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HANFORD MEDIUM/LOW CURIE WASTE PRETREATMENT PROJECT - PRETREATMENT PROCESS PLAN

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Abstract: A fractional crystallization (FC) process is being developed to supplement tank waste pretreatment capabilities provided by the Waste Treatment and Immobilization Plant (WTP). FC can process many tank wastes, separating wastes into a low-activity fraction (LAW) and a high-activity fraction (HLW). The low-activity fraction can be immobilized in a glass waste form by processing in the bulk vitrification (BV) system.

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ABSTRACT

A fractional crystallization process is being developed to supplement tank waste pretreatment capabilities provided by the Waste Treatment and Immobilization Plant (WTP). Fractional crystallization can process the vast majority of tank wastes comprised of dissolved salts with relatively low to medium soluble radioactivity, separating wastes into a low-activity fraction and a high-activity fraction. The low-activity fraction can be immobilized in a glass waste form by processing in the bulk vitrification (BV) system. The high-activity fraction will be returned to the double-shell tank (DST) system for feed to the WTP.

The Hanford Medium/Low Curie Waste Pretreatment Project Phase I Process Plan reviews process theory, discusses thermodynamic chemical process modeling results, and presents a preliminary conceptual design for the fractional crystallization process. A preliminary cost estimate and schedule are provided for deploying the fractional crystallization process to treat Hanford tank wastes.

KEY WORDS

Fractional crystallization, BV feed, waste pretreatment system, sulfate removal, cesium removal, ESP model, thermodynamic chemical process model, Hanford Medium/Low Curie Pretreatment Project, burkeite

EXECUTIVE SUMMARY

In accordance with the Hanford Federal Facility Agreement and Consent Order jointly agreed to by the Washington State Department of Ecology (Ecology), the U.S. Environmental Protection Agency (EPA), and the U.S. Department of Energy – Office of River Protection (DOE-ORP), all Hanford underground tank wastes must be treated by 2028. Key to achieving this goal is to develop and deploy technologies to treat and immobilize the low activity wastes (LAW) which comprise the bulk of the tank contents. Since sodium nitrate comprises the bulk (about 67%) of the tank wastes, its removal is essential to achieving the deadline. In 2004 DOE-ORP decided that a process known as bulk vitrification (BV), a commercially proven process for immobilizing hazardous wastes, would undergo further development as a way to treat the LAW. BV was selected because it can tolerate higher levels of certain waste components, primarily sulfate, than the LAW melters currently being developed for the Hanford Waste Treatment Plant (WTP). Although the BV process is robust and can accommodate a wider range of sulfate bearing feed stocks than the WTP, it is limited in the amount of radioactive constituents (primarily cesium – ^{137}Cs) it can receive because of considerations for the radiological dose rate to operating personnel and the total curie content of the waste package. The liquid waste feed to BV is mixed with a glass former (sand), heated to remove excess moisture, and fed to a melter until the waste container is full. To condition the feed for BV (i.e. increase sulfate loading and remove ^{137}Cs), while removing sodium nitrate from tank wastes, DOE-ORP sought a pretreatment system that could process dissolved saltcake waste (retrieved from single shell tanks – SSTs) and dissolved salt slurry waste (from double shell tanks – DSTs). In December 2004 fractional crystallization was selected for evaluation as the pretreatment system and it would be evaluated by a two-phased program.

Fractional crystallization is another commercially proven process, typically used for pharmaceuticals (purifying drugs) and industrial chemicals (cleansers, fertilizers, etc.), that works by evaporating feed stocks and selectively (by varying process parameters) forming pure crystalline products. During formation of pure crystalline products, impurities (of particular interest is ^{137}Cs) are excluded from the growing crystal lattices due to differences in ionic radii. In addition, for the operating ranges proposed, the soluble radionuclides are far from their saturation concentrations and do not crystallize from solution during evaporation.

The two-phased program would determine the feasibility of using fractional crystallization by first demonstrating its use on simulants, formulated to closely resemble SST/DST waste, then using it to separate actual SST/DST tank waste. It is the goal of the process to keep radionuclides in the liquid phase while separating low-activity sodium salts; therefore, the fractional crystallization system has to demonstrate that it can successfully remove sulfates and sodium nitrate as well as provide a low curie feed to the BV process. The processed waste containing higher levels of radioactive materials, but lacking high levels of sulfate, will be routed back to the DSTs for eventual processing by the WTP.

This Process Plan developed for the first phase study – Phase I of the Medium/Low Curie Pretreatment Project – concentrates on the theoretical aspects of fractional crystallization and how it could be deployed at Hanford. Details of the laboratory testing program with results of

the simulant experiments can be reviewed in *Hanford Medium/Low Curie Waste Pretreatment Project – Phase I Laboratory Report* (RPP-RPT-27239).

This plan reviews the basic chemical engineering concepts essential to understanding the unique characteristics of the SST/DST wastes and how they can be manipulated with the fractional crystallization process variables. Key to this understanding is the use of a thermodynamic chemical process model, Environmental Simulation Program (ESP) by OLI Systems, Inc, that was used to determine what reactions could occur by investigating waste constituent properties such as Gibbs Free Energy, solution solid phases, solution ionic strength, effects of pH, temperature, water content, etc. The model was used extensively to guide laboratory simulant experiments (from two- or three-component "simple solutions" up to the complete multi-component simulants), and estimate actual waste behavior to allow conceptualizing actual process equipment. The use of carbon dioxide (carbonation), to condition the waste, was explored with the model and laboratory work. Treating two other waste components, alumina and nitrites, was evaluated with the model, but left for future laboratory work to determine feasibility. Concurrent with estimating the various crystalline salt product yields, the model can also estimate theoretical cesium removal, an important consideration for the BV feed.

Using commercial crystallization experience, ESP model predictions, and laboratory simulant work, a conceptual two-stage crystallization process has been proposed for treating the Hanford SST/DST wastes. To minimize overall project costs, a single facility is proposed for both demonstration studies (two years) and production capability (17 years). The functions/basic characteristics of the proposed process components are discussed and these are used as the bases for an ALARA Study and a qualitative Preliminary Hazard Assessment. Based on these evaluations the Fractional Crystallization Facility was conservatively designated as a Category 2, non-reactor nuclear facility in accordance with DOE-STD-1027-92. This designation was then used to evaluate a partial life cycle cost (including design, construction, testing, operation, and decontamination and decommissioning – D&D) of $187.7 million. This preliminary estimate is considered as a partial life cycle cost because it does not include DOE-ORP (owner) or Tank Farm Operator (TFO) oversight during the facility life cycle. This estimated cost also does not reflect the impact of operational decisions, i.e. tank farm interfaces (tankage/piping/solids removal) and process analytical requirements which have been deferred to Phase III of the project. A schedule, which allows for design work to proceed in parallel with Phase II radioactive waste testing, has also been proposed which provides for "hot" (radioactive) operations to commence late in CY 2009.

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LIST OF TERMS

Abbreviations and Acronyms

ALARA	As Low As Reasonably Achievable
CI	COGEMA, Inc.
DBVS	Demonstration Bulk Vitrification System
DF	Decontamination Factor
DFCS	Demonstration Fractional Crystallization System
DOE-ORP	U.S. Department of Energy – Office of River Protection
DSA	Documented Safety Analysis
DST	double-shell tank
DTB	draft tube baffle
Ecology	Washington State Department of Ecology
ENR	Engineering News Record
EPA	Environmental Protection Agency
ERDF	Environmental Restoration Disposal Facility
ES&H	Environment, Safety and Health
ESP	Environmental Simulation Program
ETF	Effluent Treatment Facility
FCF	Fractional Crystallization Facility
FCS	Fractional Crystallization System
FHA	Final Hazards Analysis
FY	fiscal year
HAMTC	Hanford Atomic Metal Trades Council
HEPA	High-Efficiency Particulate Arrestor
HLAN	Hanford Local Area Network
HLW	high-level waste
HVAC	Heating, Ventilation and Air Conditioning
IM	Information Management
LAW	low-activity waste
LCAM	Life Cycle Asset Management
MAI	Mission Acceleration Initiative
MSE	Mixed Solvent Electrolyte
NUREG	U.S. Nuclear Regulatory Commission Regulatory Guide
ORP	Office of River Protection
ORR	Operational Readiness Review
PDSA	Preliminary Documented Safety Analysis
PFD	Process Flow Diagram
PHA	Preliminary Hazards Analysis
PPE	Personal Protective Equipment
psig	pounds per square inch gage
QA	quality assurance
RCRA	Resource Conservation and Recovery Act
RPP	River Protection Project

SDD	System Design Description
SI	International System of Units
SOW	statement of work
SST	single-shell tank
TRU	transuranic
WAC	Washington Administrative Code
WBS	Work Breakdown Structure
WTP	Waste Treatment and Immobilization Plant

Units

Ci/L	Curies/Liter
cP	Centipoise
g	gram
gpm	gallons per minute
M	Molar
mL	milliliter
V	volts
wt%	weight percent

SECTION 1.0

1.0 INTRODUCTION

1.1 PROJECT BACKGROUND

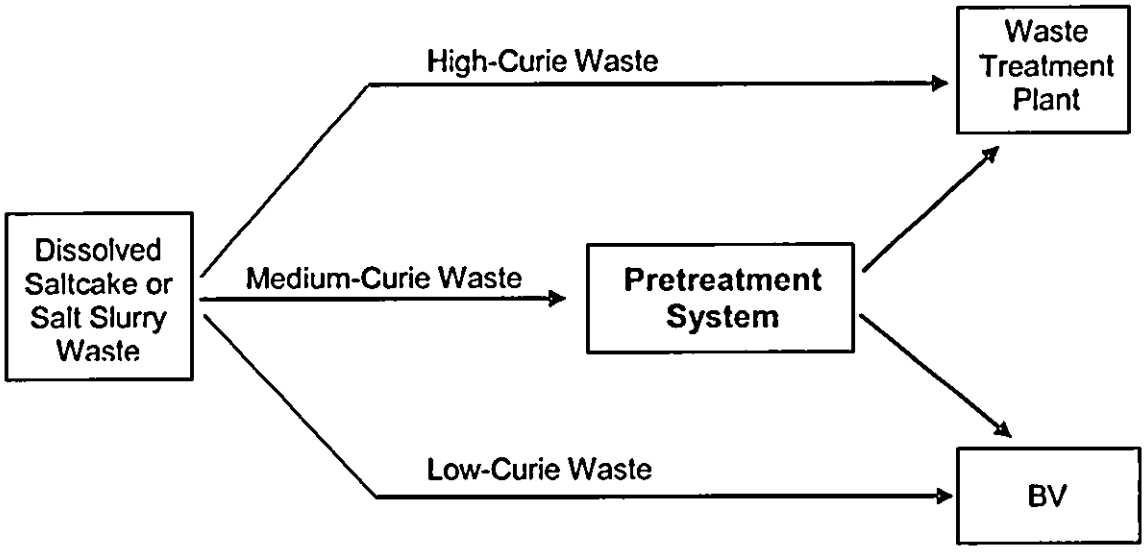
The Department of Energy-Office of River Protection (DOE-ORP) is responsible for the remediation of the Hanford Site tank farms, including 53 million gallons of mixed waste (waste with both hazardous and radioactive components) contained in 149 single-shell tanks (SST) and 28 double-shell tanks (DST). DOE-ORP manages the River Protection Project (RPP). In the current approach to tank waste remediation under the RPP, waste retrieved from the tanks will be partitioned to separate the high-level waste (HLW) constituents from the large volumes of low-activity waste (LAW) in the tanks. The HLW constituents are to be vitrified in the Waste Treatment Plant (WTP), stored onsite, and ultimately disposed of in the offsite national repository. The LAW also would be vitrified in the WTP and then disposed of onsite in trenches that comply with the Resource Conservation and Recovery Act of 1976 (RCRA) as amended, including the Land Disposal Restrictions of 1984, and with DOE Order 435.1, Radioactive Waste Management.

Under a consent order entered into by the Washington State Department of Ecology (Ecology), the U.S. Environmental Protection Agency (EPA), and the DOE-ORP, the treatment of all Hanford Site tank waste is to be completed by 2028. The Mission Acceleration Initiative (MAI) was developed to help ensure that the 2028 tank waste treatment milestone would be met. A key element of the MAI is the testing, evaluation, design and deployment of supplemental LAW treatment and immobilization technologies to provide additional LAW processing capacity.

In the first quarter of fiscal year (FY) 2004, DOE-ORP decided that the supplemental technology known as Bulk Vitrification (BV) would undergo further development. The BV process can tolerate higher levels of certain waste components (e.g. sulfate) than the WTP. In December 2004, fractional crystallization was selected for evaluation as a pretreatment process for the LAW to ensure that problematic waste components are diverted preferentially to the BV facility, while radionuclides (primarily ^{137}Cs and ^{99}Tc) are diverted to the WTP.

The Pretreatment System will receive clarified, i.e. entrained solids removed, dissolved saltcake waste (retrieved SSTs) and/or dissolved salt slurry waste (from DSTs). Entrained solids present in the LAW feeds can contain high concentrations of ^{90}Sr and transuranic (TRU) elements and must be removed to ensure the immobilized LAW meets disposal requirements for ^{90}Sr and transuranic elements. Entrained solids removal (filtration) is to be performed by the Tank Farm contractor and is outside the scope of the current project. The function of the Pretreatment System will be to use fractional crystallization to separate the waste into two or more streams, one of which will be routed to the WTP feed tanks. The remaining stream(s) will be routed to BV. The Pretreatment System will be an integral component of an overall waste treatment system (see Figure 1).

Figure 1. Tank Waste Treatment System.



1.2 SCOPE

Demonstrating fractional crystallization for waste pretreatment is a two phase process. Phase I (September 2005) establishes the basic laboratory separation processes using simulated tank wastes and guided by thermodynamic chemical process simulation models. Results of the laboratory experiments can be examined in the "Hanford Medium/Low Curie Waste Pretreatment Project - Phase I Laboratory Report" (RPP-RPT-27239). Phase II of the project repeats the Phase I experiments, but actual tank wastes will be used in place of simulants. Simulant experiments will also be conducted during Phase II to gain additional knowledge of salt behavior during crystallization.

In addition to developing the waste separation processes, an integral task of Phase I was to investigate the feasibility of deploying a fractional crystallization system (FCS) at Hanford. This plan reviews the chemical process basics, introduces a preconceptual design of the proposed FCS, and presents the estimated schedule and life cycle cost for system deployment near the Demonstration BV System (DBVS) in the Hanford 200 West Area. The proposed site location (Figure 2 and Figure 3) was selected because it is adjacent to the DBVS and close to the underground waste tanks that will supply the feed material.

Figure 2. Proposed Fractional Crystallization Site.

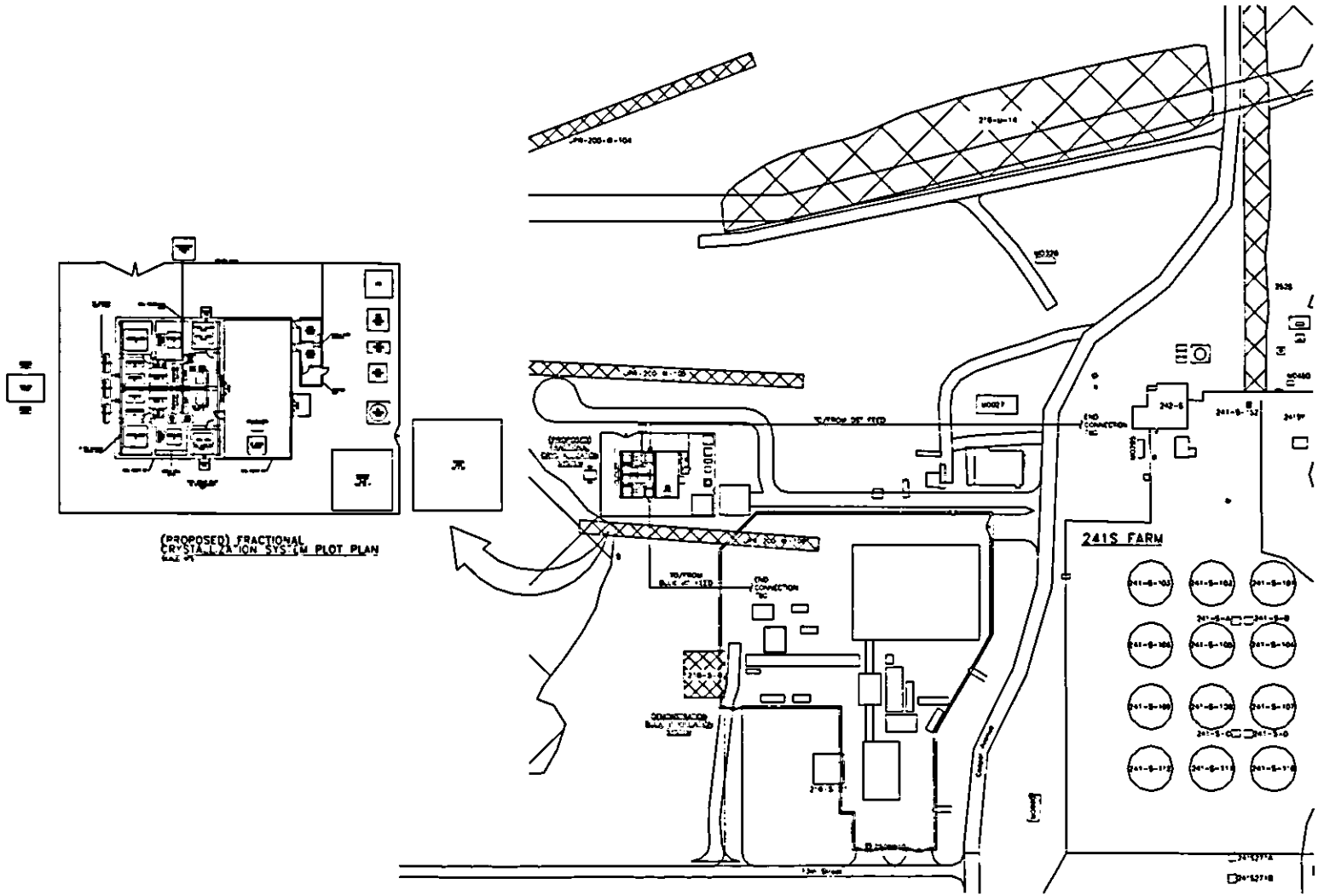
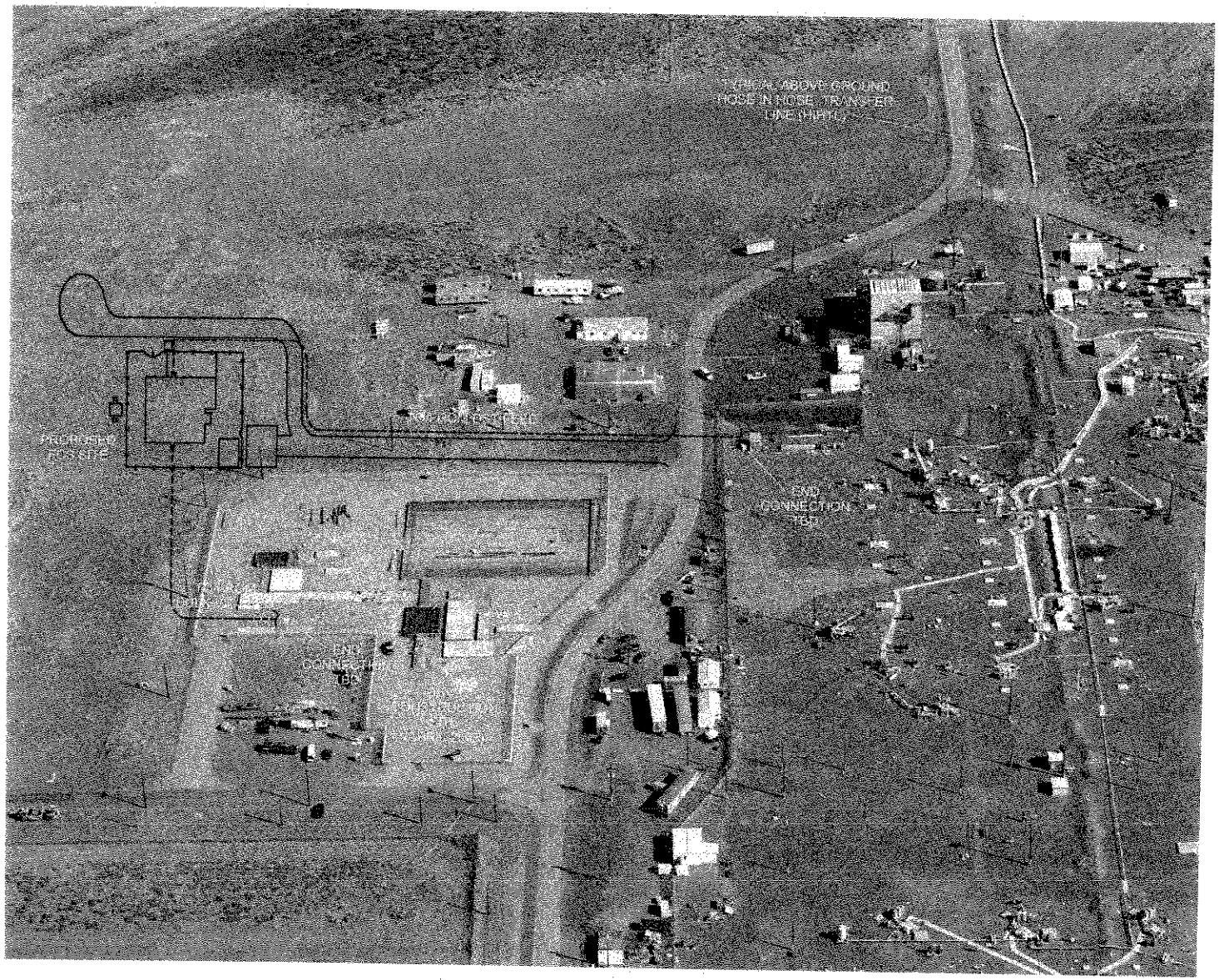


Figure 3. Aerial Photo DBVS Site



SECTION 2.0

2.0 PRETREATMENT BACKGROUND

2.1 PROCESS OVERVIEW

Crystallization of Hanford waste and Hanford-type wastes has been practiced in the Hanford 242-A, 242-S evaporators, and similar industrial processes for many years. The operational 242-A evaporator has been used to reduce waste volume by evaporating water and crystallizing sodium salts from Hanford waste. However it does not perform selective (or fractional) crystallization and the sodium salts are not separated and decontaminated from the residual liquor.

