated with uncertainties for each alternative
- Clearly focus on high-risk technology uncertainties first in developing test activities
- Use technology roadmaps as tools to aid DOE management in making informed decisions at key decision points in the project.

A *Sodium-Bearing Waste Treatment Applied Technology Plan*, INEEL/EXT-03-00477, was developed and published in June 2003 to accommodate these suggestions as follows.

An independent review of the results of steam reforming demonstrations performed in December 2002 and January 2003 was conducted in May 2003. Recommendations were:

- The IRT recommends that INEEL give first priority to continuing the Thermal Organic Reduction (THORsm) and ThermoChem Waste Remediation (TWR) steam reforming tests. The INEEL should (1) optimize the conditions on the reducing fluidized bed, (2) conduct longer tests to approach steady state conditions for product quality and throughput rate evaluations, and (3) if a test of the THORsm oxidizing fluidized bed concept is desired, reconfigure the existing bed to operate under oxidizing conditions with feed from (2) above, if possible.
- The IRT recommends that quantitative success criteria be defined, such as the following: nitrogen oxide (NO_x) gas concentrations, hydrogen (H₂) concentration in the off-gas, mercury (Hg) capture/speciation, carbon in product, density of product, and compaction of product.
- The IRT recommends that, to the extent possible, INEEL identify and quantify the solid product characteristics that would be required to satisfy the draft WIPP WAC. The extent to which the steam reforming test products meet these criteria should be determined.
- It would be desirable to have a single product stream from the steam reforming process. To approach this goal, the IRT recommends reconfiguring the test apparatus so that the cyclone product can be recycled back to the fluidized bed.
- The IRT endorses all the modifications to Science Applications International Corporation (SAIC)'s STAR equipment proposed by Bechtel BWXT Idaho, LLC (BBWI) and recommends that they install a bottom feed nozzle.

Two more demonstrations of vendor steam reforming technologies were conducted in November and December of 2003 that incorporated these recommendations. The demonstration results are included in Section 3.2.

A review performed in September 2003, focusing on FY 2003 technical results and FY 2004 plans made the following recommendations:

- **SBW Characterization:** Consideration should be given to mixing the solids in tank WM-187 prior to or during sampling to ensure representative samples and reduce uncertainties. The liquids in the tanks are adequately characterized, and further liquid sampling and analyses should not be performed at this time.

- Waste Simulant Development: The extensive planned solid simulant development effort does not appear necessary, and the required chemical and physical property data for these solids should be acquired in the characterization of actual waste solids.
- Calcination with Maximum Achievable Control Technology: Boiling the SBW with glycolic acid as a means of reducing volume, which would decrease the treatment time, should not be continued in FY 2004. Other alternative methods for reducing waste volume (and, consequently, schedule) for calcination should be evaluated and tested. No further testing (including pilot-plant scale tests) of granulated activated carbon (GAC) systems for removal of mercury from off-gas should be conducted at this time. Experimental work should continue in FY 2004 to develop adequate technology for selective and effective removal of hydrogen chloride (HCl) from calciner off-gas based on use of GAC or some other suitable sorbent.
- Direct Evaporation: No further pilot-plant scale tests of the direct evaporation process with SBW simulants, either in a Wiped Film Evaporator or with alternative evaporator equipment, should be performed until the new Idaho Cleanup Project contractor is selected (or a technology down selection has been made by DOE). Appropriate tests should be conducted in FY 2004 to establish the technical feasibility of recycling the off-gas condensate from DE process operation to the evaporator. Bench-scale tests should be conducted in FY 2004 to characterize the off-gas at the optimum evaporation end point.
- Cesium Ion Exchange: The IRT agrees that crystalline silicotitanate (CST) is the preferred sorbent and recommends that any additional ion exchange work focus on CST. Further testing should be performed in FY 2004 to resolve the uncertainties concerning the instability of CST sorbent use in plant-scale operation. Silica gel for immobilization of the ion exchange effluent should be discontinued. Development work on grouting has exceeded development needs at this time and should be suspended.

These recommendations were, for the most part, implemented during the period of October 2003 through February 2004 and the results, with the exception of Waste Characterization and Simulant Development, are included in the individual sections and appendices. More definitive characterization and simulant data are due to be published in a separate report in June 2004.

A review of data produced and analyzed for each treatment alternative and presented in this report will be conducted in March 2004 as well.

2. SBW DESCRIPTION

Radioactive liquid waste has been generated over the last five decades at the Idaho Nuclear Technology and Engineering Center (INTEC), formerly called the Idaho Chemical Processing Plant, as a result of nuclear fuel reprocessing activities. From December 1963 until June 2000, the Waste Calcining Facility (WCF; now decommissioned) and the New Waste Calcining Facility (NWCF; presently in a stand-by condition, but undergoing a reversible closure) processed the liquid waste into a granular, solid form. As of February 2004 it is anticipated that approximately 1,000,000 gallons of radioactive liquid and heel solids waste, commonly referred to as SBW, will require treatment for disposal. Additional liquid waste will be generated in the future as a result of filter leach operations, equipment and building decontamination activities, Resource Conservation and Recovery Act (RCRA) closure activities, and other operations at INTEC.

An anticipated SBW treatment facility would treat liquids and solids contained in existing tanks at the INTEC. The treatment facility may also treat additional liquid waste, called Newly Generated Liquid Waste (NGLW), that will be generated after 2005 and stored in separate tanks from the SBW.

A complete description of the feed composition for the SBW requiring treatment can be found in report INEEL/EXT-2000-01378, Revision 3. This report presents the most recent compilation of volumes and compositions of the feed streams to the five proposed alternative treatment processes. These liquid wastes have been stored in eleven 300,000-gallon underground tanks at INTEC. The underground tank facility at INTEC is referred to as the Tank Farm Facility (TFF).

Tanks WM-180 and WM-189 presently contain volumes of waste near their administrative capacities and no additions to these tanks are expected. The waste compositions in the report for waste in Tanks WM-180 and WM-189 are based on sample analyses; the compositions of waste in tank WM-187 and WM-188 are based on analyses of source streams, calculations using plant evaporator operations information, and simulation of expected future evaporation of dilute wastes.

As tanks in the TFF have been flushed and closed, solids have accumulated in Tank WM-187. The treatment process would process the solids in this tank as well as solids from the three SBW tanks (WM-180, WM-188, WM-189). Compositions are defined both for alternatives that process solids separately and together with SBW liquid.

The present estimate of the composition of Tank WM-187 solids is based on analyses of samples of tank heels taken prior to being flushed to WM-187. Not all tanks that have been flushed were sampled and analyzed; in addition there are uncertainties in estimated quantities of solids in each tank. Thus, the present estimate of the WM-187 solids composition contains uncertainty. The tank was recently sampled to obtain a more representative sample of all solids in WM-187. The analyses data from this sample should reduce the uncertainty in the WM-187 solids composition.

Projections have been made of the volumes of NGLW streams generated prior to and during operation of the SBW treatment facility. For some of these NGLW streams, chemical composition data are available and have been used in generating treatment facility feed compositions. However, data for radionuclide concentrations in NGLW are extremely limited. Thus, radionuclide concentrations in treatment facility feeds are based solely on data from existing tank waste. Starting in FY 2006, NGLW will be collected in Tanks WM-100, WM-101, and WM-102. The accumulated NGLW may later be blended with SBW for treatment in the SBW treatment facility.

Each potential treatment option would process approximately 1,000,000 gallons of SBW liquid and heel solids. SBW will initially be contained in four TFF tanks: WM-180, WM-187, WM-188, and

WM-189. Tanks WM-180, WM-188, and WM-189 will contain liquid SBW with relatively small quantities of undissolved solids, while WM-187 will contain the majority of the solids plus dilute liquid wastes. NGLW after 2005 will be collected in three other tanks, WM-100, WM-101 and WM-102. Table 1 lists the concentration range of the major constituents for the feed to the potential treatment processes described in the later sections of this report.

Table 1. Expected feed range for major SBW constituents.

Constituent	Minimum (Moles/liter)	Maximum (Moles/liter)	Max/Min
H+	1.07E+00	2.82E+00	2.6
Al+3	3.34E-01	6.51E-01	1.9
B+3	1.00E-02	1.94E-02	1.9
Ca+2	3.20E-02	6.69E-02	2.1
Cs+	2.57E-05	8.42E-05	3.3
Cl-	1.62E-02	2.86E-02	1.8
Cr+3	3.36E-03	5.30E-03	1.6
F-	1.41E-02	5.62E-02	4.0
Fe+3	1.73E-02	2.97E-02	1.7
Mg+2	1.10E-02	2.09E-02	1.9
Hg+2	1.32E-03	5.97E-03	4.5
NO ₃ -	4.93E+00	7.16E+00	1.5
PO ₄ -3	1.53E-02	1.75E-01	11
K+	1.76E-01	3.50E-01	2.0
Na+	1.35E+00	1.94E+00	1.4
SO ₄ -2	2.61E-02	9.79E-02	3.7
Zr+4	3.34E-04	6.66E-02	199

For treatment alternatives that co-process liquid and solids, the solids in WM-187 would be distributed, prior to treatment, among three of the four SBW tanks through a series of waste transfers between tanks. Mixing pumps would be installed in these three tanks to keep the solids in suspension. Four of the potential treatment options, all except the CsIX/Immobilization process, would co-process the solids. Solids would be separated from the SBW and treated separately under the CsIX/Immobilization option.

3. TECHNICAL DATA FOR TREATMENT ALTERNATIVES

The following sections present summary descriptions of the five treatment options for SBW that have been actively pursued through process engineering and applied development work since FY 2000. The most recent preferred process flow configurations and process descriptions are included. A summary of the technical performance of each option is discussed at the end of each option description section. The discussion centers on processing rate, quantity and quality of products produced, footprint of potential facilities for processing, variation of scale with throughput, and status of the technical uncertainties and potential impacts.

3.1 Calcination

Fluidized bed calcination has been used at the INTEC since the early 1960's to solidify acidic wastes that were produced in fuel reprocessing operations. WCF was operated from 1961 to 1981, and the NWCF from 1981 to 2000. Newby and O'Brien (2000) have summarized the operation of all the WCF campaigns and all but the last NWCF campaign. The WCF processed a total of 4.1 million gallons of feed, and the NWCF processed 3.9 million gallons (Staiger, 2003).

In the calcination process, liquid wastes are sprayed into a fluidized bed of heated spherical calcine particles. The calciner vessel of the WCF had a 2-ft square fluidization section; the calciner vessel of the NWCF has a 5-ft diameter fluidizing section. Until 1967, the WCF fluidized bed was heated to the calcination temperature of 400°C by recirculating liquid eutectic sodium/potassium alloy through heat exchange tubes located in the bed. After 1967, in-bed combustion using kerosene fuel provided the heat to maintain the calcination temperature of 500°C in the bed in the WCF, and later in the NWCF calciner. The NWCF calciner was operated at 600°C during two short runs in 1999 and 2000 (Law, 2000).

The WCF primarily calcined high-level waste (HLW) from reprocessing aluminum, zirconium and stainless steel-clad fuel. The first processing of SBW occurred during WCF campaign H-7, in which one part SBW was blended with four parts of zirconium waste. Later WCF campaigns included SBW blends with a maximum blend ratio of 1 part SBW to 3.5 parts of zirconium waste. Blending SBW was necessary to avoid agglomeration in the bed due to formation of molten salts of sodium and potassium.

The NWCF also processed HLW and HLW/SBW blends during its first three campaigns. The typical concentration of sodium plus potassium in the NWCF feed blends during these campaigns was about 0.25 molar, considerably less than the 2 molar sodium and potassium concentration of present SBW. The fourth NWCF campaign included processing the last of the HLW stored in the INTEC Tank Farms and also the first long-term processing of SBW, blended not with other wastes but with non-radioactive aluminum nitrate.

In 1995 and 1996, development and engineering studies were initiated to modify the calcination process to treat SBW directly without blending it with lower alkali content HLW liquids (Boardman, 1997; Welland, 1997). The result of this effort recommended increasing the operating temperature of the calciner from 500°C to 600°C. Operation at 600°C processing SBW was successfully demonstrated in the NWCF during two separate trials during 1999 and 2000 (Law, 2000; Swenson, 2000; Wood, 2001). The conclusion from these demonstration runs was that operation of the existing NWCF at 600°C is a viable long-term method for processing SBW.

The NWCF was operated under a State of Idaho Permit to Construct and under interim RCRA status. In the early and mid-1990's, DOE initiated an effort to better determine the calciner off-gas composition and emission inventory to support a RCRA permitting process for the calciner. At the same general time (1996), the Environmental Protection Agency (EPA) proposed the Hazardous Waste

Combustion (HWC) National Emission Standards for Hazardous Air Pollutants (NESHAP) based on MACT (40 CFR 63 Subpart EEE).

A multi-year emission inventory and risk assessment effort and several studies that evaluated how to upgrade the calciner facility to meet the HWC MACT standards were performed between 1997 and 2001 (Rawlings, 1997; Boardman, 1999; Boardman, 2000; Young, 2000; Ashworth, 2000; Boardman, 2001). In 2000, after off-gas sampling confirmed that the calciner facility would require modifications to become MACT-compliant, DOE temporarily shut down the calciner pending determination of how the remaining SBW should be treated for final disposal. If restarted, it is expected that the NWCF would be regulated as a miscellaneous thermal treatment unit; thus, compliance with MACT emission limits will be imposed. To meet these standards, an upgrade to the calciner off-gas treatment train will be required. Treatment of SBW in the NWCF upgraded to meet MACT standards and packaging product calcine for disposal at WIPP in a new facility is referred to as the Calciner/MACT (CMACT) alternative for processing SBW.

Three documents provided the source of the most of the rest of the information in this report for the CMACT alternative. In FY 2003, the technical and functional requirements (T&FR) for the CMACT alternative were defined (Beitel, 2003). Also in 2003, a process design was completed for upgrading the NWCF to meet MACT emission limits and to package the calcine produced in remote-handled (RH) canisters ready for shipment to WIPP (Barnes, 2003). This process design was the starting point for a more detailed feasibility study that was completed in early 2004 (Merrick, 2004).

3.1.1 Process Functions

The functions of the CMACT treatment process are as follows:

- Mix and retrieve the SBW liquids and solids from storage tanks WM-180, WM-187, WM-188, and WM-189, and tanks storing NGLW
- Prepare the SBW and NGLW feeds with additives prior to calcination
- Calcine the SBW and NGLW
- Treat the off-gas to meet MACT emission standards
- Transfer the calcine to a new Calcine Packaging Facility (CPF)
- Package the calcined waste in canisters
- Grout spent calcine scrub solution and package in canisters
- Certify that the packaged waste meets WIPP WAC
- Load the canisters into shipping casks for transfer to WIPP
- Provide adequate lag storage to allow continuous calcining operations.
- Treat, package and qualify for disposal all other wastes incidental to the treatment of SBW and NGLW.

Prior to SBW treatment, pumps would be installed in TFF tanks and transfers between tanks made to distribute the SBW solids collected in WM-187 among most of the SBW liquid. Solids need to be distributed and mixed with liquid in the tank farm to (a) avoid the expense of alternative systems that would need to transfer and treat the solids separately with new equipment in a new facility, (b) be able to transfer the solids to the NWCF with existing steam and air jets, (c) provide a homogeneous feed to the CMACT process, and (d) be able to process the solids with no changes to and minimal additives in the calcination process.

Once received in the NWCF “blend and hold” tanks, the waste must be prepared for calcination by the addition of aluminum nitrate and calcium nitrate. The aluminum additive is needed to prevent agglomeration in the calciner bed. Calcium is needed to form nonvolatile halide and phosphate salts to prevent corrosion in the calciner and off-gas equipment.

The waste is calcined to produce a dry product acceptable for disposal at WIPP. Calcination removes water and nitric acid in the waste and results in a granular product. The temperature required for calcination results in partially volatilizing certain constituents in the feed such as mercury, and forming others by chemical reaction, such as NO_x and unburned hydrocarbons. These impurities must be removed from the off-gas so that the remainder – steam, carbon dioxide (CO_2), nitrogen (N_2) and oxygen (O_2) – can be released to the atmosphere.

Primary functions of the off-gas treatment system include (a) cooling the off-gas to permit other treatment steps that require a lower temperature, (b) removing solids entrained in the gas, (c) removing volatile acids such as hydrogen chloride from the off-gas, (d) converting NO_x in the off-gas to nitrogen and water (H_2O), (e) destroying unburned hydrocarbons and carbon monoxide (CO) in the off-gas by oxidation, and (f) removing mercury from the off-gas. Ultimately, the requirements for off-gas treatment are derived from the Clean Air Act and the State of Idaho air quality standards.

In the past, calcine produced in the NWCF has been pneumatically transferred to storage bins. To package the calcine in canisters for disposal at WIPP, a new facility is required, along with associated lines to transfer the calcine to the new facility. The functions of the CPF include (a) receiving the calcine, (b) separating the solid calcine particles from its transport air, (c) cooling the calcine to avoid exceeding temperature limits on canister seal material, (d) transferring the waste into canisters, and (e) closing and decontaminating the waste canisters when full.

Certification to WIPP WAC requires measurements to determine the weight of the container, the waste composition, certain radionuclide concentrations, radiation fields, surface contamination, and the hydrogen generation rate of the waste in the container. Some of the information required for certification may come from sample analysis of waste in the Tank Farm prior to transfer to the NWCF. Certification also requires labeling the waste containers and preparing the required documentation of the waste to be shipped.

To ship the canisters of calcine to WIPP, they must be stored until transport is available, as waste will be generated at a faster rate than it can be shipped. Canisters would be loaded into shipping casks and onto transporters, as they are available.

Off-gas treatment results in a liquid radioactive waste, referred to as “scrub,” that must be purged to avoid excessive buildup of solids. The scrub is mostly purged (recycled) to the calciner, but a portion must be sent elsewhere to avoid excessive mercury buildup. To dispose of the scrub purge waste, it is solidified in a grouting operation and packaged in waste containers. After packaging the solidified scrub waste would be sent to a disposal facility. GAC, used to remove mercury from the off-gas, and spent high efficiency particulate air (HEPA) filters will also need to be packaged and disposed.

3.1.2 Process Description

Treatment of the SBW and NGLW in the CMACT alternative involves three facilities. The treatment processes in each of these facilities are summarized in this section. Additional detail can be found in the Feasibility Study Report (Merrick, 2004). Sketches showing the major unit operations of the CMACT process are shown in Figure 1 (for the Tank Farm, NWCF, and CPF) and Figure 2 (for the MACT Compliance Facility [MCF]).

3.1.2.1 New Waste Calcining Facility (NWCF). The NWCF uses a fluidized-bed calcination process to convert radioactive liquid waste into a granular solid called calcine. The NWCF houses the calciner, the Evaporative Tank System (ETS) evaporator, the filter leach system, associated process equipment, an equipment decontamination area, and eating, ventilation and air conditioning (HVAC) equipment. The NWCF building has one above-grade level and two below-grade levels, divided into a decontamination area and the calciner area.

Sodium-bearing waste is transferred by steam or air jets from the tank farm to the calciner blend and hold tanks, where aluminum nitrate and calcium nitrate are added to the SBW to form the calciner feed solution. Scrub recycle is also added to the blend tank. Calciner feed is then transferred from the blend tanks into a feed tank where it then flows by gravity to the calciner vessel. Heated fluidizing air is added to the fluidizing air distributor at the bottom of the vessel. Additional heat is added to the calciner bed using kerosene and oxygen injected through nozzles.

As feed enters the calciner, water and nitric acid in the feed are evaporated, leaving solid particles that add to the number and size of bed particles. Periodically, the oversized bed calcine particles that sink to near the bottom of the bed are removed through a side withdrawal system as calcine product.

The effluent streams from the NWCF include process off-gas, HVAC exhaust air, liquid waste, and granular calcine solids. The process off-gas consists of calciner off-gas, vessel off-gas, and solids transport return air (calcine transport air returned from the calcine storage bins to the top of the calciner vessel). The calciner vessel process off-gas passes through an extensive cleanup system consisting of a cyclone to remove calcine fines, a quench tower, a venturi scrubber, a knockout drum, a condenser, a mist eliminator, a heater, ruthenium adsorbers, a mist eliminator, a second heater, a HEPA-grade pre-filter, and double HEPA filters. Previously the process off-gas was sent to the atmospheric protection system (APS) before being exhausted to the atmosphere through the INTEC Main Stack. With the MACT upgrade, the process off-gas will be sent to the MCF prior to discharge through the INTEC Main Stack.

Liquid radioactive waste purged from the off-gas scrub system is recycled to the calciner feed stream, with a small amount of blow down to be treated for disposal. Decontamination solutions generated in the NWCF are sent to existing storage tanks and evaporators to be concentrated and then added to the NGLW awaiting treatment. Non-radioactive service waste (steam condensates and cooling water) is monitored for radioactivity before being discharged to existing percolation ponds. If the radiological contamination in the service waste stream exceeds a set of contamination limits, the stream is diverted to a waste storage tank, concentrated, and calcined.

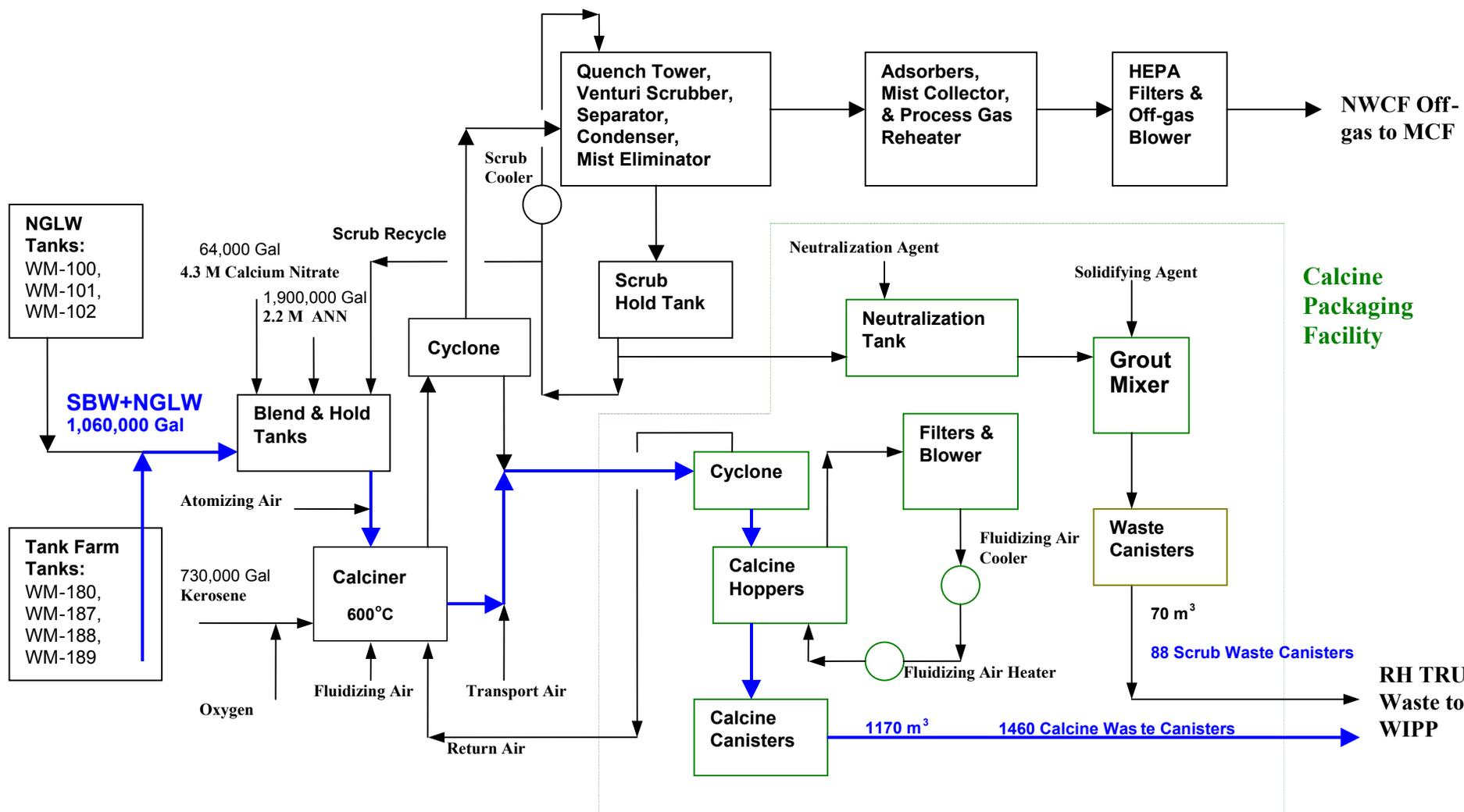


Figure 1. CMACT block flow diagram: Tank Farm, NWCF, & CPF.

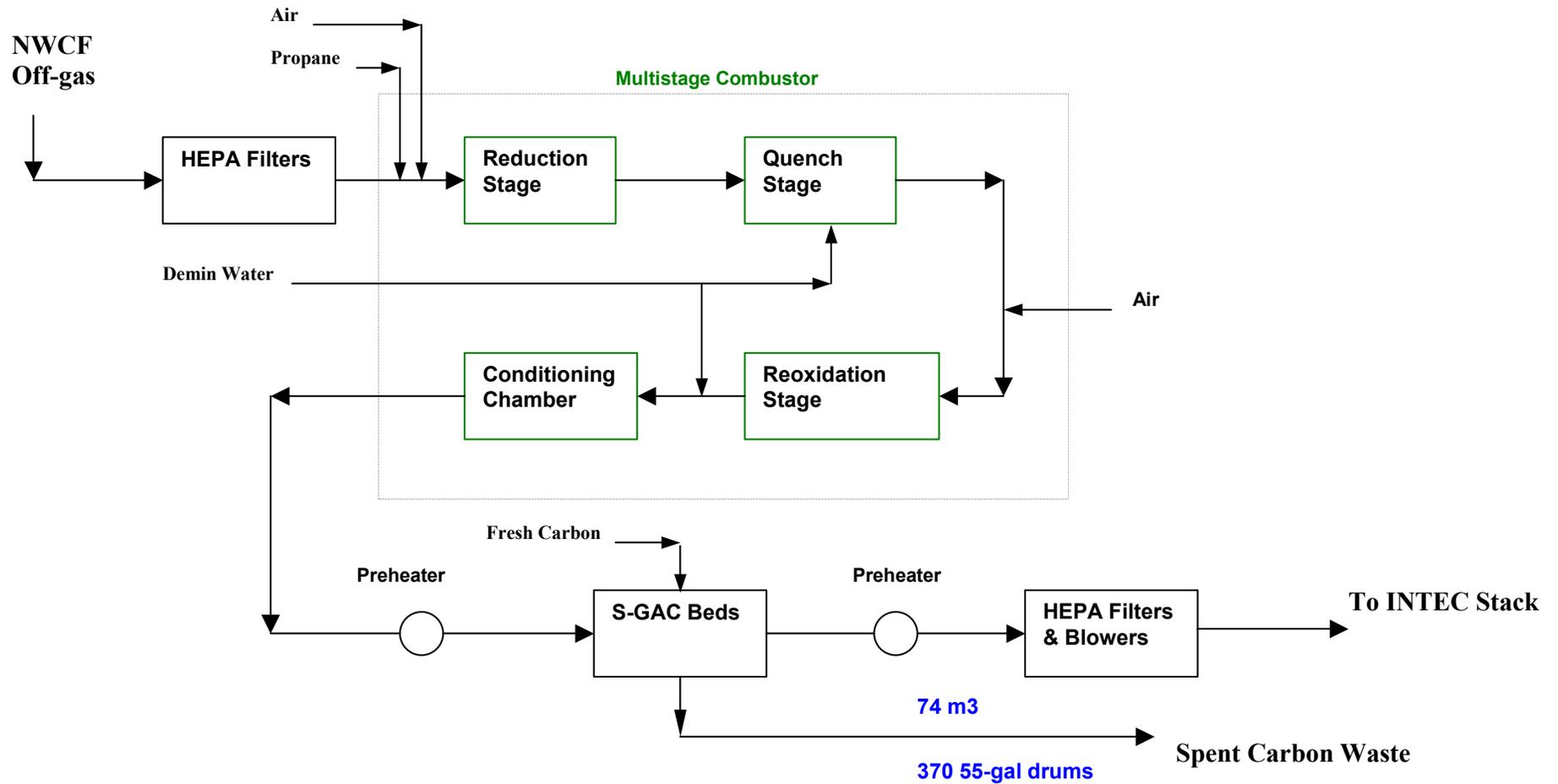


Figure 2. CMACT block flow diagram: MACT Compliance Facility.

When the calcination process in the NWCF was shut down in 2000, the system was in relatively good condition. However, some of the equipment in the facility needs to be replaced or upgraded since it will be approaching thirty years old by the time the calciner is restarted. NWCF personnel made a list of components and systems they felt should be upgraded or replaced to minimize unplanned shutdowns of the calcination system. They then prepared an engineering design file (EDF) for each of the recommended modifications, complete with a cost estimate, radiation exposure estimate, and schedule. That series of EDFs can be divided into three categories: (1) replacement of equipment or valves due to failure of that system during the last campaign, (2) replacement of equipment because spares are no longer available due to the age of the equipment, and (3) replacement of equipment with new equipment due to advancement in technology and reliability.