The processes used to crystallize and decontaminate sodium salts found in Hanford waste are currently practiced in commercial industries at high production rates[1], such as sodium carbonate and sodium nitrate production. Fractional crystallization, as a method to separate pure sodium chloride, borate, carbonate, and sulfate salts from brine containing organic matter, sulfides, tungsten, iodine, and other impurities was practiced by Kerr-McGee Chemical Corporation at Searles Lake, California. The process uses temperature swings and crystal seeding, as well as physical separations to improve yields and purity of the multi-product plant. Solubility data developed for the Searles Lake fractional crystallization processes are still in use today.[2] However, Hanford waste is unlike the feedstocks to commercial processes. The composition of the waste varies from tank to tank and even each tank is not a homogeneous mixture. This variability affects the saturation points and theoretical yields of sodium salts. The relative abundance of sodium nitrate, nitrite, carbonate, sulfate, fluoride, hydroxide, and aluminate, as well as radionuclides cesium, technetium, and iodine determine the extent of crystallization and decontamination that must be achieved to meet the process requirements.

To meet the challenges of separating pure sodium salts from Hanford waste, a graduated approach has been taken to the development of the process. Laboratory experiments have ranged from simple, two-component batch crystallizations, to multi-component semi-batch simulant mixtures. Thermodynamic modeling has been used to plan laboratory experiments and develop process flowsheets. In each case, thermodynamic modeling has proven adequate to estimate the outcome of the experiments.

Laboratory experimentation has determined that the major sodium crystal crops form in two distinct sizes in batch crystallization. Burkeite and sodium carbonate monohydrate grow slowly and form small crystals (10-20 micron), while sodium nitrate and nitrite grow rapidly and form large crystals (>100 micron). The relative abundance of these crystal systems varies in the waste feedstocks.

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[1] A modern industrial soda ash crystallizer produces 100 tons/hour $Na_2CO_3 \cdot 1H_2O$.
[2] Teeple, J.E., 1929, The Industrial Development of Searles Lake Brines, Chemical Catalog Co., New York, NY.

To meet the requirements for sodium yield and sulfate removal, the FCS will be designed to optimize the conditions for growth of the two crystal types. A preconceptual configuration of this system is shown in Figure 4. Two crystallizers will be employed and two solids separation systems will be used for the two crystal types. The crystallizers will operate in continuous mode; fine crystals will be recycled to the evaporator bodies to provide crystal seeds and to increase fine crystal residence time. By these methods, the conditions for crystallization and separation can be controlled separately; the two crystal crops will be seeded, grown, and harvested under optimum conditions for the two crystal types.

2.2 EQUILIBRIUM MODELING OF FRACTIONAL CRYSTALLIZATION

In multi-component Hanford waste, the solubility of components cannot be predicted from solubility diagrams or by hand calculation techniques because of the complexity of the chemistry. Solubility of components is a function of the water content, initial concentrations of the salts, free hydroxide, temperature, and ionic strength. To predict the solubility of components, the yield during crystallization, and the extent of decontamination, computational thermodynamic models are used.

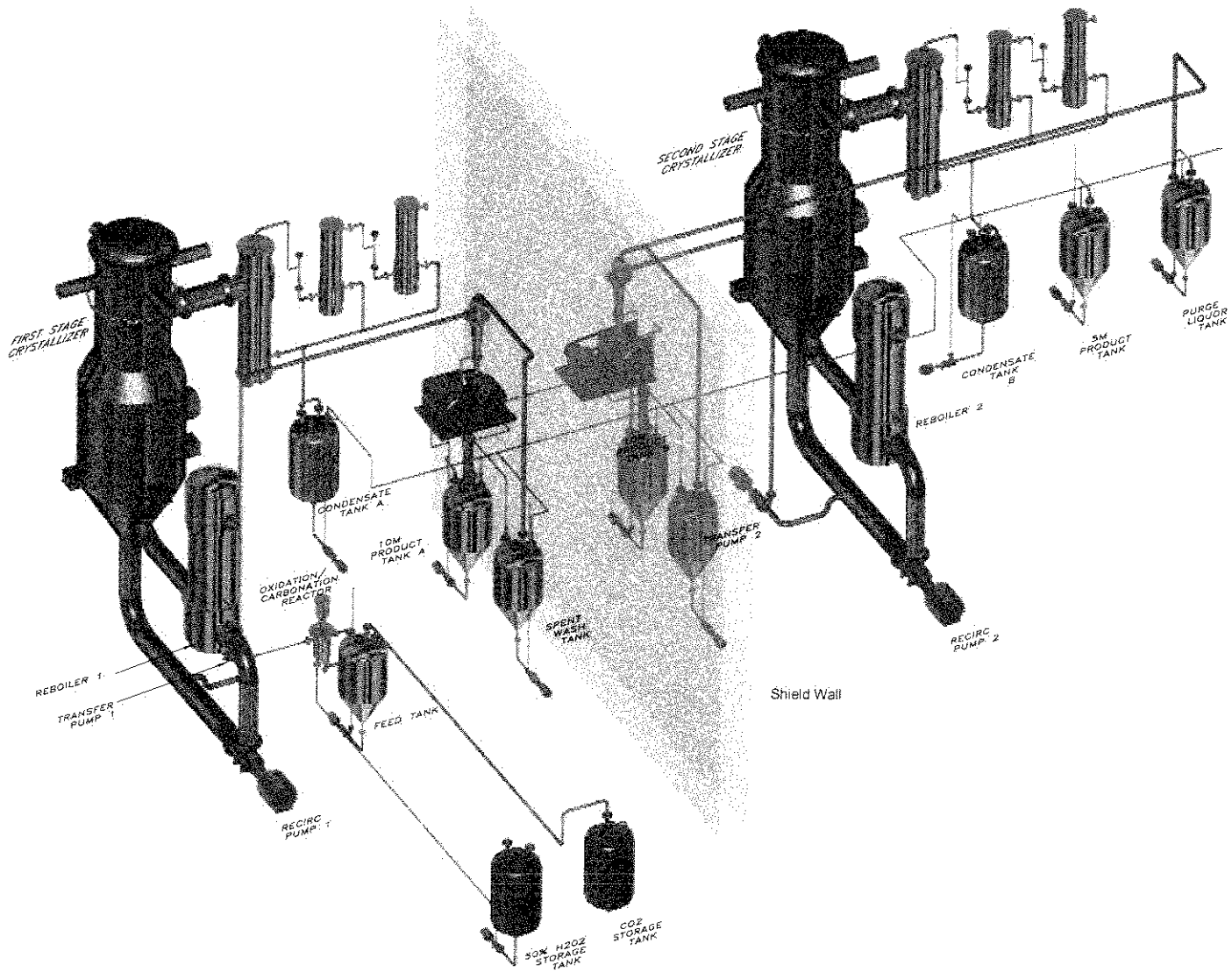
ESP software[3] has been enhanced to simulate high ionic strength aqueous systems, such as Hanford waste. Recently, improvements were made in the sodium carbonate, sulfate, fluoride, nitrate, and nitrite databanks[4] to accurately predict sodium salt solubilities and physical properties of Hanford waste. The ESP model was used for the development of the solubility phase diagrams and evaporation survey graphs presented in this report. Mixed Solvent Electrolyte (MSE) software has recently been developed by OLI systems to model high ionic strength solutions such as crystallization liquors. The software is more stable than ESP; however at this time it is not as accurate as the ESP software using the WTPBASE databank.

Equilibrium modeling has limitations in modeling fractional crystallization. Firstly, although sodium salts rapidly[5] achieve equilibrium in aqueous solution, metals (such as alumina) do not. Thus, although metal and mineral precipitates may be thermodynamically favored, their formation may be kinetically limited. Secondly, although the models can accurately predict solubility of salts in known solutions (i.e. simulants), the accuracy of the model is limited to the accuracy of the sampling and analysis of an unknown material (i.e. large non-homogeneous waste tanks). Thirdly, a thermodynamic model cannot predict solubility of unknown compounds. Until recently[6], solubility data for the $Na_7F(PO_4)_2 \cdot 19H_2O$ system were scarce. Finally, although the model can predict a theoretical Decontamination Factor (DF - ratio of influent activity to effluent activity), the actual DF achieved depends heavily on solid/liquid separation and washing efficiencies which can not be predicted by thermodynamic modeling alone.

---

[3] Leased from OLI Systems of Morristown, N.J.
[4] WTPBASE databank was developed by OLI Systems for use on Hanford waste chemistry.
[5] "Rapidly", in this context, is a relative term
[6] Internal Memo, Herting, D. L. to Nguyen, D. M., "Phosphate Solubility Under C Farm Retrieval Conditions," 7S110-DLH-5-027, dated July 18, 2005.

Figure 4. Conceptual Two-Stage Crystallizer System.



Despite the limitations, thermodynamic modeling has proven very valuable in understanding multi-component solubility, planning crystallization experiments, and developing the fractional crystallization process.

Process thermodynamic modeling has been performed on Hanford waste simulant chemistries to develop the preliminary FCS process flowsheets and determine the maximum theoretical yield of sodium salts in fractional crystallization processes. The preliminary flowsheets and mass balances of the proposed two-stage crystallization process are shown in Figures 5, 6, and 7. Appendix A provides SI units for the SST Early Feed flowsheet, Appendix B provides SI units for the SST Late Feed flowsheet, and Appendix C provides the SI units for the DST flowsheet. The flowsheets use the technique of carbonation (see Section 3.7) to reduce solubility of sodium salts and improve theoretical sodium yield.

Soluble alumina salts, e.g. sodium aluminate ($NaAlO_2$), resulting from spent nuclear fuel processing are contained in the tank wastes. To maintain the alumina in solution, substantial amounts of sodium salts ($NaOH$, Na_2CO_3, etc.) are needed and if these salts are removed by the FCS to obtain current required sodium yields, an alumina gel can form in tank wastes with high soluble alumina content. One way to obtain high sodium yield is to remove the alumina through Gibbsite ($Al(OH)_3$) crystallization; however, alumina removal is not currently included in the scope of the fractional crystallization (FC) process.

Gibbsite $Al(OH)_3$ crystallization is thermodynamically favored and is widely practiced in the aluminum industry; however, the crystallization rate, compared to sodium salts, is too slow to produce separable crystals by the current process. Although carbonation may be applied to trim "excess" free hydroxide from the waste during fractional crystallization, it is not intended to precipitate alumina as gibbsite. At this time, it is the intent of the FCS to maintain alumina in solution during the crystallization process by moderating the extent of carbonation to maintain alumina solubility, but gibbsite crystallization should be considered for future development.

Another potential method to increase sodium yield is through partial oxidation of the waste to convert sodium nitrite to sodium nitrate. This method has been proven experimentally on Hanford waste with the use of ozone. However, the use of 50% hydrogen peroxide solution, under control of redox (oxidation-reduction potential) measurement has not been demonstrated. The use of a controlled hydrogen peroxide solution has several safety advantages over the use of ozone gas for partial oxidation of the waste; however, this technology will require further development prior to implementation.

Figure 5. SST Early Feed Flowsheet.

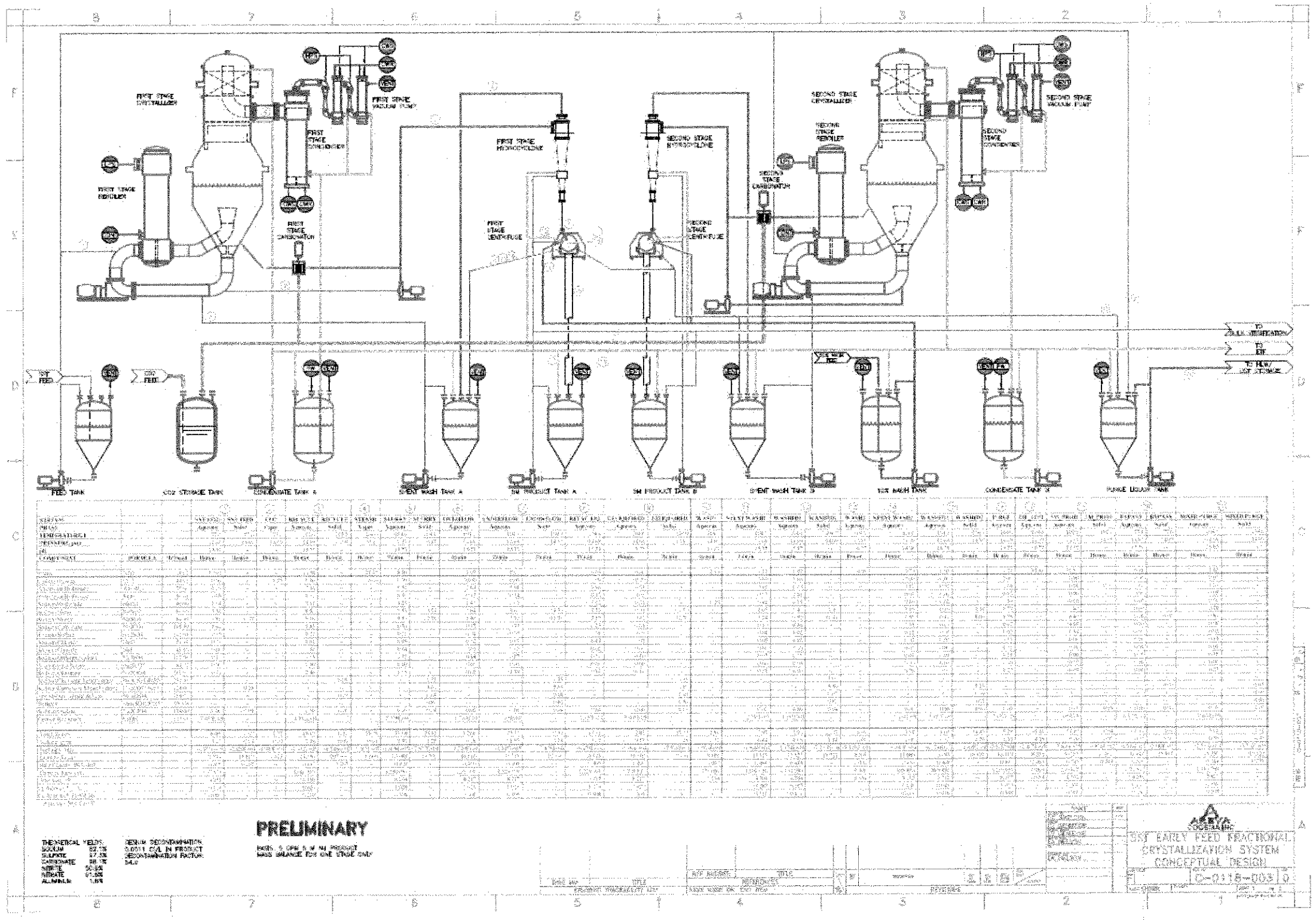


Figure 6. SST Late Feed Flowsheet.

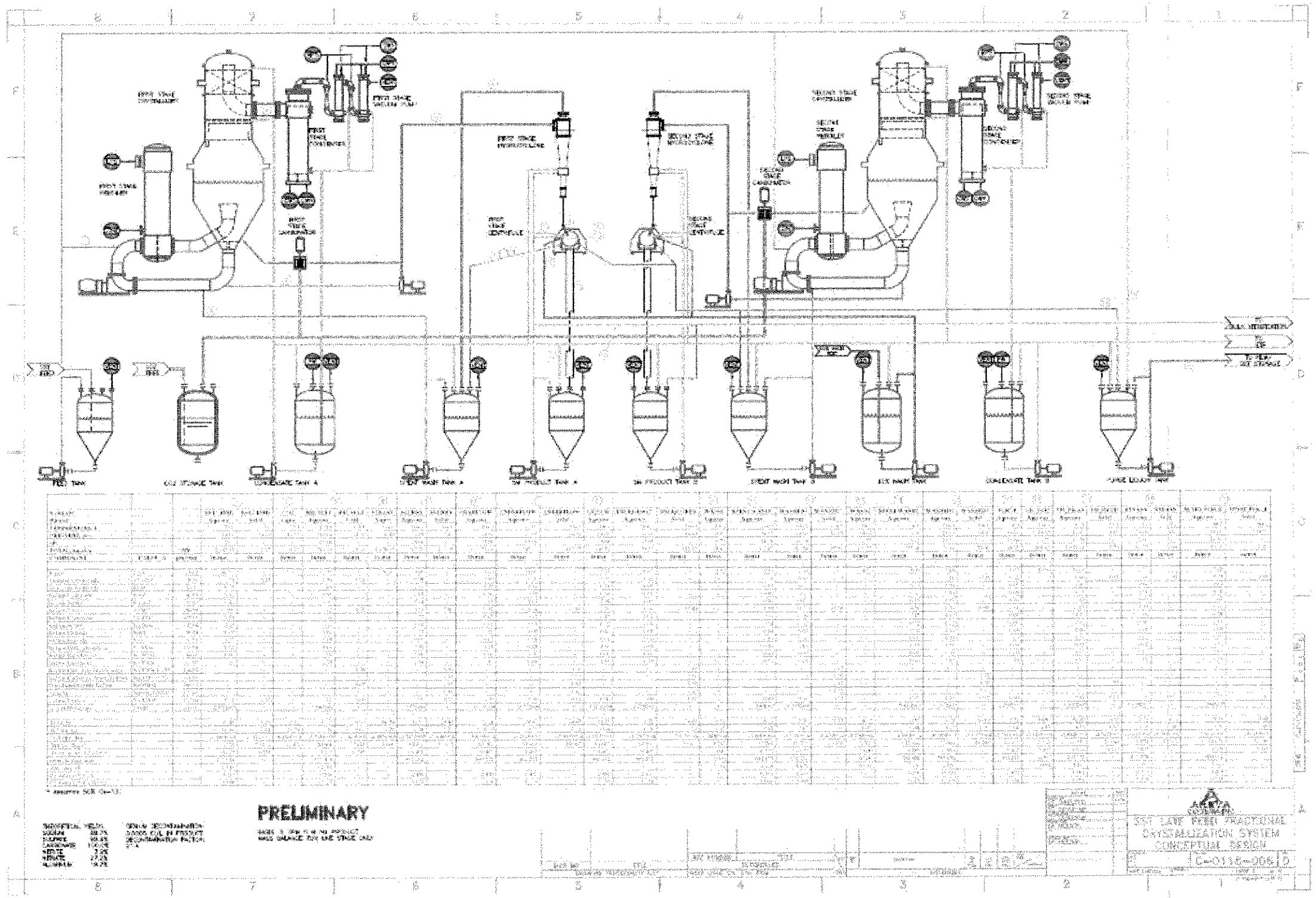
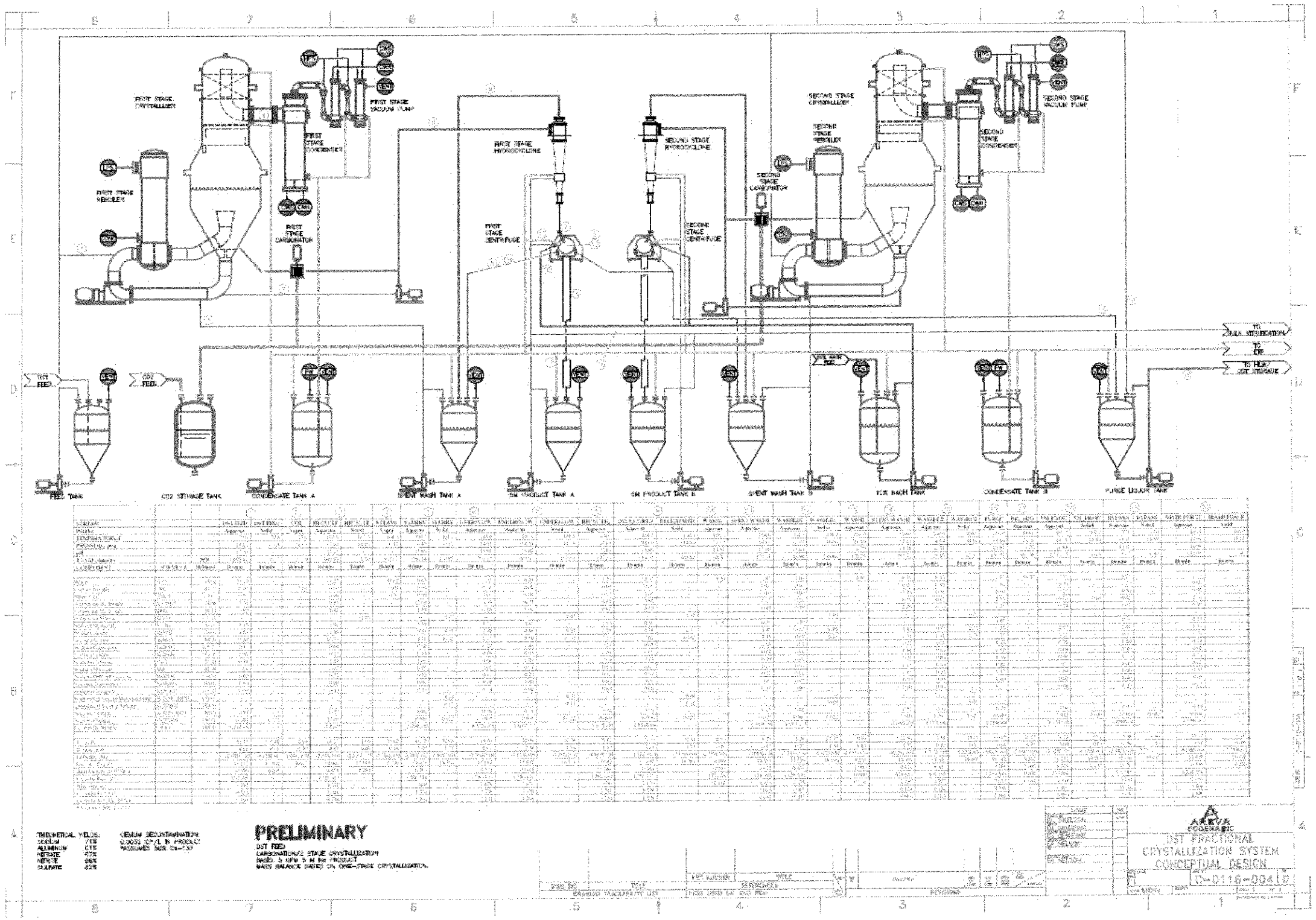


Figure 7. DST Flowsheet.