Replacement of equipment in the calcination system of the NWCF will expose workers to radiation doses that total an estimated 268.3 man-rem (Bates, 2000). The current administrative limit at the INEEL is 0.700 rem/year while the goal for construction workers is 0.270 rem/year. Depending on the control level, this work could potentially “burn out” from 135 to 1000 workers. Thus, the timing of this work is important. The schedule shows the upgrades to the calcination system of the NWCF occurring simultaneously with the construction of the MCF and CPF. This approach allows workers to rotate to either the MCF or CPF after having received an allowable radiation dose in the NWCF.

3.1.2.2 MACT Compliance Facility (MCF). Off-gas from the existing NWCF facility must be further treated in a new MCF to meet regulatory standards. That process includes several steps that clean the off-gas. The off-gas coming to the MCF is initially passed through HEPA filters to capture entrained particulates, which is the major transport mode for non-gaseous radioactive isotopes. Once in the MCF, the off-gas is routed in one of two directions, either through the MACT process equipment, where it is treated before exhausting through the INTEC stack, or through a bypass line that routes the off-gas to the existing APS system. This bypass will allow the calciner to continue to operate for brief periods if there should be a problem in the MCF that necessitates its shutdown. The off-gas that enters the MACT facility will be HEPA-filtered again to minimize downstream contamination. Off-gas leaving the HEPA filters will pass through a flow meter and then to the NO_x reduction furnace.

The reduction furnace is a cylindrical refractory-lined vessel (nominally 8.5 ft diameter by 27 ft long) heated by burning auxiliary fuel (propane) with excess combustion air in a high-intensity burner that is mounted at the front of this furnace. A burner control system is used to sequence operations to safely control and monitor combustion with interlocks to shut off feeds in the event of malfunctions. When the desired operating temperature (~2200°F) is reached, the system is switched to reducing mode prior to initiating waste gas flow. The reduction furnace is maintained in a stable reducing state by adjusting fuel gas and/or the waste gas such that the amount of oxygen fed is insufficient to fully convert the combustibles in the off-gas to carbon dioxide and water. The waste gas passes through designed spin vanes in the burner to promote turbulent mixing with the fuel gas in the reduction furnace. The exothermic combustion of the fuel gas and residual hydrocarbons in the waste gas rapidly consumes the available oxygen during the typical residence time of 1.5 to 2.0 seconds to yield an off-gas mixture of hydrogen, carbon monoxide, water, carbon dioxide, nitrogen, trace quantities of NO_x, and unburned hydrocarbons. Metered quantities of liquid water are sprayed through quench guns to limit the maximum temperature reached in the reduction furnace to about 2200°F.

The reduction furnace effluent is then fed to the refractory-lined cylindrical quench chamber (5.5 ft diameter by 17 ft long) where liquid water is sprayed through quench guns to cool the off-gas to about 1600°F. This cooling is needed to minimize nitrogen oxide (NO) formation in the subsequent re-oxidation stage where excess combustion air is added.

Excess combustion air is introduced by a blower through a number of injection pipes in a third section to maintain an exiting oxygen level of about 2 vol % (dry basis) after oxidizing the combustible gases (hydrogen and carbon monoxide) to fully oxidized species (water and carbon dioxide). This re-oxidation stage, 6.5 ft diameter by 24.5 ft long, has a residence time of one second and operates at a temperature of about 1800°F. Higher temperatures would lead to NO_x formation in this stage.

The effluent from the re-oxidation stage is then cooled to 250°F by direct contact with liquid water sprayed from five quench guns into the cylindrical refractory-lined conditioning chamber (5.5 ft diameter by 15.5 ft long). This exit temperature is the desired inlet temperature to the downstream mercury removal unit.

The quench water used in the staged combustor is provided from a new demineralized water system and storage tank. This vessel provides 30 minutes surge capacity for the staged combustor quench system. The new demineralizer system will supply at least 30 gpm of demineralized water. Additionally, a connection to the existing plant demineralized water system will be made to the storage tank to provide backup demineralized water flow.

After processing the calciner off-gas for NO_x abatement in a staged combustion unit (which also destroys trace organics and products of incomplete combustion), additional unit operations are needed to achieve compliance with the MACT regulatory standard for mercury emissions of less than 45 µg/dscm (corrected to 7% oxygen content). Since the off-gas effluent from the staged combustion unit will include a significant fraction of the mercury in the SBW feed as predominately vapor phase elemental mercury plus minor quantities of mercuric halide (Barnes, 2003), a mercury removal efficiency of 99.9% is needed (Soelberg, 2003). Sulfur-impregnated GAC (S-GAC) pellets are placed in large beds to adsorb this vapor phase mercury.

The effluent off-gas from the conditioning chamber of the staged combustion unit passes through the tubes of a heat exchanger where it can be heated by 150 pound saturated steam in the shell to ensure this off-gas enters the following S-GAC at the desired temperature of 250°F with no entrained liquid droplets.

The S-GACs vessels purify the off-gas stream by chemisorption of gaseous mercury compounds plus physical adsorption of residual organic and halogenated compounds using packed beds consisting of S-GAC pellets. The gaseous mercury compounds will react with an equimolar amount of sulfur to form insoluble mercuric sulfide. Residual organic compounds and halogenated compounds will be physically trapped in the tortuous pore structure of the high surface area activated carbon. The spent carbon will thus contain progressively higher quantities of adsorbed mercury plus residual organic and possibly halogenated compounds as processing proceeds. The configuration consists of two parallel beds (one on-line and one idle) of S-GAC pellets followed by a “guard bed” containing the same material.

The cleaned off-gas from one of the two parallel S-GAC beds then passes through an identical cylindrical vessel (16 ft diameter by 10 ft tall tangent to tangent) containing a 5-ft guard bed filled with the same 3 mm S-GAC pellets. Hence, this bed has the same mercury sorption capacity as either of the upstream S-GAC beds.

The purpose of this guard bed is to ensure that the minimum overall desired mercury removal is achieved. If there is a large mercury spike through either of the two upstream S-GAC beds, as shown by the mercury monitor, this guard bed will have sufficient capacity to adsorb mercury over the lifetime of the remaining SBW operation and prevent exceeding emissions limits.

The off-gas leaving the S-GAC units will be reheated in a steam heat exchanger to above its dew point to avoid condensation in the lines or in the HEPA housings. The heated gas is then filtered through a HEPA filter to capture any particulate carbon fines (containing mercury, halogens, etc.) and remove any residual contamination prior to discharge to the atmosphere through the blowers and stack.

Off-gas will be sampled and the overall off-gas flow rate determined before it is discharged to the atmosphere via the INTEC stack. A new 20-inch line will connect the outlet of the blowers to the stack. The off-gas that has been treated in the MACT facility will not pass through the INTEC APS. However, any off-gas that bypasses the MACT facility, in the case of an emergency shutdown or for brief periods to resolve operating problems, will go to the APS for final filtering before discharge.

3.1.2.3 Calcine Packaging Facility (CPF). The CPF provides three important functions: calcine packaging for shipment to WIPP, immobilization of scrubber liquid, and lag storage of filled calcine and scrubber solution canisters. The calcine packaging portion of the CPF consists of three subsystems. These are the calcine receiving and storage subsystem, the fluidization subsystem, and the canister filling subsystem.

The calcine receiving and storage subsystem consists of a diverter valve, cyclone, two parallel storage hoppers, two parallel sintered metal filters and associated instrumentation. The diverter valve is installed in the solids transport line from the NWCF and allows solids to be bypassed around the CPF to Bin Set 6 (to be used only for short periods of time or in the case of an emergency). This ensures that calciner operations are isolated and independent from the CPF. Transported solids that enter the CPF pass through a cyclone and are discharged into one of two parallel storage/cooling hoppers.

The storage/cooling hoppers are two parallel, fluidized beds. Each bed is sized to hold 45 ft³ solids working volume and 60 ft³ total solids volume. The nominal solids production rate from the calciner is 45 ft³/day. This additional solids volume allows the hoppers to retain a heel of material during canister filling operations and keep the bed well fluidized. A 4-ft freeboard is provided above the fluidized beds to allow the particles that are elutriated from the bed to disentrain from the fluidizing gas and return to the bed. During normal operation, one hopper will be filled/cooled as the other is emptied. The fluidizing gas cools the bed solids as it flows through the bed.

Two parallel sintered metal or ceramic filters are provided, one on each bed outlet, to remove entrained particles from the fluidizing gas. These filters provide a minimum 2- μ m absolute filtration capacity for the entrained particles. The filters are equipped with an automatic blowback system to clean the filters as particles build up on the filter elements.

The fluidization subsystem consists of parallel HEPA filters; parallel fluidizing gas recirculation blowers, a cooler, an electrical heater and associated instrumentation and controls. Fluidizing gas exiting the filters on the top of the fluidized beds passes through the HEPA filter to remove any entrained particulate contamination that has passed through the bed-sintered metal blowback filters. The blowers provide the motive force to fluidize the solids in the hoppers and sufficient pressure to recirculate the fluidizing gas. Since a major function of the storage/cooling hoppers is to cool the solids before they are placed in the storage canisters, this heat must be removed from the gas before it is recirculated to the fluidized hoppers. A water-cooled heat exchanger is used for this purpose. Any condensate produced in the heat exchanger is drained to the facility decontamination sump. An electric heater is used to slightly reheat the fluidizing gas and prevent condensation from forming in the fluidizing gas lines or in the bed.

The canister filling subsystem consists of two parallel canister filling stations, one for each of the two storage/cooling hoppers (see Figure 3). Solids will be drained from the hoppers into canisters through a slide valve, a fill spout, a sacrificial seal tube, and through a modified fill-through pintle on the

shipping canister. The loadout hood will allow manipulator access to the flex hose connector while providing secondary confinement of solids that may become airborne when the fill tube is separated from the filling dock on the bottom of the hood. A two-stage HEPA filter and blower system will be used to control any dust that may escape from the equipment as the canisters are connected to the fill spout and filled. A disposable seal tube will be used for each canister to ensure that the outside of the canister remains clean during the filling operation. Each disposable seal will be replaced with a new one for each canister that is filled. After the canister is filled, the canister is lowered and the plastic bagout bag is sealed using a radio frequency sealing mechanism. The seal is cut, the bag is withdrawn into the top of the canister, and the pintle top blind flange is bolted onto the pintle using remote manipulators. The used seal tube with the other half of the sealed bagout bag is pushed upwards through the hood floor by the subsequent shipping canister's seal tube. This operation assures that no contamination falls onto the shipping containers. The recovered used seal tube is crushed and size reduced to allow the manipulator to drop through the fill port of the subsequent shipping container prior to moving the fill spout from its idle dock to the in-use dock.

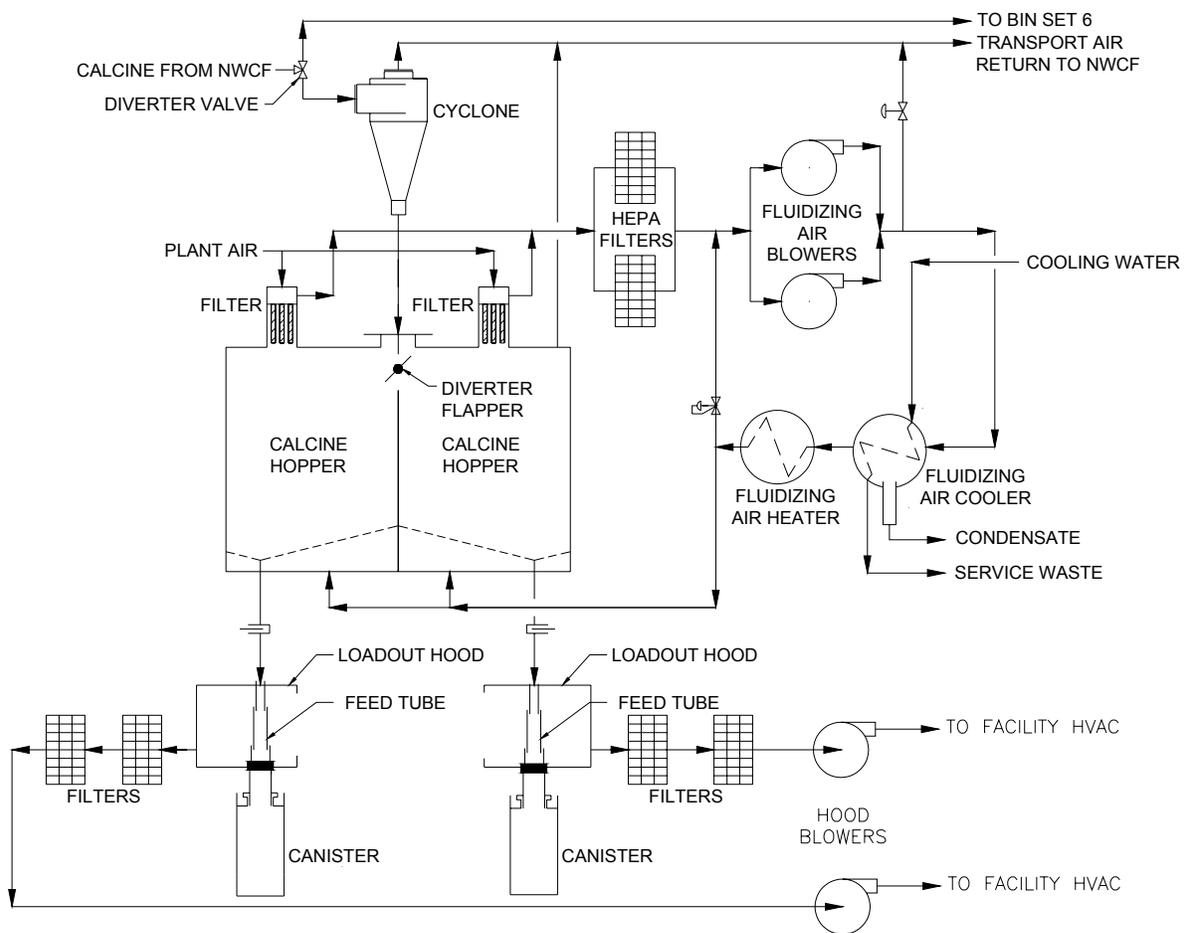


Figure 3. Calcine filling subsystem.

The spent scrub solidification facility consists of four subsystems: the neutralization subsystem, the solidification subsystem, the canister filling subsystem, and the balance of plant subsystem.

The neutralization subsystem consists of a neutralizing agent storage tank, a neutralizing agent metering pump, a spent scrub neutralization and storage tank, and a mixing/recirculation pump. Spent

scrub from the calciner scrub tank is transferred to the neutralization and storage tank in the CPF. The spent scrub mixes with recirculated scrub and enters the tank through an internal mixing eductor. This helps to mix the tank contents and keep any solids in suspension. A clamp-on cooling jacket is attached to the outside of the neutralization tank and is used to absorb any heat generated by the neutralization reaction. Neutralizing agent is pumped into the neutralization tank as needed to reach the desired pH.

The solidification subsystem consists of a solidification agent storage hopper, a solidification agent loss-in-weight feeder, a continuous in-line mixer, a close-coupled slurry auger, and a mass-flow meter and control valve system. The neutralized scrub is fed to a continuous mixer where it is mixed with a solidifying agent to form a slurry. The slurry is discharged into a vertical auger standpipe where it drops into the canister.

The solidifying agent is fed to the loss-in-weight from a Super Sack[®] hopper. The loss-in-weight feeder is used to ensure that the proper amount of solidifying agent is fed to the mixer to verify that the product specifications are met. Solids leaving the loss-in-weight feeder pass through a transfer auger (or chute) through the shield wall to the continuous mixer. This allows the Super Sack[®] hopper and feeder to be outside the remote maintenance area.

The mixed scrub/solidification agent slurry drops into the canister through the vertical standpipe attached to the vertical auger. A weigh cell is used to verify that the canister is not overfilled with slurry. The last few inches of the canister are filled with absorbent clay to ensure that there is no free liquid in the canister. A control valve system is also used to ensure the canister is not overfilled. The canisters are moved under the feed standpipe and lifted into place using a dedicated trolley and lift system. The balance of plant for the spent scrub solidification system consists of a monitored sump, cooling water, and other utilities.

Once the canisters of scrub solution or calcine are filled, lidded, and decontaminated, they are transferred to lag storage. Lag storage provides monitored storage for up to 500 canisters.

3.1.2.4 Tank Mixing System. Three tank-mixing pumps will be installed in each of three tanks - VES-WM-187, VES-WM-188, and VES-WM-189 - through existing 12-inch tank risers. These mixing pumps will ensure that solids are homogeneously mixed with tank liquids. The submersible pump motor is located in the tank at the suction head. The submerged pump is installed directly in the waste tank liquid near the bottom of the tank. The unit is supported by a vertical column that, in turn, is supported by a rotational turntable assembly mounted to a riser structure at the top of the waste tank. Each mixing pump weighs in excess of 2000 lbs and cannot be supported from the tank risers. A steel truss will be installed that spans the length of the tank substructure that will support the mixer pumps vertically, laterally, and torsionally.

Power for the Tank Farm area will be provided from existing Substation No. 60. This existing substation is a 13.8 kV-2400V double-ended unit, and the 13.8kV feeders are from a redundant INEEL 138kV-13.8kV loop.

3.1.3 Summary of Technical Performance

3.1.3.1 Processing Rate, Availability. In 2002, Barry O'Brien reviewed operating performance and throughput history of the calciner to select credible SBW feed rates, expected campaign lengths and maintenance turnaround times to be used for the CMACT design (O'Brien, 2002). Based on NWCF operation from 1982 to 2000, O'Brien recommended an average feed rate (SBW plus additives plus scrub recycle) of 182 gph, an on-stream factor of 73%, and two turnarounds of 173 days each. Based on a feed aluminum to alkali mole ratio (AAR) of 2.25, these recommendations would result in a 4-year processing

schedule for the full inventory of SBW and NGLW. O'Brien noted that aggressive preventative maintenance could improve the on-stream efficiency for at least the first part of the campaign from 73% to 85%, such as was experienced on Part 1 of the H-4 campaign. O'Brien also noted that if the AAR could be reduced to 1.8, which was later demonstrated in pilot tests performed in January 2004, the total processing time, including turnarounds, could be reduced to 3.5 years (O'Brien, 2002). If the maximum historical sustained feedrate of 223 gph were also achieved, the processing time would be reduced to 3.0 years (O'Brien, 2002).

Two other studies have been performed in attempts to increase throughput or reduce downtime for the CMACT alternative. Doug Stacey developed 14 recommendations that could reduce maintenance turnaround times from 173 to 85 days (Stacey, 2003). Steve Bates reviewed the advantages and feasibility of replacing the cyclone, which currently only removes about 63% of the carryover calcine fines (Bates, 2003). By replacing the cyclone with one achieving higher efficiency, the fraction of scrub recycle in the calciner feed could be reduced, allowing for an increase in the SBW feed rate and a corresponding reduction in operating schedule. Bates showed that a schedule reduction of 139 days could be achieved by cyclone replacement. The cost to replace the cyclone was later estimated to be \$2.45 million (Adams, 2003).

The recent CMACT Feasibility Study (Merrick, 2004) included a reliability, availability, and maintainability (RAM) analysis, which concluded that the availability of the MCF taken alone is 91%, the CPF taken alone is 83%, and the scrub solidification system is 93%. Since the availability of each of these new facilities is higher than that of the NWCF (72%), it was assumed that maintenance would be performed during NWCF shutdowns; hence, they would not affect the availability of the total processing system.

3.1.3.2 Waste Products Quantity and Quality. The CMACT process would produce an estimated 1168 m³ or 1460 canisters of calcine waste, an RH-TRU waste product. Calcine is a granular solid with a bimodal size distribution of particles. Based on NWCF operation at 600°C, bed particles average about 0.6 mm (Swenson, 2000). Based on calcine generated at 600°C in 10-cm pilot calciner runs, fines average about 0.05 mm^b. In the recent pilot calcine tests, the median size of the fines was about 0.01 mm (Boardman, 2004b). A typical bulk density for SBW calcine, mixed bed and fines, is 1.2 kg/liter.

Two other waste streams, grouted scrub waste and spent GAC, would be produced intermittently during processing or at the end of processing SBW. Like calcine, the grouted scrub will be an RH-TRU waste. The spent GAC will be a low-level mixed waste. Estimated volumes of these wastes and calcine are shown in Table 2.

Table 2. CMACT primary waste products.

	WM-180	WM-187	WM-188	WM-189	D&D	Total containers	Total m ³
Calcine, canisters	394	280	377	409		1460	1168
Scrub waste, canisters	0	16	17	35	20	88	70
S-GAC, 55-gal drums	0	0	0	0	370	370	74

b See Figure 1 of Appendix B5 of Welland, 1997 for particle size distribution curves.

The uncertainty in the above estimate of both scrub and carbon waste is high. Both scrub and carbon wastes are outlets for mercury volatilized in the calciner. The uncertainty in the behavior of mercury downstream of the calciner results in the uncertainty in the waste volumes. The amount of carbon shown in Table 2 assumes two full-sized carbon beds require disposal at the end of processing, and that the third GAC bed is not used during processing. If a bed requires bypass or changeout due to more mercury in the off-gas than presently expected or adsorption of hydrogen chloride (HCl), the amount of carbon waste would increase by 50%.

If more mercury partitions to the off-gas than is presently predicted, the amount of scrub waste will be less. The amount of scrub waste shown in Table 2 is based on purging the scrub when the mercury concentration reaches 55-60 g/liter, a concentration range that was experienced in the NWCF H-4 campaign. The effects on the process of allowing mercury to build up to higher concentrations are not known.

The number of shipments to WIPP of RH waste (i.e., both calcine and scrub waste) is equal to the number of canisters. Carbon beds are sized such that they will not be changed until treatment is complete. However, due to the volume generated, multiple shipping vehicles will be required. A specific shipping schedule of the carbon waste to its disposal site, tentatively identified as Envirocare, has not been determined. Radioactive properties of the CMACT waste streams are shown in Table 3.

Table 3. Radioactive properties of primary waste products.

Calcine	Range
All radionuclides, Ci/canister	250 - 840
Fissile gram equivalent, g/canister	55 - 73
²³⁹ Pu Equivalent Curies, Ci/canister	2.7 - 3.1
TRU content, nCi/g	2,400 - 3,400
Surface dose rate, Jan 2008, Rem/hr	19 - 66
Heat generation rate, Watts	0.8 - 2.4
Grouted Scrub Waste	
All radionuclides, Ci/canister	20 - 50
Fissile gram equivalent, g/canister	2.2 - 4.2
²³⁹ Pu Equivalent Curies, Ci/canister	0.1 - 0.2
TRU content, nCi/g	110 - 220
Surface dose rate, Jan 2008	2.4 - 3.6
Heat generation rate, Watts	0.06 - 0.15
Spent GAC (average)	
All radionuclides, μCi/drum	2
TRU content, nCi/g	2.0E-06
Sum of fractions compared to Hanford Category 1 WAC	0.006
Sum of fractions compared to Envirocare WAC	0.001

3.1.3.3 Size, Footprint of Processing Facility. The following facility descriptions and estimates are taken from the *Calcination with MACT Upgrade Feasibility Study Report* (Merrick, 2004). Additional details, including floor plans and elevation drawings, can be found in the referenced report.

The NWCF, an existing facility, is housed in a concrete and steel building that has three main levels, one above grade and two below grade. The building is further divided into two main areas, the decontamination area and the calciner area. The NWCF is approximately 250 feet long and 145 feet wide, and extends 57 feet below grade and 43 feet above grade. The calciner area on the first level is approximately 132 feet wide by 160 feet long and occupies a space about 90 feet wide by 160 feet long on the two below grade levels.

Process control and administrative functions take place on the level above grade. Decontamination area activities are located on Level 1 and on Level 2, which is the first below grade level. Calcination and the evaporation of liquid waste also take place on Level 2 as well as on Level 3 of the NWCF.

The calciner, the High Level Liquid Waste Evaporator (HLLWE), and other associated equipment are located in steel reinforced concrete cells located on Levels 2 and 3. These concrete cells provide the appropriate confinement and shielding of radioactive sources to allow manned entry into adjacent corridors on these levels. All equipment located within these cells is arranged for ease of operation and remote maintenance.

The upper portion of the calciner cells, valve cubicles, and liquid and solid sample stations are located on Level 2. An operating and access corridor borders the cells and cubicles. Shielded viewing windows, tool ports, and master-slave manipulators provide visual and working access from the corridor into the cells. Self-monitoring personnel decontamination stations and double-door passageways are installed at the stairs for personnel protection and contamination control.

A new MCF will be located between the existing NWCF and the existing exhaust stack. The 35-ft tall single story building will house MACT process equipment including the MCF feed filters, staged combustion system, the S-GAC beds, the MCF discharge filters, the off-gas blowers, and associated variable frequency drive units. Adjoining rooms house the analyzers for the S-impregnated Carbon Beds, the continuous emissions monitors for the off-gas stack exhaust, the water treatment system equipment used to provide demineralized water to MACT system, and the atomizing air system, which provides atomizing air to the MACT quench system. The building is approximately 107 feet long by 77 feet wide, plus an additional 33 feet by 37 feet that houses a utility room.

The MCF will be a metal building with flat roof. The rooms housing the staged combustion unit and S-GACs will be lined (floor, walls and ceiling) with a stainless steel liner to facilitate decontamination. The entire building will be protected by a wet pipe sprinkler system supplied from the underground fire water supply at the site. The floor in the process areas will be surrounded with an eight-inch curb to provide containment in the event of a sprinkler head discharge.

The CPF is comprised of two buildings. The first is approximately 90 feet tall and houses the process equipment, hot cells, canister fill stations, grout fill station, and lag storage. This building is approximately 240 feet long by 115 feet wide. Lower levels extend about 22 feet below grade. The second is the CPF Administration Building. This 82-ft by 54-ft single-story building will house offices, a radiological laboratory, the control room, the health physics room, restrooms, lockers, showers, personnel decontamination stations, a break/conference room, and a mechanical/electrical equipment room.

The two buildings are connected by a covered walkway. Consideration was given to make the CPF a single building that would be classified as a PC-2, non-reactor nuclear facility. It was found to be more

cost effective to separate the two buildings, with the CPF meeting the PC-2, non-reactor nuclear facility classification, while allowing the CPF Administration Building to be designed as a non-nuclear facility.

3.1.4 Technical Uncertainties and Potential Impacts

3.1.4.1 Uncertainties identified in the SBW Treatment Applied Technology Plan. The *Sodium-Bearing Waste Treatment Applied Technology Plan* (INEEL/EXT-03-00477, June 2003) identified thirteen uncertainties resulting from technical and operational risk assessments for the CMACT process. These were, for the most part, uncertainties that would have supported the selection of a treatment technology and were not a complete listing of technical issues requiring resolution to support detailed design efforts. The uncertainties were prioritized as High (H), Medium (M), or Low (L) risks. A high risk is categorized as an issue that is likely to occur and would have a significant (\$25 million - \$125 million impact) or critical (>\$125 million) consequence. Issues that are unlikely but have significant or critical consequences, or are likely but have marginal (\$5 million – \$25 million) consequences are categorized as medium risks. Issues that have a probability of occurrence of less than 10%, or a higher probability but negligible or marginal consequences are categorized as low risk. Table 4 lists the uncertainties, a short description, and their status as of the writing of this report.

Table 4. Summary of CMACT uncertainties identified in the Applied Technology Plan.

Uncertainty	Description	Status
Aluminum Nitrate Ratio (H)	Based on NWCF-demonstrated AARs, processing the entire inventory of SBW will take longer than 4 years, which will not meet the required completion date for SBW treatment. Reducing the AAR would result in an increased throughput and reduce processing time.	Pilot tests in January 2004 demonstrated calcination of WM-180 simulant at AARs of 2.25 and 1.75. At an AAR of 1.75 the treatment schedule would be reduced by about 6 months. It is still uncertain whether an AAR of 1.75 is acceptable for wastes from the other tanks, and whether pilot results directly correlate with full-scale calciner operation.
Effects of Zr and phosphate on bed agglomeration (H)	Tanks solids are very high in Zr and phosphate. The effect that these solids will have on bed agglomeration is uncertain, and whether additional calcium nitrate will need to be added to the feed due to the additional phosphate.	No tests have been performed to determine the effect of tank solids on bed agglomeration.
Scrub recycle minimization evaluation (H)	Based on operating data, the cyclone efficiency is about 63%, requiring a scrub recycle rate of 23% of the total calciner feed. Replacing the recycle with a higher efficiency cyclone would allow a reduction in recycle rate, an increase in SBW feed rate and a reduction in required operating time.	EDF-3646 (Bates, 2003) concluded that replacing the cyclone would reduce operating time by 139 days. The cost to replace the cyclone was estimated to be \$2.45 million (Adams, 2003). Additional study is needed to determine what additional modifications if any are needed to accommodate the increased pressure drop of a new cyclone.

Table 4. Summary of CMACT uncertainties identified in Applied Technology Plan (continued).