2.3 TANK WASTE COMPOSITION

The composition of tank waste feed solutions to the fractional crystallization process will vary significantly during the course of retrieval. Samples of the expected ranges of SST and DST chemical compositions are listed in Table 2 and Table 3 and were used to develop the SST/DST simulants that are the modeling bases for the preliminary flowsheets. However to provide the required yields and minimize FCS process upsets, the source batch of feed should be as large and homogeneous as possible. Operation in this mode will allow steady state operation for long periods of time with the highest levels of product yield and decontamination.

2.4 PRETREATMENT CRITERIA

The fractional crystallization process generates two major streams; a low-curie, sodium salt product stream which is transferred to supplemental treatment, and a high-curie purge stream which is transferred to the WTP. For the current work, minimum requirements and desired target performance are defined in the contract and shown in Table 1.

Table 1. Minimum Acceptable Requirements and Desired Targets for Pretreatment Process.

Pretreatment Output Stream	Criterion	Minimum Acceptable Requirement	Desired Target
BV Feed	^{137}Cs activity	<0.05 Ci/L	<0.0012 Ci/L
	Na^+ concentration	5 M (+/- 20%)	5 M (+/- 10%)
	Na^+ split	Contain at least 50% of the Na^+ in the input stream	Contain at least 90% of the Na^+ in the input stream
	Contaminants of concern[a]	TRU concentration must be less than 100 nCi/g	TRU concentration must be less than 100 nCi/g
WTP Feed	Sulfate:sodium mole ratio	<0.01	≤0.0022
	DST storage	Must meet DST storage requirements and pipeline transfer requirements[b]	Must meet DST storage requirements and pipeline transfer requirements[b]

[a]Contaminants of Concern include ^{137}Cs, ^{129}I, ^{99}Tc, ^{90}Sr, ^{79}Se, ^{14}C, total uranium, total alpha isotopes, Cr(VI), nitrate, nitrite, sulfate, and phosphate.

[b]HNF-SD-WM-OCD-015 and RPP-10726

The minimum requirements for the fractional crystallization purge are sulfate-to-sodium mole ratio less than 0.01, and the purge must meet the DST transfer and storage requirements. The desired sulfate-to-sodium mole ratio is less than 0.0022.

Table 2. Approximate Expected Chemical Concentrations (Molarity) in SST Feed Solutions.

Analyte	Early[a] Feed	Late[a] Feed
Density (g/mL)	1.41	1.16
Na^{+1}	8.70	2.90
Al^{+3}	0.48	0.04
Cr^{+6}	0.08	0.01
K^{+1}	0.03	0.01
NO_3^{-1}	3.90	1.60
OH^{-1}	1.50	0.01
CO_3^{-2}	0.92	0.27
NO_2^{-1}	0.59	0.07
SO_4^{-2}	0.14	0.17
PO_4^{-3}	0.04	0.05
Cl^{-1}	0.08	0.01
F^{-1}	0.03	0.10
$C_2O_4^{-2}$	0.01	0.02
^{137}Cs[b] (μCi/mL)	100	10

[a]Early Feed means composition of dissolved saltcake early in the retrieval process; Late Feed means composition of dissolved saltcake late in the retrieval process.

[b]The activity shown in the table is representative of the levels expected in actual waste.

Table 3. Approximate Expected Supernatant Chemical Concentrations (Molarity) in DST Feed Solutions.

Analyte	AN-103	AN-104	AN-105	AW-101
Density (g/mL)	1.46	1.41	1.43	1.45
Na^{+1}	7.00	7.00	7.00	7.00
Al^{+3}	0.74	0.91	1.01	0.76
K^{+1}	0.28	0.11	0.11	0.59
Cr^{+6}	0.007	0.004	0.003	0.001
OH^{-1}	3.68	2.46	2.11	3.72
NO_3^{-1}	1.34	1.74	1.71	1.78
NO_2^{-1}	1.86	1.68	1.71	1.49
Cl^{-1}	0.18	0.15	0.18	0.11
CO_3^{-2}	0.06	0.12	0.12	0.08
$C_2H_3O_2^{-1}$[a]	0.08	0.08	0.12	0.09
F^{-1}	0.019	0.003	0.013	0.025
SO_4^{-2}	0.008	0.011	0.008	0.005
PO_4^{-3}	0.006	0.016	0.005	0.004
$C_2O_4^{-2}$	0.004	0.005	0.004	0.004
^{137}Cs[b] (μCi/mL)	490	370	310	300

[a]Acetate may be considered a stand-in for total organic carbon, consisting of a number of small-molecule oxy-anions such as formate, acetate, or citrate.

[b]The simulant will not contain radioactive cesium: the activity shown in the table is representative of the levels expected in actual waste (e.g. Phase II samples). The simulant will contain non-radioactive cesium at a concentration representative of the total cesium present in the DST Feed Solutions.

The process requirements for 5 M sodium concentration in the product will be controlled during dissolution of the product crystals while insoluble contaminants will be controlled prior to fractional crystallization by filtration of the feed at the tank farms.

Although the minimum process requirements are at cross purposes, they are not mutually exclusive. Laboratory work[7] by Dr. Dan Herting indicates a trade-off between sodium yield and cesium decontamination. This has also proven to be the case in thermodynamic modeling of laboratory experiments. However based on operating industrial systems, full-scale crystallation has several improvements over laboratory methods. First, slurry density (weight percent suspended solids) can be increased from 20% to 40% per stage in full scale thereby improving sodium yield. Residual product moisture (deliquoring) can be reduced from 20% to 10% improving cesium decontamination during the washing process. In the full-scale process, partially saturated wash solutions may be used to minimize product loss during washing. Contaminant crystal inclusions should be reduced due to the higher intensity of mixing and greater control of supersaturation in the full-scale process. Also, continuous operation at the full-scale allows monitoring of operating conditions (i.e. product yield and contamination) to allow automatic control process parameters (evaporation rate, washing rate) to meet the minimum requirements and approach the desired targets. Thus, it is expected that sodium yield and product decontamination will be improved in full-scale operations due to higher slurry density, better product washing, higher deliquoring efficiency, and process control.

Although high sodium yields (90%) have been shown to be thermodynamically possible by fractional crystallization of Hanford waste, it is expected that chemical or physical limitations will restrict the extent of sodium salt recovery. For example, the presence of high solubility salts, such as sodium hydroxide (NaOH) and sodium aluminate ($NaAlO_2$) and/or complementary solubility of sodium nitrite ($NaNO_2$) and sodium nitrate ($NaNO_3$) increase the density and viscosity of the liquid phase thereby hindering diffusion and phase separation. Further research may be done on potential methods (i.e. oxidation of nitrite, alumina crystallization) to enhance the yield of fractional crystallization.

The purge stream generated from the fractional crystallization process must meet Hanford Tank Farms' storage and transfer requirements. These requirements are intended to prevent or control the corrosion of storage tanks and associated transfer systems. The transfer and storage requirements are provided in Table 4.

[7] RPP-RPT-26474.

Table 4. Tank Farms Waste Storage and Transfer Chemistry Requirements.

$[NO_3^-]$ Range	Variable	Waste Temperature Range		
		T < 167°F	167°F ≤T ≤212°F	T > 212°F
$[NO_3^-]$ ≤1.0 M	$[OH^-]$	0.010 M ≤$[OH^-]$ ≤ 8.0 M	0.010 M ≤$[OH^-]$ ≤ 5.0 M	0.010 M ≤$[OH^-]$ < 4.0 M
	$[NO_2^-]$	0.011 M ≤$[NO_2^-]$ ≤ 5.5 M	0.011 M ≤$[NO_2^-]$ ≤ 5.5 M	0.011 M ≤$[NO_2^-]$ ≤ 5.50 M
	$[NO_3^-]$/ ($[OH^-]$+$[NO_2^-]$)	< 2.5	< 2.5	< 2.5
1.0 M < $[NO_3^-]$ ≤ 3.0 M	$[OH^-]$	0.1$[NO_3^-]$ ≤$[OH^-]$< 10 M	0.1$[NO_3^-]$ ≤$[OH^-]$< 10 M	0.1$[NO_3^-]$ ≤$[OH^-]$< 4.0 M
	$[OH^-]$+$[NO_2^-]$	≥ 0.4$[NO_3^-]$	≥ 0.4 $[NO_3^-]$	≥ 0.4 $[NO_3^-]$
$[NO_3^-]$ > 3.0 M	$[OH^-]$	0.3 M ≤$[OH^-]$ < 10 M	0.3 M ≤$[OH^-]$ < 10 M	0.3 M ≤$[OH^-]$ < 4.0 M
	$[OH^-]$+$[NO_2^-]$	≥ 1.2 M	≥ 1.2 M	≥ 1.2 M
	$[NO_3^-]$	≤5.5 M	≤5.5 M	≤5.5 M

*RPP-10726, Rev. 1

Because fractional crystallization is performed under vacuum, it is expected that all streams exiting the fractional crystallization system will have a temperature less than 167°F (75°C).

Since the concentrations of salts in the purge stream are not readily adjustable, it is necessary to plan the extent of crystallization to ensure that the minimum requirements for tank farm chemistry can be met. However, depending on the target yield and the extent of evaporation and carbonation, the concentrations of sodium hydroxide and nitrite may not be present in the required quantities in the fractional crystallization purge stream.

It is undesirable to add NaOH and/or $NaNO_2$ to the purge stream, so it may be beneficial to blend the purge stream with another (existing) waste stream to meet the requirements. In many cases, this can be done by bypassing a portion of the feed stream into the purge stream and, in general, amounts to less than 2 percent of the total feed. By this method, the chemistry requirements for storage and transfer can be met without adding additional sodium salts to the waste.

In the case that carbonation is not used, concentrations of sodium hydroxide and nitrite will increase during fractional crystallization. Thus, if the feed material meets the storage and transfer chemistry requirements, theoretically the purge stream will also meet the requirements.

SECTION 3.0

3.0 PROCESS THEORY

3.1 PROCESS DEVELOPMENT

In general, the chemical properties of the salts occurring in Hanford waste have been well studied and well documented[8]. The solubility of these salts behaves the same in radioactive and non-radioactive solutions; however, trace species may be present in Hanford wastes that affect the formation and growth rates of sodium salt crystals[9].

For this reason, the fractional crystallization process is being developed using a graduated approach. That is, the simplest chemical systems are studied, tested, and validated against thermodynamic models, and then more and more complex systems are tested until representative SST/DST waste simulants are used. Once the properties of these systems are understood, "hot" crystallization tests will be conducted on actual Hanford SST/DST waste.

This section discusses process fundamentals and example calculations for different process scenarios. The results are used to guide process definition and process testing activities and form an important part of the process development effort.

Crystallization occurs when an ionic species exceeds saturation in solution. The solubility of a species depends on concentration, temperature, and the presence of other species in solution. Fractional crystallization utilizes the conditions and concentrations of the solution to selectively crystallize salts from solution. By this method, pure solid phases may be created that can be separated from a contaminated liquid phase.

In Hanford waste chemistry, several species compete for solubility and several solids compete for precipitation of ions. The dominant ions (i.e. Na^{+1}, SO_4^{-2}, CO_3^{-2}, NO_3^{-1}) form common salts (i.e. $NaNO_3$, $Na_2CO_3 \cdot 1H_2O$) and double salts (i.e. $Na_6(SO_4)_2CO_3$) upon evaporation of water.

Soluble radionuclides (i.e. ^{137}Cs, ^{99}Tc, ^{129}I) are far from their saturation concentrations and do not crystallize from solution during evaporation. Insoluble radionuclides (e.g. uranium, plutonium, americium) are removed by filtration prior to the fractional crystallization process[10]. By this method, nearly pure sodium salts may be separated from radioactive contaminants in the liquid phase with the exception of ^{14}C which will be contained in carbonate crystals in proportion to its concentration in the liquid phase.

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[8] For example, "Crystal Properties and Nucleation Kinetics from Aqueous Solutions of Na_2CO_3 and Na_2SO_4," Shi, B., Rousseau, R., Ind. Eng. Chem. Res. 2001, 40, 1541-1547.

[9] For example, "Effects of Calcium and Other Ionic Impurities on the Primary Nucleation of Burkeite," Shi, B., Frederick, J., Rousseau, R., Ind. Eng. Chem. Res 2003, 42, 2861-2869.

[10] Organic complexed radionuclides, as in tanks AN-102 & AN-107, will not be treated by the fractional crystallization process.

Initial process simulation calculations focused on direct evaporative crystallization of the tank waste simulants, and evaporative crystallization combined with carbonation (conversion of hydroxide to carbonate by reaction with carbon dioxide). During the course of the work, it became clear that that high concentrations of nitrite and alumina in some waste types result in process difficulties that may significantly restrict achievable removal efficiency of sodium. Two methods were identified for reducing these problems: 1) oxidation of nitrite to nitrate using hydrogen peroxide or ozone; and 2) crystallization of alumina. These methods require additional testing to verify performance but, based on thermodynamic modeling, show good promise of improving performance of the fractional crystallization process. A discussion of the modeling investigation for process enhancement is contained in Appendix D.

One output of the process simulation calculations is estimated efficiencies for crystallization of waste components during a batch evaporative crystallization process. Table 5 provides a summary of results of example calculations discussed in more detail later in Appendix E. These examples are based on evaporation to 20 molar ionic strength. If evaporation is continued much past this level, high viscosity and liquid density are expected to slow crystallization kinetics and make solids/liquid separation difficult.

Table 5. *Summary of Batch Crystallization Simulation Yield Calculations.*

		Na	SO4	CO3	NO3	NO2
Example 1	Base Case	57.9%	98.5%	99.6%	97.9%	N/A
Example 2	Carbonation of NaOH	88.0%	98.3%	99.9%	99.4%	N/A
Example 3	Sodium Aluminate	56.6%	98.2%	99.6%	98.9%	N/A
Example 4	Gibbsite	87.0%	98.3%	99.9%	99.4%	N/A
Example 5	SST Early Feed 40°C	76.1%	99.6%	99.5%	99.1%	92.5%
Example 6	SST Late Feed	88.2%	99.9%	85.0%	92.2%	0%
Example 7	DST	56.0%	94.1%	95.7%	91.8%	94.9%

N/A = Did not appear in process simulation example.

While not all cases have been modeled, the results presented illustrate the effect of carbonation and nitrite oxidation to approach the desired targets defined in Table 1.

The calculations summarized in Table 5 are based on theoretical batch evaporations and do not account for losses during crystal decontamination or recycle of supernate. These topics are discussed further in Sections 3.10 and 3.11.

Results summarized in this section were used to help select the proposed process described in Section 6.0.

3.2 CRYSTALLIZATION OF HANFORD WASTE

Solubilities of binary (one salt + water) solutions for common Hanford waste salts at 40°C and 60°C are shown in Table 6[11]. Solubilities are in weight percent (g solute/100 g solution).

Table 6. Solubilities of Binary Solutions for Common Hanford Waste Salts.

Salt	Formula	40°C	60°C
Sodium Oxalate	$Na_2C_2O_4$	3.06	3.47
Sodium Fluoride	NaF	4.18	4.33
Sodium Phosphate	Na_3PO_4	17.9	27.2
Sodium Chloride	NaCl	26.6	27.1
Sodium Sulfate	Na_2SO_4	32.5	31.1
Sodium Carbonate	Na_2CO_3	32.5	31.4
Sodium Nitrite	$NaNO_2$	42.2	45.2
Sodium Nitrate	$NaNO_3$	51.7	55.5
Sodium Aluminate	$NaAlO_2$	47.7	50.4
Sodium Hydroxide	NaOH	56.2	63.3

The sequence in which these salts crystallize upon heating, cooling, or evaporation depends upon their relative abundance and the approach to saturation in the feed material. Thus, a high-solubility salt may crystallize before a low-solubility salt. So, no generalization can be made for the sequence of salt crystallization in variable multi-component systems.

Hydrated salts (i.e. $Na_2CO_3 \cdot 10H_2O$) can form altering salt solubility and water concentration. Double salts (i.e. Na_3FSO_4, $Na_7F(PO_4)_2 \cdot 19H_2O$) can form in which one component (i.e. NaF) dramatically reduces the solubility (scavenges) of a second component (i.e. Na_2SO_4, Na_3PO_4). "Eutectics" can form in which two (or more) salts (i.e. $NaNO_2$ and $NaNO_3$, KNO_2 and KNO_3) exhibit complementary solubility where the combined solubility for two (or more) salts is greater than the solubilities of the single salts.

Also, the presence of other cations (e.g. Li^{+1}, K^{+1}, Ca^{+2}, Mg^{+2}) may increase or decrease the solubility of the corresponding anion ($Al(OH)_4^{-1}$, NO_3^{-1}, CO_3^{-2}, OH^{-1}). For these reasons,

[11] Solubility data from ESP version 6.7.

thermodynamic modeling is used to predict saturation points and yields of crystallization products.

Crystals are solids in which the atoms are arranged in a periodic repeating pattern that extends in three dimensions (crystal lattice). A disruption of the repeating pattern of atoms is said to be an imperfection and when it is caused by a foreign atom in the lattice, it is termed a "substitutional impurity." Goldschmidt's Rules for Ionic Substitution explain how Cs^{+1} can be excluded from Na^{+1} based crystals produced by the FCS. Even though they both have the same oxidation state (+1), the Na^{+1} ion is smaller (Na^{+1} ionic radius is 1.02 Å and Cs^{+1} ionic radius is 1.67 Å) and therefore forms a stronger bond with the anion in the lattice. In general, extensive substitution does not occur between elements whose radii differ by more than 15%.

Crystal habit refers to the external appearance (shape, size) of a crystal and is not only controlled by its internal structure, but also by the conditions at which the crystal grows. The rate of growth, the solvent used, and the impurities present can have a major impact on crystal habit. Crystal habit will affect the rheological properties of the suspension, the filtration or centrifugation efficiency, the bulk density of the solid, and the flow properties of the solid. Control of crystal habit, along with crystal size distribution, is an important part of the crystallization process.

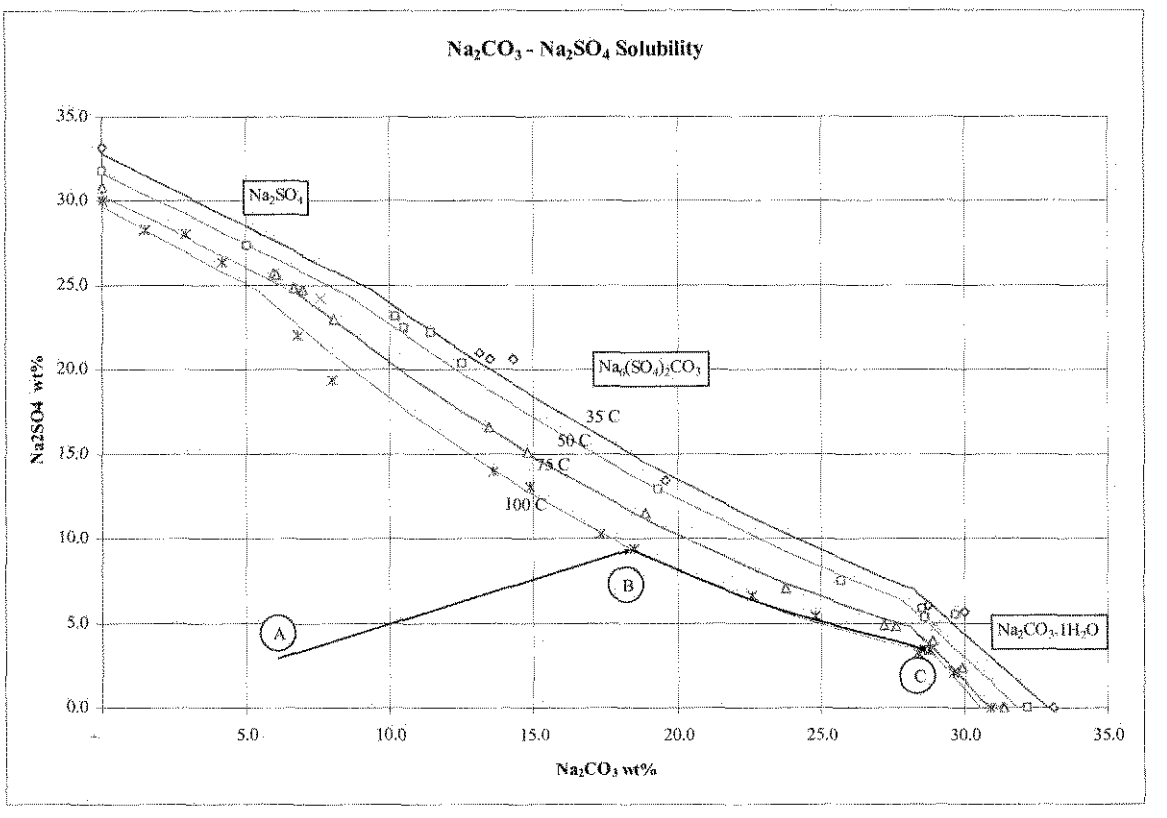
Crystallization can be considered a two-step process beginning with the "birth" of the crystal from the supersaturated solution followed by growth of the crystals to larger sizes. These processes are called nucleation and crystal growth, respectively. A supersaturated solution is not at equilibrium and in order to move toward equilibrium the solution crystallizes. Once crystallization starts, supersaturation can be relieved by a combination of nucleation and growth. It is the relation between the extent of nucleation to crystal growth that controls the final crystal size and size distribution and thus is a crucial control aspect of the FCS.