Uncertainty	Description	Status
GAC bed chloride removal – HCl/Cl ₂ Emissions (H)	Analyses for HCl and Cl ₂ in NWCF off-gas samples taken in 1999 and 2000 showed concentrations below detection limits (10-55 ppm total Cl, dry basis) which brackets the MACT limit of 21 ppmv. If the GAC bed does not remove HCl, and no other unit operations are added to the process to remove Cl, there is a risk the MACT Cl limit would be exceeded.	Long-term GAC tests showed negligible removal of Cl (Del Debbio, 2003). Recent pilot tests (Boardman, 2004b) also show negligible Cl removal by the GAC bed. In the pilots tests levels of HCl in the off-gas were well below the MACT limit. However it is still uncertain whether HCl concentrations in the off-gas of the full-scale facility will increase to above the MACT limit as chlorides build up in the scrub system.
Minimization of O ₂ in calciner off-gas (M)	To destroy NO _x in the MCF, the initial stage of the staged combustor must operate at reducing conditions. The O ₂ content of the stage combustor feed is near 21% on a dry basis, requiring large quantities of fuel in the combustor to reach reducing conditions and resulting in large off-gas flow rates. Optimization/replacement of calciner air inflows could result in reductions in MCF throughput and MCF footprint and cost.	Discussions with John Zink, (a staged combustor supplier) during the CMACT feasibility study resulted in a design increase in the staged combustor feed oxygen content (Merrick, 2004). This was needed in order to ensure proper burner operation.
Combustor operating and performance parameters (M)	The fuel, water and air additions in the staged combustor result in more than a 3-fold increase in volumetric gas rate, based on data obtained in 1999-2000 during tests at MSE. Because of limitations of the MSE test equipment, it was uncertain whether optimization of operating parameters could result in a significant decrease in combustor throughput.	Engineering of the staged combustor for the CMACT feasibility study (Merrick, 2004) and recent kinetic and CFD modeling of the staged combustor (Wood, 2004) have shown that no significant reduction of throughput is possible.
GAC bed design and performance (M)	The GAC beds are large – 16 feet diameter by 10 feet tall (Soelberg, 2003; Merrick, 2004) and the design calls for two in series (because of uncertainty in off-gas Hg content, Hg loading on the bed, and Hg removal by the bed) and a third in parallel (because of uncertainty in GAC HCl removal and loading). Because of these uncertainties, the bed could be oversized or fewer beds required.	Long term small scale tests have demonstrated 100.0 ± 2.4% Hg removal and negligible (1.6 ± 7.5%) HCl removal (Del Debbio, 2003). Recent pilot test data (Boardman, 2003b) also show adequate Hg removal and negligible chloride removal. These results indicate that a parallel bed to allow for changeout is unnecessary. Uncertainties remain regarding the GAC bed feed Hg concentration, the GAC bed carbon loading and performance at higher superficial velocities.

Table 4. Summary of CMACT uncertainties identified in Applied Technology Plan (continued).

Uncertainty	Description	Status
Mercury vapor liquid equilibrium data (M)	Past attempts have failed to achieve good closure for Hg in NWCF mass balances. This uncertainty in partitioning of Hg between off-gas and scrub impacts the GAC bed size, the amount of scrub waste produced, and the timing of scrub purges. Also the limiting scrub Hg concentration is unknown, as NWCF data goes only to about 60 g/liter.	Progress was made developing models for predicting Hg VLE (Nichols, 2003, Taylor, 2003), but management terminated this work before it was completed.
Off-gas Cl concentration and speciation (M)	Analyses for HCl and Cl ₂ in NWCF off-gas samples taken in 1999 and 2000 showed concentrations below detection limits (10-55 ppm total Cl, dry basis) which brackets the MACT limit of 21 ppmv. The uncertainty in off-gas HCl/Cl ₂ concentrations could lead to unnecessary off-gas treatment steps or to Cl emissions exceeding MACT the limit.	The present process flow diagram shows no unit operations designed specifically to remove HCl. Recent pilot test data (Boardman, 2004b) shows off-gas chloride levels far below the MACT limit. Uncertainty remains, however, because in the full-scale plant, chlorides build up in the scrub system and could result in higher levels in the off-gas.
Scrub treatment method and parameters (M)	Several treatment methods for high-mercury scrub blow down have been considered, and an initial evaluation favored either grout or absorption on silica gel placed on top of calcine in the packaging process. Subsequent testing provided parameters (loading, formulations) for these two methods and also showed that absorption on silica gel would be feasible. Uncertainties remaining include radiolytic hydrogen generation rates and mixing requirements for the absorbed waste forms.	No additional data has been obtained to resolve the uncertainties for the absorbed waste forms. Present designs assume the waste scrub is grouted.
Effects of solids on calcination (M)	The effects of undissolved solids on calcination parameters (feed additive quantities and calciner operating parameters) are uncertain.	The scale of the pilot plant was inadequate to feed solids; thus the effect of solids remains uncertain.
Feed acidity (L)	The waste in three of four SBW tanks has a higher acid molarity than most waste that has been processed in the NWCF. It is uncertain whether this higher acid molarity will cause agglomeration in the bed.	This issue has not been resolved; the recent pilot tests used WM-180 simulant that has the lowest acid concentration of the SBW waste tanks.

Table 4. Summary of CMACT uncertainties identified in Applied Technology Plan (continued).

Uncertainty	Description	Status
Calcine densification (L)	Calcine densification has been suggested as a means of reducing the volume of calcine waste in order to reduce the number of waste shipments and the required lag storage space. However, no methods of densification have been tested.	Calcine densification is not shown in the present process flow diagrams and has undergone neither further evaluation nor testing.

One of the highest probability risks for the CMACT alternative is not meeting the required treatment deadline of December 31, 2012. Because there are process changes that could reduce the treatment schedule, risks associated with these changes are considered technical risks. Two of these are shown in Table 4, “Aluminum nitrate ratio” and “Scrub recycle minimization evaluation.”

Reducing the AAR in the blended feed allows for increasing the SBW rate. The SBW high temperature run in 1999 ran with a feed blend having an AAR ratio of 2.0 for two weeks, but the particle size could not be controlled during this time (Wood, 2001). For the 2000 SBW high temperature run, the AAR began at 3.8, was decreased to between 3.5 and 3.0 for most of the run, decreased to 2.8 for seven days, and finally decreased to 2.6 for the last 8 days of the run (Law, 2000). The bed particle size remained constant at about 0.6 mm for the last month of the run, confirming that it could be controlled at an acceptable size and for the reduced AAR ratio. Guided by this data that showed that an AAR of 2.0 was too low and 2.6 acceptable, O’Brien assumed an AAR of 2.25 in estimating a four-year operating schedule for processing all SBW (O’Brien, 2002).

The first 50-hr calcination pilot test in 2004 used an AAR ratio of 2.25; in the second test the AAR ratio was reduced to 1.75. No problems with bed growth were seen in either test. Some nozzle plugging was seen with the lower AAR. Also, the feed used for these tests was a surrogate for Tank WM-180 waste, which has less phosphate and zirconium than will the other tank wastes after mixing with tank solids. The effect of the high zirconium phosphate in the tank solids on the bed has not been determined. Thus, while the acceptability of using an AAR ratio of 2.25 was verified, there is still uncertainty whether it can be reduced as low as 1.75.

A second way to reduce the total operating time is to replace the cyclone separator. The efficiency of the current cyclone separating carryover particulate is only about 63%. With a higher efficiency cyclone, less calcine particles would be carried into the scrub system. Since the recycle rate is determined by the rate the scrub accumulates solids, fewer solids in the cyclone off-gas means a lower rate of scrub recycle to the calciner. Thus, the SBW feed could be increased by the amount that the scrub recycle is reduced. An increase in cyclone efficiency from 63% to 90% translates to a reduction in the scrub recycle from 23% of the total calciner feed to about 6% and a net increase of 22% in SBW feedrate.

Bates (2003) estimated the savings in processing time to be 139 days, and Adams (2003) estimated the cost to replace the cyclone would be about \$2.45 million. A high-efficiency (98%) cyclone was demonstrated in the 2004 calcination tests, although occasional plugging was observed (Boardman, 2004). Several uncertainties remain in the evaluation of cyclone replacement. A higher efficiency cyclone will have a higher pressure drop; further evaluation is needed to determine how to accommodate this change in pressure profile with the existing off-gas equipment, or whether modifications to the compressor would be required. Modeling the higher efficiency cyclone was based on a scrub recycle rate that kept the aluminum concentration in the scrub below 1.6 molar. Although this constraint is similar to

historical operation of the NWCF, other constraints, such as chloride buildup or total solids buildup, may affect the actual recycle rate achievable.

There has been uncertainty in the concentrations of hydrogen chloride and chlorine in the off-gas both upstream and downstream of the S-GAC bed. Hydrogen chloride and chlorine in NWCF off-gas sample were not detected, however, detection limits bracket the MACT emission limit. Hydrogen chloride was measured at a concentration of 0.5 ppm in the pilot test off-gas (Boardman, 2004b), much lower than the MACT limit of 21 ppm. However, in the full-scale plant, recycle of scrub to the calciner could cause higher hydrogen chloride concentrations in the off-gas as chlorides buildup in the scrub solution. Thus, hydrogen chloride emissions and the need for HCl/Cl₂ removal remain uncertain. Both long-term GAC bed testing (Del Debbio, 2003) and recent pilot tests (Boardman, 2004b) indicate that the S-GAC will not remove a significant amount of hydrogen chloride from the off-gas.

Many of the uncertainties in the CMACT design relate not to performance but to whether a given design is optimized. Some of the questions regarding the MCF have been resolved in design and modeling studies and in the recent calcine pilot tests. The fuel, water, and air feeds to the staged combustor result in a 3-fold increase in throughput in the combustor. Reducing the oxygen content of the calciner off-gas or combustor air rates were suggested as ways to reduce this increase. Kinetic/CFD modeling studies (Wood, 2004), the CMACT Feasibility Study (Merrick, 2004), and the FY 2004 pilot tests (Boardman, 2004b) all showed that combustor throughput reductions are not possible.

Both long-term GAC bed testing (Del Debbio, 2003) and recent pilot testing (Boardman, 2004) have demonstrated that the GAC bed can achieve the required mercury removal efficiency. However, the small-scale, long-term tests were performed at lower velocities and with smaller size carbon particles than expected in the design. In addition, uncertainties in the mercury partitioning between off-gas and scrub and inconsistent test results regarding mercury loading on carbon lead to a design that may not be optimum (i.e., the design may have more beds or larger beds than needed).

The CMACT design (Merrick, 2004) has three carbon beds, 16 feet in diameter by 10 feet in height. Two beds are operated in parallel with the third in series. The purpose of the parallel bed was to allow for changeout of a bed while still operating. However, since each bed is sized for capture of all the expected mercury in the off-gas and since the test data shows that hydrogen chloride is not adsorbed in the S-GAC bed, there appears to be no need to have a parallel bed. The need for a second bed in series is uncertain. The pilot data (Boardman, 2004b) shows significantly more capture of mercury in the scrub than assumed in sizing the GAC bed. However, in the full-scale plant, the mercury concentration will increase over time in the scrub and the off-gas. Since nearly all the scrub is recycled, the concentration in the off-gas will increase. Additional GAC bed testing at higher velocities would be needed to evaluate whether the GAC bed diameter can be decreased.

Three methods to solidify the waste scrub have been demonstrated (Herbst, 2003; Scholes, 2003; Raman, 2003). While the option to dispose of the scrub by absorbing it onto calcine is attractive because it eliminates a waste stream, gas generation, foaming, and crusting observed in tests negate this advantage. For the option of absorbing the scrub on silica gel, a higher waste loading could be achieved than if the scrub was grouted. But uncertainties are greater for a silica gel waste form, namely, whether water would desorb over time, whether the higher waste loading and water content would result in excessive radiolytic hydrogen generation, and what mechanical mixing would be needed. Because these questions have not been answered, the present flowsheet shows grouting as the method for treating the scrub.

3.1.4.2 Risks identified in the Merrick Risk Analysis. The recent CMACT Feasibility Study (Merrick, 2004) included an assessment of program and project risks for the SBW Treatment Projects.

Merrick identified risks using the *Risk Identification Checklist contained in the Risk Management Plan* for the Sodium Bearing Waste Treatment Facility Project (Bonnema, 2002). These risks were then described, categorized, and risk levels determined. Merrick identified no technical or design risks that rated as critical or high. Two risks categorized as technical or design were rated as moderate and are briefly discussed below.

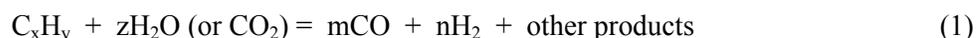
One moderate risk falls under the title “New application of an existing technology”. The CMACT alternative includes use of mixing pumps that must fit down 12-in diameter risers in 300,000-gal tanks, a new off-gas treatment system, and remote handling packaging systems. The individual components used with the modified process all involve established technologies. However, they will be applied in a new combination and to some degree in new applications. Off-gas treatment in particular involves many steps that will need to be integrally coordinated. Routine, efficient, and effective performance cannot be guaranteed, particularly during initial operations. Short-term air quality permit violations may occur. Redesign and additional project costs may also occur.

A design risk was identified relating to complex design features and ranked moderate. The remote handling of feed material and product and the treatment of off-gas both involve complex design features. Each component of the off-gas treatment system has certain operating conditions that must be integrated with other unit operations. The off-gas treatment will involve a complex integrated control system to control startup, operation and shutdown, as well as emergency shutdown. Dust control in the CPF is of particular concern. Should the system not integrate properly, air quality objectives and permit limits may not be achieved and there could be contamination issues with packaging calcine.

3.1.4.3 Other Risks. The recent calcination pilot tests confirmed the possibility of another risk involving the GAC bed. Several times during the test, there were temperature excursions in the carbon bed. Additional testing is needed to determine the causes of GAC bed temperature excursions and control measures to avoid these excursions.

3.2 Steam Reforming

Steam reforming is a process for producing hydrogen. This is generally done by reacting an organic feed with an oxygen source (e.g., water or carbon dioxide) at elevated temperature (possibly with a catalyst) to form carbon monoxide and hydrogen and various other products (e.g., carbon and/or other hydrocarbons via reactions such as the following:



Steam reforming is considered an alternative to other thermal processes for treating SBW for the following reasons:

- Under favorable conditions, total decomposition of organics can be achieved without open-flame combustion and its associated emissions.
- Also under favorable conditions, oxides of nitrogen can be converted to nitrogen. This feature is relevant due to nitrates in SBW that generally produce high levels of NO_x in off-gas from thermal treatment processes.

Steam reforming processes have long been used commercially to generate hydrogen for ammonia production, for petroleum refining, and to generate synthesis gas. More recently it has been used to generate hydrogen for fuel cells, to extract hydrogen from biomass, to treat paper mill black liquor, and to destroy various hazardous wastes. The latter two applications have led to its consideration by DOE for

treatment of its radioactive wastes. In 1994, steam reforming was tested to treat Hanford Tank waste in the Synthetica process. In 1996, DOE again funded testing of steam reforming on low-level mixed waste and Hanford tank waste. TWR tested a 42-inch steam reforming fluidized bed reactor at the Portsmouth Gaseous Diffusion Plant for treatment of soil, debris, and aqueous liquids containing PCBs and hazardous organic wastes.

Steam reforming treatment of INEEL SBW was initially considered as a method to convert a low activity liquid waste into a solid that would then be grouted to a final waste form. In tests performed during 2000 a simulant similar to SBW was fed to a bench-scale fluidized bed steam reformer. By operating the test bed with and without added reductants and catalysts these tests also showed that waste denitration could be achieved. In 2001, when DOE was evaluating vitrification of SBW, steam reforming was suggested as a possible alternative treatment. The DOE Idaho Operations Office then sponsored a Tank Focus Area Review Team to review the technology and make a recommendation. The team concluded that although steam reforming by itself is not a feasible alternative to produce an acceptable final waste product it might have merit as a pretreatment prior to vitrification.

In 2002, DOE discontinued funding of SBW vitrification process development and issued guidance to BBWI to assess alternative processes to produce waste forms that would be disposable at WIPP. Pursuant to that decision two analyses were completed (Murphy, et al. 2002 and Perry 2002) which reviewed all processes that had been considered up to that point for treatment of SBW. Also, a feasibility study to treat SBW by steam reforming was prepared in 2002 (Williams 2002) which included a preliminary design, cost estimate, schedule, and risk assessment.

From the 2002 analyses, four processes emerged for final consideration, one of which was steam reforming. Following formulation of the selection process two subcontractors (TWR and THORsm Treatment Technologies [TTT]) were asked to provide technical input for fluidized bed treatment of SBW by steam reforming, based on their experience and expertise. (TTT currently uses steam reforming to process commercial radioactive treatment operations at the Studsvik Processing Facility in Erwin, Tennessee, while TWR uses a similar process to treat black liquor from paper/pulp processing.) A bench-scale test facility was provided by the INEEL and an SBW surrogate was formulated to use as feed for the tests. The principal test objective was to resolve steam reforming process uncertainties regarding:

- Continuous operability of the process
- Solid product composition and handling/flow characteristics
- Off-gas composition, including NO_x
- Fate of radionuclides and mercury.

In addition to these tests with SBW, similar tests were performed in 2001 on simulated Hanford low activity waste liquid/sludge wastes.

3.2.1 Process Functions

The most recent process design anticipates that a Steam Reforming Facility will retrieve waste (including SBW, flushed tank solids, and NGLW from the INTEC TFF) and co-process these wastes through a fluidized-bed, steam-reforming reactor. The functions of this reactor are to:

- Convert the wastes to a solid product that retains most of the radionuclide and hazardous components
- Convert nitrates in the waste to nitrogen with minimum NO_x formation.

The process must also treat off-gas to remove and collect product fines, control emissions to comply with MACT requirements, remove radionuclides to applicable regulatory levels (NESHAP), and reduce NO_x levels to meet project directed emission targets. Additional steam reforming facility functions are to certify, package, and ship the final waste products to disposal sites. The steam reformed product solids will be withdrawn as granular bed particles directly from the reactor vessel and as elutriated fines from the sintered metal filter downstream. Since the reactor will operate at ~700°C the products will be cooled prior to packaging. Due to low bulk densities of the fines the product may also require densification before or during packaging in 2-ft x 10-ft waste containers.

The solid waste product will have a high radiation field due to its ¹³⁷Cs/¹³⁷Ba content. The steam reformed solids, co-processed SBW, and heel solids are expected to contain TRU radionuclides at concentrations greater than 100 nCi/g, the minimum value for acceptance at the WIPP. Therefore, they will be packaged and certified for disposal at WIPP as RH-TRU waste by the following procedures:

- Visual inspection and acceptance
- Canister closure by placement and locking of a lid
- Survey and decontamination as required
- Determination of canister weight, waste composition (including isotope concentrations of interest), and hydrogen generation rate
- Labeling and logging (for recordkeeping)
- Transfer to lag storage or loading into a shipping cask.
- Due to high radiation fields all packaging and certification operations with the canisters will be performed remotely.

Secondary wastes expected from the steam reforming facility include scrub liquor from scrubber blow down and scrub residual after process shutdown, spent GAC, and spent HEPA filters. The classification of the scrub waste is uncertain. The other secondary wastes are expected to be treated as mixed low-level wastes to comply with acceptance criteria at target disposal sites. After waste processing is complete the Steam Reforming Facility and associated subsystems will be closed for decommissioning.

3.2.2 Process Description

A process block flow diagram of the steam reforming process is shown in Figure 4. Though either the TTT or the TWR process could be selected the figure is sufficiently generic to represent either process.

The blended waste is retrieved into the processing facility via existing steam jets and mixed with an organic reductant that facilitates reduction of nitrates to nitrogen. This mixture is then pumped into the reactor bed through an atomizing nozzle. The reactor bed is an inert, inorganic granular material fluidized by a flowing gas entering the base of the reactor. Other solids (e.g., a catalyst or a second solid reductant) may also be added to the bed. The SBW and additives undergo various reactions that produce a granular solid mineral product (e.g., alkali carbonates, aluminum oxides, alumino-silicates, etc.) and off-gases (mostly nitrogen, NO_x, carbon dioxide, carbon monoxide, hydrogen, steam, and hydrocarbons).

Solid product emerges from the reactor either as elutriated fines or as granular bed product extracted from the bottom of the reactor. The proportion of bed product-to-fines depends on the choice of operating conditions and additives. Bed product and fines are combined in hoppers, cooled to 56°C, and transferred to disposal canisters. These are then weighed, inspected, sealed, decontaminated, labeled, and logged prior to interim storage or shipment to WIPP.

Off-gas from the steam reforming vessel is treated prior to release by the following series of unit operations:

- Filtration through a high temperature, pulsed, sintered metal filter to separate out elutriated product fines
- Thermal oxidization to consume hydrogen, carbon monoxide, methane, and unburned hydrocarbons
- Quench cooling
- Wet scrubbing to extract acid gases, soluble mercury, and residual volatile metals (e.g., Cs, Pb, Cd) that are not extracted by filtration
- HEPA filtration for removing ultra-fine particles
- Activated carbon filtration for polishing residual mercury and iodine.

Compliance with off-gas emission limits is verified by a continuous emission monitor (CEM) system prior to discharge.

Elevated mercury levels may develop in the recirculated scrub solution over time, necessitating periodic replacement of the solution. In addition some residual scrub solution will remain after processing of SBW is completed. The spent scrub solution from these two sources must also be treated for disposal. ¹³⁷Cs is the major contributor to the gamma radiation dose of the SBW and is expected to partition to the solid products and not to the scrubber liquor. The same behavior is expected for the TRU contaminants. For these reasons the treated scrubber liquor will likely *not* be disposable at WIPP, but *will* be disposable as mixed low-level radioactive waste, provided the hazardous metals in the solution are immobilized. The spent scrub is therefore treated to achieve this immobilization and ensure that the acceptance criteria of identified waste disposal sites (e.g., Hanford or Envirocare) are satisfied.

The primary unit operations constituting the scrub liquor treatment process are as follows:

- Partial neutralization
- Mercury precipitation
- Solidification.

Precipitation of mercury from the solution with sulfide will be accomplished by mixing and reaction with calcium sulfide (CaS). The product is mercuric sulfide (HgS, or cinnabar) that is highly insoluble. Precipitation of mercury in this manner immobilizes it in the grouted scrub product and ensures that the waste form meets land disposal restriction (LDR) standards for disposal at a MLLW disposal site. Partial neutralization of the scrub liquor is required to prevent sulfur/acid reactions that can form toxic H₂S during the mercury precipitation step.

The final step in treating the scrub liquor is to solidify the mercury-precipitated slurry by grouting. The three treatment steps (neutralization, precipitation, and grouting) are all represented in the single box labeled "Spent Scrub Tank" in Figure 4. Grouting will be done by mixing 25 wt% of treated scrub slurry with 75 wt% of dry additive (Portland cement, blast furnace slag, calcium hydroxide) in a screw mixer and pouring it directly into drums. The final waste form will meet Nuclear Regulatory Commission (NRC) requirements for performance grout. Each filled drum will be decontaminated, as required, and then cured for ~24 hours prior to being inspected and moved to temporary storage prior to shipment for disposal.

Two additional secondary waste streams, HEPA filters and spent GAC, will also be treated and disposed. HEPA filters may be treated in the INTEC filter leach facility. It is anticipated that GAC will be packaged and disposed of without treatment. However, this is contingent upon the material passing TCLP. Both wastes are expected to be disposed ultimately as mixed low-level wastes.

It should be noted that the preliminary process design configuration, described above, might not be what a steam reforming technology vendor may propose for treating SBW, particularly TTT. There are perhaps other methods of oxidizing the steam reforming reactor off-gas, and minimizing the number of off-gas treatment unit operations to meet emissions requirements and secondary waste quantities. The preliminary process design described above represents INEEL's initial thoughts, and optimization of the design has not been within the work scope performed.

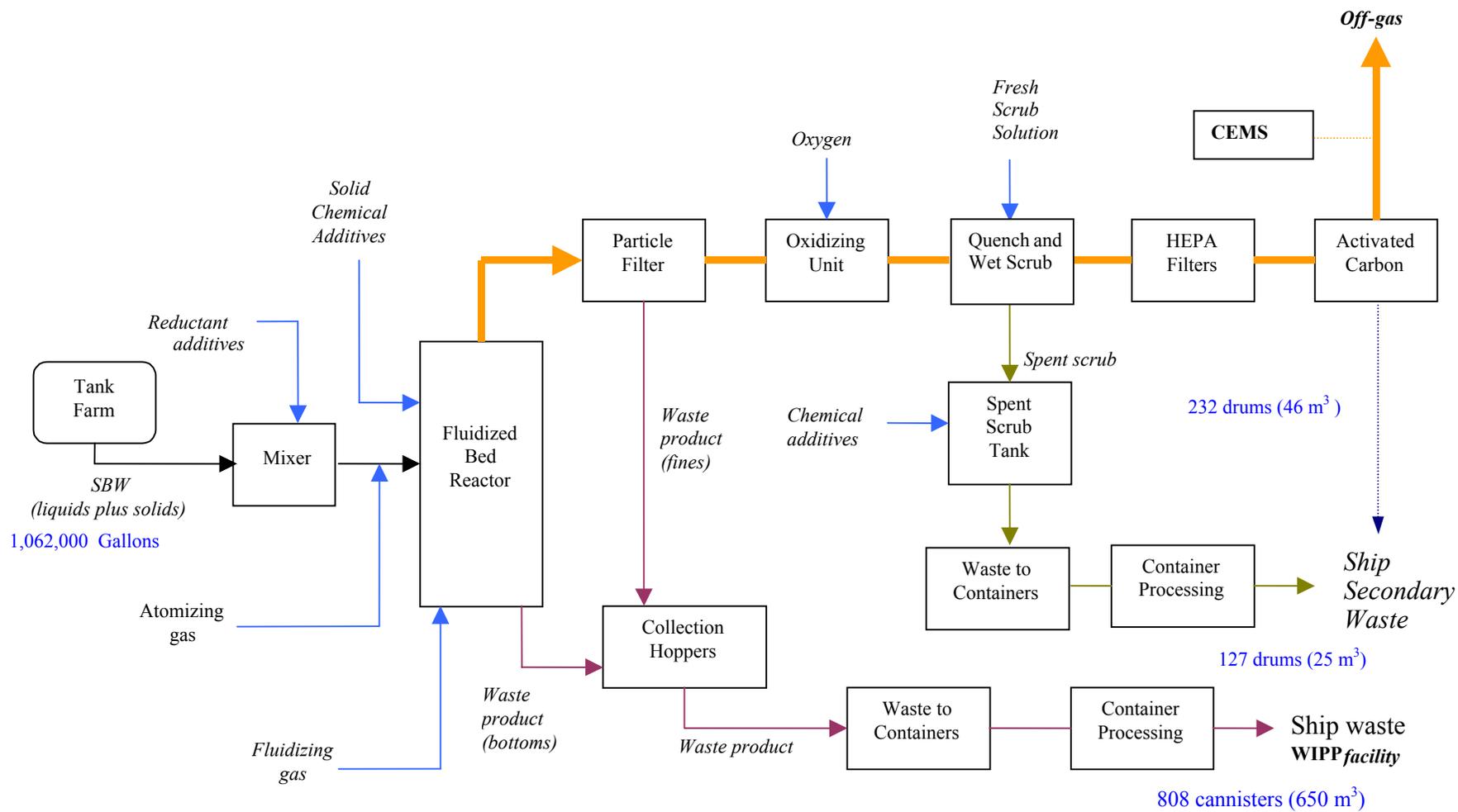


Figure 4. Block diagram of the steam reforming process.

3.2.3 Summary of Technical Performance

3.2.3.1 Processing Rate, Availability. A 3-year waste processing period is assumed, which includes six months of transition to processing radioactive waste. Facility availability is assumed to be 200 days per year and 24 hours per day during that period. This translates to an average processing rate of 88.5 gal/hr or 1.5 gal/min of combined (SBW liquid + heel solids) feed.

The facility availability is based on many years of operating experience at the INEEL working within DOE regulations. Changes in this operating environment could significantly alter the assumed availability and processing rate. Ideally, the fluidized bed reactor would operate without interruption. Fouling of feed spray nozzles and agglomeration of the bed are two scenarios that could hinder smooth operations; both problems were experienced during bench-scale demonstration tests. Failure to achieve a stable size distribution of the bed particles was also experienced, and could impact the facility availability factor, as could other process uncertainties discussed below in Technical Uncertainties and Potential Impacts.

3.2.3.2 Waste Products Quantity & Quality. The primary waste product from this option is the steam reformed solid from the SBW feed.

Secondary wastes include the grouted scrub, spent GAC, and contaminated HEPA filters. A quantitative summary of these waste products is shown in Table 5. It has not been determined whether spent GAC will require treatment prior to disposal as mixed low level waste. Volume and mass of the treated HEPA filters have not been estimated.

Table 5. Volumetric summary of waste products.

Waste Products	WM-180	WM-187	WM-188	WM-189	Total#	Total kg	Total m ³
Steam Reforming Solids, kg	220,000	160,000	230,000	260,000		860,000	650
RH canisters, # (a)	205	149	211	243	808		
CH Grout (from scrub), kg	14,000	9,000	15,000	14,000		52,000	25 ^a
CH or RH drums, #	35	22	36	34	127		
CH Carbon (spent GAC), kg	3,300	5,000	9,200	9,500		27,000	46
CH drums, # (b)	28	43	79	82	232		
HEPA Filters					Unknown		
Totals					1167	939,000	721

^a Assumes aggregated steam reformed solids can be densified to 1.33 g/cm³ bulk density

^b Assumes GAC will pass TCLP test and is direct-disposed after packaging in 55-gal drums

The solid steam reformed product consists of granular bed particles extracted directly from the fluidized bed reactor and elutriated fines that are collected from the off-gas stream by cyclonic action or high-temperature filtration. The bed particles are generally spheroidal in shape and may contain multiple solid phases, depending on processing conditions. In bench-scale tests they ranged between 0.2 and 1.1 mm in diameter. Bed particle densities were 2.7-3.6 gm/cm³ for individual particles and 1.2-2.2 gm/cm³ in bulk.

The fines product is a freely flowing ash-like powder with limited cohesiveness (forming loose clumps that readily crumble and fluidize when agitated). The portion of the fines collected by cyclonic

action has higher bulk density than that collected by filtration, and has a broad size spectrum ranging from 10 to as high as 300 μm . The filter product has a multimodal particle size distribution with a significant fraction in the 0.1-1.0 μm range, with bulk densities as low as 0.34 gm/cm^3 . The fines product bulk density can be increased by a factor of 70-160% by mechanical agitation or tamping.

Depending on reactor operating conditions (especially stoichiometric proportion of reductant added) the fines product may contain significant amounts of un-oxidized carbon (as high as 50 wt% in some tests). Data also show that several species (Pb, Cd, NH_3 , Cr, Ni, K, Re [Tc surrogate], Na, and SO_4) may be volatile and concentrate in the fine particles.

Radioactive properties of the waste products are shown in Table 6, based on the mass balances in Appendix A. Where a range is specified, the lower limit of the range was determined by using for each radionuclide the minimum concentration from the eight calculated mass balances (four feed cases [tanks WM-180, WM-187, WM-188, WM-189] for each of two flowsheets [TWR and TTT]), and the upper limit was similarly determined. Thus, to the extent that the numbers in the table are sums of minima and maxima (rather than minima and maxima of sums), the ranges are conservative.

Dose rates and heat generation rates have not been calculated for the waste compositions shown in Appendix A. However, these rates are expected to be very similar to those calculated from earlier mass balances (Bohn 2002). For steam reformed product, a canister contact dose rate of 4.5×10^4 mR/hr and a heat generation rate of 1.92 watts were estimated previously, based on decay to 2010.

For the grouted scrub product the corresponding dose rates from an earlier study (Quigley et al 2000) were 460 mR/hr and 0.0034 watts, respectively, based on an assumed set of radionuclide removal efficiencies in unit operations upstream of the scrubber. For the current mass balance these removal efficiencies were revised based on measurements from the FY 2003 steam reforming tests, and new radionuclide concentrations in the grouted scrub were calculated for the four tank farm feeds. The dose and heating rates for the grouted waste were then re-estimated by scaling the dose rate from the 2000 report by the Cs-137 ratio in the two grouts (Cs-137 is the major contributor to dose). The results indicate dose rates of 145-328 mR/hr and heating rates of 0.00107-0.00242 watts. If the four tanks were perfectly blended, the volume-averaged rates would be 225 mR/hr and 0.00166 watts, respectively. Thus, it remains uncertain whether the grouted scrub product would be contact-handled (CH) or RH. Additional work is needed to determine whether the contact dose rate can be reduced below the 200 mR/hr limit for CH waste.

For the drummed, spent GAC the estimated rates from the 2000 feasibility study were <5 mR/hr and <0.001 watts. Since iodine was not tracked in the FY03 tests these numbers have not been changed and are the best estimates available.

Table 6. Radioactive properties of waste products

Steam Reformed Solids	Range
All Radionuclides (Ci/canister)	520 – 1050
Fissile Gram Equivalent (g/canister)	110 – 280
²³⁹ Pu Equivalent Curies (Ci/canister)	4.3 – 8.0
TRU Content (nCi/g)	4,300 – 7,500
Grouted Scrub	
All Radionuclides (Ci/drum)	0.04 – 7.3
Sum of fractions (Hanford Cat 3)	0.003 – 0.03
Sum of fractions (NRC Class A)	0.016 – 0.3
TRU Content (nCi/g)	0.2 – 40
Spent GAC	
All Radionuclides (Ci/drum)	1.0E-6-4.3E-6
Sum of fractions (Hanford Cat 1)	0.003
Sum of fractions (Envirocare)	2E-5
TRU Content (nCi/g)	0

3.2.3.3 Size, Footprint of Processing Facility. Preliminary equipment sizing and facility layout were initially performed in 2002 (Williams 2002). This work was revised in late 2003 to reflect process changes (e.g., addition of scrub grouting operations) and updated mass balances. The revised plan drawings are provided in Appendix A. Equipment and room arrangements have not been optimized, as the effort to date has been focused on a preliminary process design only. Also, the latest mass balances, based on FY04 bench-scale test data, are not reflected in the drawings.

Per this layout the steam reforming facility would include two buildings— one for waste treatment, packaging, and certification and one for empty canister storage. These buildings have dimensions of roughly 150 ft x 250 ft and 55 ft x 65 ft, respectively, with footprints of 30,000 ft² and 3,600 ft². The processing building has four floors and includes 10,200 ft² of hot cell area. The hot cell consists of 3,600 ft² of processing area, 1000 ft² for packaging/handling of steam reformed solids, 2,000 ft² of storage space for filled waste canisters, and the balance (~3,600 ft²) for equipment maintenance, decontamination, cell access, and shielding walls. A control room, offices, personnel decontamination room, manipulator repair room, and other support areas are located on the ground floor.

The plot space estimates for the facility are summarized in Table 7. It should be noted that the facility plan was done for an earlier process design that did not include treatment of spent scrub liquor or packaging of spent GAC. Thus, there was no explicit allowance in the facility layout for these operations. The required area can be estimated from a recent study (Merrick, 2004) that included grouting scrub from SBW calcination. The hot cell space for grouting plus calcine packaging in Merrick’s study amounted to about 1000 ft². Assuming half of this area for scrub processing would result in an area of 500 ft².

Table 7. Steam reforming facility space estimates.

Area Description	Area ft ²
Process Equipment	3,600
GAC Polishing Columns	2,000
Grouting Equipment/Drum Storage	500
Waste Packaging and Canister Handling	1,000
Lag Storage for RH Canister	2,000
Administrative	10,400
Mechanical/Electrical	9,700

3.2.3.4 Effects of Scale, Variation with Throughput. Changing the scale of the process, i.e., designing for an accelerated treatment schedule, would have the most effect on the process operations performed on the lowest floor of the facility. Two areas in particular – the process hot cells and the lag storage area for full waste canisters – would be affected.

Major process equipment in the hot cells includes SBW feed tanks, steam reformer vessel, product cooling bins, and the off-gas treatment train. Decreasing the processing time would increase the floor space required for most of this equipment by the inverse ratio of the processing times to the two-thirds power. Reducing the schedule from 2.5 years to 1 year, the floor space for storage vessels would thus increase by a factor of $\sim(2.5/1)^{0.667} = 1.84$, and for process equipment by a factor of $\sim(2.5/1)^{1.0} = 2.5$.

Interim storage for RH waste canisters is driven by (a) the initial lag time between certification of the first canister of waste and actual shipment of it to WIPP, and (b) the excess of the rate at which certified waste canisters are produced over the rate at which WIPP can accept them. For a 2.5 year processing schedule the lag storage requirement is 304 canisters (176 from (a) and 128 from (b), above). For a 1-year schedule the lag storage requirement increases to 728 canisters, necessitating a 140% increase in the requirement from 2,000 to 4,800 ft². The processing areas for GAC beds to remove mercury from off-gas and for treating/package spent scrub liquor may also require scaleup by the same factor as for the process hot cells. The estimated plot space estimates for the facility with a 1-year processing schedule are summarized in Table 8.

Table 8. Steam reforming facility space estimates for 1 year processing schedule.

Area Description	Area ft ²
Process Equipment	9,000
GAC Polishing Columns	5,000
Grouting Equipment/Drum Storage	500
Waste Packaging and Canister Handling	1,800
Lag Storage for RH Canister	4,800
Administrative	10,400
Mechanical/Electrical	9,700

3.2.4 Technical Uncertainties and Potential Impacts

The *Sodium-Bearing Waste Treatment Applied Technology Plan* (INEEL/EXT-03-00477, June 2003) identified uncertainties resulting from technical and operational risk assessments. These uncertainties were identified primarily to guide the selection of a treatment technology and were not a complete listing of technical issues requiring resolution during detailed design efforts. The uncertainties were prioritized as High (H), Medium (M), or Low (L) risks. A high risk is categorized as an issue that is likely to occur and would have a significant (\$25 million - \$125 million impact) or critical (>\$125 million) consequence. Issues that are unlikely but have significant or critical consequences, or are likely but have marginal (\$5 million – \$25 million) consequences are categorized as medium risks. Issues that have a probability of occurrence of less than 10%, or a higher probability but negligible or marginal consequences are categorized as low risk. Table 9 lists and describes these uncertainties as well as their status as of the writing of this report.

Table 9. Summary of steam reforming uncertainties identified in risk assessment.

Uncertainty	Description	Status
Reformer Chemistry and Operational Mode (H):	Steam reforming chemistry is not understood sufficiently to define (a) target product (carbonates or alumino-silicate), (b) needed additive types (e.g., reductant) and blend ratios, (c) ideal processing temperature, and (d) off-gas composition.	Bench-scale tests of two commercial steam reforming processes were done in FY03 and 04. Parametric testing indicated sensitivities of product and off-gas composition to additive types, stoichiometry, and process temperature. Some questions remain regarding carbon and hydrocarbon contents of solids and off-gas fluidized bed stability, and control of bed agglomeration.
Product Characterization (M):	Handling characteristics and volume of product produced from unit feed volume are needed to design packaging system and plan for disposal of final waste forms.	Bench-scale tests have provided measurements of solid product mass per unit of SBW and density; also, qualitative data on product flowability, compactability, and particle sizes, and process-specific partitioning between coarse and fine particles.
Product Densification (L):	The level to which bulk density of steam reformed solids may be increased is not known, leaving uncertainty as to the final waste volumes that must be transported and disposed.	Fines product was compacted during FY03-04 steam reformer tests by hand tamping and vibration. Overall product bulk density achievable by remote, mechanized means has not been determined.

Table 9. Summary of steam reforming uncertainties identified in risk assessment. (continued)

Uncertainty	Description	Status
Off-gas Characterization (H):	Off-gas compositions and effectiveness of emissions control technologies must be established by pilot-scale testing.	Off-gas measurements of H ₂ , CO, CO ₂ , CH ₄ , H ₂ O, NO ₂ , NO, SO ₂ , HCl, Hg, and THC were made in bench-scale tests at various locations in the off-gas system. Not all measurements were done at all times and locations and some measurements were unreliable. In particular, THC measurements were limited. Some significant questions were raised (see discussion following table).
Speciation & Fate of Key Components (H):	Data are needed on fate and speciation of Hg, Cs, Tc, and I in order to design off-gas system to meet emissions requirements.	Elemental and oxidized Hg concentrations were measured at some off-gas locations in bench-scale tests. Cs and Re (Tc surrogate) concentrations were measured in solid products and scrub solutions. Iodine data was not obtained.
Thermal Oxidizer Kinetics (M):	Due to high water content and low oxygen kinetic limitations could drive destruction efficiency for CO and organics below what is required.	Bench scale thermal oxidizer was tested in FY03-04 pilot tests. Measured output CO and THC concentrations indicate the oxidizer was effective.
Off-gas Treatment Configuration (H)	Off-gas system design has not been optimized. Off-gas characterization data are needed before this can be done.	Off-gas measurements from FY03-04 bench-scale tests are now available. Optimization of the off-gas system has not been performed.

Mass balances were developed for the preliminary process design to provide a basis to size equipment, determine feed chemical requirements, determine utility requirements, estimate emissions and determine waste volumes, compositions and properties. In order to prepare the mass balances a set of design basis elements (DBEs) was assembled in lieu of hard data addressing the technical uncertainties. The DBEs are assumptions about uncertainties and represent a level of risk to the successful implementation of a production steam reforming facility. Each DBE will require acceptance of technical risk or Applied Technology/Engineering development/demonstration efforts for validation before the next process design steps are taken. Fifty-five DBEs are identified for the preliminary process design. It is expected that more would be identified if this treatment option were selected for implementation. The individual DBEs are amplified with background information, references, explanation, and, in some cases, a discussion of uncertainties in Appendix A. The following is a summary discussion of major outstanding technical uncertainties.

3.2.4.1 Feed.

- There are uncertainties in the physical properties of the SBW inventories in tanks WM-180, 187, 188, 189, in NGLW, and in tank farm heel solids. There are also uncertainties associated

with mixing and transfer of heel solids for co-processing with liquid SBW. These uncertainties are discussed in Section 2.

- The steam reforming process assumes that heel solids will be co-processed with the SBW liquid. During Phase 2 bench-scale tests in FY04 the initial test feed contained both SBW simulant and simulated heel solids. Severe nozzle plugging problems developed until the solids concentration was reduced. This brought to light an uncertainty regarding co-processing of feed solids. At a minimum it indicates the need for feed nozzle design evaluation at a production scale.
- The target carbon ratio in adding reductant to the feed has been set at 5.3 moles C per mole NO_3^- (2.7 moles C from sucrose and 2.6 from solid carbon in the bed). This ratio represents a compromise between maximizing NO_x destruction and minimizing unburned carbon (or hydrocarbons) in the steam reformed products. It was determined on the basis of the FY03-04 bench-scale tests where NO_x destruction efficiencies of 89-95% were achieved.
- No addition of solid catalyst is needed. This assumes there is already sufficient of the catalytic agent in the SBW to achieve the needed NO_x conversion rate. However, a threshold concentration, below which there is insufficient or no catalytic effect, has not been determined.

3.2.4.2 Bed Stability.

- A major operational requirement implementing the steam reforming technology is to be able to control the dynamics of bed particle growth and attrition so that the growth of particles from the input of solids in the feed is balanced by diminution through friction, collision, fracturing and spallation. In addition, the total volume of the bed must be maintained within specified limits through elutriation of fines and/or withdrawal of bed product from the vessel. Finally, the bed must not be prone to agglomeration. When these criteria are satisfied the bed remains fluidized throughout operation and the bed particle size distribution eventually becomes static or mildly oscillatory within static limits. Under these conditions the bed is described as “stable”. Such a stable condition was not demonstrated during the FY03-04 bench-scale testing. Rather, a fairly broad spectrum of particle sizes was observed during most of the tests, and bed agglomeration occurred during most (if not all) of the tests. Thus, a major outstanding uncertainty is whether or not a stable bed can be achieved and maintained through extended operating periods.
- Liquid fed to the steam reformer is atomized by a pressurized gas stream. The intensity of the atomization is characterized by the ratio of the standardized volumetric flow rates of gas and liquid (nozzle-air-ratio [NAR]). This ratio has been arbitrarily set at 800 (average of high and low values that were successfully tested). The NAR value influences the bed dynamics through its impact on particle attrition and will almost certainly require adjustment in the search for a set of conditions that ensure a stable bed.

3.2.4.3 Stream Factor.

- The facility design is based on a 2.5-year operating schedule. This, in turn, assumes a three-year processing time that allows six months of start up and 200 days/year of productive operations. Bench scale testing clearly indicated the potential for off-normal conditions resulting in frequent shutdown of the process. The assumption of 200 days of operation per year thus remains an uncertainty that (if overly optimistic) could impact the schedule.

3.2.4.4 Reformer Product.

- The mass balance assumes a 58-42% split of the reformer product solids between coarse bed particles and fines collected in the filter. Process equipment is sized partly on the basis of this split ratio. However, the bench-scale tests showed a wide variation (94-2% in the TWR test, with 4% in the cyclone product) so the assumed split ratio constitutes an outstanding uncertainty. Additionally, it has not been determined whether it is feasible to recycle both filter and cyclone fines to the reformer and eliminate the fines product altogether.
- Fines product is very airy and light with a low bulk density ($\sim 0.3 \text{ gm/cm}^3$). Handling such a product will likely be problematic due concerns with suspension of respirable fines containing alpha-emitting radionuclides. The extent of these problems and their resolution constitutes another technical uncertainty. Included is the question of feasibility of remote mechanical densification to reduce product volume where roughly half of the product mass (and up to 90% of the initial product volume) is fines.

3.2.4.5 Mass Balance.

- Mercury mass balances were done for all FY03-04 tests and reasonable closures were obtained. From the mass balances the performance of the GAC bed in removing mercury from the off-gas was assessed. Performance during the FY03 tests was poor with only 14-76% of the off-gas mercury removed by the GAC. Resulting stack concentrations of mercury were several times higher than the MACT limit. Performance during the FY04 tests was excellent with mercury removal efficiencies $>99.5\%$ and stack concentrations less than half the MACT limit. The difference in performance was attributed to saturation of available sorption sites in the GAC by unburned hydrocarbons in the off-gas from the earlier tests and consequent poor sorption of mercury. This points to the fact that unburned organic carbon in the off-gas must be tightly controlled in order to achieve MACT-compliant mercury emissions from the process. Whether this can control can be achieved for extended periods of time will need to be demonstrated, especially in light of the following uncertainty.
- In FY03-04 bench scale tests significant amounts of organic carbon were observed in the fines products. The amount of carbon in the solid product was sensitive to the reductant:SBW feed ratio. In one of the FY04 tests a noteworthy discrepancy was observed in the hydrogen balance (as discussed in Appendix A, Section A-6.1). Analysis of the data suggests that either the hydrogen concentration was higher than measurements indicated and/or a significant amount of unburned hydrocarbons were present in the off-gas from the steam reformer. Either possibility raises issues in regard to safety, hydrogen generation in steam reformed solids, accumulation of organics or carbon in scrub liquor, and the likelihood of rendering GAC columns ineffective in removing mercury from off-gas.
- Radioactive iodine will be present in SBW could be the major dose contributor in the stack gas. The fate of iodine in the steam reforming process has not been demonstrated to date.

3.2.4.6 Filtration Temperature.

- During bench-scale tests the temperature of the sintered metal filter was $>500^\circ\text{C}$, though a temperature of 400°C was recommended by a commercial vendor to capture semi-volatile metals (especially Cs and Tc) and still prevent mercury from condensing and plugging the filter. In some tests Cs and Re (Tc surrogate) were detected in the scrub solution suggesting some penetration of the filter by these semi-volatile metals. Heat loss is expected to be a

smaller factor in a production scale system, so a cooler may be required to reduce the off-gas temperature upstream from the sintered metal filters. The upper limit on the filtration temperature, however, is not known; if it were the off-gas cooling requirement could possibly be eliminated.

3.2.4.7 Scrubbing System Design.

- The current process flow diagrams show an acidic scrub to extract mercury and acid gases from the off-gas. In bench-scale tests to date, however the scrub solution was plain water that became slightly acidified ($\text{pH} > 4.5$) by the dissolution of acid gases. Moreover, the measured fraction of mercury scrubbed in these tests was $< 0.5\%$. The assumed fraction in the system design is ~ 100 times higher (44%), presumably due to higher HNO_3 concentrations in the scrub. Whether this can actually be achieved has not been demonstrated. Moreover, the benefit of doing so may be marginal, since the GAC columns could be sized to capture all mercury (assuming the above-cited uncertainty is resolved). If the scrub were basic rather than highly acidified with HNO_3 , neutralization and mercury precipitation may be unnecessary and acid gas scrubbing would be more effective. In addition the need for scrub blow down may vanish and the volume of scrub requiring grouting may be significantly reduced. Total scrub recycle may be possible since mass balances from the tests indicate $> 90\%$ of Cl and fluoride (F) partitions to the solids (however, mass balance closure for F was poor—50% or less). Thus, there remains considerable uncertainty regarding the design requirements and optimization of the scrubbing system.

3.2.4.8 Facilities Interfaces.

- A comparison of projected utilities requirements of the steam reforming process against INTEC capabilities is needed to ensure that no modifications are needed to these systems. A new SBW steam reforming facility would be interfaced with existing INTEC facilities (INTEC TFF, main stack, and APS) and infrastructure (notably, the low pressure steam system, water systems [de-mineralized, de-ionized, distilled, fire water, treated water], power grid for electricity, and high-pressure air supply for process maintenance). The existing facilities have set capacities that must be accounted for in the process design and new equipment selection.

3.3 Cesium Removal and Immobilization

Filtration, ion exchange, and grouting are common practices that have been used to treat various radioactive wastes at West Valley, Savannah River, Hanford, Oak Ridge and other DOE complex sites.

Two types of filters have been tested for solid/liquid separation at the INEEL. Tests in 1997-1998 demonstrated the removal of undissolved calcine solids and undissolved solids in SBW using a cross-flow type filter (Tripp, 1997; Mann, 1998). As part of the FY 2000 feasibility study of the CsIX process (Raytheon, 2000, Appendix F), initial tests were performed to demonstrate a cartridge type filter for removal of solids from SBW. The cartridge filter demonstration used a 0.13-ft^2 filter and test feeds of TiO_2 and $\text{TiO}_2 - \text{SiO}_2 - \text{ZrO}_2$ mixtures. An improved SBW solids simulant has been developed (Barnes, 2003) based on additional SBW solids characterization in late FY 2003. Reviews of both crossflow and Fundabac filtration have been performed in light of this characterization (Pao, 2003)

Development of ion exchange technology for the selective removal of cesium from SBW, NGLW, and dissolved calcine began in the mid-1990s (Miller et. al, 1995). Gary Stegen proposed processing SBW by cesium ion exchange followed by grouting in late 1997 (Stegen, 1997). Alan Herbst and others began developing and testing grout formulations for anticipated INEEL liquid wastes in 1996 (Herbst,

1996), and in later years the grout stabilization development program included testing formulations for the liquid effluent from the CsIX process. The original premise behind the CsIX/TRU grout process was that the SBW would be classified as a TRU waste (either as feed to treatment or certainly sans the cesium and tank solids) and could therefore be disposed at WIPP. Cesium was to be removed in order to reduce the dose rate for the waste product containers to under the limit for contact handled waste containers. This was important because of the limited capacity of WIPP for remote handled waste, and to reduce costs of the treatment facility as well as for shipment to and disposal at the repository. As of this writing, a permit for accepting RH waste at WIPP has not been granted. Engineering evaluations and Feasibility Studies were performed for the treatment of SBW with this process in 1998 (Losinski, et. al 1998), 1999 (Valles, et. al, 1999) and 2000 (Raytheon, 2000). Evaluation of this processing alternative was also performed in the High-Level Waste and Facilities Disposition Environmental Impact Statement. Development of the CsIX/TRU Grout Process for treating SBW continued at the INEEL through CY 2003.

3.3.1 Process Functions

The most recent process design anticipates that a CsIX TRU Grout Facility will retrieve waste (including SBW, flushed tank solids, and NGLW), treat these wastes, and certify, package, and ship the final waste products to disposal sites. After completion of processing, the CsIX TRU Grout Facility and associated subsystems will be closed for decommissioning (although, as with other proposed SBW treatment systems, it could be left in place to support closure of INTEC and other INEEL facilities).

The CsIX TRU Grout process is intended to treat the SBW so that the majority of the waste products can be disposed of as CH-TRU waste. Liquid waste would be treated in the CsIX TRU Grout process by the following primary unit operations:

- Partial neutralization
- Solid-liquid separation
- Cesium ion exchange
- Solidification.

Partial neutralization of the SBW is required, prior to being fed to the ion exchange columns, to prevent excessive chemical degradation of the baseline ion exchange media by acid.

Solid-liquid separation is required for two reasons: (1) to remove high activity solids that would contaminate the grout product (primarily with ^{137}Cs), and (2) to prevent the solids from collecting in and interfering with operation of the ion exchange columns.

^{137}Cs in the SBW is the major contributor to the gamma radiation dose of the SBW. Removal of the cesium from the bulk liquid is necessary to reduce the dose of the treated liquid to less than 200 mrem/hr to meet WIPP WAC for CH waste.

The Cs-free liquid is solidified in order to meet the “no free liquid” criterion for disposal of waste at WIPP.

The spent CsIX sorbent will have a high radiation field due to its $^{137}\text{Cs}/^{137}\text{Ba}$ content and is also expected to be contaminated with TRU radionuclides to greater than 100 nCi/g, the minimum value for acceptance at the WIPP. Therefore, it would be packaged and disposed of at WIPP as RH-TRU waste.

The solids from the INTEC TFF tanks, as well as the solids removed from the liquid SBW (essentially the same material with an expected smaller particle size distribution), contain sufficient

activity to be classified as RH-TRU. These solids would be separated from the slurry feed stream, dried and packaged to meet the WIPP RH-WAC, and disposed of at WIPP. The function of the solids treatment steps of decanting, filtration and drying is to reduce the volume of the waste product and produce a waste meeting the WIPP WAC.

3.3.2 Process Description

SBW and NGLW would be transferred from INTEC storage tanks by currently existing steam jets to the treatment facility. One tank (WM-187) contains the bulk of the SBW solids, while three other 300,000-gal tanks (WM-180, WM-188 and WM-189) and three 14,000-gal tanks (WM-100, WM-101, WM-102) contain the remainder of the waste to be processed.

A process block flow diagram of the anticipated CsIX/TRU Grout process is shown in Figure 5. The treatment facility would have both liquid and solids processing sections. SBW from Tanks WM-180, WM-188, WM-189 and NGLW would be processed in the liquid processing section, while the inventory of Tank WM-187, containing the bulk of the undissolved heel solids from the other tanks, would be processed in the solids processing section.

The first step in treating SBW liquid is to partially neutralize the waste. Neutralization is performed to reduce chemical degradation of the ion exchange media by acid and to enhance grout formulation and curing. Neutralization is performed by mixing the SBW with a 50% caustic solution. A jet mixer at the discharge of the recirculation/feed pump enhances mixing and acid adjustment. There will be two tanks, one for acid adjustment and the other for process feed. The feed pump just performs recirculation during acid adjustment. Cooling water in the cooling coils or jacket removes the heat of solution and neutralization. A control valve is opened to a set point value while some liquid recirculates when the tank is feeding the process.

The second step in treating SBW liquid would be to remove trace amounts of undissolved solids by filtration. The undissolved solids are small particulate (~1-100 micron) and are quite radioactive. If the solids are not separated and removed from the liquid they could contaminate the grout waste product such that the CH dose limit would be exceeded. The solids would be removed using a cross-flow filter. The cross-flow filtration system uses a large recirculation flow to ensure a high axial velocity to minimize particle buildup on the walls of the sintered metal filter elements. The particle concentration in the slurry to be filtered is controlled via a turbidimeter to ensure that the total suspended solids are less than 30 g/L. The turbidimeter controls a steam jet orifice that transfers slurry to the clarifier upon reaching the set point.

The third step in treating SBW liquid is to remove cesium by ion exchange. The baseline ion exchange media is IONSIV IE-911, a commercially available CST granular product with high selectivity for cesium. Columns would be preloaded with fresh CST. It is envisioned that the waste will pass through three columns in series. When one column becomes loaded with cesium, it would be taken off-line and the media would be in-place rinsed and dried. Then the entire column, with spent media, would be loaded into a waste canister. A new column would be rinsed to remove virgin sorbent fines and placed in the removed column's position. The control sequence will continually switch the 1st column feed to the next column such that a typical sequence will be 1 – 2 – 3, 2 – 3 – 4, 3 – 4 – 1, etc. There will be four column positions but only three columns used at any particular time, the other being replaced with a new one.

The final step in treating SBW liquid is to solidify the ion exchange effluent by mixing it with Portland cement, blast furnace slag and slaked lime (calcium hydroxide) in a mixing vessel. The ¹³⁷Cs depleted SBW should be partially neutralized prior to final waste forming to avoid negative interaction /

degradation of the cement. The partial neutralization step in front of CsIX is performs this activity. The mixture would be discharged into 55-gal drum. The drum would then be moved into a decontamination area where the drum exterior would be checked for contamination and decontaminated if needed. The drum would then be held for about 24-hours to complete curing. After additional inspection, the drum would be moved to temporary storage to await shipment to WIPP.

Tank solids would be treated separately from the liquid SBW. Undissolved solids from WM-187 would be received in the treatment facility as a slurry of varying solids concentration. The receiving tanks are used as solids settling and decant tanks to increase and maintain the solids concentration in the feed to a filter. Sodium hydroxide is added to the settling tanks to promote flocculation that reduces settling time. After concentration by settling, the slurry is mixed, sampled, and then pumped to a filter that contains multiple filter elements or “candles.” The envisioned filter would be of the type manufactured by Fundabac. Solids collect on a filter cloth, while filtrate passes through the cloth and discharges at the top of the unit from a central collection tube. When the solids cake has built up to a given thickness, feed flow is stopped, and steam is passed through the filter to dry the solids in place. Then compressed air is used to expand the filter cloth, causing the solids to fall by gravity into a waste canister.