3.3 SODIUM SULFATE – SODIUM CARBONATE SOLUBILITY

Depending on relative abundance, sodium sulfate double salts may crystallize first upon evaporation of waste liquor. Dominant sulfate salts are the sodium sulfate-carbonate double salt burkeite ($Na_6(SO_4)_2CO_3$) or the sodium sulfate-fluoride double salt shairerite (Na_3FSO_4).

The phase diagram, developed using the ESP model, for the H_2O-Na_2SO_4-Na_2CO_3 ternary system is shown in Figure 8.

Figure 8. $NaSO_4$-$NaCO_3$ Solubility (U.S. Patent 6,787,120)[12].



Operating line A-B depicts a solution with an initial concentration of 3 wt % Na_2SO_4 and 6 wt% Na_2CO_3 evaporated to saturation at 100°C. Burkeite saturation is reached after 75 g H_2O are evaporated, at a concentration of 9 wt% Na_2SO_4 and 18 wt% Na_2CO_3 and at an ionic strength of 9 M sodium. Further evaporation crystallizes $Na_6(SO_4)_2CO_3$, depleting the solution of sodium sulfate and carbonate in a 2:1 mole ratio and follows the saturation curve from B to C. At point C, 88 g of water have evaporated and 3.3 g $Na_6(SO_4)_2CO_3$ have crystallized from solution at a concentration of 3.3 wt% Na_2SO_4 and 29 wt% Na_2CO_3 and an ionic strength of 12 M Na.

Sodium carbonate monohydrate ($Na_2CO_3 \cdot 1H_2O$) reaches saturation at point C and co-crystallizes with burkeite upon further evaporation. In a binary H_2O-Na_2CO_3 system, the monohydrate crystal typically forms between 35°C and 106°C; sodium carbonate decahydrate ($Na_2CO_3 \cdot 10H_2O$) forms below 35°C. However, in multi-component Hanford waste, the stability range of sodium carbonate monohydrate is extended below 35°C due to low water activity (concentration).

As shown in Figure 8, further evaporation at point C co-crystallizes $Na_6(SO_4)_2CO_3$ and $Na_2CO_3 \cdot 1H_2O$ in equimolar proportions, so the solution is depleted in sodium sulfate and sodium carbonate in the same proportions. At this point, ionic strength remains constant at 12 M. At the

[12] U.S. Patent 6,787,120, Volume Reduction of Aqueous Waste by Evaporative Crystallization of Burkeite and Sodium Salts, September 7, 2000, Geniesse, D.

invariant point, the relative concentrations of sodium carbonate and sulfate in solution remain the same while the two salts co-crystallize.

At the invariant point, additional sodium carbonate-sulfate double salts may form such as "high carb" burkeite $Na_6SO_4(CO_3)_2$.[13] The additional salts deplete the aqueous phase of sodium sulfate and carbonate upon further evaporation.

3.4 SODIUM NITRATE – SODIUM NITRITE SOLUBILITY

The behavior of sodium nitrite and nitrate vary depending on other ions present and evaporation temperatures.

Depending on relative abundance, sodium nitrate and/or sodium nitrite may crystallize upon further evaporation. In other cases, sodium nitrate and/or nitrite will co-crystallize with burkeite and/or sodium carbonate monohydrate. In some cases, sodium nitrate and nitrite will not reach saturation until all of the sodium sulfate and carbonate are depleted from the aqueous phase. In other cases, sodium nitrate or sodium nitrite will reach saturation and crystallize before the sodium sulfate or carbonate reach saturation.

A phase diagram of sodium nitrate and nitrite is shown in Figure 9. Sodium nitrate and sodium nitrite exhibit temperature-dependant and complementary solubility. The solubility of each species increases with temperature.

The two species form a "eutectic" in which the total sodium solubility is increased when both species are present. The solubility of a two-salt system increases with further evaporation up to the $NaNO_3$-$NaNO_2$ invariant – the point where the two salts co-crystallize. Thus, a ternary solution containing H_2O-$NaNO_3$-$NaNO_2$ has greater solubility than binary solutions of H_2O-$NaNO_3$ or H_2O-$NaNO_2$.

In binary solutions at 52°C, the solubility of $NaNO_3$ is 118 g/100 g H_2O; the solubility of $NaNO_2$ is 109 g/100 g H_2O. In a ternary H_2O-$NaNO_3$-$NaNO_2$ system, the total solubility increases to 182 g $NaNO_3$ + $NaNO_2$/100 g H_2O at the $NaNO_3$-$NaNO_2$ invariant point.

The increase in solubility upon evaporation is shown by the operating lines A-B and B-C. An initial solution of 100 g H_2O, 40 g $NaNO_3$, and 10 g $NaNO_2$ (Point A) is evaporated to $NaNO_3$ saturation (Point B). The solution is further evaporated to $NaNO_2$ saturation (Point C). At a total of 90 g of H_2O evaporated, the net yield of $NaNO_3$ is 33 g or 62.6% of the total sodium. During crystallization, ionic strength increases from 15 M to 21 M Na.

Because the solubility is temperature dependent, the crystallization yield may be increased by reducing temperature. In the above example, if the evaporation occurred at 40°C, the sodium yield would be 68.3% at 90 g of water evaporated. Ionic strength at this point is 19.2 M Na.

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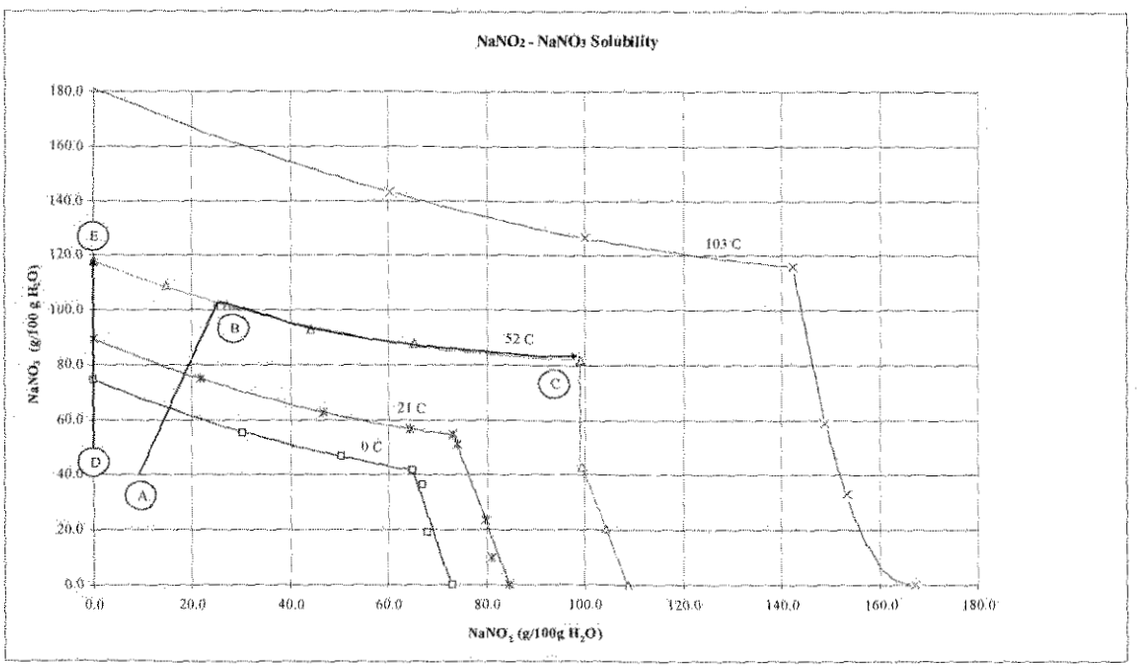
[13] Shi, B., Rousseau, R., "Structure of burkeite and a New Crystalline Species Obtained from Solutions of Sodium Carbonate and Sodium Sulfate," J. Phys. Chem. B. 2003, 107, 6932-6937.

Figure 9. Phase Diagram of Sodium Nitrate and Nitrite.



Thus, reducing temperature can increase the yields of sodium nitrate and nitrite in a batch evaporation process at constant ionic strength.

3.5 ALUMINA SOLUBILITY

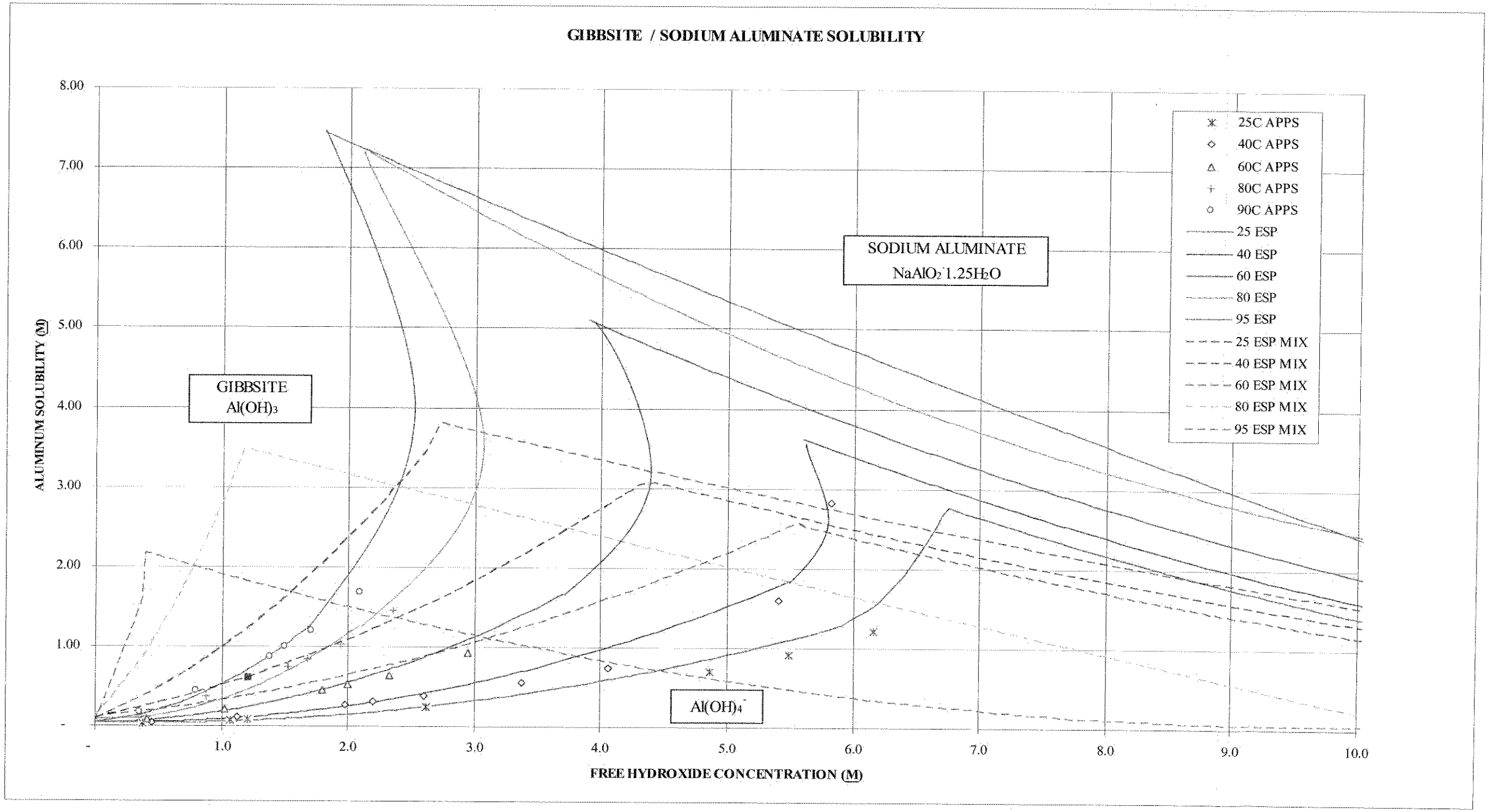
A diagram of alumina solubility versus free hydroxide is shown in Figure 10. This diagram is valid for alkaline solutions only, where $Al(OH)_4^{-1}$ is the dominant aqueous specie.

The solid lines (ESP) are isotherms in a ternary $Al(OH)_3$-NaOH-H_2O system[14]. The dashed lines (ESP MIX) are in a multi-component $Al(OH)_3$-NaOH-H_2O system saturated with Na_2CO_3, Na_2SO_4, $NaNO_2$, and $NaNO_3$. Experimental points (APPS) on the graph are from the J.A. Apps report (see reference Section 9.0). Thermodynamic state properties (G_f, H_f, S_f) of gibbsite $Al(OH)_3$, used in the calculation of alumina solubility, were developed in the Apps study.

As shown in the diagram, alumina solubility is a complex function of temperature, free hydroxide, and ionic strength. Increasing ionic strength by addition of additional sodium species increases gibbsite solubility but decreases sodium aluminate solubility. The increase in alumina solubility with ionic strength is due to the shift in the partition of hydroxide to aluminum tetrahydroxide ($Al(OH)_4^-$) with increasing sodium concentration.

[14] The backward curve of the gibbsite phase boundary is caused by the formation of sodium aluminate 2.5 hydrate. This precipitation removes water from solution, thus increasing the concentration (shown in weight percent) of aluminum in solution. If the diagram were on a molality scale, the "backward curve" would not exist.

Figure 10. Aluminum Solubility Versus Free Hydroxide Diagram.

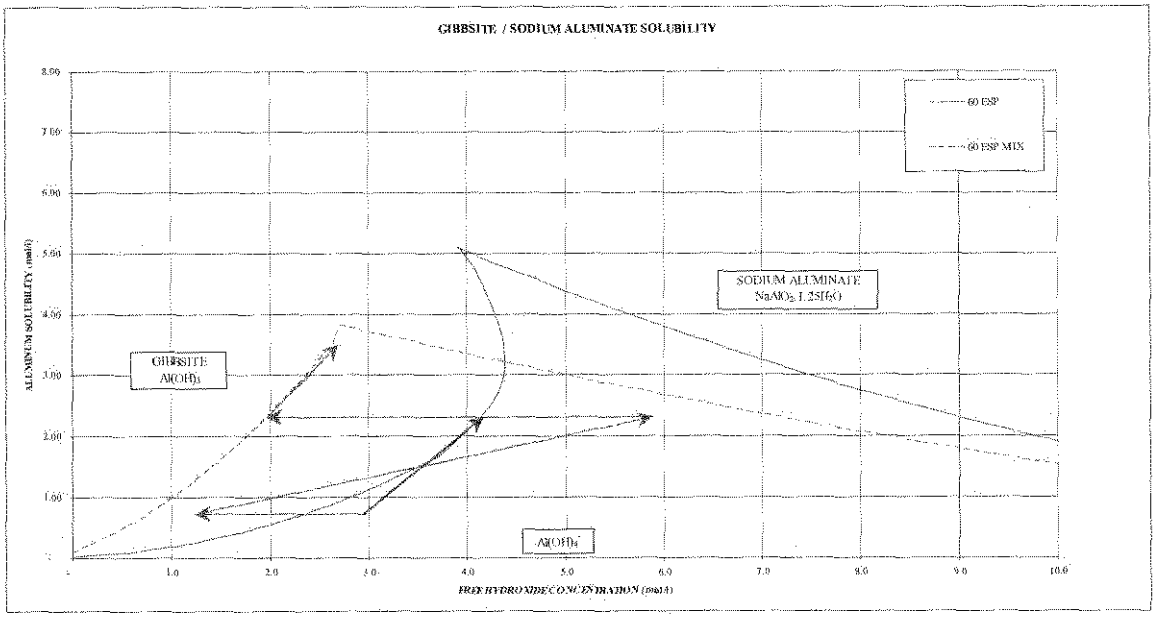


It desirable to maintain alumina in solution during the crystallization of sodium salts. This is because the kinetics of gibbsite crystallization are far slower than sodium salt crystallization and supersaturation of gibbsite can result in amorphous, high-viscosity gel formation.

During crystallization of sodium salts, evaporation increases free hydroxide concentration and ionic strength of the solution. Thus, in most cases, alumina becomes more soluble up to the sodium aluminate phase boundary during the evaporative crystallization process.

Operating lines of a DST carbonation/crystallization process are shown on 60°C isotherms in Figure 11.

Figure 11. Operating Lines of a DST Carbonation/Crystallization Process.



The green lines are solubility curves of gibbsite and sodium aluminate for binary (solid lines) and sodium salt saturated (dotted lines) multi-component systems at 60°C. The red lines are successive batch steps of first carbonation, first evaporation, second carbonation, and second evaporation. Each step is designed to maintain alumina in the soluble ($Al(OH)_4^{-1}$) region during the crystallization process.

The blue line is a one-stage continuous carbonation/crystallization operating line. As indicated by this example, continuous carbonation/crystallization allows a greater margin between the operating line and the alumina solid phase boundaries.

3.6 OXIDATION-REDUCTION (REDOX) CHEMISTRY

Sodium nitrate and sodium nitrite differ in the oxidation state of nitrogen. Nitrogen in sodium nitrate has a +5 valence state; nitrogen in sodium nitrite has a +3 valence state. When ionized in aqueous solution, nitrogen retains its valence state in nitrate and nitrite ions.[15] Nitrate and nitrite ions are the dominant redox couple in aqueous Hanford waste[16]. They provide a "redox buffer" for the system. That is, with both ions present in abundance the system is redox neutral and oxidants (such as ozone) or reductants (such as hydrogen) react with nitrite or nitrate ions without significantly changing the overall redox state of the system.

$$NO_2^{-1} + O_3 \rightarrow NO_3^{-1} + O_2 \tag{3-1}$$

$$NO_3^{-1} + H_2 \rightarrow NO_2^{-1} + H_2O \tag{3-2}$$

These redox reactions occur due to radiolytic hydrolysis of water and organic compounds in Hanford waste. The radiolysis reactions produce reactive oxygen and hydrogen species which are respectively reduced and oxidized with nitrite and nitrate ions.

An ESP thermodynamic simulation of a redox survey of Hanford tank waste is shown in Figure 12. The simulation indicates the dominant oxidation states of elements from fully reducing to fully oxidizing aqueous conditions at the specific pH and temperature of one type of waste.

In this case, when nitrite and nitrate are equal, the redox potential of the system is +0.33 volts. At a redox potential of +0.33 volts, the dominant form of manganese is Mn_3O_4, a combination of Mn(+2) and Mn(+3). The dominant form of silver and mercury are their metallic forms Ag(0) and Hg(0). The dominant form of plutonium is insoluble Pu(+4). At an oxidation potential of +2.4 volts, plutonium is equally distributed to insoluble Pu(+4) and soluble Pu(+6). Above a redox potential of +2.4 volts, soluble Pu(+6) is the dominant form of plutonium.