Waste water decanted from the solids receiving tank, filtrate from the Fundabac filter and wash waters from other plant operations is collected in a waste water tank. The wastewater is treated by evaporation in the existing ETS. The concentrate from the ETS is returned for treatment through the SBW liquid treatment portion of the facility. Overhead from the ETS is condensed and then fractionated in the existing Liquid Effluent Treatment and Disposal (LET&D) system, another facility at the INTEC. Overheads (water vapor) from the LET&D are released to the atmosphere through the INTEC stack. LET&D bottoms, which consist of about 12 molar nitric acid with mercury and chloride impurities, would be sent to WM-100, WM-101 or WM-102 for future processing in the SBW treatment facility.

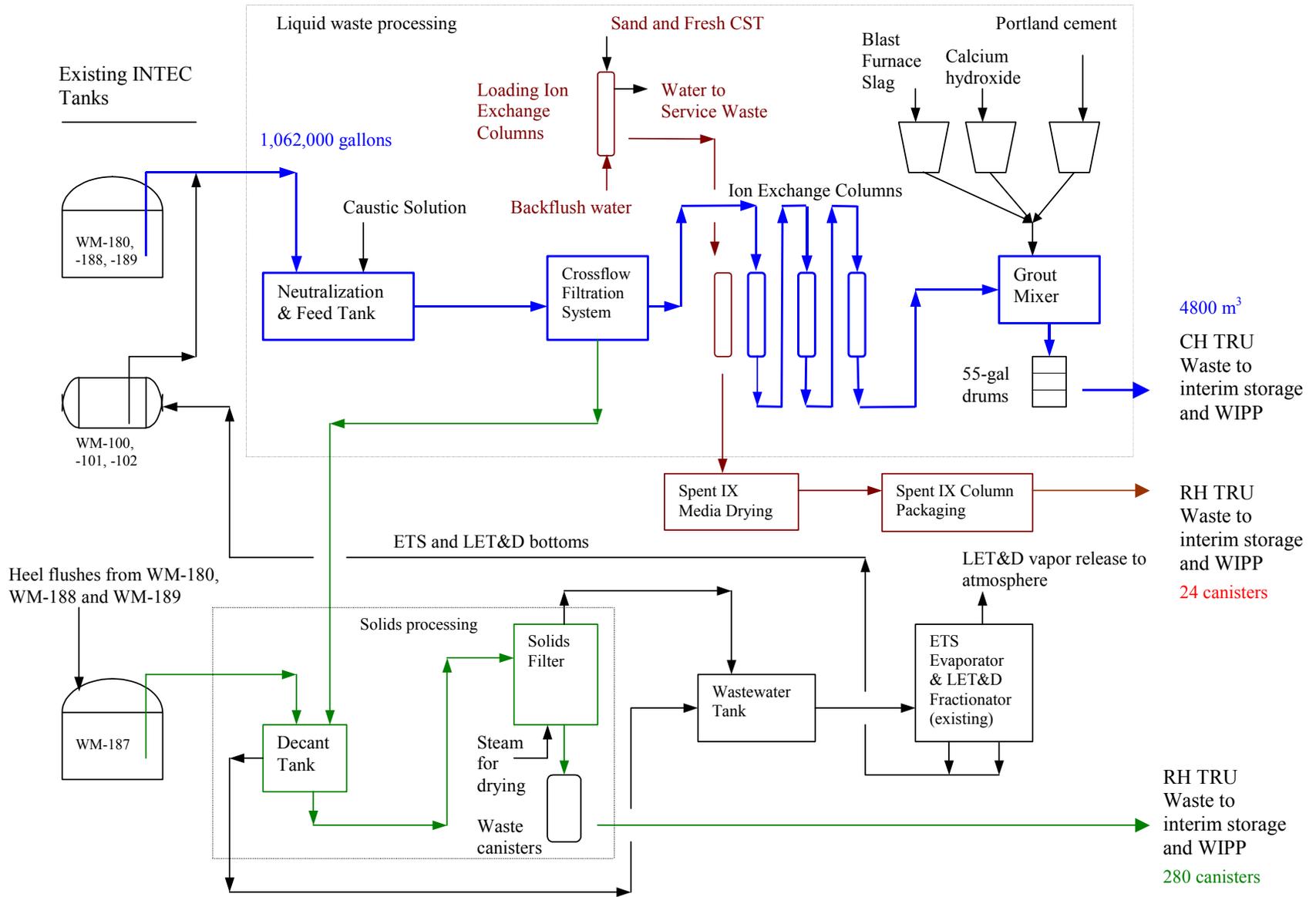


Figure 5. CsIX/TRU grout block flow diagram.

3.3.3 Summary of Technical Performance

3.3.3.1 Processing Rate, Availability. A 3-year waste processing period is assumed, which includes six months of transition to processing radioactive waste. Facility availability is assumed to be 200 days per year and 24 hours per day during that period. It is also assumed that a throughput rate of 5 vol% in excess of the feed volume should be allowed for. This translates to an average liquid processing rate of 85 gal/hr or 1.4 gal/min and a feed rate of slurry to the solids processing equipment of 65.9 gal/hr or 1.1 gal/min. This processing period can be decreased, but at the cost of increased facility size. This is discussed later.

The facility availability, and thus processing rate, is based on many years of operating experience at the INEEL working within DOE regulations. Changes in this operating environment could significantly alter the assumed availability and processing rate either positively or negatively.

A formal RAM analysis has not been performed for this preliminary process design. However, some qualitative statements can be made about the operability and maintainability of the envisioned process and facility. The proposed unit operations are, for the most part, standard industrial practices routinely performed. Mean time to failure data would exist to perform formal analyses for the process. Some experience factors may need to be applied to account for remote operation required by a relatively high radiation environment.

There are at least two issues that may affect operating time, but it is believed they can be resolved by detailed engineering efforts. The first is generation of out-of-specification product; appropriate decoupling of unit operations and interim storage will resolve this, but a drawback is perhaps capital cost. The second is restriction of the crossflow filter pores by particles that cannot be dissolved away; this can be resolved by designing the filter for remote removal and replacement. Other issues may be discovered during detailed design, but major ones are not anticipated.

As previously stated, new facilities would be interfaced with existing INTEC facilities to achieve the SBW treatment objectives with this option. The existing facilities have set throughputs and waste composition acceptance criteria that must be accounted for. These must be accounted for in the process design, and have been in the data presented in this report, or new equipment, systems, and/or facilities provided for.

3.3.3.2 Waste Products Quantity & Quality. Three primary waste products would be produced for disposal with this option. A volumetric and waste package summary of products is shown in Table 10. Tank heel solids and spent ion exchange media are packaged in 2-ft diameter by 10-ft RH canisters. The ion exchange effluent is grouted and packaged in 55-gal drums as CH waste.

Table 10. Volumetric summary of waste products.

Waste Products	WM-180	WM-188	WM-189	NGLW	Decommissioning	Total	Total m ³
Tank Solids							223
RH canisters	87	90	89	13		279	
Spent CST							10a
RH canisters	5	8	7	1	3	24	
CH Grout							4,800
CH drums	6,820	8,030	7,950	1,200		24,000	

a Volume of spent CST based on volume of IX columns and includes sand filter

Tank solids would be dried with steam to a moisture content of about 25 wt% and will be friable with a bulk density of about 0.68 g/cm³. This density is based on a measured density of a sample of solids, washed and dried, taken from WM-187 in FY 2004. It is not known whether the dried filter cake density will differ from this value. They would then be packaged in WIPP RH TRU canisters, which have a capacity of 0.89 m³. On average, the solids waste will fill 90% of the canister volume, or 0.8 m³. Approximately 2-inches of silica gel, equivalent to 0.015 m³ per canister will be added on top of the waste.

Spent ion exchange columns would be disposed in RH-TRU waste canisters, one column per canister. Each column contains about 8 ft³ of CST sorbent (bulk density of 60 lbs/ft³, particle density of 2.44 g/cm³) and a sand volume of 0.9 ft³. A spent column will be washed with water to reduce the acidity of the spent ion exchange media and then dried to a moisture content of 25 wt% or less to meet WIPP WAC. Twenty-one spent columns are calculated to be produced during treatment, and three additional columns would be packaged for disposal during decommissioning.

The CH monolithic grout is 75 wt% waste partially neutralized with 50% NaOH, and contains 7 wt% calcium hydroxide, 6 wt% blast furnace slag and 12 wt% Portland cement. The density of this waste form is 1.5 kg/m³. Grout will be packaged in 55-gal drums. A drum fill volume of 0.2 m³ is assumed, equivalent to approximately 94% of the capacity of standard 55-gal drums.

Radioactive properties of the waste products are shown in Table 11. Dose rates and heat generation rates have not been calculated for waste compositions shown in the present mass balances. However, the grout dose rate is expected to be very similar to that calculated previously. Estimated surface dose rates of 11-21 mR/hr for grout from WM-180 waste and 74-84 mR/hr for grout from WM-188 waste, based on decay to 2010. It was concluded that one-third of the waste drums from the CsIX process would have a surface dose rate less than 50 mR/hr and two-thirds between 50 and 100 MR/hr if shipped in the 2010-2012 time period. The estimated heat generation rate for the grouted waste is 0.04 Watts.

Shielding calculations for the spent ion exchange media waste indicate the RH canister, with 0.5-inch of steel shielding, would have a surface dose rate of 758 R/hr. A normal shipping cask, again with 0.5-inch of steel shielding on the canister, would have a 1-meter dose rate of 5.8 mR/hr.

The estimated average surface dose rate for the waste solids canisters in 2010 is 86 R/hr and heat generation rate 3.2 watts/canister.

Table 11. Radioactive properties of waste products

Grouted Waste	Range
All Radionuclides (Ci/drum)	7.15 – 14.0
Fissile Gram Equivalent, g/drum	3.3 – 6.4
²³⁹ Pu Equivalent Curies, Ci/drum	0.082 – 0.11
TRU Content (nCi/g)	290 - 400
Spent Ion Exchange Media	
All Radionuclides (Ci/canister)	8,600 – 12,000
Fissile Gram Equivalent, g/canister	1.1 – 2.3
²³⁹ Pu Equivalent Curies, Ci/canister	0.03 – 0.038
TRU Content (nCi/g)	104 - 135
Dried Tank Solids	
All Radionuclides (Ci/canister)	60 -320
Fissile Gram Equivalent, g/canister	15 – 47
²³⁹ Pu Equivalent Curies, Ci/canister	0.3 - 5.2
TRU Content (nCi/g)	580 – 10,200

3.3.3.3 Size, Footprint of Processing Facility. Preliminary equipment sizing, based on the throughput noted above, has been performed. The sizing information provided the basis for generating layout (plan) drawings for a treatment facility that would accommodate the preliminary process design as described in previous sections. Details and the plan drawings are located in Appendix B. Equipment and room arrangements have not been optimized. Sufficient engineering design has not been performed to provide a strong basis for all of the areas of the facility, as this effort has only been focused on a preliminary process design.

The envisioned facility for the preliminary process design would encompass an area approximately 145 ft wide by 364 ft long at the ground level. It includes waste loading and canister handling operations in the lower level; hot cell process equipment for both liquid and solids processing on the ground floor and non-radioactive activities on the second floor. Equipment in the process hot cell includes the ion exchange columns, seven tanks and both the cross flow and Fundabac filters. The control room, offices, a decontamination room, a manipulator repair room and other support activities are also located on the ground floor. A summary of plot space estimates is given in Table 12.

Table 12. Estimated plot space for cesium removal facility.

Area Description	Area, ft²
Process equipment	2,000
Grouting equipment and drum storage	13,000
Waste packaging & canister handling	5,800
Lag storage for RH canisters	800

3.3.3.4 Effects of Scale, Variation with Throughput. Changing the scale of the process, i.e., designing for an accelerated treatment schedule, would primarily affect two areas of the facility – the process hot cell and the grouting operation floor space. Minimal effects are expected in the basement with waste packaging, canister handling, and canister storage, based on this preliminary process design effort.

Equipment in the process hot cell includes the ion exchange columns, seven tanks and both the cross-flow and Fundabac filtration equipment. A maximum of about a 40% increase in capacity of the ion exchange columns (in length and diameter) could be achieved without exceeding the dimension that would fit a RH 2-ft by 10-ft canister. Thus, reducing the operating schedule up to about 1.8 years would have no effect on the ion exchange columns. Reducing the schedule further would mean more frequent change-out of columns.

Keeping all other factors equal, decreasing the processing schedule would increase the floor space required for process tanks by the ratio of the decrease to the two-thirds power. For example if the schedule was decreased from 2.5 years to 1 year, the floor space would increase by $(2.5/1)^{0.667} = 1.84$ or an 84% increase. Approximately the same increase in space requirements could be expected for the filters, although a trade off study would be needed to better evaluate whether to increase the filter size or install multiple smaller filters.

For the 2.5-year, 200 operating days per year operating schedule, 24,000 drums of grout are produced, equivalent to an average of 2 drums per hour. If in-drum mixing (not the baseline) were used, multiple grouting lines would be required. The FY 2000 feasibility study for the CsIX TRU grout process (Raytheon, 2000) included three grouting lines. However, by using an out-of-drum mixer, a single line could meet the production rate in 2.5 years or a shorter schedule as well. The area required for grouting equipment would increase by the ratio of the schedule decrease to the two-thirds power. However, the area required for storage of grouted waste drums depends only on the lag storage requirement. The lag storage in turn depends of the rate at which WIPP can receive shipments and the initial lag between start of production and sending the first shipment. The projected/assumed shipping rate of CH handled grout to WIPP is 17 shipments (3 HalfPACTs per shipment, 7 drums per HalfPACT) per week for about 68 weeks of the 2.5-year operating schedule (US DOE-ID, 2003). If the treatment schedule is shortened, it is likely WIPP could receive additional shipments per week. Thus additional storage is not required because of shipping rate limitations. Also, the initial lag time for sending shipments to WIPP could likely be shortened for a shorter schedule, resulting in no dependency of drum storage area on processing schedule.

Insufficient design work has been performed on the RH packaging systems for the CsIX process to evaluate the effect of reducing schedule on basement floor space. The number of ion exchange columns would decrease for a shorter schedule because each would hold more ion exchange media, hence it is unlikely there would be any significant change in floor space for spent ion exchange column packaging. For the same 1-year processing schedule, the rate of production of solids canisters would increase from one per 43 hours to one per 17 hours. Whether this higher rate would require multiple packaging lines has yet to be determined.

Finally, the interim storage for packaged waste is dependent on the initial lag period between producing the first container of waste, having approval to ship that container to WIPP, and the rate at which WIPP can accept waste. While the process will generate, for a 2.5 year schedule, an average of 800 drums of grout and 9 canisters of solids per month, it will take about 3 months to generate the second spent IX column. Perhaps this period could be shortened by starting up on waste with the highest cesium content. However; it is not certain what WIPP would require before qualifying the spent ion exchange media waste canisters.

Based on discussions with WIPP, it is expected that the disposal facility can receive at least 6 RH canisters per week from the INEEL, or about 300 per year. The total number of RH canisters generated for a 2.5-year production schedule is about 300, 3 would be disposed during decommissioning. A shorter schedule would generate less than 300, but more than 280. Hence, WIPP could receive waste without any increase in storage at the INEEL for any treatment schedule of a year or longer.

The facility plot space estimated increase, due to an increased throughput/reduction in processing period to one year, is given in Table 13.

Table 13. Estimated increase of facility plot space for cesium removal facility.

Area Description	Area, ft ²
Process equipment	3,400
Grouting equipment and drum storage	21,000
Waste packaging & canister handling	5,800
Lag storage for RH canisters	800

3.3.4 Technical Uncertainties and Potential Impacts

The *Sodium-Bearing Waste Treatment Applied Technology Plan* (INEEL/EXT-03-00477, June 2003) identified uncertainties resulting from technical and operational risk assessments. These were, for the most part, uncertainties that would have supported the selection of a treatment technology and were not complete listings of technical issues requiring resolution to support detailed design efforts. The uncertainties were prioritized as High (H), Medium (M), or Low (L) risks. A high risk is categorized as an issue that is likely to occur and would have a significant (\$25 million - \$125 million impact) or critical (>\$125 million) consequence. Issues that are unlikely but have significant or critical consequences, or are likely but have marginal (\$5 million – \$25 million) consequences are categorized as medium risks. Issues that have a probability of occurrence of less than 10%, or a higher probability but negligible or marginal consequences are categorized as low risk. Table 14 lists the uncertainties, a short description, and uncertainty status as of the writing of this report.

Mass balances were developed for the preliminary process design to provide a basis for sizing equipment, determining feed chemical requirements, determining utility requirements, estimating emissions and determining waste volumes, compositions and properties. A set of DBEs provides the technical background for preparation of the mass balances. These DBEs are assumptions or uncertainties that represent some level of risk to the successful implementation of a production facility that incorporates this technology; and will require a decision, acceptance of risk, or Applied Technology/Engineering effort to resolve them. Twenty-three DBEs are identified for this preliminary process design. It is expected that several more would be identified as detailed design progresses if this treatment option were to be selected for implementation. The individual DBEs are amplified with background information, references, explanation, and, in some cases, a discussion of uncertainties in Appendix B. The following is a summary discussion.

Table 14. Summary of cesium removal uncertainties identified in risk assessment.

Uncertainty	Description	Status
Solid/Liquid Separation Technology (H):	Inappropriately selected/applied solid-liquid separation equipment can lead to waste product contamination and/or filter restrictions leading to downtime.	Lack of heel solids physical/rheological characterization data has delayed resolution of this issue. An appropriate simulant is required for validation experiments. A simulant preparation procedure is awaiting heel solids data that is due on June 30, 2004.
Solids Processing and Disposal (H):	Collection of filtered solids, drying, and packaging to meet WIPP WAC has not been demonstrated.	Lack of heel solids characterization data has delayed resolution of this issue. An appropriate simulant is required for validation experiments. A simulant preparation procedure is awaiting heel solids data that is due on June 30, 2004.
Sorbent Performance/Selection and Disposal (H):	The sorbent must selectively remove enough Cs to render the effluent waste CH, not deteriorate during processing, and contain enough TRU constituents to be disposable at WIPP after loading.	A baseline sorbent has been selected. Latest experimental results indicate satisfactory Cs removal and sorbent stability. Another disposal location for a non-TRU, high-rad package could be used.
Grout Formulation (L):	Immobilized product physical and chemical properties are needed to validate design parameters and assure product acceptance at WIPP.	Baseline formulation selected, with properties measured. Long-term performance not validated if >90 days storage is required.
Silica Gel (L):	Immobilization of IX effluent is an alternate waste form to grouting. Physical and chemical properties are needed to validate design parameters and assure product acceptance at WIPP.	Experiments performed and data obtained indicate that this waste form is not desirable.
Grout Mixing (L):	Data are required with regard to in-drum or out-of-drum mixing to determine the waste immobilization mixing method. This has implications on the system design, amount of waste produced, and number of immobilization lines.	Data gathered with regard to out-of-drum mixing experiments and process design led to selection of out-of-drum mixing as baseline.

3.3.4.1 Feed. The characteristics of the actual waste to be processed are not entirely certain at this juncture. The liquid in two full tanks (WM-180 and WM-189) has been sampled, plus solids which were acquired during the sampling event, and the physical, chemical, and radiochemical properties have been documented. Reports are due to be published in June 2004 that detail the results of characterization activities for two other tanks (WM-187 and WM-188) and a plan for synthesizing a representative simulant. The June 2004 characterization report will have the best available solids characterization data. The major issues associated with feed uncertainties are:

- The quantity of dispersed and heel solids is an estimate based on observations during tank cleaning. The properties of the solids may not be representative of the entire mass. Samples were obtained with existing systems and equipment that only come from one spot in the 50-ft diameter tanks.
- The composition of the NGLW is estimated, and is only a prediction based on past operating experience and sampling events. Future operations at INTEC that involve more decontamination and decommissioning activities than recently experienced could have a significant affect on the volume and characteristics of the NGLW.

These uncertainties affect the following processing activities:

- Solid/liquid separation performance could be negatively affected if the solids quantity and properties differ significantly from simulants used in filter demonstration tests. The quantity of solids can affect the size and processing rate of the solids processing equipment.
- Tanks WM-100, WM-101 and WM-102 are projected to hold all of the NGLW generated from 2006 through 2011. However, the NGLW volume is projected to be a small fraction of the total SBW and is expected to be similar to the SBW composition. The effect of this uncertainty on the process design should be negligible, but devising an appropriate schedule or strategy for processing NGLW in the SBW treatment facility may be challenging.
- This solids concentration affects the operation and schedule of solids treatment. The concentration of solids at which settling would occur in pipes during transfer is not well known, and thought to be much lower than the initial solids content of the tank waste. The amount of water required to transfer the solids is also not known with precision.

3.3.4.2 Solids Separation. The major issue with solids separation is that design parameters have not been determined experimentally with either actual waste or a suitably representative simulant. Lack of characterization data has caused this delay, but the data are expected to be available in July 2004. The following uncertainties merit the most attention:

- The waste recirculation rate and behavior of very small solids (<0.5 micron) for cross flow filter operation needs to be determined experimentally.
- Solids from different TFF tanks have shown significant differences in settling rates. Based on this data the process flow diagram shows a flocculating agent added to the solids decant tank to decrease settling time. Experiments should be performed to validate the selection of a flocculating agent and the quantity required.
- Small-scale demonstration testing of the Fundabac filtration equipment has been successful. However, the performance of the Fundabac filter with regard to whether the solids can be dried to the required moisture level and then completely removed from the filter into waste disposal containers needs to be validated with a suitably representative simulant or actual waste.

3.3.4.3 Ion Exchange. The major issue with ion exchange is the selection of suitably performing sorbent media. Several sorbents have been experimentally investigated since the mid 1990's. Primary criteria evaluated have been selectivity, capacity, stability with regard to waste composition, and commercial availability. Evaluation of the available data has led to the selection of CST, available commercially in engineered form as IONSIV™ IE-911, as a baseline sorbent. Uncertainties meriting the most attention with ion exchange are:

- The Zr binder in CST dissolves to some degree in the acidic waste environment. Partial neutralization of the feed will decrease the degree of dissolution. The quantity of the fines produced by the dissolution and then migrating out of the column could compromise disposal of the grouted waste. A sand layer added to the ion exchange columns to trap sorbent fines is a design feature to reduce the impact of this uncertainty. The most recent experiments (Tranter, 2004a and 2004b) indicate that approximately 2 wt% of the mass of the sorbent will dissolve during column loading. Cs uptake does not appear to be compromised and is acceptable. However, further radioactive experiments to validate surrogate testing is recommended if this processing option is selected.
- Estimates of TRU activity trapped on/within the spent sorbent, based on tests with a solution spiked with ²³⁹Pu, indicate that a residual concentration of about 3.7 times the minimum 100 nCi/g needed for WIPP disposal will remain. However, this was a scoping experiment and additional experiments should be performed to verify that the sorbent waste would exceed 100 nCi/g TRU for all feed cases. Disposal of spent sorbent at a different location would be required if the residual TRU content is below the minimum required at the WIPP, but is not necessarily an issue.
- The method for determining ¹³⁷Cs breakthrough on an individual column is undetermined. A gamma-measuring device may not be effective, since premature breakthrough may be triggered by ¹³⁷Ba.

3.3.4.4 Immobilized Waste Performance. The major issue with the grout waste form is its performance over time. The potential for, and quantity of, gas generation, water release, and drum corrosion have not been validated. The waste form will be interim stored for an unknown period prior to shipment for disposal at the WIPP. Actual waste immobilized according to the appropriate formula should be tested according to the criteria noted above to validate performance between generation and disposal.

The strategy for Waste Certification has not been investigated in detail. The planning basis has been to “qualify” the process operation such that waste produced under certain operating parameters, and with appropriate analytical data from sampling events, would be “certified” for transportation and disposal (US DOE-ID, 2003). Detailed design efforts, negotiation with WIPP personnel, and perhaps pilot scale demonstrations will be required to satisfy waste certification requirements.

3.3.4.5 Waste Packaging & Handling. Equipment and systems associated with the canister filling and handling system for the spent sorbent waste and the tank solids waste have not been addressed in detail. Detailed design studies should be performed to more appropriately define these systems. The systems would undoubtedly require remote application test mockups to validate operability.

3.3.4.6 Facilities Interfaces. The major issue with interfaces is the projected utilities requirement of the process design compared against existing capabilities/capacity at INTEC. An analysis is needed to identify additions and modifications that might be needed for these systems.

3.4 Direct Evaporation

Evaporators have a long history of processing radioactive waste at the INEEL and other DOE sites. Development of evaporation specifically for processing SBW into a disposable waste dates back to 1997. At that time, an initial laboratory-scoping test showed that the process was feasible (Kirkham, 1998). Additional development and testing of the process was performed in 2002 using simulated waste from Tank WM-180 (McCray, 2002). In one series of tests, evaporation was carried out in an open one-liter

stainless steel beaker to represent an “in-can” approach. In a second series, evaporation was carried out in a one-liter flask under vacuum conditions. Results from these tests provided the basis for initial estimates of mass balances (Barnes, 2002a) for the direct evaporation process. Additional testing was performed in 2003 to obtain data at larger scale, to test a second SBW tank waste stimulant, to confirm acceptable performance of a feed containing undissolved tank solids and to test an alternative direct evaporation scheme (Griffith, 2003a, Griffith, 2003b, Griffith 2004, Kirkham, 2003, Kirkham, 2004).

A feasibility study for the direct evaporation process was performed in FY 2002 (Kimmitt, 2003). In this study, the process and facility were defined, equipment sized, mass balances prepared, architectural drawings prepared, development needs defined and project costs estimated.

The direct evaporation process as described in FY 2002 documents has two primary waste products – concentrated, solidified SBW and grouted nitric acid recovered from the SBW evaporator condensate. An engineering evaluation of direct evaporation process variations (Barnes, 2003a) recommended an alternative process scheme that produced a single primary waste product. Both of these process schemes are described in this report. The scheme that grouts recovered acid is referred to as the “Revised Baseline,” while the scheme producing a single waste is referred to as the “Alkaline Scrub” process.

3.4.1 Process Functions

The Direct Evaporation facility will retrieve waste, including SBW liquids and solids and NGLW, treat the waste so that it can be disposed offsite, and certify, package, and prepare final waste products for shipment to disposal sites. After completion of the processing, the Direct Evaporation facility and associated subsystems will be closed until decommissioning.

The Direct Evaporation process produces a solidified waste from the SBW feed by evaporation to the point that upon cooling the concentrated waste solidifies. The process functions, including both existing and new equipment, are as follows:

Revised Baseline Process Functions

- Mix TFF solids and liquids
- Transfer waste from the TFF and receive SBW and NGLW in the Direct Evaporation Facility
- Evaporate the waste
- Package, cool, store and prepare the concentrated waste for shipment to WIPP
- Condense evaporator overheads, fractionate condensate to reduce the volume, and grout fractionator’s bottoms to solidify the recovered nitric acid to permit disposal
- Treat evaporator non-condensable gases for release to the atmosphere
- Treat vent gases for release to the atmosphere.

Alkaline Scrubber Process Functions

- Mix TFF solids and liquids
- Transfer waste from the TFF and receive SBW and NGLW in the Direct Evaporation Facility

- Evaporate treatment facility feed
- Package, cool, store and ship the concentrated waste
- Treat evaporator overhead for release to the atmosphere by removing particulate, nitric and hydrochloric acid vapors, and mercury
- Treat vent gases for release to the atmosphere.

Prior to SBW treatment, pumps would be installed in TFF tanks and transfers between tanks made to distribute the SBW solids collected in WM-187 within the SBW liquid. Solids would be distributed and mixed with liquid in the tank farm to (a) avoid the expense of alternative systems that would need to transfer and treat the solids separately in the direct evaporation facility, (b) be able to transfer the solids to the facility with existing steam and air jets, and (c) provide a homogeneous feed to the direct evaporation process.

The treatment facility feed, mixed SBW solids and liquids, as well as NGLW, is evaporated so that when the concentrate cools, it solidifies. Sufficient water and nitric acid in the feed are volatilized during evaporation such that upon cooling solids crystallize and incorporate the remaining water into the waste product as water of hydration.

The two process schemes treat the evaporator overheads differently. The revised baseline process condenses the overheads in order to be able to process it in the existing LET&D facility. A second function of the condenser is to remove or reduce contaminants in the non-condensable gases, thereby avoiding additional downstream treatment steps for the gases.

It is expected that demister pads, both internal and external to the evaporator, will be required to remove solids, containing both hazardous and radioactive compounds, to levels meeting the LET&D WAC. The function of the LET&D is to remove the bulk of the water from the condensate and release it to the atmosphere. The concentrated acid recovered by the LET&D must then be solidified in order to meet disposal site WAC. Also, the concentrated acid contains hazardous impurities such as mercury that must be rendered non-leachable in the solidified waste.

The final function of the revised baseline process is to treat the non-condensable gases, both process gases and vent gases, to allow release to the atmosphere. These two gas stream are kept separate upstream of their respective blowers because their pressure levels are different.

The alkaline scrubber process also has a demister on the evaporator overheads. The purpose of the demister in this scheme is to reduce the radioactivity in the feed to the scrubber by removal of particulate, thereby allowing easier access to downstream equipment for maintenance.

The purpose of the alkaline scrubber is to remove acid vapors (nitric acid and hydrochloric acid) by reaction with an alkaline compound. The scrubber is expected to also remove additional particulate and some of the mercury. However, an additional unit operation to remove mercury from the gas will also likely be needed. A carbon bed is included in the process for this purpose.

3.4.2 Process Description

Prior to treatment in the Direct Evaporation Treatment Facility, mixing pumps would be installed in Tanks WM-187, WM-188 and WM-189. Transfers would be made between tanks to distribute solids

somewhat evenly between these three tanks. After mixing, SBW and NGLW would be transferred from these tanks by existing steam jets to the new treatment facility feed tank.

Block flow diagrams of both schemes for the direct evaporation process are shown in Figures 1 and 2. SBW would be received from the TFF by the SBW Feed Tank, equipped with an air sparge or other mixing device. Fluid is also mixed in the tank by use of the discharge pump. The SBW liquid/solids mixture would be continuously pumped at a rate of 1.5 gpm to the SBW Evaporator, an agitated thin film type evaporator that is expected to operate at about 120°C and about 8.6 psia pressure. Evaporator concentrate will fall from the evaporator discharge into a waste container, also maintained at vacuum pressure. The evaporator is heated with high-pressure steam that is generated within the new facility.

Evaporator vapor would first pass through an internal mist eliminator and then an external demister. The demister provides separation of entrained liquid and solids from the evaporator vapor. Liquid collected in the demister would be periodically pumped to the SBW Feed Tank. The mesh pads in the demister could also be washed with water or condensate.

In the revised baseline scheme, vapor from the demister is condensed by heat exchange with cooling water. Non-condensable gases are superheated and HEPA-filtered before being boosted in pressure and released to the atmosphere through the INTEC stack. Condensate is collected in a tank and periodically transferred to the feed tank of the LET&D.

Potential corrosion in the Condensate Tank by hydrofluoric acid is controlled by the addition of aluminum nitrate solution, which will form aluminum fluoride complexes. Aluminum nitrate solution is received from a supplier into a small storage tank or drums and pumped as needed to the Condensate Tank.

The existing LET&D Fractionator would be used to concentrate the condensate, thereby reducing the amount of waste that would require disposal. The condensate is fed by gravity from the LET&D Feed Tank to one of two identical fractionators, each containing 15 sieve trays. Each fractionator typically recovers at least 99% of the nitric acid from the feed into the bottoms product. The bottoms product is typically 12 molar nitric acid and contains a high fraction of the other impurities in the feed condensate (hydrogen chloride, fluoride, HgCl_2). The fractionator overhead is steam with trace impurities. A partial condenser provides reflux to the column. The effluent from the condenser goes to a vapor/liquid separator, with the vapor from the separator superheated, filtered and discharged via a blower to the INTEC-708 stack. When the desired density of the fractionator bottoms is reached, a portion of the solution is drained out of the column and stored in the Bottoms Tank. This recovered acid is cooled by heat exchange with cooling water prior to entering the Bottoms Tank.

LET&D bottoms would be transferred in batches to a Neutralization Tank. Once a batch was received, solid calcium hydroxide would be added to the tank to neutralize the recovered nitric acid. The Neutralization Tank is equipped with a mixer to ensure adequate mixing of the solid calcium hydroxide with the acid waste, and with a cooling jacket or cooling coils to remove heat generated by the neutralization reaction. The acid waste is expected to contain very low levels of radioactivity, and have a dose rate of $\ll 1\text{mR/hr}$.

After the addition and mixing of calcium hydroxide is complete, the neutralized acid would be pumped through a continuous grout mixer. Blended Portland cement and blast furnace slag in a weight ratio of 3:1 cement:slag would be mixed with the neutralized waste in the grout mixer, which would discharge directly into 55-gal drums, the final waste container. Blast furnace slag is used to bind the mercury in the waste. Filled drums would be conveyed to a swipe/decontamination area where the drum exterior surface would be swiped to test for radioactive contamination. If contamination were found, the

drum would be decontaminated and re-swiped. Drums that pass the surface swipe would be transferred to a curing area and held for 24-72 hours to complete curing.

Following curing, the drum would be visually inspected for free water. If water were found, silica gel would be added. Following inspection, the drum would move by conveyor to a pallet loading area. A gantry crane would place four drums on a pallet, which when full would be moved to temporary storage until a full load of drums (approximately 60) is available for shipment to the disposal site. An average of 14 drums would be produced per day, although, depending on the feed, as few as 7 or as many as 17 drums would be produced in a day.

The high activity concentrate from the evaporator would be discharged at a rate of about 26 gph into a waste canister, and allowed to cool in the canister. Cooling would be aided by clamp-on cooling jackets. During filling and cooling the canisters would be under vacuum and vented to the process off-gas header.

Empty canisters would be lowered into the Treatment Facility using an overhead crane and placed in a temporary storage area. As needed, the canister would be moved along the canister alley. After being weighed, the canister would be moved into an airlock and then out of the airlock into the fill position. The canister sealing surfaces and seals would be inspected. If the inspection finds any defects, the canister would be moved back to the airlock. The connection of the canister to the evaporator would result in a vacuum in the canister. Gas initially in the canister, and moisture and acid released by the waste during filling would flow up through the evaporator into the process off-gas header. After filling, the canister would be moved to a cooling station to allow the waste additional time to cool and solidify. A cooling jacket could be attached to the canister to reduce the cooling time. When cooling is complete, the cooling jacket and vacuum connection would be detached and a plug inserted into the lid fill hole. A surface swipe of the canister would be performed. If analysis shows no contamination, the canister would be weighed, the dose rate of the canister measured, and the canister moved out of the airlock. If surface contamination were found on the swipe, the canister would be decontaminated, dried, and re-swiped. The canister would then be moved to lag storage area to await loading into a cast for transport to WIPP.

In separate operations, a cask would be loaded onto a transporter and the transporter would be positioned over the canister load-out port. The filled canister would be lifted out of the treatment facility and into the cask. An inner lid would be attached to the cask. The transporter would then be repositioned and the outer lid attached to the cask. The cask would then be rotated into the transport position; the transporter inspected and then would depart from the facility.

In the alkaline scrub scheme, overhead from the SBW evaporator would pass through both an internal mist eliminator and then an external demister vessel as in the revised baseline scheme. However, the vapor from the demister would then enter a packed bed scrubber to contact the overhead vapors with magnesium oxide pellets. The MgO would react with nitric and halogen acids in the overheads, forming salts that would be transferred to the liquid phase as dissolved solids. Some mercury would also be removed from the vapors. The scrubber temperature would be controlled by a cooler on the scrub circulation stream. Magnesium oxide pellets would be continually added to the bed as a slurry to make up for pellets that dissolve in the scrub liquid and are carried out of the scrubber as dissolved salts.

Vapors exiting the scrubber would be superheated and pass through a GAC bed to remove additional mercury. The mercury-free gas would then be HEPA-filtered, and boosted in pressure to be exhausted through the INTEC stack. Liquid exiting the scrubber would be recycled to the top of the scrubber, with a small portion bled to the evaporator feed.

A third alternative scheme for direct evaporation is a hybrid of that shown in Figures 6 and 7. Like the revised baseline scheme, the evaporator overhead would be condensed and processed by the existing LET&D. The LET&D bottoms would be neutralized with magnesium oxide or aluminum hydroxide and recycled to the evaporator. This scheme would require use of the LET&D facility, and produce a single final waste product equivalent in volume to that of the alkaline scrub scheme.

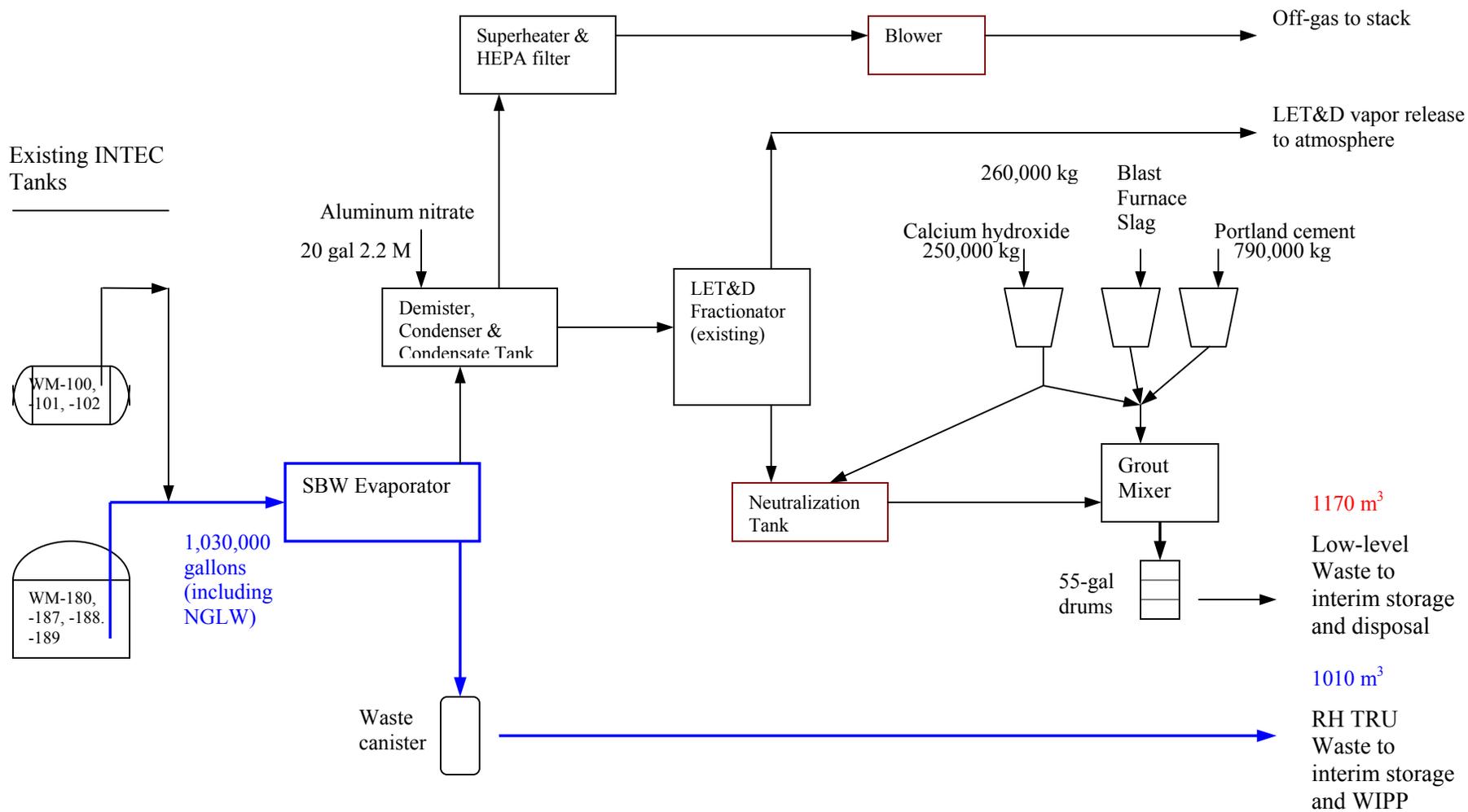


Figure 6. Revised baseline direct evaporation block flow diagram.

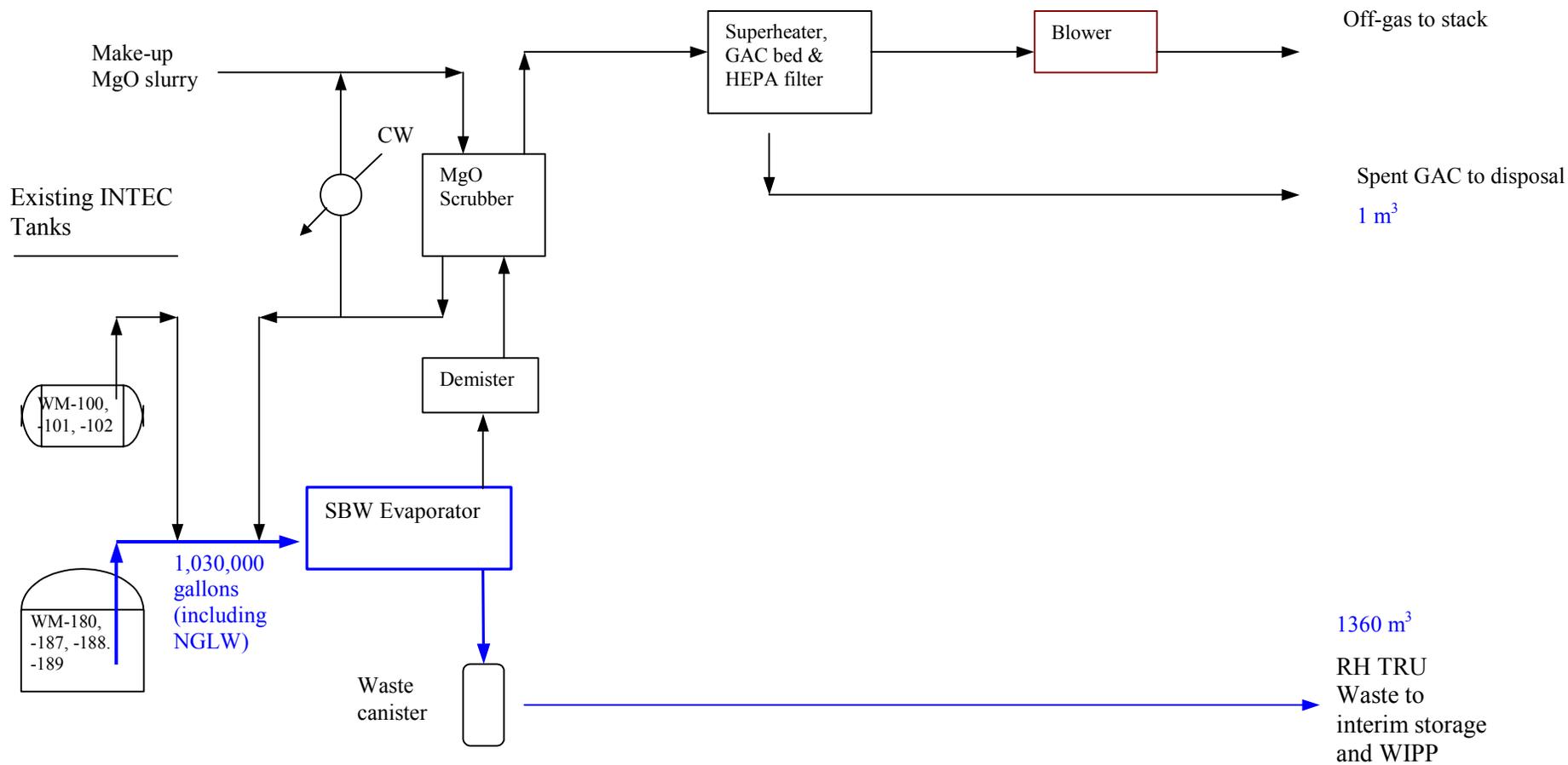


Figure 7. Alkaline scrubber direct evaporation block flow diagram.

3.4.3 Summary of Technical Performance

3.4.3.1 Processing Rate, Availability. Mass balances contained in Appendix C assume a feed rate of about 86 gph based on 12,000 operating hours. The operating time is consistent with the Direct Evaporation T&FR documents, (Barden, 2003) and is based on 24-hr per day operation, 200 operating days per year and 2.5 years of operation. However, the mass balances are equally applicable to any 500-day operating, such as 2 years at 250 days/year or 20 months at 300 days per year.

The facility availability has not been well established for this type of process. The 200-days/year assumption is based on past operating experience at the INEEL working within DOE regulations. Changes in the operating environment could significantly alter the assumed availability and processing rate.

An analysis of calciner operation 1982-2000 showed an average radioactive on-stream efficiency of 73% (O'Brien, 2002), equivalent to 266 days per year. Evaporators typically have very high operating efficiencies. For example, 1.3 million gallons of HLW at Hanford was evaporated with an operational efficiency of 99.7% (Eckard, 2000).

Based on the short test runs to date the availability for an agitated thin film evaporator processing SBW is expected to be high, but cannot be quantified. A major factor in the on-stream time for the direct evaporation process is expected to be the down time required to change-out a canister from under the evaporator. A rough estimate of canister change-out time results in an operating on-stream factor of the process of 70-80%. When combined with downtime for other equipment in the process, the overall on-stream time is expected to be 200-250 days per year.

3.4.3.2 Waste Products Quantity and Quality. The revised baseline version of the direct evaporation process produces two primary waste products – the solidified evaporator bottoms and a grouted LET&D bottoms waste. The alkaline scrubber scheme or the neutralized and recycled LET&D bottoms scheme would produce a single primary waste, the solidified evaporator bottoms. For the alkaline scrubber scheme, at the completion of processing, a small amount of spent activated carbon would also need to be disposed. The volumes of waste generated by the revised baseline and alkaline scrubber schemes are shown in Table 15. The volume of waste generated for the neutralized, recycled LET&D bottoms scheme is equivalent to the alkaline scrubber, except that no spent GAC would be produced.

Table 15. Direct evaporation primary waste products.

	WM-180	WM-187 & NGLW	WM-188	WM-189	Total containers	Total m ³
Revised Baseline Scheme						
Canisters of SBW evaporator waste	340	182	354	382	1,259	1,007
Drums of grouted LET&D bottoms	971	712	1,997	2,161	5,841	1,168
Alkaline Scrub Scheme						
Canisters of SBW evaporator waste	425	224	499	557	1,705	1,364
Drums of spent GAC					6	1

The number of shipments of SBW evaporator waste is equal to the number of canisters produced, i.e., 1007 for the revised baseline scenario or 1364 for the alkaline scrubber scheme. WIPP is expected to

be able to receive about 300 shipments of RH waste per year, thus shipping will require 4-4.5 years. Based on shipments of sixty drums of grout, 20 shipments of grouted waste would be made. The preferred disposal site for grout is Envirocare; an alternative is Hanford.

The SBW evaporator waste is a solid monolith with an expected bulk density of about 1.75 kg/liter. In the pilot tests that included solids or magnesium oxide in the test feeds, the range of product bulk density was 1.57-1.86 kg/liter (Griffith, 2004). Photos of the product produced in various tests can be found in Griffith (2004), Griffith (2003a), Griffith (2003b) and Kirkham (2003).

The grouted LET&D bottoms waste is also a solid monolith, with a density of about 2.06 kg/liter (Herbst, 2002). The spent carbon is in granular form, have a particle size of 3 mm and a bulk density of 0.48 kg/liter.

Radioactive properties of the waste products are shown in Table 16. Dose rates and heat generation rates have not been calculated for waste compositions shown in the present mass balances (Appendix C). However, the evaporator waste dose rate is expected to be very similar to that calculated for previous material balances. Based on a date of 2010, the evaporator product canisters are expected to have an average dose rate of 28 R/hr and generate 1.4 Watts of heat per canister (Bohn, 2002). The drums of grouted acid are estimated to have a dose rate of 0.015 mR/hr and a heat generation rate of 1.3×10^{-7} Watts per drum (Bohn, 2002).

Table 16. Radioactive properties of primary waste products.

Revised Baseline Case	
SBW Evaporator Bottoms	
All radionuclides, Ci/canister	290 - 500
Fissile gram equivalent, g/canister	60 - 130
²³⁹ Pu Equivalent Curies, Ci/canister	2.7 - 4
TRU content, nCi/g	2,100 - 3,100
Grouted LET&D Bottoms	
All radionuclides, Ci/drum	7.8E-04 - 1.3E-03
TRU content, nCi/g	0.001 - 0.004
Sum of fractions compared to Hanford Cat 1 WAC	0.02 - 0.05
Sum of fractions compared to Envirocare WAC	0.004 - 0.006
Alkaline Scrub Case	
SBW Evaporator Bottoms	
All radionuclides, Ci/canister	240 - 390
Fissile gram equivalent, g/canister	50 - 90
²³⁹ Pu Equivalent Curies, Ci/canister	1.8 - 3.2
TRU content, nCi/g	1,400 - 2,500

3.4.3.3 Size, Footprint of Processing Facility. Preliminary equipment sizing, based on the throughput noted above, has been performed. The equipment sizing information, along with previous work performed for the Direct Evaporation Feasibility Study (Kimmitt, 2003), provided the basis for

generating layout (plan) drawings for a treatment facility that would accommodate the preliminary process design as described in previous sections. Details and the plan drawings are located in Appendix C. Equipment and room arrangements have not been optimized. Insufficient engineering design has been performed to provide a strong basis for all of the areas of the facility, as this effort has only been focused on a preliminary process design. The discussion of facility footprint and scale below applies to the revised baseline scheme. For the alkaline scrubber scheme, no grouting equipment is required, which would result in a smaller footprint.

The Direct Evaporation Treatment Facility includes waste loading and canister handling operations in the lower level; hot cell process equipment on the ground floor and cold (non-radioactive) activities plus process and vent gas HEPA filtration on the second floor. The overall dimensions of the facility for the revised baseline scheme are about 310 feet by 140 feet. The control room, offices, a decontamination room, a manipulator repair room and other support activities are located on the ground floor. A summary of plot space estimates is given in Table 17.

Table 17. Estimated plot space for direct evaporation treatment facility.

Area Description	Area, ft ²
Process equipment (hot cell space, ground floor)	5,200 ft ²
Grouting equipment and drum storage	18,000 ft ²
Waste packaging & canister handling	1,200 ft ²
Lag storage for RH canisters	3,300 ft ²

3.4.3.4 Effects of Scale, Variation with Throughput. Changing the scale of the process, i.e., designing for an accelerated treatment schedule, would primarily affect four areas of the facility – the process hot cells, the grouting operation floor space, waste packaging and canister handling in the basement and lag storage for waste canisters.

The major equipment in the process hot cell includes the evaporator and four tanks. Other equipment is small and affects of scale on floor space for this equipment is minimal. The evaporator as sized for 2.5 years operation has an outside diameter of 19¼ inches, a length of 10-ft 8-in, and heat transfer area of 21.6 ft². For a shorter schedule, the heat transfer area would need to be increased by the schedule reduction ratio. Thus for a schedule of 1-year, the heat transfer area would be $21.6 \times 2.5 = 54$ ft². This area could be achieved in an evaporator 1.5-ft inside diameter by about 17 feet or 2-ft inside diameter by 14-ft. The effect on floor space due would be small, but the hot cell and building height would need to increase to accommodate clearance for evaporator shaft and rotor removal. Alternatively, two evaporators could be used.

Keeping all other factors equal, decreasing the processing schedule would increase the floor space required for process tanks by the inverse ratio of the decrease to the two-thirds power. For example if the schedule was decreased from 2.5 years to 1 year, the floor space for tanks would increase by $(2.5/1)^{0.667} = 1.84$ or an 84% increase.

For the 2.5-year operating schedule, 5,840 drums of grout are produced, equivalent to an average of 12 drums per operating day. At this production rate, a single grouting line is adequate and would be adequate for shorter treatment schedules as well. Additional space would likely be included in a facility designed for a shorter schedule for empty 55-gal drums fed to the grouting line, to maintain the same schedule for receiving drums.

The area required for storage of grouted waste drums depends only on the lag storage requirement. Lag storage space in turn depends on the rate at which the disposal site can receive shipments and the initial lag between start of production and sending the first shipment. The intended disposal site for the grouted waste from the direct evaporator process has been Hanford or Envirocare. It is expected that either site could receive this waste at a shipment rate equal to the rate generated for either a 2.5-yr or a shorter schedule. However, this assumption has not been confirmed.

The alkaline scrub variation of the direct evaporation process, as well as the variation that neutralizes LET&D bottoms, does not produce a grouted waste product. Besides eliminating the grouting equipment and floor space, these schemes eliminate two of the four major tanks of the process.

The rate at which RH canisters of evaporator product are produced is inversely proportional to any change in processing schedule. For a 2.5-year schedule, on average, one canister is filled in about 10 hours. A single fill station could accommodate shorter processing schedules, but more floor space would be required in the cooling area. The cooling time has yet to be adequately determined, but is expected to be several days. Assuming three days for cooling, space for eight canisters would be needed for a 2.5-year schedule or twenty for a 1-year schedule.

Finally, the interim storage for RH waste is dependent upon the initial lag period between producing the first container of waste and having approval to ship that container to WIPP and the rate at which WIPP can accept waste. Based on discussions with WIPP personnel, it is expected that the disposal facility can receive at least 6 RH canisters per week from the INEEL, or about 300 per year. Assuming an initial continuous 40-day operating period prior to waste shipment, storage for 80 canisters would be needed. However, since 1260 total RH canisters of waste are produced and WIPP can receive only about 300 per year, storage for 590 canisters would be required for a 2.5-year schedule, or 1,040 for a 1-year schedule. This equates to a 76% increase in storage space. Estimates of floor space for a treatment facility designed for one-year operation are given in Table 18.

Table 18. Estimated floor space for the direct evaporation treatment facility.

Area Description	Area, ft
Process equipment (hot cell space, ground floor)	6,200 ft ²
Grouting equipment and drum storage	20,000 ft ²
Waste packaging & canister handling	1,300 ft ²
Lag storage for RH canisters	5,800 ft ²

3.4.4 Technical Uncertainties and Potential Impacts

3.4.4.1 **Uncertainties Identified in the SBW Treatment Applied Technology Plan.**

The *Sodium-Bearing Waste Treatment Applied Technology Plan* (INEEL/EXT-03-00477, June 2003) identified five uncertainties resulting from technical and operational risk assessments for the direct evaporation process. These were, for the most part, uncertainties that would have supported the selection of a treatment technology and were not complete listings of technical issues requiring resolution to support detailed design efforts. The uncertainties were prioritized as High (H), Medium (M), or Low (L) risks. A high risk is categorized as an issue that is likely to occur and would have a significant (\$25 million - \$125 million impact) or critical (>\$125 million) consequence. Issues that are unlikely but have significant or critical consequences, or are likely but have marginal (\$5 million – \$25 million) consequences are categorized as medium risks. Issues that have a probability of occurrence of less than

10%, or a higher probability but negligible or marginal consequences are categorized as low risk. Table 19 lists the uncertainties, a short description, and their status as of the writing of this report.

Table 19. Summary of direct evaporation uncertainties identified in risk assessment.

Uncertainty	Description	Status
Product Characterization (H):	The product from processing all of the SBW wastes may not always meet WIPP WAC and DOT requirements.	Data from tests with WM-180 and WM-189 simulants indicate that if 55-60% of the feed mass is evaporated, the product will be a monolith with no free liquid. Completion of tank solids characterization and solids simulant development, along with testing the other tank waste compositions, is needed to resolve this risk relative to WIPP WAC. The issues of radiolytic hydrogen generation and NO _x release in the waste canisters also have not been resolved. Production and testing of product from actual SBW is needed to confirm product stability and determine hydrogen generation under radiation fields.
Liquid and Heel Solids Co-processing (M):	Co-processing the solids with the SBW liquid could potentially cause fouling and deposition in the evaporator, leading to downtime for maintenance. Also, a plan is needed to process the final tank heel solids.	Testing has demonstrated that several types of solids, when added to SBW surrogate feed, present no challenges to the operation of a pilot-scale agitated thin film evaporator. Completion of solids characterization and solids simulant development, followed by additional evaporator tests, would resolve this uncertainty. Planned installation of mixing pumps in three of the SBW tanks eliminates the need to process solids after completion of all liquid SBW processing. Demonstration of mixing solids in the TFF tanks is needed to resolve risks of solids co-processing.
Evaporator Type (M):	Different evaporator types have potential advantages and disadvantages for processing SBW. Evaporator demonstrations are needed to verify performance, establish design parameters, and reduce the risk of operation problems for any evaporator type selected.	Three test series have been performed using an agitated thin film evaporator. The success of these tests has led to foregoing plans for testing other evaporator types.
Materials Evaluation (L):	The high acid and chloride concentrations in the evaporator bottoms will be corrosive.	No materials tests have been performed.
Condensate Treatment (L):	The initial conception of the direct evaporator process (as defined in Barnes, 2002a) was not optimized. Evaluations supported by test data are needed to optimize the process.	An evaluation of condensate treatment methods was completed (Barnes, 2003a), and resulted in several improvements to the process. Most of the recommended improvements have been verified by test data and/or cost estimates.

3.4.4.2 Product Characterization. “Product characterization” was the only high-risk uncertainty identified for the direct evaporation process. The uncertainty encompasses several potential concerns that could lead to waste failing either WIPP WAC or transportation requirements. These concerns included the possibility of (1) free liquids present in the waste due to inadequate control of the process or later phase change of the waste product in its disposal container (2) excessive hydrogen gas generation in the waste canister, (3) excessive NO_x generation by the waste, (4) corrosion in the canister due to the formation of acidic liquids, (5) waste deliquescence and (6) the possibility of classification of the waste as an oxidation hazard because of its nitrate content.