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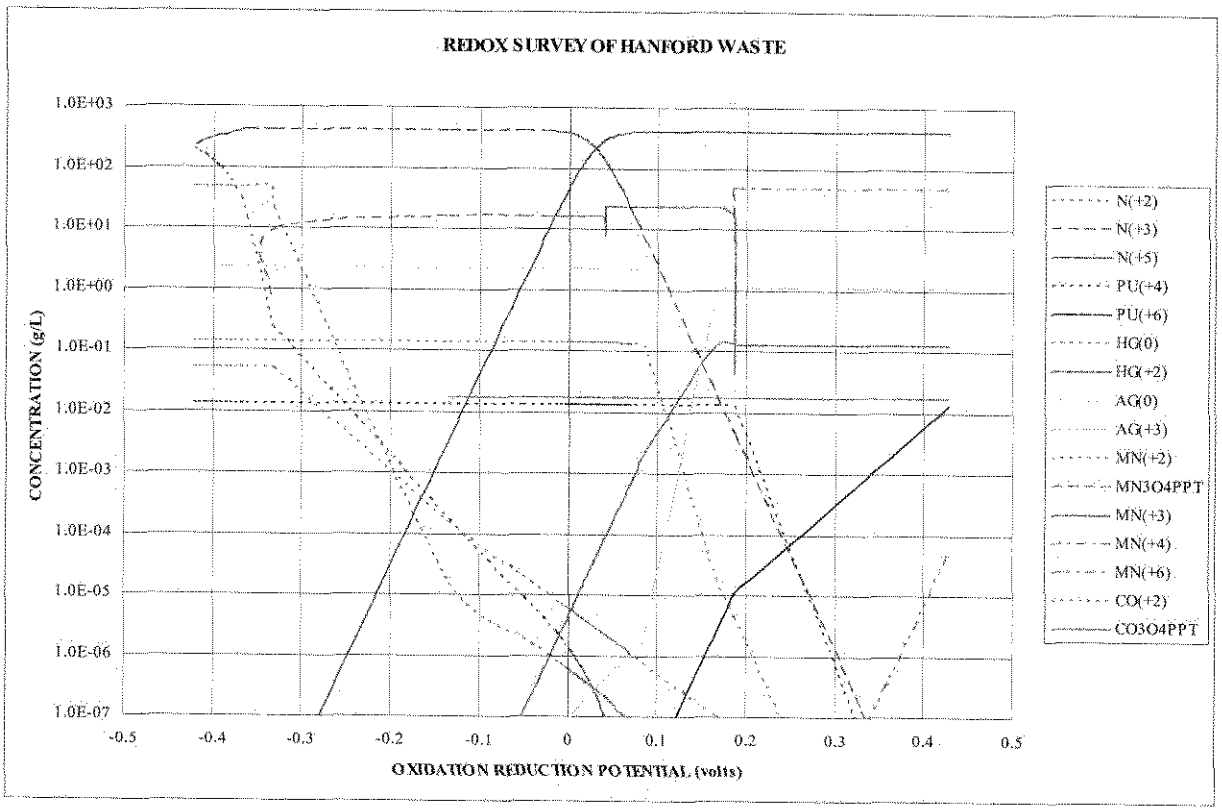
[15] Thermodynamically, in oxidizing conditions (such as in air) nitrite will oxidize to nitrate.

[16] Chromium +6 and chromium +3 are a secondary redox couple in Hanford waste. However, the stability of Cr^{+3} depends upon the solid phase present ($Cr(OH)_3$, CrOOH, Cr_2O_3). The equivalence point of Cr^{+3} and Cr^{+6} is affected by the Cr^{+3} solid phase.

Figure 12. ESP Thermodynamic Simulation of a Redox Survey of Hanford Tank Waste.



3.7 CARBONATION

Sodium hydroxide (NaOH) and sodium aluminate ($NaAlO_2$) have very high solubility and cannot be easily crystallized from the waste by evaporative crystallization. At their solubility limits, the solution exhibits high viscosity and density, greatly hindering crystallization and crystal separation.

Sodium aluminate may be considered the sodium hydroxide salt of aluminum hydroxide.

$$Al(OH)_3 + NaOH \rightarrow NaAlO_2 + 2H_2O \tag{3-3}$$

To improve the yield of sodium salts by evaporative crystallization, carbon dioxide (CO_2) may be used to convert the highly soluble sodium hydroxide and sodium aluminate to produce low solubility sodium carbonate (Na_2CO_3) and aluminum trihydroxide (gibbsite).

$$2NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O \tag{3-4}$$

$$2NaAlO_2 + CO_2 + 3H_2O \rightarrow Na_2CO_3 + 2Al(OH)_3(s) \tag{3-5}$$

These are neutralization reactions, with carbon dioxide acting as an acid anhydride. The reaction liberates heat, and the temperature rise depends on the initial concentrations of the reactants. In highly concentrated systems, water may be added to reduce the temperature rise.

The rate of reaction of sodium hydroxide to sodium carbonate is very rapid. However, the rate of gibbsite crystallization is very slow.[17] At 50°C, gibbsite crystals grow at a rate of 1-2 microns per hour. Thus, carbonation may cause rapid supersaturation of sodium aluminate solutions.

High-viscosity gels have been observed to occur in sodium aluminate solutions that are rapidly neutralized or carbonated. These gels are caused by the stripping of hydroxide from the $Al(OH)_4^{-1}$ ion and creating amorphous $Al(OH)_3$. The slow growth rate of gibbsite prevents large, separable crystals from forming upon neutralization of unseeded sodium aluminate solutions.

To avoid alumina gel formation, carbonation should be controlled to maintain sufficient free hydroxide[18] in solution to maintain alumina solubility. In general, alumina solubility increases during evaporation due to increasing free hydroxide concentration and ionic strength up to the sodium aluminate phase boundary.

Thus, the goal of carbonation is to increase sodium yield by converting excess sodium hydroxide to sodium carbonate which can be crystallized, while maintaining sufficient free hydroxide to maintain aluminum solubility. Ideally, the solution is maintained near the gibbsite phase boundary during evaporation.

Further carbonation of sodium carbonate and sodium aluminate can produce the sodium bicarbonate ($NaHCO_3$) and sodium alumina carbonate hydroxide, known as the mineral dawsonite ($NaAlCO_3(OH)_2$).

$$Na_2CO_3 + 2CO_2 + H_2O \rightarrow 2NaHCO_3 \tag{3-6}$$

$$NaAlO_2 + CO_2 + 2H_2O \rightarrow NaHCO_3 + Al(OH)_3 \rightarrow NaAlCO_3(OH)_2 + H_2O \tag{3-7}$$

Dawsonite is formed in natural systems from the precipitation of alumina at near-neutral conditions. Dawsonite has an acicular crystal habit,[19] making it difficult to separate, deliquor, and decontaminate. A scanning electron photomicrograph of dawsonite is shown in Figure 13. Thus, dawsonite is not a preferred method to crystallize alumina in Hanford waste.

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[17] D. L. Herting, "Fractional Crystallization of Waste From Tank 241-S-112," July 2005.
[18] Free hydroxide is in addition to hydroxide bound to aluminum as $Al(OH)_4^{-1}$ ion.
[19] "Hydrothermal Synthesis and Thermodynamic Analysis of Dawsonite-type Compounds," Zhang, X., et al. Journal of Solid State Chemistry, 177 (2004) 849-855.

Figure 13. Scanning Electron Photomicrograph of Dawsonite (U.S. Patent 5,997,836).[20]

3.8 PARTIAL NEUTRALIZATION WITH NITRIC ACID

Nitric acid (HNO_3) may be used in place of CO_2 for partial neutralization of the excess free hydroxide for increasing sodium salt yield.

$$NaOH + HNO_3 \rightarrow NaNO_3 + H_2O \tag{3-8}$$

As in the case of carbon dioxide, the reaction liberates heat, and the temperature rise may be moderated by the addition of water in highly concentrated systems.

Rapid neutralization with nitric acid can also cause alumina gel formation. Thus, it is important to determine the extent of neutralization that will maintain alumina solubility. However, the use of nitric acid instead of carbon dioxide reduces the likelihood of dawsonite formation.

3.9 SOLUBILITY PRODUCT CALCULATIONS

Equilibrium models allow prediction of saturation of species and the excess amount that is crystallized during evaporation. In general, solubility of a species follows the "the law of mass

[20] U.S. Patent 5,997,836, Alkalai Aluminum Complex Hydroxide Carbonate Salt, and a Process for Producing Said Salt and Its Uses, Sato, T.; Komatsu, Y.; Higuchi, K.; Kondo, M.; Tatebe, A.

action". When applied to crystallization, the law balances the rates of dissolution and precipitation. For the reaction:

$$Ba^{+2} + SO_4^{-2} \leftrightarrow BaSO_4(s) \tag{3-9}$$

The reaction has achieved equilibrium once the forward (precipitation) and reverse (dissolution) rates have become equal. The equality is quantified in terms of a solubility product in which the ionic concentrations are raised to their stoichiometric coefficients. Using the above reaction:

$$K = \left[Ba^{+2}\right]\left[SO_4^{-2}\right] = 1.07835x10^{-10} \tag{3-10}$$

This solubility product is applicable to only slightly soluble salts in highly dilute (or "ideal") solutions. For concentrated solutions, activity-corrected solubility products are used to adjust the equation for interionic interactions. Activity-corrected solubility products use activity coefficients (γ) to adjust ionic concentrations for the "active" and "inactive" fractions of ions in solution. For the reaction[21]

$$6Na^{+1} + 2SO_4^{-2} + CO_3^{-2} \leftrightarrow Na(SO_4)_2CO_3(s) \tag{3-11}$$

The activity corrected solubility product is:

$$K = \left\{\gamma_{Na} Na^{+1}\right\}^6 \left\{\gamma_{SO_4} SO_4^{-2}\right\}^2 \left\{\gamma_{CO_3} CO_3^{-2}\right\} \tag{3-12}$$

Activity coefficients are correlated from experimental data of vapor pressure, freezing point, and/or osmotic measurements from simple and multi-component solutions. They are strongly dependent upon concentration of all ionic species in the particular solution. The above activity-corrected solubility product can be abbreviated to the following form:

$$K = \left\{\alpha_{Na+}\right\}^6 \left\{\alpha_{SO_4^{-2}}\right\}^2 \left\{\alpha_{CO_3^{-2}}\right\} \tag{3-13}$$

Or more generally:

$$K = \Pi \alpha_i i^{vi} \tag{3-14}$$

Where α_i is the species activity (activity coefficient x concentration) and *vi* is the stoichiometric coefficient. Further, the extent of saturation may be expressed as a saturation ratio (S) which is the ratio of the calculated to the saturated solubility product.

---

[21] For simplicity, fully dissociated ions are used in this study. Actual ionic speciation may include partial dissociations and/or neutral species:

$Na^{+1} + CO_3^{-2} \leftrightarrow NaCO_3^{-1}$
$Na^{+1} + SO4^{-2} \leftrightarrow NaSO_4^{-1}$
$Na^{+1} + NO_3^{-1} \leftrightarrow NaNO_3^{0}$

For crystallizations, the convention is to use fully dissociated species in the precipitation reactions. This pushes the above reactions to the left, so that quantities of partly dissociated species may be disregarded in this study. However, the partial dissociations are included in to the calculation of ionic strength.

$$S = K_{calc}/K_{sat} \tag{3-15}$$

For unsaturated solutions	$S < 1$
For saturated solutions	$S = 1$
For supersaturated solutions	$S > 1$

Activity-corrected solubility products are species and model dependent. They are developed for a specific set of specific chemical equations for a limited temperature range. For the crystallizations of interest, Table 7 is a set of solubility products at 40°C.

Table 7. Solubility Products at 40°C.

Species	*K*
$Na_6(SO_4)_2CO_3(s)$	1.007×10^{-2}
$Na_3FSO_4(s)$	4.458×10^{-3}
$Na_2CO_3 \cdot 1H_2O(s)$	7.108×10^{-1}
$NaNO_2(s)$	4.625×10^{1}
$NaNO_3(s)$	1.579×10^{1}
$Na_2Al_2O_4 \cdot 2\frac{1}{2}H_2O(s)$	1.156×10^{4}
$Al(OH)_3(s)$	9.429×10^{-2}

The units for concentration for these solubility products are molality[22] (g moles solute/1000 g H_2O).

Ionic strength, *I*, is a measure of the interionic effect resulting primarily from electrical attractions and repulsions between ions. It is defined by the equation:

$$I = \frac{1}{2}\Sigma_i c_i Z_i^2 \tag{3-16}$$

Where c_i is ionic concentration in moles per liter and Z_i is its ionic charge. For Hanford waste, where sodium is the dominant cation, ionic strength can be roughly approximated by the aqueous sodium concentration.[23]

[22] Using molality units, the molality for H_2O is constant (55.5 moles H_2O/1000 g H_2O), so that water concentration is removed from the calculation of water activity. In these units, the activity of water is equal to the water activity coefficient ($\alpha_{H2O} = \gamma_{H2O}$).

[23] In reality, the sodium is speciated into several ionic and non-ionic forms (i.e. Na^{+1}, $NaCO_3^{-1}$, $NaSO_4^{-1}$, $NaNO_3^{0}$) so that calculation of ionic strength is not straightforward.

To illustrate the effects of ionic activities and solubility products on sodium salt yield during crystallization, several examples in Appendix E depict batch evaporative crystallizations of sodium salt systems. These systems are similar to those found in Hanford waste.

3.10 PRODUCT DECONTAMINATION

The concentrations of soluble radionuclides in feed liquor can increase by a factor of ten in the crystallizer. The extent of concentration is approximately[24] equal to the inverse of the sodium yield. Thus, a 90% sodium yield increases the concentration of cesium from 0.2 Ci/L in the feed to 2.0 Ci/L in the crystallizer.

The bulk of the radioactive contamination is removed from the crystallizer by the purge stream and depending on the sodium yield, the purge stream flowrate ranges from 10 to 50% of the feed rate. The remaining contamination is carried with the crystal product to the separation system.

Radioactive contamination of product crystals can occur in two forms: interstitial contamination, which is due to soluble radionuclides in interstitial liquor, and mother liquor inclusions, which occur due to crystal imperfections. Mother liquor inclusions are usually caused by rapid crystal growth rates, typically due to extreme supersaturation. Interstitial contamination is caused by entrainment of liquor with the crystal cake.

To remove interstitial contamination, mother liquor is separated and washed from the filter cake. So, the extent of decontamination is proportional to the extent of deliquoring. To achieve the highest degree of decontamination, highest extent of deliquoring is required. Centrifugation offers the highest extent of deliquoring and for this study interstitial liquor is assumed to be reduced to 10% of the cake mass. This is conservative since industrial applications of sodium salt centrifugation typically reduce interstitial liquor to 5%[25].

To further reduce interstitial contamination, the crystal cake is washed during the centrifugation process to displace contaminated liquor with clean liquid. The extent of decontamination during the wash process may be estimated by:

$$\mathcal{D} = 1 - (1/(1+W/L))^n \qquad (3\text{-}17)$$

Where $\mathcal{D}$ is the fraction of residual contamination, n is the number of wash stages, and W/L is the ratio of wash liquid to interstitial liquor. This calculation assumes that the wash liquid is well-mixed with the interstitial liquor[26], and that the residual liquor is equal to the initial interstitial liquor amount. Also, wash liquor must have lower contaminant concentrations than the interstitial liquor.

---

[24] The concentration increase is higher if the initial feed is not saturated in sodium salts.

[25] Garett, D.E. "Soda Ash", Van Nostrand Reinhold

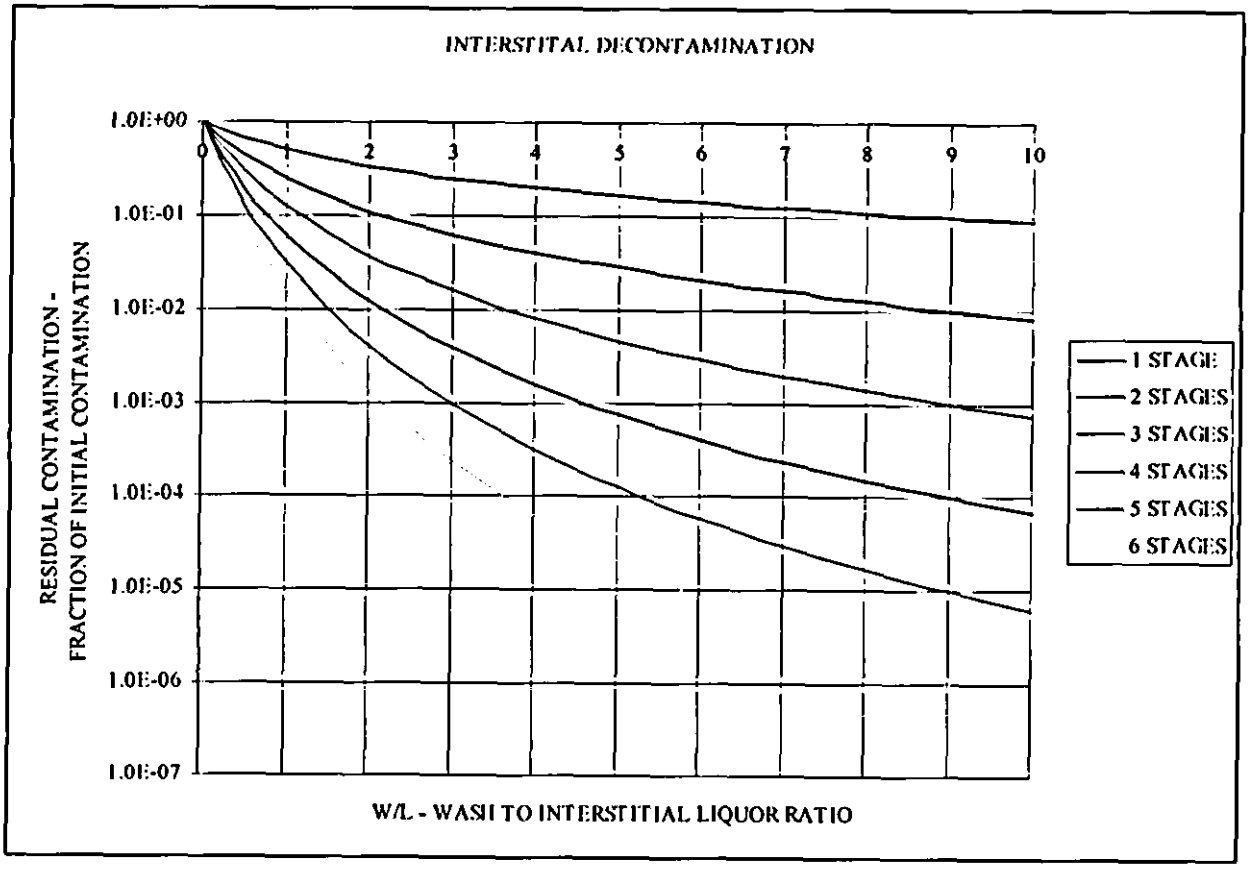
[26] Typically, the wash liquor is not well mixed with interstitial liquor in a centrifuge. Instead, plug flow displaces interstitial liquor with wash liquid with little mixing between the liquids. Thus, plug flow displacement has a higher decontamination efficiency than equilibrium models predict.

Thus, a three stage washing process using a wash solution that is four times the interstitial liquor mass has a theoretical decontamination of

$$\mathcal{D} = 1 - (1/(1+4))^3 = 99.2\% \qquad (3\text{-}18)$$

A graph of residual contamination as a function of wash to liquor ratio and the number of wash stages is shown in Figure 14.

Figure 14. Interstitial Decontamination.



As shown in the graph, a W/L ratio of 1, the number of wash stages has a greater effect on the extent of decontamination than the amount of wash liquid. Thus, given sufficient wash volume and washing stages, there is no theoretical limit to the extent of interstitial decontamination that can be achieved by displacement of interstitial liquor by wash solution.

Ideally, wash liquid is saturated with sodium salts to reduce product dissolution.[27] This wash solution may be made from product liquor and the spent wash liquor may be recycled to the evaporator to recover the sodium salts. By this method, no additional sodium salts are added to

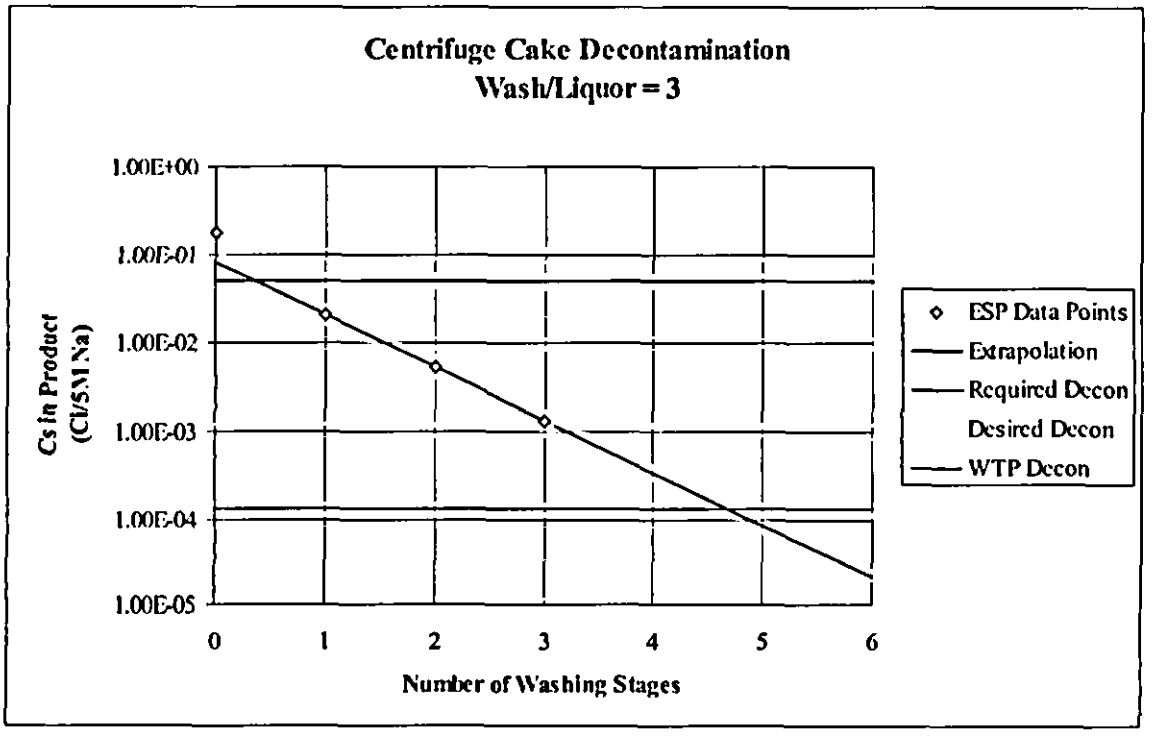
[27] *Theoretically, a three component ($NaNO_3$, Na_2CO_3, Na_2SO_4) saturated solution is not possible to formulate.* However, a solution approaching saturation will reduce dissolution during washing.

the system. However, recycling of spent wash liquor requires a proportional increase in capacity of the crystallization system to evaporate, recrystallize, deliquor, and decontaminate the recycle stream.

To maintain alumina solubility in the interstitial liquor during the first wash, a 10 wt% sodium hydroxide solution may be required. Sodium hydroxide maintains the pH of the interstitial liquor to prevent alumina gel formation in the centrifuge cake.

An example of centrifuge cake decontamination is shown in Figure 15. The initial cake contains 50% liquor and a cesium concentration of 0.178 Ci/5 M Na. The first centrifuge wash stage deliquors the cake to 10% moisture and washes the cake with saturated solution. In this case, the wash solution to cake liquor ratio is 3. Successive wash stages reduce contamination by displacing interstitial liquor with wash solution.

Figure 15. Centrifuge Cake Decontamination.



In this case, the extent of decontamination meets the required specification (0.05 Ci/5 M Na) after one wash stage. It meets the desired specification (0.0012 Ci/5 M Na) after three washing stages. To meet the required decontamination for WTP LAW feed (0.00013 Ci/5 M Na), five stages of washing are necessary.

This example is based on 10% cake liquor and perfect mixing during the wash stages, which are conservative estimates. However, it does not consider contamination due to crystal inclusions. Crystal inclusions are minimized in the full scale system by intensive mixing and a controlled crystal temperature profile/evaporation rate.

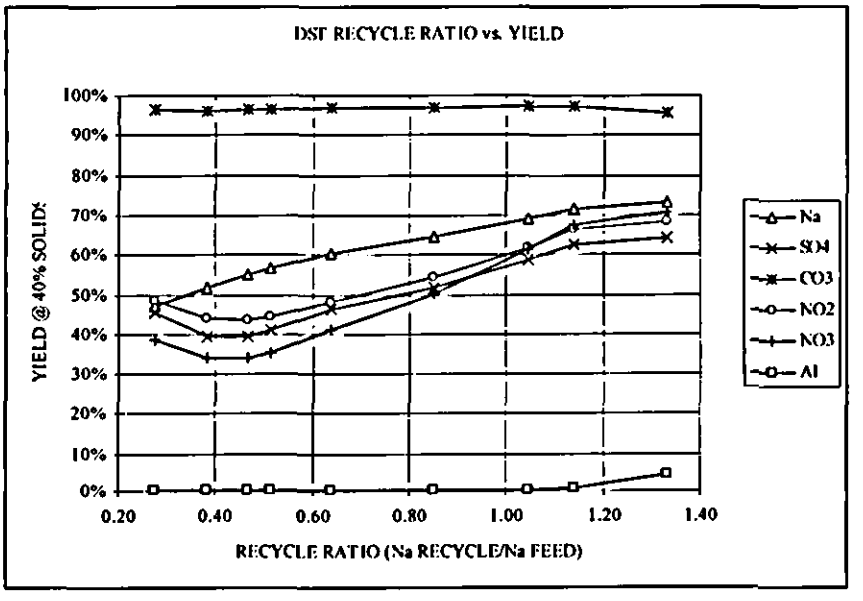
3.11 CRYSTALLIZER RECYCLE RATE

Industrial crystallizers typically have high recycle rates. That is, hydrocyclone overflow and spent wash solutions are continuously recycled to the crystallizer body, and a minimum purge stream is maintained to remove impurities.

However, because Hanford waste contains high solubility sodium salts (NaOH & $NaAlO_2$), a higher purge to recycle rate must be maintained to constantly remove these salts from the crystallizer circuit. Sodium hydroxide and sodium aluminate reduce water activity and vapor pressure and increase viscosity, density, and ionic strength of the liquid phase.

Following is a graph of yield versus recycle ratio. In this simulation, DST crystallizer was continuously carbonated to maintain the saturation ratios of $Al(OH)_3$ and $NaAlO_2 \cdot 2\frac{1}{2} H_2O$ to be equal[28] (see Figure 16) throughout the run. By this method, alumina solubility is maximized. Solids density in the slurry takeoff was 40%.

Figure 16. DST Recycle Ratio Versus Yield

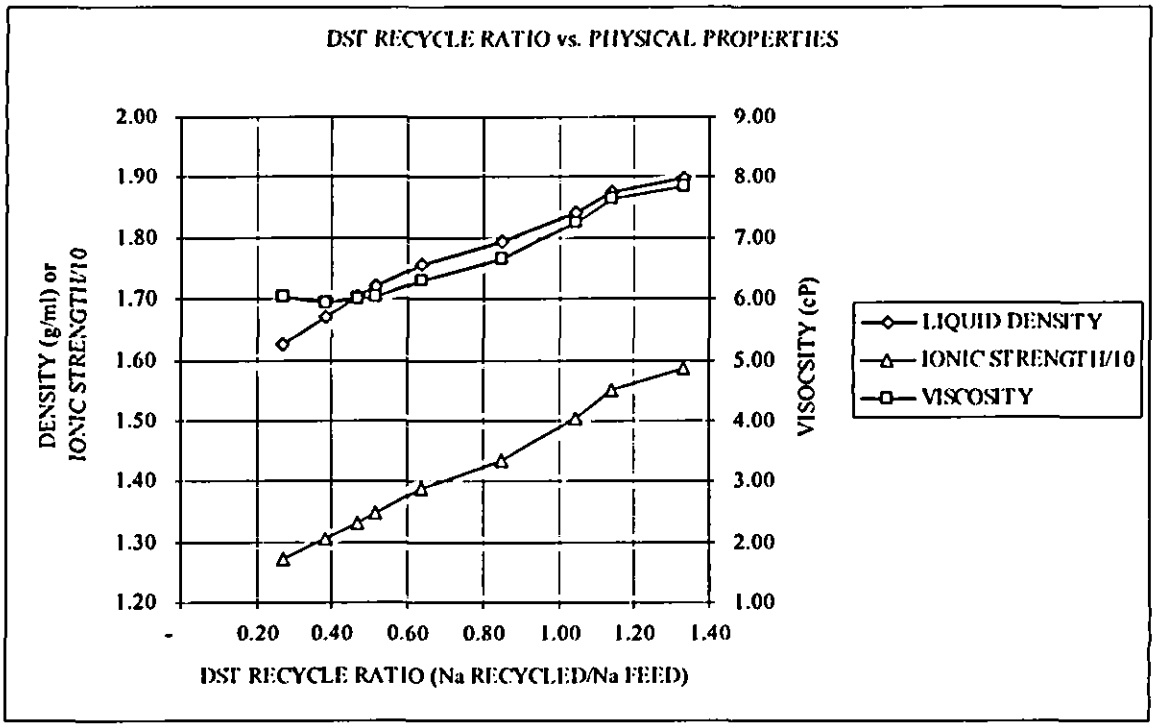


As shown by the graph, sodium, sulfate, carbonate, nitrite, and nitrate yields increase with increasing recycle up to a ratio of 1.14:1 Recycled Na/Feed Na. Beyond this point, alumina solubility is reached, and gibbsite and sodium aluminate are supersaturated. Thus, for this system, the maximum theoretical recycle ratio is 1.14 before maximum alumina solubility is reached.

The effect of the recycle ratio on physical properties is shown in Figure 17.

[28] The saturation ratios for gibbsite and SAH are both first order with respect to aluminum.

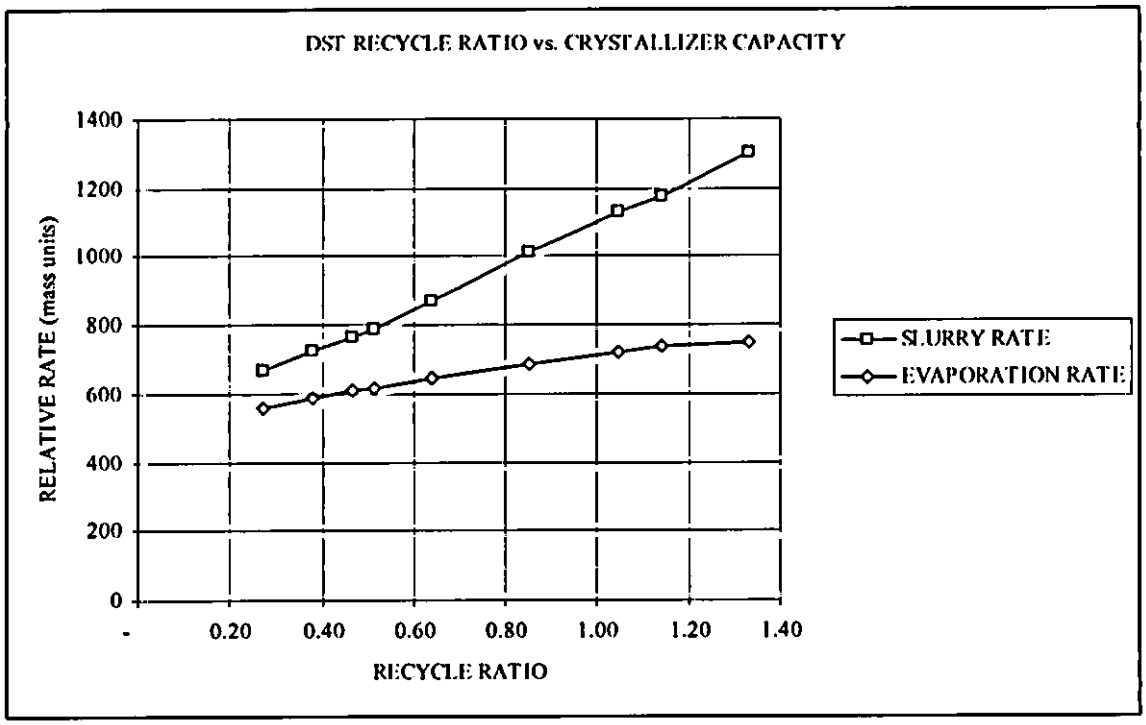
Figure 17. DST Recycle Ratio Versus Physical Properties.



Liquid density increases from 1.6 to 1.9 g/mL; viscosity increases from 6.0 to 7.8 cP; ionic strength increases from 12.8 to 15.8 as the recycle ratio is increased from 0.27 to 1.33. Thus, increasing the recycle ratio increases liquid density, viscosity, and ionic strength by recycling high solubility salts. These properties hinder diffusion and liquid-solid separability. The maximum liquid properties that allow separation may be reached before the theoretical maximum recycle rate. The maximum liquid properties for liquid-solid separation must be determined by pilot plant studies.

Increasing the recycle rate also increases the required capacity of the crystallizer system as shown in Figure 18. As the recycle ratio is increased from 0.27 to 1.33, the evaporation rate increases by 35%. The required volume to maintain the same residence time, determined by the slurry take-off rate, is increased by 94%. Thus, the extent of recycle must be factored into the design of the full-scale unit.

Figure 18. DST Recycle Ratio Versus Crystallizer Capacity.



SECTION 4.0

4.0 LABORATORY CRYSTALLIZATION EXPERIMENTS

Laboratory crystallizations of Hanford waste simulants performed at Georgia Tech were thermodynamically modeled to plan the operating conditions, the extent of evaporation, the saturation points, and the theoretical yields. Initially, lab crystallization experiments followed the same operating path as the evaporation surveys in the examples in Appendix E. In laboratory batch crystallization, the feed is charged into the vessel, vacuum is drawn, and heat applied by external heating. The batch is boiled down until the crystal slurry reaches the maximum slurry density (or suspended solids) that can be maintained in the vessel. Lab crystallizations were terminated after the slurry density reached ~35 wt% solids. At this point, the condenser is turned to total reflux, vacuum is broken, and the charge is emptied from the vessel to a separator.

Because of the low sodium yield at 35 wt% solids, filtrate and/or wash liquor were recombined and evaporated in a second stage of crystallization. This method allowed higher sodium yield while maintaining a maximum slurry density of 35 wt% per stage. The conditions of the crystallization steps (i.e. temperature, pressure) may vary from stage to stage to improve the yield or quality of the crystal fractions. As previously discussed, higher temperatures favor burkeite and sodium monohydrate yield; lower temperatures favor sodium nitrate yield.

A second method, semi-batch crystallization, was developed to solve several problems associated with laboratory batch crystallization. In semi-batch crystallization, evaporations are performed incrementally, and the vessel is incrementally recharged with feed to refill the vessel. By this method, the amount of solid accumulation on the vessel walls is minimized. An example of a laboratory two-stage semi-batch crystallization simulation flowsheet is shown in Figure 19 with the mass balance of the flowsheet shown in Table 8.

In this flowsheet, the first crystallization stage is operated at 40°C and evaporated to 35 wt% solids. The second crystallization stage is operated at 50°C and evaporated to 35 wt% solids.

Each stage is filtered and washed using a saturated solution. In laboratory crystallization, filtration typically deliquors the product to 20% liquid in the filter cake. The wash solution is saturated with the product salts, and the amount of wash solution is equal to the mass of the crystal cake. The final product contains 20% liquid by mass.

Two-stage crystallization was found to be necessary to obtain the required sodium yield using a maximum slurry density of 35 wt%. In addition, two-stage crystallization allows tailoring of the operating conditions and residence times for the relative abundance of the sodium salts in the feedstock. For a production-size process, downstream equipment such as hydrocyclones and centrifuges must be tailored for the dominant crystal type from each crystallizer.

Details of the laboratory crystallization experiments (equipment, testing protocols, observations, results, etc.) can be reviewed in the Hanford medium/Low Curie Waste Pretreatment Project – Phase I Laboratory Report (RPP-RPT-27239).

Figure 19. Laboratory SST Early Feed Simulation.

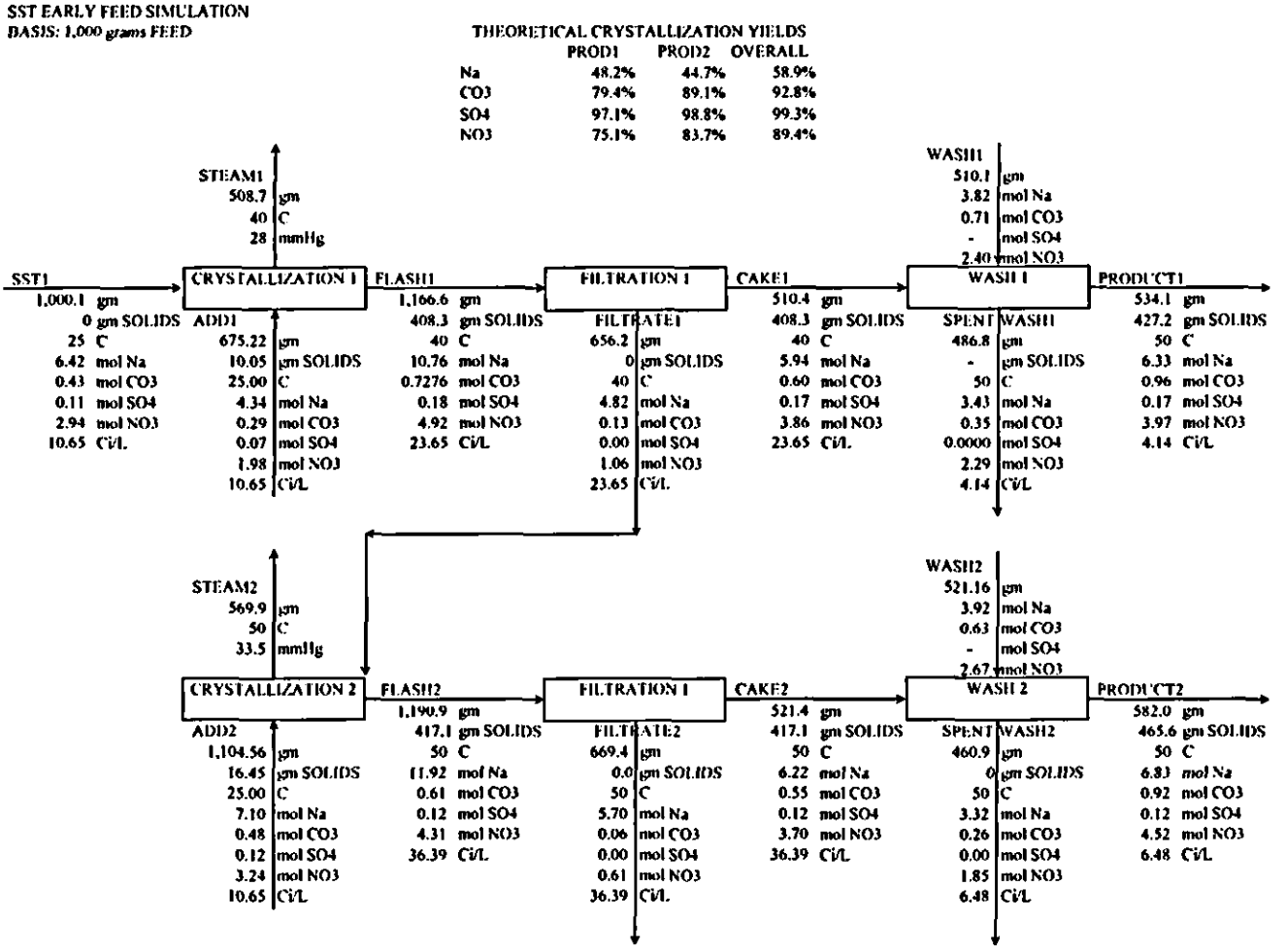


Table 8. Laboratory SST Early Feed Mass Balance.

STREAM #	BASIS 1,000 GM FEED										
STREAM			SST1	SST1	ADD1	ADD1	FLASH1	FLASH1	FLASH1	STEAM1	FILTRATE1
PHASE			Aqueous	Solid	Aqueous	Solid	Aqueous	Solid	Vapor	Vapor	Aqueous
TEMPERATURE, C			25.00	25.00	25.00	25.00	40.00	40.00	40.00	40.00	40.00
PRESSURE, atm			1.00	1.00	1.00	1.00	0.04	0.04	0.04	0.04	0.04
pH			15.19	-	15.19	-	15.30	-	-	-	15.30
TOTAL, gmmoles		MW	41.86	0.17	28.26	0.11	32.61	4.27	28.23	28.23	28.22
COMPONENT	FORMULA	gm/gmol	gm	gm	gm	gm	gm	gm	gm	gm	gm
Water	H2O	18.02	542.24	-	366.11	-	390.82	-	508.66	508.66	338.21
Aluminum Hydroxide	Al(OH)3	78.00	32.80	-	22.14	-	54.94	-	-	-	47.54
Sodium Hydroxide	NaOH	40.00	71.69	-	48.41	-	120.10	-	-	-	103.93
Sodium Nitrite	NaNO2	69.00	42.52	-	28.71	-	71.24	-	-	-	61.65
Sodium Nitrate	NaNO3	84.99	235.50	14.15	159.00	9.55	104.27	313.93	-	-	90.24
Sodium Carbonate	Na2CO3	105.99	45.83	-	30.95	-	15.87	-	-	-	13.74
Sodium Sulfate	Na2SO4	142.04	14.38	-	9.71	-	0.71	-	-	-	0.62
Sodium Carbonate Monohydrate	Na2CO3.1H2O	124.00	-	-	-	-	-	61.05	-	-	-
Burkeite	Na6(SO4)2CO3	390.08	-	0.74	-	0.50	-	33.35	-	-	-
Cesium Hydroxide*	CsOH	149.91	2.026E-01		1.368E-01		3.394E-01				2.937E-01
Total, gm			985.17	14.89	665.16	10.05	758.29	408.33	508.66	508.66	656.21
Total, kg			0.99	0.01	0.67	0.01	0.76	0.41	0.51	0.51	0.66
Volume, L			0.73	0.01	0.49	0.00	0.55	0.18	0.03	0.03	0.48
Enthalpy, cal			-2.880E+06	-2.006E+04	-1.944E+06	-1.354E+04	-2.271E+06	-6.525E+05	-1.629E+06	-1.629E+06	-1.965E+06
Density, g/L			1,352.00	2,270.72	1,352.00	2,270.72	1,380.04	2,278.55	0.03	0.03	1,380.04

Cs IS 100 TIMES THE TRUE CONCENTRATION
FOR ANALYSIS PURPOSES ONLY

STREAM #	BASIS 1,000 GM FEED										
STREAM			PRODUCT1	ADD2	ADD2	FLASH2	FLASH2	FLASH2	STEAM2	FILTRATE2	CAKE2
PHASE			Solid	Aqueous	Solid	Aqueous	Solid	Vapor	Vapor	Aqueous	Aqueous
TEMPERATURE, C			50.00	25.00	25.00	50.00	50.00	50.00	50.00	50.00	50.00
PRESSURE, atm			1.00	1.00	1.00	0.04	0.04	0.04	0.04	0.04	0.04
pH			-	15.19	-	15.53	-	-	-	15.53	15.53
TOTAL, gmmoles		MW	4.35	46.23	0.19	32.97	4.55	31.63	31.63	28.53	4.44
COMPONENT	FORMULA	gm/gmol	gm	gm	gm	gm	gm	gm	gm	gm	gm
Water	H2O	18.02	-	598.90	-	358.51	-	569.90	569.90	310.18	48.32
Aluminum Hydroxide	Al(OH)3	78.00	-	36.22	-	83.77	-	-	-	72.48	11.29
Sodium Hydroxide	NaOH	40.00	-	79.19	-	183.12	-	-	-	158.44	24.68
Sodium Nitrite	NaNO2	69.00	-	46.97	-	81.07	27.54	-	-	70.14	10.93
Sodium Nitrate	NaNO3	84.99	294.81	260.10	15.63	59.49	306.47	-	-	51.47	8.02
Sodium Carbonate	Na2CO3	105.99	-	50.62	-	7.06	-	-	-	6.11	0.95
Sodium Sulfate	Na2SO4	142.04	-	15.88	-	0.20	-	-	-	0.17	0.03
Sodium Carbonate Monohydrate	Na2CO3.1H2O	124.00	98.96	-	-	-	59.92	-	-	-	-
Burkeite	Na6(SO4)2CO3	390.08	33.47	-	0.82	-	23.21	-	-	-	-
Cesium Hydroxide*	CsOH	149.91		2.238E-01		5.175E-01				4.478E-01	6.975E-02
Total, gm			427.25	1,088.11	16.45	773.73	417.14	569.90	569.90	669.45	104.29
Total, kg			0.43	1.09	0.02	0.77	0.42	0.57	0.57	0.67	0.10
Volume, L			0.19	0.80	0.01	0.54	0.18	0.03	0.03	0.47	0.07
Enthalpy, cal			-7.319E+05	-3.180E+06	-2.215E+04	-2.353E+06	-6.482E+05	-1.822E+06	-1.822E+06	-2.036E+06	-3.171E+05
Density, g/L			2,277.05	1,352.00	2,270.72	1,420.94	2,265.17	0.03	0.03	1,420.94	1,420.94

Cs IS 100 TIMES THE TRUE CONCENTRATION
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SECTION 5.0

5.0 OPERATION MODES

5.1 BATCH EVAPORATIVE CRYSTALLIZATION

Batch evaporative crystallization is similar to the methods that were initially practiced in laboratory experiments. In batch crystallization, the feed is charged into the vessel, vacuum is drawn, and heat is applied. The batch is boiled down until the crystal slurry reaches the maximum slurry density that can be suspended in the vessel. The charge is then transferred to separation equipment for deliquoring and washing.