The second and third series of pilot tests (Griffith, 2003b; Griffith, 2004) demonstrated that the fraction of feed evaporated, and hence the bottoms composition, correlated with the bottoms temperature. The bottoms temperature, and hence the product composition, can thus be controlled by controlling the steam pressure. The tests have thus demonstrated a means of controlling the water content of the bottoms product and ensuring that all water will be incorporated into the solid product. A collection and review of all direct evaporation test data concluded that if 55-60 wt% of SBW is removed by evaporation, the product will be an acceptable form for disposal (Kirkham, 2004). Continued observations of product up to 2 months after being generated have shown that the solid shows no tendency to reliquify or release water or acid (Griffith, 2004).

Given the radionuclide content of the SBW, the rate of hydrogen generation in the waste product canister depends primarily on the water content of the product waste. Mass balances show a water content of 22-33 wt%, and pilot-scale test data shows 27-33 wt%, based on the taking the difference between feed and condensate. Wendt (2003) modeled hydrogen generation from SBW dried to different levels and recommended removal of water to less than 20 wt%. However Wendt also reported that nitrates present in the waste could inhibit hydrogen generation and allow water in excess of 35% to be present. The issue of hydrogen generation in the direct evaporation waste product is hence not resolved and requires tests with actual SBW.

Sampling of the head space of cooled waste drums has shown that the head space gas contains levels of NO_x of up to 100 ppm, and if the drum is purged with air and resealed, the NO_x will return to approximately the same level within days (Griffith, 2004). A specific limit for NO_x in the headspace has not been determined but the issue has been raised because of the possible effect it would have on the o-rings used in the 72B shipping cask. This issue of the presence and acceptability of NO_x in the waste containers is not resolved.

After two months of storage of product produced in the pilot tests, lids were removed to verify the absence of liquids. No liquid was found in any of the drums (Griffith, 2004). Thus the risk of corrosion of canisters due to acidic liquids is very small. However, because the waste is deliquescent, any storage of unsealed waste containers will need to have humidity control. Also, based on observations of these waste drums, the evaporator waste contains no particulate and is not friable. Thus it will not be classified as a DOT oxidizer.

3.4.4.3 Solids Co-processing. Prior to testing, there was a concern that co-processing solids with SBW liquid could cause fouling of heating surfaces or plugging of the product outlet. In 2003, tests were performed with a pilot-scale agitated thin film evaporator (Griffith, 2003b) and several types of solids added to the feed, including 2 μm silica particles, 5 μm silica particles, kaolin clay, zirconia phosphate particles and a composite of the four types of solids. Results from the tests showed that there was no fouling of heating surfaces. No plugging of the outlet was observed in any of the solids tests, even though one run of each feed was made at the expected maximum extent of evaporation. A later test series (Griffith, 2004), confirmed the results regarding no fouling, although bottom plugging was seen in one

experiment. The plug in this one experiment was attributed to solidified material that remained in the evaporator from the previous experiment.

While the test results seem to allay concerns regarding fouling and plugging, tests with a better solids simulant, i.e., solids that have been demonstrated to behave as actual solids, and tests for longer time periods are still needed to fully resolve this risk. Also, tests of a full-scale evaporator, for which the discharge configuration and method may differ from the pilot-scale unit, are needed to fully resolve this uncertainty.

Another concern raised relative to co-processing was the ability of the evaporator to process solids flushed from the last tank. The presumption was that these solids would be in a very dilute aqueous solution rather than the high salt SBW solution that produces a monolithic waste product. Current plans for co-processing involve the installation of mixing pumps in INTEC Tank Farm tanks. These pumps would deliver a homogeneous SBW liquid/solids feed until heel level is reached. At that time about 99% of the solids will have been removed from the Tank Farm tank. The heel, if flushed with water, would be concentrated to its original salt concentration by existing INTEC evaporators prior to being sent to treatment, for the last tank as well as the previous ones. Other engineering options have also been suggested for treating the final heel, including putting additional pumps in TFF tanks to directly remove the concentrated SBW heel, or adding cold chemicals to the evaporator feed to maintain evaporator bottoms chemistry if processing solids in a more dilute liquid.

All co-processing scenarios under consideration involve installation of mixing pumps in at least one Tank Farm tank. Mock up tests are needed to verify the performance of these mix pumps.

3.4.4.4 Evaporator Type. Several types of evaporators could potentially be used for SBW evaporation (Packer, 2003). Prior to any testing, there were concerns about maintenance requirements for thin film type evaporators in SBW service. Other types of evaporators had other concerns. Since then three series of tests have been performed with an agitated thin film evaporator (Griffith, 2003a; Griffith, 2003b; Griffith, 2004). While these tests have been too short in duration to quantify maintenance requirements, the smooth operation seen during all of these tests has alleviated the initial concerns about this type of evaporator. The success of the agitated thin film tests also led to cancellation of plans to test alternative evaporator types.

3.4.4.5 Materials Evaluation. High acid and chloride concentrations in the evaporator bottoms will be corrosive. Materials testing has been recommended to identify a material of construction for the evaporator and connecting line to the waste canister that will have an acceptable corrosion rate during the lifetime of the processing facility. These tests have not been performed.

Observations of wastes two months after being generated in pilot tests have shown no liquids, indicating corrosion would not occur once the waste solidified.

3.4.4.6 Condensate Treatment and Process Optimization. Several improvements to the direct evaporation process have been made since it was defined in 2002 (see Kimmitt, 2003 or Barnes, 2002 for the original process configuration). Barnes (2003a) evaluated various options relative to condensate treatment, based on engineering evaluations, new test data and cost estimates, and made several recommendations that have been incorporated into the present design. Appendix C discusses variations of the direct evaporation process and also contains process flow diagrams, mass balances and equipment lists for two different process schemes. One of the recommended improvements is the use of MgO to neutralize acid in the evaporator condensate or vapor and recycle the magnesium salt back to the SBW evaporator. This concept was demonstrated in the most recent pilot-scale tests (Griffith, 2004), and eliminates the grouting equipment and grout waste form of the “baseline” process. However, while the

alkaline scheme process shows savings in equipment cost and facility space, it also produces 35% more RH waste. The elusiveness of a definitive WIPP disposal cost precludes making an easy selection between these two options.

Relative to other treatment alternatives the direct evaporation process involves few unit operations. However, additional optimization could still be performed. No economic evaluation has been performed to compare the alkaline scrubber scheme to the LET&D bottoms neutralization and recycle scheme. Also, significant engineering work needs to be performed relative to canister handling operations.

3.4.5 Additional Performance Uncertainties

Mass balances for the direct evaporation process, contained in Appendix C, were developed in order to provide a basis for sizing process equipment, determine utility requirements, determine waste volumes and properties and estimate emissions. A set of DBEs provides the technical background and basis for the mass balances. These DBEs include many assumptions or uncertainties that represent some level of risk to the successful implementation of a production facility that incorporates direct evaporation technology. A summary of the DBEs having the highest uncertainty or impact to plant performance is provided in the following paragraphs. Also included in the discussion below are issues that don't directly affect the mass balance but could significantly impact the cost, schedule or operability of the process.

3.4.5.1 Feed Characterization.

- Analysis of tank solids is incomplete, and past sampling of tank solids may not have resulted in representative samples. Also there is uncertainty in the total amount of tank solids that will be present at the time of treatment. Changes in the amount or composition of the tank solids from present estimates would likely require changes in plant operating parameters. For example, if fewer solids were present than current estimates, the degree of evaporation could be increased and less volume of waste product would be produced. Impacts of this uncertainty are thought to be minimal because of the successful tests using a range of solids in the pilot-scale evaporator (Griffith, 2003b).
- There is uncertainty that Tanks WM-100, WM-101 and WM-102 have sufficient capacity to hold all of the NGLW expected to be generated from 2006 through 2011. The Tank Farm Management Plan needs updating with new projections of NGLW volumes and a workable strategy of NGLW storage and treatment. Changes of the Tank Farm Management Plan will result in changes of the feed composition envelope to the SBW treatment facility. While the impact of these changes on plant performance is expected to be small because concentrated NGLW is similar in composition to SBW, the treatment schedule could be impacted, particularly if use of another TFF tank was required.

3.4.5.2 Tank Mixing Pump Performance.

- There is uncertainty in the design and performance of mixing pumps for the Tank Farm tanks. Mock-up testing of Tank Farm Tank mixing pumps is needed to better predict performance. If the mix pumps cannot adequately mix the solids in the tanks, additional equipment would be required in the treatment facility to ensure that the swings in feed solids content can be sufficiently dampened to maintain production of a product with acceptable properties.

3.4.5.3 Evaporator Performance and Product Characterization.

- Surrogates for WM-180 and WM-189 have been tested and from these tests the extent of evaporation has been determined and product wastes characterized. However the feed composition envelope will include WM-180, three TFF tanks contained mixed SBW liquids and solids of different compositions, and NGLW. After validation of solids simulants is complete, tests with these validated solids and the other tank compositions are needed to confirm and complete the envelope of evaporator operational parameters that will ensure an acceptable product.
- Until testing is performed with actual waste, there will be uncertainty in the fate of certain radionuclides and the effect of the radiation field on the product waste. Evaporation tests with actual waste are needed to evaluate product stability under a radiation field and to determine hydrogen generation in the waste product.
- There are uncertainties in the evaporator performance at full scale. Demonstration tests to date have been at lab and pilot scale. Full-scale tests are needed to confirm operating parameters determined in pilot tests and in particular to validate a design for discharging waste into product canisters. Remote handling of the waste canisters present requirements not present in the pilot tests. Testing is needed to ensure all the components of the packaging system function reliably under the challenging conditions of the highly viscous, corrosive, and rapidly changing waste form as it exits the evaporator and begins to cool.

3.4.5.4 Product Cooling.

- There is uncertainty in the time requirement for product cooling and the processing requirements of gases released during cooling. Modeling of product cooling could supply some of the missing information. If these data are not obtained, the product cooling area could be under designed, resulting in a bottleneck that impacts the treatment schedule; over designed, resulting in a larger area than needed; or inadequately designed, requiring delays for modifications.

3.4.5.5 LET&D Modifications.

- There are uncertainties in modifications needed to the LET&D to process the evaporator condensate. An initial review suggests that the only change needed is to change the feed tray. But a more thorough evaluation of processing the evaporator condensate, which has a much higher acid concentration than previous feedstock to the LET&D, i.e., the Process Effluent Waste Evaporator (PEWE) overhead is needed to determine if other modifications in equipment or operating procedures would be required.

3.4.5.6 Off-gas Treatment.

- There is uncertainty in what emissions standards will be applied to the direct evaporation facility. MACT requirements are not expected to be imposed, but additional off-gas treatment could be required if they are.
- There is uncertainty in both the rate and composition of the evaporator non-condensable off-gas. These data are needed to adequately design treatment equipment for the off-gas prior to release to the atmosphere and/or incorporation into secondary waste streams. Of particular interest are mercury, cesium, and NO_x and hydrogen chloride. While this off-gas treatment

equipment is expected to amount to a very small part of the capital expenditure of the treatment facility, not including treatment steps because of lack of data could result in unexpected emissions that would cause shutdown and schedule delays for modifications.

- An investigation of blower and compressor capabilities and requirements to better select this equipment, determine the vacuum air rate, and determine whether multiple compression stages are needed.

3.4.5.7 Alkaline Scrubber Uncertainties.

- A cost/benefit analysis is needed to select between the revised baseline scheme, the alkaline scrub scheme and the scheme in which the evaporator overhead is condensed, processed in the LET&D, and the LET&D bottoms neutralized and returned to the SBW evaporator.
- No testing of an alkaline scrubber has been performed. Thus the chemistry and mass flow performance of the scrubber contain uncertainty. Removal of nitric acid and hydrogen chloride vapors is expected to be complete but has not been demonstrated. Also, if a packed bed scrubber is used, dissolution of nitrate and chloride salt products is expected to be complete, but has not been confirmed. The extent of mercury removal by the scrubber is unknown. Testing is needed to verify the liquid to gas ratio needed to achieve complete acid gas removal, and to determine the extent of mercury removal. Experimental data is also needed to determine the behavior of the alkaline bed solids (confirmation of negligible pellet degradation or swelling), the build up, if any, of solids in the scrub liquid, and the buildup of soluble species in the scrub purge. Testing is needed to determine the optimum purge rate of scrub solution to the evaporator.

3.5 Vitrification

3.5.1 Brief Background of Process/Alternative

3.5.1.1 What Is Vitrification? Vitrification is the process of converting materials into glass or a glass-like substance typically through a thermal process. Glass is an amorphous, rigid, noncrystalline structure of low porosity composed primarily of silica, alumina, and oxides of alkali and alkaline earth elements, distinguished from crystalline structures by lack of a definite melting point. When heated it gradually deforms and forms a viscous liquid. Glass has been investigated as a radioactive waste form because of its chemical, thermal, and mechanical stability. Other reasons include the following:

- Organic contaminants are destroyed during vitrification,
- Inorganic contaminants and radionuclides can be stabilized by chemical bonding or by encapsulation in the glass matrix,
- Glass accepts a wide range of waste compositions,
- Glass is less susceptible to radiation damage than crystalline materials,
- Industrial-scale vitrification of radioactive waste has been demonstrated in a number of countries,
- EPA has declared vitrification a treatment standard for mixed HLW.

Glass has been viewed from a performance perspective as filling three possible roles in radioactive waste disposal:

- As the sole barrier between the radioactive wastes and the biosphere,
- As one barrier of a multi-barrier system (i.e., glass, canister, backfill, and geology) which adequately inhibits radionuclide migration,
- As a convenient container for transport and temporary surface storage.

The single most important characteristic of glass as a waste form is chemical immobilization--the ability to resist leaching of contaminants from the matrix when exposed to liquids--without which the costs of vitrification would not be justified compared with other alternative treatments.

3.5.1.2 Glass Types and Characteristics. Borosilicate glass (BSG), based on the $\text{SiO}_2\text{-B}_2\text{O}_3\text{-Na}_2\text{O}$ matrix with SiO_2 as the main constituent, is a preferred waste form in most countries. Such glasses have been examined for their suitability since the fifties. They are characterized by a high solubility of oxides, and by low melting temperatures (850–1200°C) and they are now being used in the USA, France, the United Kingdom, Japan and Germany. In the former Soviet Union a phosphate glass was developed for its two vitrification plants. However, Russia is also developing vitrification processes that also will use a BSG.

BSG was the first glass formulated for use in radionuclide waste disposal. Boron is used to reduce the melt viscosity and temperature below 1150°C. The lower temperature is desirable to reduce the corrosiveness of the melt and to increase the retention of volatile radionuclides such as cesium and technetium. Aluminosilicate glasses have excellent chemical, thermal, and mechanical durability (better than BSG) but also have higher melting temperatures and are thus more corrosive and difficult to process. Other glass types that have been considered include pyrex, glass ceramic (which has a crystalline structure), Synroc (a synthetic three-phase crystalline titanate), iron-enriched basalt (or IEB--an analog to natural basaltic rock), and IEB4 (similar to IEB but with zirconium and titanium added to increase the solubility of uranium oxide and TRU radionuclides (notably, Plutonium).

3.5.1.3 Glass Processing. The combination of high temperature and high-level radioactivity in vitrifying HLW requires sophisticated technologies to meet safety requirements and to permit remote processing. Glass formulations must be designed keeping in mind those species present in target waste streams, which can change the properties of the glass. Sodium, for example, can increase the electric conductivity of the glass melt while decreasing its viscosity. The sodium fraction in the glass must be adapted accordingly to achieve the desired processing characteristics.

Many materials contain adequate quantities of the essential ingredients for glass. However, not all waste materials contain the proper ratios of ingredients so custom formulated additives (known collectively as “frit”) are added to tailor the glass to meet performance requirements. Frit components have specific functions for various waste types, one of which is to maximize glass waste loading (typically 15-25 wt% in BSG). However, the maximum achievable loading is determined by elements with the lowest solubilities in the melt. Low BSG solubility is characteristic of molybdenum, chromium, and sulfur. When solubility limits are exceeded the melt becomes supersaturated and a separate immiscible phase emerges. Accumulation of separate melt phases can have negative impacts on glass quality and on the vitrification process. Limited sulfate solubility, for example, can produce a molten sulfate phase, which can introduce a steam explosion hazard into the process. In technical operation, such accumulations are excluded by the process flowsheet and process control.

3.5.1.4 Historical Evolution of Radioactive Waste Vitrification. Glass technology has a long history traceable to ancient times, and BSGs have been used since the early 1900s. As early as the 1950s glass was considered an important potential waste form for radioactive materials. Process development for vitrification purposes began in the early 1960s and the basis for current vitrification technology has been created in research facilities worldwide over the last 25-30 years. From these efforts two major production scale processes have emerged. One, developed in France, is the AVM process, which is based on a two-step procedure. The first step is a thermal pretreatment in a rotary tube calciner. The product from this step is melted in an induction-heated metallic furnace. The AVM plant in Marcoule, France was the first vitrification plant worldwide and started radioactive operations in 1978. This technology was adopted by the commercial vitrification plants of La Hague, France, and with minor modifications, in Sellafield, UK, in the 1980s. There is now a long history of industrial scale processing, particularly at La Hague, where over 6,000 canisters have been filled with vitrified HLW.

The second process, developed especially in the United States from the late 1970s, is based on a liquid-fed ceramic melter. Ceramic melters originated from conventional glassmaking technology and were adapted to meet the requirements of nuclear materials. Their major advantage lies in their potential for high throughput and service life. In Germany development of this melter type has been conducted at the INE of FZK (Institut für Nukleare Entsorgungstechnik of Forschungszentrum Karlsruhe) for over twenty years. Under various national and international programs long-term tests of various types of melters were done on simulated waste. Process technology for the PAMELA vitrification plant in Mol, Belgium was supplied through these activities. Radioactive processing of liquid waste at this facility was begun in 1985 and by the end of operation in 1991, the plant had vitrified 900 m³ of waste.

In the meantime, three more nuclear vitrification plants were equipped with ceramic melting furnaces. The first of these was the Defense Waste Processing Facility (DWPF) at DOE's Savannah River Site (SRS), which began radioactive operations in March 1996. Its purpose is to vitrify into BSG 37 million gallons of high-level radioactive waste in underground tanks. As of October 2001 DWPF had produced 1,178 canisters of HLW glass, representing 20% of the total required for all SRS high-level tank waste.

The second plant was the West Valley Demonstration Project (WVDP), 30 miles south of Buffalo, New York. Under congressional authorization given in 1980, DOE directed vitrification of 600,000 gal of high-level liquid waste from reprocessing of 700 tons of spent commercial nuclear fuel. The waste was generated by Nuclear Fuel Services, a subsidiary of the W. R. Grace Company. The waste was primarily from the plutonium-uranium extraction (PUREX) raffinates together with about 8,000 gal of thorium extraction (THOREX) process waste. In 1983, DOE selected BSG waste form for the WVDP. From July 1996 until June 1998 the WVDP, operating with an availability factor of 71%, produced 211 canisters of HLW glass.

The third of the three plants mentioned above was at Japan (Tokai Mura). Other facilities were also planned, including the Karlsruhe vitrification plant to manage the HLW from operation of the decommissioned WAK (Wiederaufarbeitungsanlage Karlsruhe) reprocessing plant.

Under the framework of the 1993 Hanford Federal Facility Agreement and Consent Order, signed by the State of Washington, the EPA, and DOE, a Tank Waste Remediation System program was established by DOE to process Hanford Site tank waste for permanent disposal. Under this program the waste will be separated into low- and high-activity streams and vitrified. The inventory to be processed includes 11 million m³ of radioactive fluids, of which, 216,000 m³ (57 million gal) are HLW fluids and sludge, and 6,900 metric tons are nuclear material (including 4,100 metric tons of uranium and 15 metric tons of cesium and strontium capsules). The Hanford vitrification plant is currently under construction.

3.5.1.5 Vitrification of SBW. In December, 1999 NE-ID requested that BBWI recommend a process to treat SBW stored in the INEEL's INTEC TFF. A broad-based team reviewed work performed over the prior 5–7 years and recommended that an A&E firm be contracted to provide a preliminary process design to treat SBW by extracting ¹³⁷Cs, grouting the residual liquid as CH TRU waste, and disposing the grouted waste at WIPP. However, during the summer of 2000, DOE-ID requested that the Tanks Focus Area convene a team of nationally recognized experts to independently evaluate all SBW treatment alternatives encompassed by the Draft EIS. This team recommended direct vitrification of SBW as the preferred treatment option, with the CsIX process as a backup.

Pursuant to this recommendation a feasibility study (Quigley 2000) was performed which defined a vitrification process and designed a facility to treat SBW. The study included schedules and cost estimates for construction and operation of the facility, a facility layout with drawings, a process description and flow diagrams, and preliminary equipment requirements and layouts. In late summer of 2000 BBWI prepared a technology roadmap to define the needed development work to resolve technical uncertainties for three possible treatment processes: Direct Vitrification, CsIX, and Solvent Extraction.

At the direction of DOE-ID BBWI focused FY01 development work toward direct vitrification of SBW. Under this mandate development activities for FY01 were revised to implement activities identified in the SBW technology roadmap. In April, 2001 a decision analysis meeting was convened to review candidate flowsheets for vitrification of SBW (Seward 2001). This meeting satisfied DOE PEMP 2.1.7.4 and resulted in the selection of a process baseline for vitrification. Later in FY01 a follow up feasibility study (Bates 2001) was performed to study the impacts to the baseline facility if it were designed to treat calcined HLW solids as well as SBW. In addition, an evaluation was performed (McDannel 2001) to assess feasibility of retrofitting the INTEC NWCF to process SBW (and possibly calcine) by installing a series of cold crucible induction melters (CCIMs). Finally, a technical baseline for SBW vitrification was established (Taylor 2001), based on the development work completed in FY01.

In FY02 DOE-ID directed BBWI to discontinue development of the SBW vitrification process and issued guidance to assess alternative processes to produce waste forms that would be disposable at WIPP. A summary report was generated by BBWI (Barnes 2002) documenting vitrification development work that was completed during FY01, and documenting outstanding uncertainties that had not been resolved.

[The above summary information was extracted from (NAS 2000), (Roth et al 2000), (Fullmer et al 2000), (Valenti et al 1999), (Norton et al 2002), and (Weber et al 1995).]

3.5.2 Process Functions

The primary function of a proposed Idaho Waste Vitrification Facility (IWVF) is to process SBW into a containerized glass waste form that can be transported to a final disposal site. To achieve this, the facility would perform a number of ancillary and subordinate functions. These functions are listed below, based on the processing assumptions current at the time the SBW vitrification baseline was established [see (Taylor et al 2001)]. The facility would:

- Retrieve SBW from the INTEC TFF into holding tanks in the IWVF (“SBW” includes concentrated SBW liquids, NGLW, and suspended solids. Heel solids and solid calcines may eventually also be retrieved and treated; however, the 2001 technical baseline addressed only liquid and suspended solids),
- Blend SBW feed with frit and sugar solution and homogenize the mixture to provide a qualified feed to produce a BSG waste product in a joule-heated melter,

- Vitrify the blended waste feed and cast the RH waste glass product into 2'x15' disposal canisters,
- Sample and analyze melter feeds and control the vitrification process according to an established quality assurance protocol to ensure that the vitrified waste product will meet WAC of the proposed disposal facility including packaging and shipping requirements,
- Filter and scrub process off-gases to extract solid particles, radionuclides, and gaseous pollutants (mercury, Cl, carbon monoxide, volatile/semi-volatile metals, and hydrocarbons) to comply with MACT and NESHAP requirements,
- Reduce off-gas NO_x concentration to meet project directed emission targets,
- Extract ¹³⁷Cs from scrub purge liquid to reduce radioactive content,
- Grout scrub purge and package it in suitable containers for disposal,
- Vitrify spent ion exchange resin used to extract ¹³⁷Cs from scrub purge liquid (or store for future vitrification with solid calcine),
- Treat and package other low-activity waste streams from the vitrification process (granular activated carbon from off-gas mercury removal, spent HEPA filters),
- Prepare packaged wastes for storage/disposal by performing (a) canister/drum closure, (b) decontamination, (c) certification by visual inspection and acceptance, (d) weighing, (e) determination of waste composition (including isotope concentrations of interest), and hydrogen generation rates, (f) labeling and logging (for recordkeeping), (g) transfer to lag storage or loading into shipping casks.
- Store all packaged wastes awaiting shipment for disposal,
- Receive, store, and blend required process additives (frit and sugar solution),
- Shield and decontaminate personnel to minimize radiation exposure.

3.5.3 Process Description

3.5.3.1 Feed Preparation. A process block flow diagram of the SBW vitrification process is shown in Figure 8. One INTEC TFF tank contains SBW tank heel solids (WM-187), and three other 300,000-gal tanks (WM-180, WM-188 and WM-189) together with three 14,000-gal tanks (WM-100, WM-101, and WM-102) contain concentrated SBW (liquid and suspended solids) and NGLW to be processed. These wastes, and possibly solid calcine stored at INTEC, are considered candidate wastes to be processed through the IWVF. However, the 2001 baseline SBW vitrification process addresses only processing of concentrated SBW liquids with suspended solids. With this in mind, the first processing step (performed over several years) is a series of tank transfers, evaporations, and consolidations to homogenize all concentrated liquid waste in the TFF. This is presumed necessary to the degree required by the Waste Form Qualification Plan (WFQP) in order to ensure that the variation in melter feed composition is within acceptable limits for the pre-qualified glass recipe used.

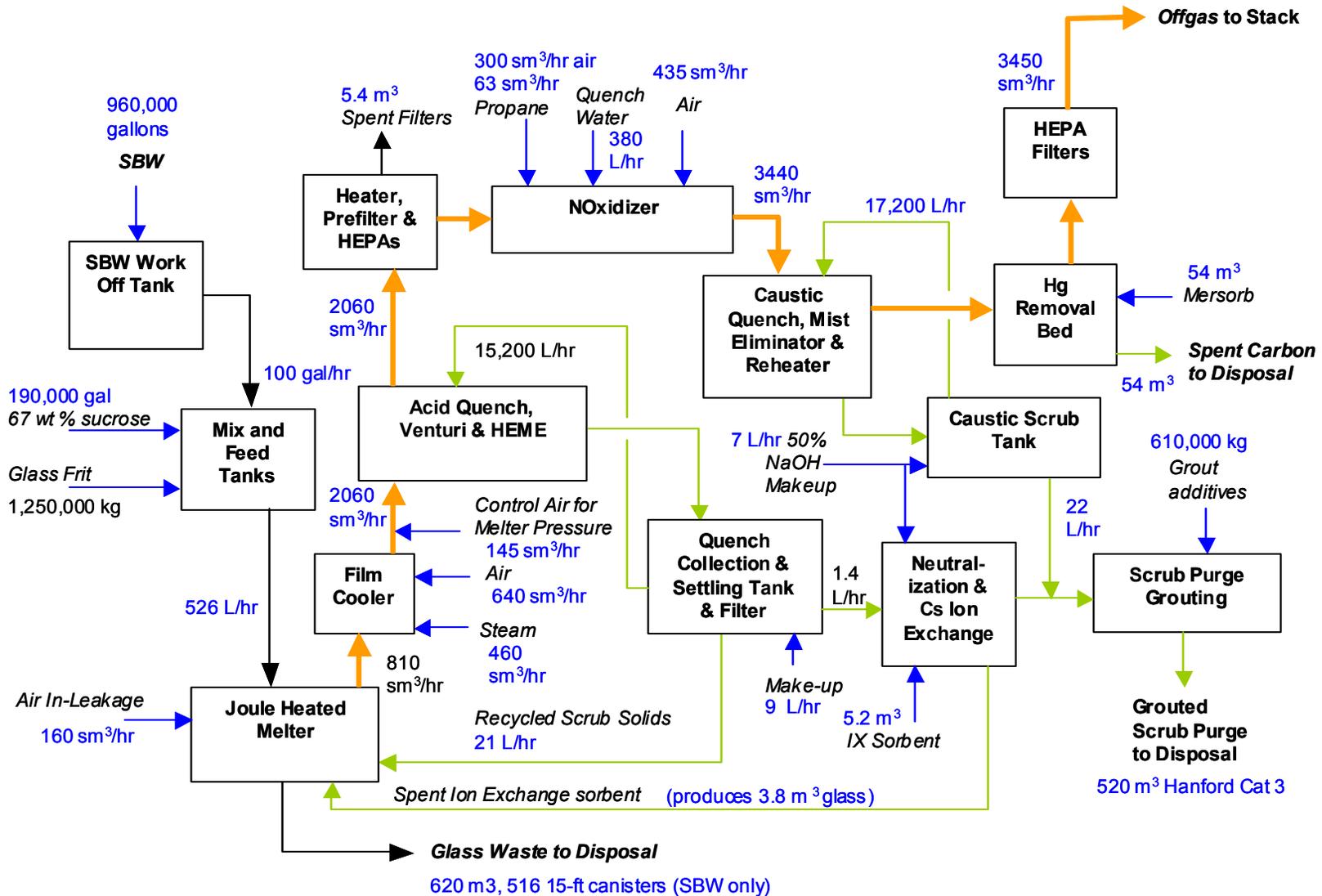


Figure 8. Block diagram of the SBW vitrification process.