Because of the low yield in a one-pass batch crystallization, the separated filtrate and spent wash may be returned to the crystallizer, and the process is repeated. Depending on the required yield and the maximum slurry density, the number of batch crystallizations may be between two and five passes.

Batch crystallization has several disadvantages over continuous crystallization. Initially, the solution is undersaturated and there are no seed crystals present. Thus, upon evaporation, the solution may overshoot saturation before crystallization occurs. This results in rapid nucleation and crystal growth that can cause impurity inclusions which cannot be removed by washing.

Secondly, in batch crystallization, there is no classification and recycle of fine particles. In multi-component crystallization, this may result in bimodal size distribution. Also, fine particles are difficult to separate, deliquor, and decontaminate.

Thirdly, as observed in laboratory crystallization, as the batch is boiled down, dry wall surface area increases, and solids may accumulate on the walls. Crystals formed by thin-film evaporation on the walls may not have the same composition or size distribution as crystals formed in the mother liquor and the thin-film crystals may not be equilibrated with the bulk of the solution.

5.2 SEMI-BATCH CRYSTALLIZATION

To overcome some of the disadvantages of batch crystallization, a semi-batch method was developed for laboratory crystallization. In semi-batch mode, the crystallizer is initially charged with solution, vacuum is drawn, the vessel is heated, and a fixed amount of condensate (~20% of the liquid volume) is evaporated. At that point, the vessel is refilled with fresh solution. The incremental evaporations and recharges are continued until a slurry density of 30 wt% is reached. Then, the slurry is filtered to separate the product from residual liquor. The technique may be continued to a second semi-batch stage to increase the sodium yield.

Semi-batch crystallization can increase crystal size by dissolving fines and wall accumulation during recharge. Fresh solution is undersaturated, so it will dissolve crystals from the prior evaporation. Because of higher surface area to mass ratio, fine crystals dissolve faster than coarse crystals, therefore the remaining coarse crystals can provide seed crystals for the next

evaporation step. By this method, the extent of supersaturation is decreased, the size distribution is increased, and the potential for contaminant inclusions decreases. Semi-batch crystallization also reduces the exposed area of the crystallizer wall and thereby reduces solids accumulation. Any solids buildup on the walls is redissolved upon recharging the vessel.

Carbonation may be carried out after the initial batch is charged, as well as after each subsequent recharge. By this method, excess hydroxide can be trimmed while alumina solubility increases due to ionic strength increases during evaporation. This method prevents alumina gel formation by allowing the alumina to remain near the gibbsite phase boundary during the crystallization process.

5.3 CONTINUOUS EVAPORATIVE CRYSTALLIZATION

Continuous evaporative crystallization operates in steady-state mode; feed material is constantly fed to the crystallizer while steam, purge, and product slurry are constantly removed from the crystallizer. The slurry density is held constant by varying the heat input and product withdrawal rates. The crystallizer operates at a constant temperature and pressure.

By this method, flow surges are taken out from down-stream equipment and the amount of in-process storage capacity is reduced because the entire batch is not discharged at once. Hydrocyclones, elutriation columns, and centrifuges may operate continuously at their optimum rates.

Continuous crystallization operates at a lower degree of supersaturation than batch crystallization. In batch crystallization, the concentrations can overshoot the saturation points before nucleation occurs. This may cause rapid crystal growth rates and impurity inclusions. In continuous crystallization, crystal nuclei are always present, so that the extent of supersaturation is minimized.

For a continuous process, two crystallizers may be required; one for slow-growth retrograde-soluble salts such as sodium carbonate and sulfate and one for fast-growth salts such as sodium nitrate and nitrite. The first stage would crystallize sodium carbonate and sulfate at elevated temperature (~60°C) and long residence time (~3 hours) to increase crystal growth rates and crystal sizes, reduce sulfate and carbonate solubility, and increase sodium yield.

The second crystallization stage would operate at reduced temperature (~40°C) and short residence time (~30 minutes) to reduce sodium nitrate and nitrite solubility and reduce crystal growth rates. By this method, the temperature and residence time may be optimized for each crystallizer to increase the yield and quality of the crystal fractions. This method has not been demonstrated in the Phase I laboratory experiments; however, it is a necessary next step (pilot operation) before actual plant equipment can be sized and designed.

SECTION 6.0

6.0 PROCESS DESCRIPTION

6.1 PROCESS OVERVIEW

As noted in previous sections, fractional crystallization can be selective to sodium salts and therefore has been chosen to be demonstrated as the preferred method of supplemental pretreatment. Because of their abundance, sodium salts crystallize upon evaporation long before radioactive trace components cesium nitrate ($CsNO_3$), sodium pertectnetate ($NaTcO_4$), and sodium iodide (NaI) reach their solubility limits.

Fractional crystallization parameters can be adapted to the feedstock such that low solubility sodium salts (Na_2CO_3, Na_2SO_4) can be readily crystallized by evaporation and temperature dependent salts ($NaNO_3$) may be crystallized by cooling and/or evaporation. Slow-growth crystals ($Na_6(SO_4)_2CO_3$) require more residence time than fast-growth crystals ($NaNO_3$). Carbonation may be used to convert high solubility NaOH to low solubility Na_2CO_3 for crystallization.

As previously discussed, other processes may be developed in the future to improve fractional crystallization yield. Oxidation may be used to convert sodium nitrite to sodium nitrate to reduce total solubility of the $NaNO_2$-$NaNO_3$ system. Alumina may be crystallized prior to sodium salt crystallization to reduce the sodium hydroxide requirement for alumina solubility.

For all of these unit operations (evaporation, carbonation, cooling, etc.) the fractional crystallization system must be designed to adapt to the feedstock to achieve high yield and product decontamination. For these reasons, a two-stage forced-circulation vacuum crystallizer system has been selected. The two-stage system has the flexibility to allow high- and low-temperature operation and it allows feed to be applied to one or both stages. It also allows the recycle of fine crystals to improve residence time and crystal size and allows tailoring of deliquoring equipment (i.e. centrifuges) for the dominant crystal types produced from each stage.

The crystallizer system will ideally operate as a continuous process that provides continuous measurement and control of process variables to create and maintain constant growing conditions for the crystal products. Particle size distribution, radioactivity, liquid composition, flow rates, levels, temperatures, and pressures will be measured. Steaming rates, wash rates, and recycle rates will be continuously controlled to maintain steady operation within the desired operating ranges.

Ideally, continuous operation allows minimizing the above ground inventory of radioactive waste because feed material is continuously fed from the tank retrieval facility while product is continuously pumped to the BV receipt tanks. Purge is continuously transferred to an existing DST. This minimizes above-ground storage volumes of radioactive waste solutions and is similar to the existing 242-A Evaporator operations; however, the continuous flow to and from the FCS requires further evaluation once the interfacing tank farm systems are more fully defined.

In the event of a process interruption, the crystallizer system will be put on total recycle. The product will be dissolved in condensate and recycled to the feed tank while the purge may be continuously removed or recycled to the feed tank. The method of total recycle keeps the crystallizer system on-line and operating at steady-state during interruptions in feed or product receiving systems.

Utilities, such as steam, cooling water, and process water will be supplied by package ("skid mounted") units. Process water supplied to the process, cooling tower, and the boiler will be conditioned by a demineralizing system to remove hard water compounds (Ca, Mg, Si). This will reduce scale deposits on heat transfer surfaces and minimize the formation of minerals in the process. Non-contaminated condensate, not used in the process, will be returned to the boiler to minimize waste water sent to the Effluent Treatment Facility (ETF).

Workers' exposure to radioactivity will be minimized by incorporating As Low As Reasonably Achievable (ALARA) principles in the design. The processing equipment used to handle and treat tank wastes is housed in shielded structures to reduce radiation exposure to workers. The structure also protects equipment from damage due to environmental conditions and provides an enclosed area to perform maintenance. Tanks that are used to contain tank wastes or treated tank wastes will be double contained (as applicable) to prevent inadvertent discharge to the environment and include shielding to meet ALARA considerations.

The fractional crystallization system proposed will operate for two years in a pilot demonstration mode prior to shifting to full production capacity (up to 5 gpm) to supply a Production BV Facility. During the pilot demonstration mode, the system will operate on cold simulants to establish operating parameters and determine the need for modifications to process equipment. In the "hot" demonstration mode, actual tank waste will be processed to allow feed to the Demonstration BV Facility to vary from 0.76 to 2.2 gpm.

6.2 PROCESS FLOW DIAGRAMS

Process Flow Diagrams (PFDs) containing preliminary mass balances for SST and DST wastes are in shown in Figures 5, 6, and 7, respectively. The basis for the flowsheet mass balances is 5 gpm of 5 M Na in the product stream to supplemental treatment (BV). Mass balances on the flowsheets are in English units (lbm). Mass balances in metric units (g & g-mole) normalized to 1000 g feed are given in Appendices A, B, and C.

The simulant feed chemistry is based on the SST early/late feed and DST chemical concentrations (see Section 2.1, Table 2 and Table 3). For simplification and model limitations, the mass balances are based upon one-stage crystallization. Thus, the required capacity for each stream of the proposed two-stage system is one-half of the mass balance value. The mass balances were developed using ESP/MSE thermodynamic models.

Each flowsheet is based on the maximum theoretical yield at the maximum alumina solubility. This technique is used to determine the maximum radiological dose rate. The processes use continuous carbonation to maintain the saturation ratios of gibbsite and sodium aluminate to be near-equal and near-saturated at 40°C.

Flowsheet yields and cesium (Cs) decontamination are compared to the required and desired targets in Table 9. Actual physical properties (viscosity and liquid density) may limit the yield to less than the theoretical amount shown in the flowsheets.

Table 9. Theoretical Flowsheet Yields.

PRETREATMENT OUTPUT STREAM	CRITERION	MINIMUM ACCEPTABLE REQUIREMENT	DESIRED TARGET	SST EARLY FEED FLOWSHEET	SST LATE FEED FLOWSHEET	DST FLOWSHEET
BV FEED	^{137}Cs activity	<0.05 Ci/L	<0.0012 Ci/L	0.0011 Ci/L	0.0008 Ci/L	0.0029 Ci/L
	Na^+ concentration	5 M (+/- 20%)	5 M (+/- 10%)	5 M	5 M	5 M
	Na^+ split	Contain at least 50% of the Na^+ in the input stream	Contain at least 90% of the Na^+ in the input stream	82.1%	88.77%	71.5%
	Contaminants of concern	TRU concentration must be less than 100 nCi/g	TRU concentration must be less than 100 nCi/g	N/A*	N/A	N/A
WTP FEED	Sulfate:sodium mole ratio	<0.01	≤0.0022	0.0030	0.01**	0.0018
	DST storage	Must meet DST storage requirements and pipeline transfer requirements	Must meet DST storage requirements and pipeline transfer requirements	YES	YES	YES

* N/A – TRU are not included in the recipes.
**Although sulfate yield is 99.9%, high Na^+ yield increases the sulfate to sodium mole ratio.

Alumina solubility is maintained throughout the flowsheets. A 10 wt% NaOH solution is used for the first wash to maintain the pH of the interstitial liquor to prevent alumina gel formation. This wash solution adds 2.8% to the total sodium at the maximum sodium salt yield. The Cs DF, defined as ([Cs]/5 M Na Feed)/([Cs]/5 M Product)), is 54.9 for the SST Early Feed Flowsheet, 21.4 for the SST Late Feed Flowsheet, and 124.0 for the DST Flowsheet.

Tank Farm Waste Storage and Transfer Chemistry Requirements (Table 2) for the purge streams are met by bypassing a small fraction (0.8%) of the feed stream to the purge tank. The bypass increases the free hydroxide concentration in the purge to 0.3 M for corrosion control.

Chemical oxidation can potentially improve sodium yield by reducing ionic strength, liquid density, and viscosity by converting sodium nitrite to sodium nitrate and reducing total $NaNO_x$ solubility. However, at this point, this technology has not been developed for this process and it is not included in the current flowsheets.

6.3 PROCESS OPERATIONS

Chemical characterization data of the selected feed will be used to optimize the operation of the FCS. The process will be thermodynamically modeled to determine flow rates, temperatures, and pressures of the system to achieve optimum yields and decontamination of the product. The section below describes the currently proposed process system operation.

Dissolved saltcake and supernatant liquid are retrieved from Hanford underground storage tanks by Tank Farms and sent to the FCS feed tank for pretreatment. Prior to transfer, the feed is filtered to remove suspended solids.

Referring to a process flowsheet (Figures 5, 6, and 7) the feed tank provides surge capacity for fluctuations in transfers from Tank farms. The feed rate to the crystallizer system is balanced to maintain the required production rate (0.76 to 5.0 gpm of 5 M solution) to BV. Depending on the concentration of the feed solution and the sodium yield, the feed rate may be higher or lower.

From the feed tank, solution is pumped to the first and/or second stage crystallizer and the purge tank. Depending on sodium yield and extent of carbonation, a small portion of the feed may bypass the crystallizers to provide the purge solution with additional sodium hydroxide and/or sodium nitrite to meet DST Storage and Transfer Chemistry Requirements.

The bulk of the feed solution enters the crystallizer(s) in the recirculation piping where it is blended with crystallizer slurry. The recirculation stream has a much higher flow rate than the feed stream. By blending in the feed stream, minor variations in the feed stream composition make little or no impact to the composition of the large recirculation stream.

The recirculation stream is heated by the external heat exchanger (reboiler) and provides the heat of evaporation to the crystallizer by heating the recycle stream. The reboiler is heated by low pressure steam on the shell side of the heat exchanger. To reduce the possibility of contaminating the boiler in the event of a tube failure, an intermediate heat exchanger may be used.

The recirculation stream enters the crystallizer body through a draft tube in the center of the crystallizer body. At this point, back pressure from the recirculation line is released, water boils off, and the solution becomes super-saturated in sodium salts. Crystal nucleation and growth occur in this region. The center draft tube design allows crystal growth to occur in the crystallizer body rather than on the crystallizer walls. Recirculation of "fines" (small crystals) from the hydrocyclones provide seed crystals for the crystal growth.

Carbon dioxide is continuously fed to a "carbonator" in a crystallizer recycle line where the recycle line provides sufficient back-pressure to allow carbon dioxide to react with the waste. Because the crystallizer operates under vacuum, CO_2 injection in the crystallizer would result in off-gassing through the condenser system if the back pressure is not maintained. The rate of carbonation will be determined by thermodynamic modeling.

Above the liquid interface, a de-entrainment section ("top hat") on the crystallizer allows disengagement of foam, solid particles, liquid droplets, and aerosols. Foam is disengaged from the steam in the lower section with the aid of a defoamer solution. Solid particles and liquid

droplets are disengaged with the use of bubble trays with counter-current condensate flow. Aerosols are disengaged with the use of mesh pads ("mist eliminators") in the top section of the crystallizer.

Overhead steam is condensed by a series of condensers. The first stage condenser uses cooling water to condense the bulk of the steam at ambient dew point temperature. A set of two vacuum jet steam ejectors are used to pull vacuum on the system and each ejector has a condenser. Condensate from the overhead condensers flows to a condensate receiver which is used to supply condensate to the wash and dilution processes.

Slurry from the crystallizers is processed to separate and decontaminate product crystals from the mother liquor. A hydrocyclone is used to separate coarse ("product") crystals from fine ("seed") crystals and concentrate the underflow slurry to ~50 wt% solids. Overflow slurry, containing the seed crystals, is recycled to the crystallizer through the spent wash tank.

The underflow stream is deliquored and washed in a multi-stage centrifuge. The deliquoring step expresses most of the residual liquor, which contains the highest concentration of cesium, from the crystal cake. It may be forwarded to the next crystallization stage or the purge tank. Washing steps displace interstitial liquor from the crystal cake. The first wash may use a 10% NaOH solution to prevent alumina gel and reduce crystal dissolution. The second wash may use condensate or recycled 5 M product to remove most of the residual cesium. Spent wash from the centrifuge is recycled to the crystallizer through a spent wash tank.

Crystal cake is discharged from the centrifuge through a chute to the 5 M Product Tank where it is dissolved in condensate to make a 5 M sodium salt solution for transfer to BV.

Liquor from the deliquoring stage is routed to the purge liquor tank. The purge liquor tank accumulates the cesium rich liquid prior to transferring it to Tank Farms for WTP treatment. The purge liquor is adjusted for composition using "bypassed feed" and transferred to a receiving DST in Tank Farms.

All process operations will be controlled from a modular control room that is detached from the process equipment building.

6.4 MAJOR EQUIPMENT LIST

The major process system components are listed below and do not include all the support systems or equipment that may be required in the final facility. This information will be developed as design activities progress. All materials that contain, may contain, or contact tank waste or treated waste should be constructed of 304L stainless steel or other compatible corrosion resistant alloys that will allow use of a wide range of decontamination or descaling solutions. Equipment sizes and required operating parameters will be based upon data obtained in pilot plant operations.

Process Equipment

- CO_2 Storage Tank
- 10% NaOH Storage Tank
- Feed Tank
- Carbonators
- First Stage Crystallizer
- Second Stage Crystallizer
- First Stage Crystallizer Reboilers
- Second Stage Crystallizer Reboilers
- First Stage Crystallizer Condenser
- Second Stage Crystallizer Condenser
- First Stage Steam Jet Vacuum Pump
- Second Stage Steam Jet Vacuum Pump
- Condensate Tank A
- Condensate Tank B
- First Stage Hydrocyclone
- Second Stage Hydrocyclone
- First Stage Centrifuge
- Second Stage Centrifuge
- 5 M Product Tank A
- 5 M Product Tank B
- Spent Wash Tank A
- Spent Wash Tank B
- Purge Liquor Tank

Utility Equipment

- Steam Generator
- Cooling Water System
- HVAC

6.5 PROCESS EQUIPMENT

6.5.1 CO_2 Storage Tank

A liquefied carbon dioxide storage tank provides a continuous supply of CO_2 to carbonate the crystallizer slurry. The tank will be provided by a CO_2 supplier and equipped with an evaporation system to vaporize the liquid and regulate the gas supply pressure to the process. The storage vessel must be large enough to supply the FCS between deliveries. The CO_2 storage tank does not require shielding or secondary containment.

6.5.2 10% NaOH Storage Tank

A NaOH storage vessel provides a continuous supply of 10% sodium hydroxide ("caustic") solution for centrifuge wash. The storage vessel must be large enough to treat the waste between deliveries of additional solution. Caustic will be received in 50wt% solution; it will be diluted to 10wt% using non-contaminated condensate or treated water. The 10% NaOH storage tank will require secondary containment for spill prevention, but does not require radioactive shielding.

6.5.3 Feed Tank

Tank Farms continuously transfers tank waste to the feed tank(s). The feed tank provides surge capacity for fluctuations in feed supply from Tank Farms and provides continuous feed to the crystallizers. The tank has a cone bottom to prevent solids accumulation and mixing is provided by recirculating the tank contents through the feed pump.

The headspace of the feed tank and all other waste storage tanks may be continuously purged with compressed air to prevent flammable gas accumulation. Exhaust air from the tank is routed to the facility HVAC system.

6.5.4 Carbonator

Carbon dioxide is injected into the "carbonator" in the crystallizer recycle stream. The carbonator increases sodium salt yield by converting highly soluble sodium hydroxide into low solubility sodium carbonate. In the current process, carbonation will be used to trim "excess" NaOH only to avoid alumina gel formation.

The configuration of the carbonator will be determined in pilot plant tests. It will be designed to maximize gas-liquid contacting and minimize crystal attrition (breakage).

The feed rate of CO_2 will be determined by thermodynamic modeling. The extent of CO_2 reaction during neutralization (an exothermic reaction) will be measured by temperature rise across the carbonator.

6.5.5 Crystallizers

The FCS crystallizers provide the conditions for sodium salt crystallization by established residence time and selected temperature for optimum crystal growth. The volumes of the crystallizers will be determined in pilot plant studies by the required residence time for growing separable crystals. The crystallizers are currently proposed as the draft tube baffle (DTB) type.