Quantities in Figure 8 apply only to the waste stream “Total SBW”. This stream represents the July, 2001 projection (Barnes 2001) of the blended compositions of all liquid waste in the tank farm (excluding heel solids), including the contents of WM-180, WM-188, and WM-189, plus all partially full tanks (as of the time of the projection), plus all concentrated waste from NGLW expected through FY2011.

3.5.3.2 SBW Vitrification. When SBW vitrification begins the liquid waste is transferred from the INTEC Tank Farm into the IWVF SBW Work Off Tank. Feed additives, consisting of glass frit and 67% sucrose solution are received from offsite and stored until they are metered to a Mix Tank and blended with SBW and with recycled scrub purge liquor from the acid scrub system. The Mix Tanks are cooled to minimize reaction of sucrose with nitric acid. The tanks are also agitated to keep frit and undissolved waste solids in suspension and maintain a uniform composition. When one of the tanks is filled, the tank is sampled to verify that the feed composition is within the limits of the WFQP. After any required adjustments the slurry is transferred to a Feed Tank. The Mix and Feed Tanks are sized to allow time for sample analysis and feed adjustment in the Mix Tanks while maintaining the design melter feed rate from the Feed Tanks.

The Feed Tanks are heated with steam to evaporate water and promote reaction between sugar and nitric acid. NO_x, carbon monoxide, water, and heat are evolved and the remaining solid/liquid slurry and evolved gases are routed to the melter through separate lines. The joule-heated melter is similar to those used at the DWPF and the WVDP. Resistance heating in the molten glass maintains glass temperature at 1150°C and evaporates water from the liquid feed. Refractory lining protects the melter vessel from the corrosive melt and power is supplied to embedded Inconel 690 electrodes. Heaters in the melter plenum are used to start the melter and to increase evaporation of water from the feed.

Inside the melter all water evaporates. Sugar and nitrates decompose to form NO_x, nitrogen, carbon monoxide, carbon dioxide, hydrogen, and additional steam. Portions of the mercury, halides, and other volatile and semi-volatile components in the feed leave in the melter off-gas, together with steam and a fraction of the input solids and molten glass entrained by convective processes in the melter.

Empty waste glass canisters brought from offsite are quality checked, cleaned (if necessary), and moved to temporary storage in the IWVF by forklift. Cranes and specially fitted forklifts are used to move the canisters through the facility. When an empty canister is required, it is moved from storage to the melter cell onto a turntable with which it is positioned to receive molten glass. Heated taps on the side of the melter transfer molten glass into a canister. The glass level in the canister is monitored and the tap is closed for canister changeout when the 80% fill level is reached. Once a canister is filled it is cooled, and then transferred to other cells where it is closed by remote welding, decontaminated, and smeared. It is then moved to interim storage to await shipment for disposal.

3.5.3.3 Off-gas Treatment. As melter off-gas exits the melter it first enters a film cooler, a double-walled duct designed to introduce a film of cool gas (steam and/or air) between the inner duct wall and the melter off-gas. The injected gas cools particles in the off-gas below their softening point to minimize deposits in the duct. Additional air is injected downstream of the film cooler to provide pressure control in the melter. The temperature of the off-gas after the second air addition is about 330°C. It is cooled further to its dew point temperature (about 80°C) in the quench tower where scrubbing of large-diameter (>10 mm) solids in the off-gas occurs. The quench liquid is initially plain water but it becomes acidic by scrubbing of NO₂, hydrogen chloride, and HF from the off-gas.

The off-gas next enters a venturi scrubber where extraction of smaller particles and soluble gases continues through intimate gas/liquid contact from spray-atomization of scrub liquor. Most of the atomized liquid droplets are subsequently de-entrained by passage through a knockout drum and high-

efficiency mist eliminator (HEME). Both water droplets and fine (submicron) particles are collected on the HEME mesh. Water coalesced from the demisting process and from continuous spraying onto the inner face of the mesh provide a washing action, which flushes accumulated solids into the scrub liquid, which exits the HEME.

Removal of ultra-fine solid particles from the off-gas is completed in HEPA filters. The off-gas is heated just prior to entering the HEPA filters to prevent condensation and wetting of the filter fabric. The HEPA's are designed for >99.97% removal of particles larger than 0.3 μm . The filters are replaced when the pressure drop across them reaches a predetermined limit.

After filtration the off-gas is free of most radionuclides and can leave the hot cell. It next enters a three-stage combustion process, which destroys NO_x . In the first stage propane is burned in a fuel-rich, high-temperature (1200-1400°C) environment to reduce NO_x to nitrogen. In the second stage the gas is quenched by water injection to a temperature of 760-870°C. Sufficient air is then bled into the third stage to oxidize the residual hydrocarbons, carbon monoxide, and hydrogen. Reformation of NO_x is minimal due to kinetic limitations at the reduced temperature.

Following the De- NO_x process, the off-gas is cooled and scrubbed in a caustic quench scrubber to remove remaining hydrogen chloride, sulfur dioxide (SO_2), carbon dioxide, and NO_2 , and also to remove as much HI as possible. Scrubbing of HI reduces the amount of ^{129}I collected downstream in the GAC beds. The scrub solution is refreshed using 4 molar makeup caustic. Following the caustic scrubber, the off-gas is again demisted before passing through GAC beds and a final bank of HEPA filters. High-efficiency removal of mercury from the off-gas is achieved in the GAC beds with S-GAC. The second bank of HEPA filters removes any carbon from the GAC beds and provides backup to remove any radioactive solids that may have penetrated the upstream unit operations.

3.5.3.4 Spent Scrub Liquor Treatment. Spent scrub liquor from the initial quench, venturi scrubber, and HEME are collected in the acid scrub tank. There the solids separate from the liquid and the supernate is recycled to the quench tower and venturi scrubber. Concentrated solids are recycled to the melter and a portion of the scrub solution is purged. The purge stream is treated by filtering the solids, neutralizing with caustic, removing ^{137}Cs by ion exchange, and grouting the residual liquid. The filtered solids are recycled to the melter with the concentrated solids stream from the scrub tank. Inorganic, spent ion exchange resin is stored, accumulated, and later vitrified.

Grouting the cesium-free scrub purge requires preconditioning the liquid. Caustic is added to achieve pH 11-12 and calcium hydroxide is added to complex free fluoride. The preconditioned liquid is then blended with blast furnace slag and Portland cement and cast into 55- or 71-gal drums. The grouted drums are decontaminated, surveyed, labeled, and stored until shipment to a disposal site.

3.5.3.5 Treatment of Other Secondary Wastes. Spent GAC is assumed to pass TCLP and will be directly disposed as mixed low-level waste at either Hanford or the Nevada test site. The only treatment assumed is packaging in 55-gal drums and storage until offsite shipment. The process will also generate two classes of spent HEPA filters: High-activity filters (upstream of the NO_x abatement system) and low-activity filters (downstream of NO_x abatement, upstream of the stack). Both classes will be packaged without treatment and disposed, the former as RH waste at Hanford, and the latter as low-level waste at the Nevada Test Site or Envirocare.

Spent refractory from the NO_x abatement system will also be generated. However, the operating life of the refractory is expected to extend beyond the processing schedule. It is therefore considered a D&D item and its treatment and disposal are outside the scope of the SBW vitrification process.

3.5.4 Summary of Technical Performance

3.5.4.1 Quantity and Quality of Feed. A number of processing options and schedules were considered in establishing the FY01 processing baseline. These options included processing of SBW liquids (with suspended solids), concentrated NGLW, tank farm heels solids, and existing calcine solids at INTEC. Two candidate processing schedules emerged, both of which assumed construction of a new tank farm to allow emptying of all current tanks by 2012 in compliance with the 1995 Settlement Agreement with the State of Idaho. The first schedule (or “2012 Schedule”) assumed at least two vitrification campaigns. The first campaign, from October 2011 through November 2012, would vitrify 931,000 gal of the concentrated liquid waste inventory (mostly SBW with a small fraction of NGLW). The second campaign, from April 2016 through July 2016 would process the remaining 2012 inventory (44,000 gal) plus 75,000 gal of new liquids (mostly NGLW with a small fraction of SBW). This would leave 75,000 gal of slurry containing about 15 wt% of tank farm heel solids in dilute liquid waste (from sluicing of solids from emptied tanks). The slurry would be vitrified in a third campaign or stored for later processing with calcine.

The second candidate schedule (the “2016 Schedule”) would store all wastes in the new tank farm until June 2016 at which time waste vitrification would begin. The projected waste inventory at that time would consist of 1,025,000 gal of concentrated liquid plus 75,000 gal of heel solids slurry. These wastes, together with 36,000 gal of new waste liquid (generated during vitrification) would be processed between June 2016 and July 2018 (Barnes 2001).

Either schedule would require that the vitrification facility be designed to accommodate multiple feed types (concentrated liquid with a small concentration of suspended solids, slurry with up to 15 wt% solids, and possibly solid calcine). However, the 2001 vitrification process baseline addresses only concentrated SBW liquid and suspended solids. It should be borne in mind that the process information for SBW vitrification presented here deals only with this baseline.

Table 20 gives the calculated blended composition of the major constituents in the composite SBW waste. Concentrations in the table include contributions from the concentrated SBW liquids plus 2.73 g/L of suspended solids. The solids concentration is the weighted average of individual tank contributions listed in (Barnes 2001). Solids composition was assumed to be that of WM-180 solids as given in (Christian 2001). The variability in feed composition indicated in the last column represents the range of concentrations in tanks WM-180, WM-188, and WM-189 as listed in (Taylor et al 2001). A more detailed feed composition can be found in the last reference.

Table 20. Concentration range of major SBW constituents

Constituent Units	Nominal (mol/liter)	Max/Min Ratio
H+	2.4	3.4
Al+3	0.56	1.2
B+3	0.019	1.82
Ca+2	0.052	1.5
Cs+	0.000022	2.7
Cl-	0.024	1.4
Cr+3	0.0046	2.0
F-	0.082	2.4
Fe+3	0.022	1.2
Mg+2	0.0088	1.6
Hg+2	0.0038	3.3
NO3-	5.9	1.3
PO4-3	0.011	3.5
K+	0.16	1.4
Na+	1.5	1.7
SO4-2	0.051	1.6
Zr+4	0.012	310.

3.5.4.2 Processing Rate, Availability. Processing rates for the IWVF are based on the 2012 Schedule. A 2-year processing period is thus assumed for vitrification operations. Facility availability is assumed to be 200 days per year, 24 hours per day during that period. This translates to an average processing rate of 100 gal/hr or 1.7 gal/min of SBW liquid feed.

The facility availability is based on operating experience at the INEEL working within DOE regulations. Changes in this operating environment could significantly alter the assumed availability and processing rate. Ideally, the glass melter would operate without interruption. Off-spec blends of SBW and frit and feed system plugging are two scenarios that could hinder smooth operations. Corrosion failure of melter electrodes could also impact the facility availability factor, as could other process uncertainties discussed below in Technical Uncertainties and Potential Impacts.

3.5.4.3 Waste Products Quantity & Quality. The primary waste product from this option is glass vitrified from the SBW feed. This product could be disposed at either WIPP or the Federal HLW Repository (Yucca Mountain).

Secondary wastes include glass from vitrification of spent ion exchange resin, the grouted scrub, spent GAC, and contaminated HEPA filters. Spent resin glass, grouted scrub, and untreated HEPA filters could be disposed at Hanford (as Cat 3 waste) or the Nevada Test Site (as NRC Class C waste). Spent GAC could be disposed at Hanford (as Cat 1 waste) or Envirocare. Note that glass from spent resin would not qualify to disposal at WIPP because its TRU content is below 100 nCi/g.

A quantitative summary of these waste products is shown in Table 21. It is assumed that spent GAC will not require treatment prior to packaging in 55-gal drums and disposal as mixed low level waste.

Table 21. Volumetric summary of waste products.

Waste Products	Total#	Total kg	Total m ³
Vitrified SBW		1,600,000	618
RH canisters (a)	515		
Vitrified Ion Exchange Resin		9,900	3.8
RH canisters (a)	3		
CH Grout (from scrub)		940,000	521
CH drums (b)	2,500		
CH Carbon (spent GAC)		30,000	54
CH drums (b)	260		
HEPA Filters			6.3
Totals	3,300	2,600,000	1200

^a Vitrified wastes are cast in 2'x15' canisters which each hold 1.2 m³ of glass.

^b Mixed, low-level wastes are assumed to be packaged for disposal in 55-gal drums.

Radioactive properties of the waste products are shown in Table 22, based on mass balances in Taylor et al, 2001. Dose rates and heat generation rates were not calculated for these mass balances. However, these rates are expected to be approximately equal to those calculated from the earlier mass balance for the vitrification feasibility study (Quigley et al 2000). The values from this earlier study were apparently calculated based on radionuclide concentrations in SBW in the year 2000, without accounting for radioactive decay up to the time at which vitrification begins and are therefore quite conservative. For vitrified SBW the calculated canister contact dose rate was 65 R/hr and the heat generation rate was 9.5 watts¹. For the grouted scrub product the corresponding values were 480 mR/hr and 3.4x10⁻³ watts for scrub liquor without Cs removal, and 2.6 mR/hr and 1.9x10⁻⁴ watts for the baseline case (with Cs removal).

Radiological dose and heating rates were not estimated for the other secondary wastes from the baseline process.

¹ The 2000 feasibility study assumed 2'x10' canisters for the heat generation rate was calculated at 5.7 watts/canister. The number here has been corrected for the larger 2'x15' canisters using the glass volume ratio (1.2/0.72).

Table 22. Radioactive properties of waste products

Vitrified SBW	Nominal
All Radionuclides (Ci/canister)	190 - 1400
Fissile Gram Equivalent (g/canister)	40 - 120
²³⁹ PU Equivalent Curies (Ci/canister)	2.5 – 7
TRU Content (nCi/g)	2,300 – 6,700
Grouted Scrub	
Sum of Fractions (Hanford Cat 3)	1.4E-05 – 8.0E-04
Sum of Fractions (NRC Class C)	9.0E-04 – 3.5E-03
Spent GAC	
Sum of Fractions (Hanford Cat 1)	9.5E-06
Sum of Fractions (Envirocare)	2.6E-11
Vitrified IX Sorbent	
Sum of Fractions (Hanford Cat 3)	0.047
Sum of Fractions (NRC Class C)	0.12

3.5.4.4 Size, Footprint of Processing Facility. Equipment sizing and facility layout were performed as part of the 2000 feasibility study (Quigley et al 2000). The plan drawings are provided in the referenced external report. The facility was not updated for the 2001 baseline. However, the processes are sufficiently similar that the earlier layouts are considered representative.

Per the feasibility study layout the vitrification facility would consist of two buildings. The first is a multilevel structure, which would house the process building with a footprint of roughly 380 x 169 ft. The structure would extend 32 ft below and 70 ft above grade. The second building is the administrative/support building, a single-level structure with a footprint of 190 x 70 ft, built at grade immediately adjacent to the processing building.

The processing building has five floors and includes 19,400 ft² of hot cell area on the main floor with an additional 17,000 ft² of hot cell area on the basement level. The main floor hot cell includes roughly 9,200 ft² of processing area, 1,100 ft² for canister closure, and the balance (9,100 ft²) for remote equipment maintenance, access corridors, and air locks. The control room is part of the adjacent administrative area on the ground floor. Post-casting canister closure activities (cooling, decontamination, transfer to interim storage) are done in the basement hot cells. The basement level also includes a storage area for clean canisters. The facility provides no interim storage area for filled, RH canisters.

Plot space estimates for the IWVF are summarized in Table 23.

Table 23. Vitrification facility space estimates for 2-year processing schedule.

Area Description	Area, ft ²
Main Floor	
Tankage	3,200
Vitrification	1,400
Canister Closure/Smear	1,100
NO _x Abatement	1,200
Off-gas Treatment	1,100
Scrub Purge Grouting	1,400
Equipment Decontamination	940
Mechanical/Electrical	14,000
Basement	
Clean Canister Storage (basement)	4,100
Can Cooling (basement)	1,600
Canister Decontamination (basement)	420
Tankage (basement)	2,100
Admin Area	
Administrative	13,000
Mechanical/Electrical	1,100

3.5.4.5 Effects of Scale, Variation with Throughput. Changing the scale of the process, i.e., designing for an accelerated treatment schedule, would have the most effect on the process operations performed on the main floor of the facility. Two areas in particular – the hot processing cells and the cooling area for filled waste canisters – would be affected.

Major process equipment in the hot cells includes SBW work off tank, mix/feed tanks, melter, off-gas treatment train, GAC beds, spent scrub ion exchange columns, and grout mixer. Decreasing the processing time would increase the floor space required for most of this equipment by the inverse ratio of the processing times raised to either the two-thirds power (storage vessels) or to the first power (process equipment). Reducing the schedule from 2 years to 1 year, the floor space for storage vessels would thus increase by a factor of $\sim(2/1)^{0.667} = 1.59$, and for process equipment by a factor of $\sim(2/1)^{1.0} = 2$.

Provision for interim storage, though not included in the 2000 facility plan, would also be needed. The requirement is driven by (a) the initial lag time between certification of the first canister of glass and actual shipment to the disposal site, and (b) the excess of the rate at which certified waste canisters are produced over the rate at which the disposal site can accept them. The key parameters to determine the actual area requirement are thus (a) the hot operation starting date for the melter, (b) the date at which the target disposal site (e.g., Yucca Mountain) begins accepting INEEL waste canisters, and (c) the rate at which the disposal site can receive, transport, and position the canisters in the facility. Due to large uncertainties in all these parameters, the interim storage facility requirement has not been defined.

The plot space estimates for the facility with a 1-year processing schedule, obtained from the above scaling considerations, are summarized in Table 24. (No scaleup factor has been applied to equipment items that are assumed to be underutilized in the baseline facility.)

Table 24. Vitrification facility space estimates for 1-yr processing schedule.

Area Description	Area, ft ²
Main Floor	
Tankage	5,080
Vitrification	2,800
Canister Closure/Smear	1,100
NO _x Abatement	2,400
Off-gas Treatment	2,200
Scrub Purge Grouting	1,400
Equipment Decontamination	940
Mechanical/Electrical	14,000
Basement	
Clean Canister Storage (basement)	6,508
Can Cooling (basement)	2,540
Canister Decontamination (basement)	420
Tankage (basement)	3,334
Admin Area	
Administrative	13,000
Mechanical/Electrical	1,100

3.5.5 Technical Uncertainties and Potential Impacts

In 2000 and 2002, prior to the creation of the SBW Treatment Facility Project, alternatives analyses were performed (Murphy et al 2002, Perry 2002) that reviewed processing technologies considered for treating SBW up to that point. The 2002 analysis resulted in selection of four technologies considered to be preferred options, based on the screening criteria that were applied. The subsequent applied technology plan (Lauerhass et al 2003) identified uncertainties resulting from technical and operational risk assessments associated with the four selected alternatives. Since vitrification was not among those selected it was not included in the risk assessments and the applied technology plan did not include prioritization and description of its associated technical uncertainties. For this reason there is no tabular summary status of uncertainties from the applied technology plan as there is for the other technologies discussed in this report.

Mass balances were developed for the vitrification technical baseline to provide a basis to size equipment, determine feed chemical requirements, determine utility requirements, estimate emissions, and determine waste volumes, compositions and properties. To prepare the mass balances a set of DBEs was assembled in lieu of hard data addressing technical uncertainties. The DBEs are assumptions about uncertainties and represent a level of risk to the successful implementation of an SBW vitrification facility. Each DBE will require acceptance of technical risk or Applied Technology/Engineering

development/demonstration efforts for validation before the next process design steps are taken. As of September 2001, 152 DBEs had been identified for the process. It is likely that more would be identified if this treatment option were selected. The individual DBEs are amplified with background information, references, explanation, and, in some cases, a discussion of uncertainties in (Taylor et al 2001).

At the end of FY01 a review of FY01 development work was commissioned (Barnes et al 2002) to update the status of the uncertainties and DBEs. Also, in early December 2001 an EM-50 review of the FY01 SBW vitrification work was conducted at the INEEL. The meeting provided additional insight into high-priority uncertainties that were outstanding.

The following is a summary of some of the major uncertainties that were the subject of these reports and discussions. Underlined items are DBE titles from the 2001 technical baseline. Those that were the focus of discussion by DWPF personnel at the December EM-50 review meeting are so indicated.

3.5.5.1 *Melter Chemistry.*

- *Speciation and partitioning of sulfate in melter.* Sulfur has a finite solubility limit in any glass recipe. Once the limit is reached in a melter, excess sulfur will form a separate molten salt phase. Such phases were observed in some subscale and pilot tests during FY01. The salt phase is undesirable for several reasons. First, it introduces the possibility of a steam explosion if mixed with a small amount of water. Second, a salt phase can accelerate corrosion to melter materials. An acceptable feed composition envelope and glass recipe for SBW was not firmly established in FY01. Due to the sulfate content of the SBW waste (both liquid and solid) it will be necessary to both establish and demonstrate a glass recipe which will accommodate all sulfur in the full range of expected feed compositions, or develop and demonstrate a viable means to detect and remove any molten sulfate salt layer that may develop during processing.
- *Noble metals concentration in SBW feed.* Noble metals are problematic in joule-heated melters due to their propensity to separate and form a separate molten metal phase that can cause electrical shorting between the melter electrodes. Noble metals known to be present in SBW include Ru, Rh, Pd, and Ag and estimates of their concentrations have been made. It has also been reported that selenium and tellurium influence the behavior of noble metals in a melter. However, the amount of molten metal present at steady state under varying conditions with SBW feed has not been quantified, nor has a threshold amount above which problems occur. Reliable measurements of total noble metal concentrations in SBW and of problem thresholds are needed. It may also be required to demonstrate a means to extract any molten, noble metal phase from the melter, should one develop.
- *Reductant selection and concentration in melter feed.* Sugar is the preferred candidate reductant due to its history of use for various nuclear waste treatment applications and its success in SBW vitrification tests to date. However, other organic reductants (e.g., activated carbon, glycolic acid, corn starch) have been considered for various reasons. Choice and concentration of a reductant was singled out by DWPF personnel as a high-risk uncertainty that impacts several parameters (among them nitrate destruction rates and glass redox ratio, which in turn impacts glass foaming and possibly glass durability).
- *Frit vs. glass forming chemicals in melter feed.* WAC for waste disposal at Yucca Mountain. Acceptance of INEEL's vitrified waste at Yucca Mountain will most likely be based on demonstrable conformity to a WFQP. The WFQP will document the development of a glass recipe (consisting of prescribed envelopes of feed composition and melter operating

conditions), which ensures that the resulting glass meets the Yucca Mountain acceptance criteria. The development of this recipe is heavily dependent on the choice of additives that are blended with the waste. The nature of these additives (both the composition and the physical form--as frit or as glass forming chemicals, or GFCs) influences the quality of the glass and the processing behavior. Choice of frit or GFCs will therefore dictate the course of development of the glass recipe and of the WFQP. DWPF personnel flagged this choice as a high-priority uncertainty requiring attention. In addition, it is noted that the WFQP for DWPF is a many-volume document reflecting a sizable investment of time and money. Development of a WFQP for SBW was barely started when development work for SBW vitrification was terminated at the end of FY01. The WFQP is a long-lead item that influences the system design and would require prompt attention to implement SBW vitrification in a timely fashion. A WFQP would also be required for disposal of a glass waste form at the WIPP. However, the level of effort required to achieve waste certification for WIPP disposal is not anticipated to be nearly as high as for Yucca Mountain.

3.5.5.2 Off-gas Scrubbing.

- Partitioning of acid gases and Mercury during quench/scrubbing operations. Stack concentrations of hydrogen chloride, Cl₂, mercury, and ¹²⁹I must be controlled for compliance with MACT and NESHAP standards. In addition, experience in the NWCF indicates the potential for buildup of mercury in acid scrub solutions. The fate of SO₂/SO₃/H₂SO₄ is needed in the prediction of sulfate concentrations in recycle streams to the melter to control formation of molten sulfate salts. The fate of carbon dioxide is needed to design the caustic quench column. The vapor/liquid partitioning of these species in acid and caustic scrubbing is needed in system models used to design and optimize unit operations to ensure compliance with stack emission limits.
- Species removal efficiencies in HEME / Soluble species in off-gas / Selection of quench and scrub components in off-gas treatment system. The baseline process scheme includes a film cooler, acid quench, venturi scrubber, HEME, and HEPA filters together with an oxidizer, caustic quench, mist eliminator, GAC bed, and a second HEPA filter bank. Performance of many of these systems depends on both the species solubilities and removal efficiencies in scrubbers and HEMEs. Because of the serial nature of off-gas treatment unit operations and the use of recycle streams, performance of each unit operation may be strongly influenced by (a) species behavior in other unit operations, (b) choice of system components, and (c) configuration of unit operations relative to one another. Underscored uncertainties will thus require resolution in order to design and demonstrate an off-gas system that will achieve the required performance. In particular, DWPF personnel have pointed out the need for judicious choice of quench and scrub components in light of operational problems experienced with plugging/blinding of HEMEs due to submicron particle capture, and penetration of contaminants through HEPA filters that have been wetted by condensation. It was pointed out that alternative unit operations (e.g., customized HEME mesh washing, high-energy scrubbers like the steam-atomized scrubbers used at DWPF, or wet electrostatic precipitators) may be required to preclude major operational problems after the facility is in operation.

3.5.5.3 Material Behavior.

- Corrosion of melter components. This uncertainty was among those flagged by DWPF personnel as high-risk/high-priority. SBW includes high acid, high nitrate materials. Also, the presence of sulfate and chloride provides the potential to form one or more highly destructive acids and/or molten salts in a high temperature environment. Unacceptable electrode loss was

observed in some tests that may have been due to a low redox ratio or the choice of material for the electrodes. Inadequate understanding of corrosion behavior of melter components could result in a melter design and/or operating parameters that lead to premature system failure and negative cost and schedule impacts.

3.5.5.4 Processing Alternatives.

- Canister closure method. The preferred closure method is welding and the uncertainty associated with the choice was initially assigned a low priority. However, again based on input from experienced DWPF personnel, its priority (together with the issue of selection and demonstration of a method to decontaminate filled glass canisters) was raised.
- Melter selection. An early programmatic decision was made to utilize a joule-heated melter. However, there are compelling reasons to consider other alternatives such as a cold-crucible induction melter (CCIM). A short feasibility study was performed during FY01 addressing the possibility of retrofitting the NWCF with two or more CCIMs. Though the scope of the study was limited, and some measures of feasibility were treated in insufficient detail for definitive conclusions, it was concluded that potential benefits (e.g., capital cost savings) may likely be realized and no insurmountable obstacles were discovered. The study points up the need for a systematic analysis and comparison of alternative melters before proceeding further in detailed process design.
- Effects of recycled scrub on melter and glass. The baseline process assumes that recycled scrub solution will be accumulated and fed back to the melter. The impacts of recycled scrub solution on melter performance are assumed to be (a) water dilution, (b) altered relative concentrations of major species in the glass formulation, and (c) changed mixing/pumping characteristics of the mixing tank solution. The magnitude of these impacts (e.g., the reduction in net SBW throughput resulting from dilution, and the conformity of melter feed with the qualified glass recipe in the WFQP) has not been demonstrated.

3.5.5.5 Process Control.

- Off-gas flow control system / Pressure drops through off-gas system components. The baseline flow control in the vitrification off-gas system is patterned after a system of throttling valves, air bleeds, and compressors similar to that in the NWCF. However, it was pointed out by DWPF personnel that the melter system is far less tolerant of pressure instability and fluctuations than is the NWCF due to the use of hydrostatic pressure to control the flow of molten glass through the pour spout into the canisters. No detailed design or testing has been performed to compare system dynamic behavior with that of (say) DWPF, where a considerable effort was expended before a workable system was developed and demonstrated.
- Flammability limits on hydrogen, carbon monoxide, and unburned HCs in off-gas. The total flammability of a gas mixture is the sum of the percent flammabilities of the separate flammable gases and should be less than 50% to ensure system safety. The true flammability of the melter off-gas is affected by the melter outlet gas temperature and the presence of other gas species (e.g., water) that can dilute any oxygen that is present. The flammabilities of melter off-gas upstream of the film cooler must be defined (and probably demonstrated) under all expected conditions to preclude any possibility of explosion in the melter or off-gas system. This uncertainty was flagged by DWPF personnel for elevated priority. The need was suggested to evaluate the off-gas composition envelope using the qualified flammability model developed for this purpose at SRS.

3.5.5.6 Stream Factor.

- The facility design is based on a 2-year operating schedule with 200 days of operation per year. This availability factor is based on NWCF operating experience that may be overly optimistic for a melter.

3.5.5.7 Facilities Interfaces.

- A new SBW vitrification facility would be interfaced with existing INTEC facilities (INTEC TFF, main stack, and APS) and infrastructure (notably, the low pressure steam system, water systems [de-mineralized, de-ionized, distilled, fire water, treated water, potable water], sanitary waste, service waste, power grid for electricity, and high-pressure air supply for process maintenance), and communications systems (alarm, phone, voice, and data). The existing facilities have set capacities that must be accounted for in the process design and new equipment selection.
- A comparison of projected utilities requirements of the SBW vitrification process against INTEC capabilities is needed to ensure that no modifications are needed to these systems.

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