The crystallizers will be sized to produce a nominal maximum feed rate of 5 gpm of 5 M waste solution to BV. The actual FCS influent feed stream rate will vary depending on the concentration of the feed and the crystallizer yield to produce a 5 M Na product stream.

Pressure in the first stage and second stage crystallizers is controlled by steam jet ejectors producing sufficient vacuum to allow for sub-atmospheric boiling temperatures. The operating pressures and boiling temperatures (saturated system) are controlled by the steam ejector motive steam flow rates. By this method, the salt supersaturation and crystal growth rates may be controlled.

Conditions in the crystallizers are carefully monitored and controlled to ensure steady-state operation and to ensure adequate crystal growth. The liquid levels in the crystallizers are controlled to maintain adequate residence time and the discharge rate is controlled to achieve the desired slurry density. The feed rates of tank wastes and the recycle rates to the crystallizers are monitored and controlled to maintain the liquid levels within specified ranges. The temperatures in the crystallizers are controlled by the heat input rate and the operating pressure. The overall operating conditions are adjusted to obtain the desired temperatures and residence times for crystal growth.

To provide for potential foaming and/or frothing in the boiling liquid, the crystallizers will be designed to allow for adequate vapor-liquid disengagement in the vapor headspace. If required, a defoamer will be injected in the vapor space to break the foam. A wash ring will be provided at the vapor-liquid interface to dissolve deposited salts and prevent accumulation of salts on the vessel walls during normal operations. Demisters and bubble trays will be used in the crystallizers to control the release of aerosols and spray nozzles will be used to maintain and clean the demisters.

6.5.6 Crystallizer Reboilers

Crystallizer slurry is heated in the crystallizer reboilers to a temperature that is just above the boiling point of the slurry at the crystallizer operating pressure. Back-pressure in the reboiler circulation lines prevents boiling in the reboiler, but allows boiling as the slurry is discharged to the crystallizer draft tube.

The crystallizer reboilers use saturated steam, or heated fluid from an intermediate heat exchanger, on the shell side to heat the slurry and maintain the required evaporation rate in the crystallizer. To recover the condensate from the reboiler, it must drain into a vacuum condensate receiver, where a pump is used to break vacuum.

The temperature difference between the steam and crystallizer slurry is kept low to limit the temperature rise in the heat exchangers. A temperature rise of two to three degrees Fahrenheit in the slurry is adequate to evaporate water in the crystallizers. The small temperature rise limits supersaturation of dissolved salts and prevents film boiling on the tube side of the reboiler. Film boiling may cause precipitation of minerals on the tube surface.

A pump is used to circulate the slurry through the reboiler and return it to the crystallizer while maintaining a strongly turbulent flow through the circulation line. The turbulent flow prevents deposits in the pipeline and reboiler.

6.5.7 Crystallizer Condensers

Water cooled condensers are used to condense steam from the crystallizer vapor streams. The condensate from the condensers is collected in condensate tanks and used as process water as needed in the FCS.

Since the overhead steam and condensate are at subatmospheric pressure in the condensers, the condensate must drain through a barometric leg, or into a vacuum condensate receiver, where a pump is used to break vacuum and return the water for process use.

6.5.8 Vacuum Steam Jets

Two-stage steam jet ejectors are used to produce vacuums in each of the crystallizers and are operated continuously while the FCS is in operation. The steam will be supplied by the auxiliary boiler and sized to maintain the crystallizers' vacuums over a range of operating conditions.

6.5.9 Steam Jet Condensers

Condensers are used downstream of each steam jet to condense the ejector steam and entrained vapor. Condensate is routed to the condensate tanks. Inert gas ("non-condensables") from the steam condensers is vented to the FCS HVAC system.

6.5.10 Condensate Tanks

Two condensate tanks receive condensate from the first/second stage condensers and vacuum ejector systems. The condensate is continuously reused in the FCS to dissolve the centrifuge product to a 5 M solution. The condensate can be used to adjust the purge liquor concentration, when necessary, to meet Tank Farms acceptance criteria. The condensate may also be used to control deposits and clean the demister in the crystallizers or used as the initial wash material for periodic decontamination of equipment. The condensate tanks are vented to the FCS HVAC system.

Depending on the water balance of the system, a surplus or a deficit of condensate may occur. Process water deficits are made up by the process water system. Process water surpluses are removed via tanker truck to the ETF after any required chemical analysis.

6.5.11 First Stage Hydrocyclone

The first stage hydrocyclone receives product slurry from the first stage crystallizer. The hydrocyclone increases the slurry density and separates coarse crystal from fines. The coarse slurry underflows the hydrocyclone and discharges to the first stage centrifuge where the crystals are washed and substantially dewatered. The overflow is recycled to the first stage crystallizer through the spent wash tank.

6.5.12 Second Stage Hydrocyclone

The second stage hydrocyclone receives product slurry from the second stage crystallizer and operates in the same way as the first stage hydrocyclone. The coarse underflow is directed to the second stage centrifuge, the fines overflow is recycled to the second stage crystallizer through the second stage spent wash tank.

6.5.13 Centrifuges

The centrifuges receive underflow slurry from the hydrocyclones. The slurries are deliquored and washed in the centrifuges to remove most of the interstitial cesium contamination. In the deliquoring step, excess solution is expressed from the crystal cake. This liquor, containing the bulk of the cesium, may be routed to the second stage crystallizer or transferred to the purge tank.

A 10% NaOH wash solution may be used for the first wash to maintain alumina solubility and is roughly equal to the volume of the interstitial liquor. The second wash may be condensate or recycled 5 M product liquor. Spent wash solution is routed to the spent wash tank for recycle to the crystallizer.

The centrifuges will be designed for remote operation and ease of maintenance. The operation of the centrifuges is monitored and controlled by the FCS central control system. The centrifuges may be decontaminated with process water or clean condensate when repairs or maintenance is required with the flush solution routed back to the process.

6.5.14 5 M Product Tanks

Centrifuge cake is discharged by chute to the 5 M Product Tanks where condensate is added to dissolve the solids to a 5 M solution. Mixing is provided by the recycle line and product concentration is controlled by solution density. Product solution is transferred to the BV product tank continuously at a nominal rate of up to 5 gpm. The 5 M Product Tanks have cone-bottoms to prevent solids accumulation and are vented to the FCS facility HVAC system.

6.5.15 Spent Wash Tank

Spent wash water and hydrocyclone overflow are routed to the Spent Wash Tanks which act as atmospheric pressure receivers for the discharges from these sources. The discharge from the Spent Wash Tanks is recycled to the crystallizers. The Spent Wash Tanks have cone-bottoms to prevent solids accumulation and are vented to the FCS facility HVAC system.

6.5.16 Purge Liquor Tank

The Purge Liquor Tank receives liquor from the centrifuges and discharges to the designated DST via the Tank Farm piping system. To meet the Tank Farms acceptance criteria, some of the

feed stream may be bypassed to the Purge Tank. The Purge Tank has a cone-bottom to prevent solids accumulation and is vented to the FCS facility HVAC system.

6.6 CONTROL LOGIC

The FCS will be controlled to maintain steady-state operation of the entire crystallizer system. All process variables, including temperatures, pressures, flow rates, tank levels, etc. will be measured. Input flow rates (waste feed, CO_2 feed, steaming rates) will be controlled to maintain process variables at set point values.

The control system will allow for manual operation during startup, shutdown, and abnormal operating conditions, but will operate in an automatic mode during normal conditions. In the event of system failure, an emergency shutdown mode will be provided.

Initially, the feed tank and crystallizer will be charged with fresh solution, then vacuum will be drawn on the system before feed is heated in the reboilers. Operating pressure in the crystallizers will be adjusted by control valves in the steam supply to the ejectors.

Operating temperature of the crystallizer will be allowed to float; the solution will seek its own boiling point as the concentration of dissolved salts increases at the fixed operating pressure. The operating pressure and resultant temperature may be changed during operation to increase crystal growth rate and/or to reduce solubilities.

Operating levels in the in-process storage vessels (feed tank, condensate tank, 5 M product tank, purge tank) will be controlled by the discharge rates from the tanks.

6.7 COMPATIBILITY WITH CURRENT HANFORD SITE BASELINE FACILITIES

The operation of the FCS will be very similar to current operations of the 242-A Evaporator in the 200 East Area. While the evaporator currently concentrates waste by removing a limited amount of the water added for mobilization and transport of the tank waste, the FCS extends the evaporation cycle to reach a supersaturated condition from which dissolved salts can be crystallized, separated, and removed. Therefore from a comparison of operational similarity, many of the services needed to support the FCS can either be extended from existing installations in the 200 West Area or duplicated from the 200 East Area systems. A discussion of these services is based on current Phase I studies of the proposed fractional crystallization processing facility sited in the 200 West Area.

6.7.1 Electrical Power

Electrical power will be supplied via a new drop from the 13.8 kV power lines in the vicinity of the BV because the projected load exceeds the BV process facility available margin. Preliminary estimates indicate a FCS load requirement of 465 kVA. Requirements for backup emergency power (diesel generator) have not been established, but a "placeholder" cost for an emergency generator has been included in the facility estimate.

6.7.2 Telephone/HLAN

Telephone and Hanford Local Area Network (HLAN) services currently available at the BV site will need to be extended to supply the FCS. The exact number of lines needed for the telephones and data exchange interfaces will be determined during detailed design of the facility.

6.7.3 Raw Water

Raw water is currently used for retrieval operations in the S Farm area. To supply water needs (boiler water makeup, fire protection, equipment flushing operations, sanitary service, etc.) at the FCS, a 6" main will need to be installed and connected to the closest underground water line.

6.7.4 Effluent Treatment

Condensate will be formed during the waste evaporation process and the water balance will depend on the concentration of the waste feed. Ideally, if waste concentration exceeds 5 M there will be a water deficit; if waste concentration is less than 5 M there will be a water surplus. Water that cannot be recycled for process uses, i.e. dilution, transfer line flushing, decontamination flushing, etc., will be collected and transported, via tanker truck, to the ETF.

6.7.5 Tank Waste Delivery

Tank waste will be delivered to the FCS via a hose-in-hose transfer (or other, double-contained with heating and leak detection) line originating in the area of the S/SY tank Farm. Between the time the waste is pumped from the underground tanks and received at the FCS it will be filtered to remove suspended solids. The solids removal system will be developed during the facility detailed design phase and integrated as part of the facility design or developed as a separate site infrastructure project. Included in the waste delivery system will be new, in-line instrumentation (coriolis meter, RAMAN probe analyzer, and cesium monitor) that could provide indication and/or control functions at the FCS. The waste receipt line, or another smaller, double contained, parallel line will return concentrated (high cesium) waste to the tank farm. A hose-in-hose (or other, double-contained with heating and leak detection) line will be needed to transfer processed tank waste to the DBVS facility for immobilization.

6.7.6 Analytical Services

A certain number (to be determined during Phase III of the project) of wet chemistry samples will need to be taken to provide regulatory or process confirmation data. The closest analytical facility to process the samples is the 222-S Laboratory.

6.7.7 Sanitary Service

New sanitary service leaching fields are not desirable therefore sanitary waste from change rooms and rest rooms will need to be collected in underground holding tanks. Periodic tank

pumping service, currently provided at other Hanford facilities, will have to be extended to the FCS.

6.7.8 Contaminated Solid Waste

Contaminated solid waste resulting from operations and maintenance i.e. protective clothing, contaminated tools, consumables, etc., will be collected at a designated location for pick-up and transport to the Hanford Central Waste Complex.

6.7.9 Potable Water

Potable water will be required for change room showers/washing facilities and drinking water. Current planning for extending potable water lines to the DBVS area are indeterminate, but if service lines are not extended to this location a potable water storage tank will need to be provided at the FCS site with periodic tanker truck deliveries.

6.7.10 Support Facility

During the initial FCS operations, a temporary control room (modular building) will be utilized to control the fractional crystallization process separate from the DBVS. A temporary control room was selected because it may be advantageous to control the DBVS and FCS from the same location. This will be a Phase III decision. The modular building will have space allocated for the additional operations day staff. Maintenance functions are assumed to be supplied from a "central pool" available on site. After the demonstration phase is complete, it is assumed that the operation of the fractional crystallization and BV processes can be combined into a single facility with sufficient space to accommodate all the required support staff for both processes.

6.8 UTILITIES EQUIPMENT

6.8.1 HVAC

The building HVAC will be a secondary confinement designed to prevent the dispersal of airborne contamination to the environment in the event of an accident in building space. A differential pressure will be maintained between potentially higher to lower contamination volumes starting with the process area (unoccupied) to staging area (occasionally occupied) to outside atmosphere. Airflow within the building will be from areas of less contamination to potentially higher contamination starting from the outside atmosphere to staging area to process area. The system will also provide for various process tank ventilation. Under emergency conditions, if the fans are required to be operated, the building should be capable of being maintained at a minimum negative pressure of 0.1 in. wg relative to the outside atmosphere.

The building HVAC system will use new exhaust systems of a design that is currently qualified for use in tank farm retrieval activities. The rated capacity of these exhauster systems is 3,000

cfm at 30 in. wg and they will be slightly modified to change from a portable to a permanent application. The building HVAC system will consist of several exhauster units and will have the capacity to operate the process while one unit is offline for maintenance. At the present stage of planning, each exhauster system consists of two stages of HEPA filtration preceded by a prefilter. The exhaust fan and environmental/regulatory monitoring system is located downstream of the HEPA filters. To minimize condensate on the HEPA filters, a heater is located upstream to maintain the relative humidity at 70% or below at the HEPA filters. In this application, high moisture air is not anticipated so a demister is not included however space for a demister will be provided if needed in the future. Instrumentation provided in each exhauster system includes differential pressure across prefilters and HEPA filters and temperature along various points in the system. Exhaust gas monitoring includes a continuous air monitor and record sampling system currently approved for Hanford use.

The building will be heated and cooled (as required) to allow personnel to work in the staging area of the building. The process area is not a normally occupied area and temperature in this area is controlled only to maintain process conditions and equipment temperature limits.

The actual required system capacity will depend on building configuration, but will be designed to meet regulatory requirements for this emission source. Applicable and relevant requirements include:

- ANSI/ASME N509, Nuclear Power Plant Air-Cleaning Units and Components
- ANSI/ASME N510, Testing of Nuclear Air Treatment Systems
- ANSI/ASME AG1, Code on Nuclear Air and Gas Treatment
- Gaseous and particulate effluent monitoring will comply with ANSI/HPS N13.1, Guide to Sampling Airborne Radioactive Material in Nuclear Facilities.

6.8.2 Steam Generator

Under current considerations, the steam generator will be a skid-mounted, oil-fired unit located inside the FCS building and sized to meet the maximum demand of the FCS. To avoid contaminating the steam generator with radioactive process fluids, means such as vacuum breakers, intermediate heat exchangers, etc. will need to be considered during detailed design. Fuel oil tanks, to supply the boiler, will be outside, above-ground, double-contained units compliant with WAC 173-180.

6.8.3 Cooling Water System

A counterflow, induced-draft cooling tower will produce cooling water for the condensers. The cooling tower uses ambient cooling and produces cooling water for use in the crystallizer condensers and the vacuum pump condensers. The cooling tower basin will have sufficient capacity for the entire volume of the cooling water in the system and will require treatment/blowdown systems to control biofouling and total dissolved solids.

6.8.4 Secondary Containment System

Secondary containment compliant with WAC-173-303 will be provided for the FCS tanks and tank systems that contain regulated wastes. Secondary containment required for the above ground fuel oil storage tanks and related equipment will be designed to comply with the requirements of WAC 173-180 "Facility Oil Handling and Design Standards Rule."

SECTION 7.0

7.0 PRELIMINARY HAZARD ASSESSMENT

The FCS must be integrated with the safety basis, operations, and maintenance concepts currently in place for the Hanford Site tank farms. As a first step in this process, a preliminary hazard assessment was conducted to qualitatively identify the hazards presented by this new facility, taking into account the current state of the project previously described in this document. As the design for the process, and the facility enclosing it, are further developed more rigorous reviews will be required to comply with the requirements of DOE Order 5480.23, *Nuclear Safety Analysis Report*, 10 CFR 830, and the DOE Standard *Hazard Categorization and Accident Analysis Techniques for Compliance With DOE Order 5480.23, Nuclear Safety Analysis Reports* (DOE-STD-1027-92). When eventually completed, all the hazards for the FCS will be documented in a facility specific Safety Analysis Report.

In developing this assessment for the facility two broad ranges of hazards were reviewed: a) radiological hazards, and b) occupational and non-radiological hazards. In addition hazards were reviewed for neighboring facilities that included the 241-S and 241-SY tank farms, which will supply feed to the FCS, and the DBVS, which will receive the processed waste. Hazards within these neighboring facilities are summarized in Table 10, Hazards Identification Form.

Radiological hazards within the facility consist of the inventory of radionuclides contained in the influent tank waste feed, the "in-process" solutions contained in the process system components, and the various process effluents i.e. purge stream to the DSTs, feed stream to the DBVS, ventilation system exhaust, etc. In general "time, distance, and shielding" will be the primary protective measures. Occupational and non-radiological hazards consist of common industrial hazards found in a process plant i.e. energy sources, pressurized systems, equipment maintenance, etc. Also included in this category are the chemical hazards associated with the process itself and natural phenomena which could affect the facility and its operators. Primary preventive measures for occupational/non-radioactive hazards will be engineering controls, Conduct of Operations, and proper personal protective equipment (PPE).

7.1 RADIOLOGICAL HAZARDS

The primary radiological hazard in the FCS facility is the potential dose rate from equipment and piping carrying the waste feed solutions during various stages of processing. From values presented in the project SOW, concentrations of ^{137}Cs can range from 100 μCi/mL for the SST Early Feed, to 10 μCi/mL for the SST Late Feed. Concentrations for ^{137}Cs in the DST feed can be as high as 490 μCi/mL. Based on this variability of concentrations, an ALARA study (Appendix F) was performed using an assumed facility configuration (Figure 20) and the DST feed as the basis. For simplicity, all dose rate was assumed to come from the crystallizer. Components, e.g. condenser, reboiler, etc., which in conventional crystallizers are integral with a "skid" arrangement, were spread out within the process area to begin considering maintenance accessibility. The results of this preliminary ALARA study are included as Appendix F. For estimating purposes, additional internal shield walls are proposed in the facility to minimize personnel exposure during maintenance and operation.

Table 10. Hazards Identification Form.

Energy Classification	241-SY Tank Farm[1]		241-S-Tank Farm[1]		DFCS		BV[2]	
	PT	PE	PT	PE	PF	PE	PF	PE
Electrical	7, 8, 12, 14, 15	1, 5, 7, 12, 14, 15, 16	7, 8, 12, 14, 15	10, 12, 13, 14, 15	2, 6, 7, 8, 9, 15	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	
Thermal	3	2, 3	2, 3	2	2, 3, 4, 7, 9, 13	2, 3, 4, 6, 8, 9, 10, 11, 13	2, 3, 4, 6, 8, 9, 10, 11, 13	
Friction	5	1, 2, 3, 5	3, 5, 7	NA	1, 2, 3, 4, 5, 6	1, 2, 3, 4, 5, 6	1, 2, 3, 4, 5, 6	
Corrosives	2	2	2	1, 2, 3, 4, 5, 6	2	1, 2, 3	1, 2, 3	
Kinetic – Rotational	2, 4	2, 4, 9	2, 4, 9	NA	1, 2, 4, 8	2, 4, 5, 7, 8, 9	2, 4, 5, 7, 8	
Kinetic – Linear	NA	1, 4, 5	NA	1, 4, 5	1, 4	1, 2, 4, 5, 6, 7	1, 2, 4, 5, 6, 7	
Mass, Gravity, Height	11	3, 5, 11	11	3, 5, 11, 13	13	1, 2, 3, 4, 5, 6, 7, 9, 10, 11, 12, 13, 14	1, 2, 3, 4, 5, 6, 7, 9, 10, 12, 13, 14	
Pressure – Volume	7, 10, 14	5, 6	7, 10, 14	5, 6	5, 9, 10, 11	1, 2, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14	1, 2, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14	
Explosives/ Pyrophorics	6, 7, 8	6, 7, 8	6, 7, 8	6, 7, 8	6, 7, 9	5, 6, 7 8, 12	5, 6, 7 8, 12	
Nuclear Criticality	5	NA	5	NA	NA	NA	NA	
Flammable Materials	12, 14, 15	3, 7, 9, 12, 14, 15	11, 12, 14, 15	1, 2, 3, 7, 9, 10, 11, 12, 14, 15	1, 2, 4, 10, 11, 12	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 14, 15, 16, 17	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 14, 15, 16, 17	
Hazardous Materials	2, 9	NA	NA	NA	2, 5, 6, 7	2, 5, 6, 7, 8, 9	2, 5, 6, 7, 8, 9	
Ionizing Radiation Sources	3	NA	NA	NA	3, 4	3, 4	3, 4	
Chemical Reactions	1	NA	1	NA	1	1	1	
External Events	NA	NA	NA	NA	1, 2, 3.01,	1, 2, 3.01, 3.02	1, 2, 3.01, 3.02	
					3.02			
Vehicles In Motion	NA	NA	NA	NA	4, 5	4, 5	4, 5	
Natural Events	6	NA	NA	NA	1, 2, 3, 4, 5, 6, 7, 8, 9, 10	1, 2, 3, 4, 5, 6, 7, 8, 9, 10	1, 2, 3, 4, 5, 6, 7, 8, 9, 10	

The hazard identification represents the hazards that could potentially cause an uncontrolled release of radioactive or hazardous materials only. Hazards only resulting in personnel injury are not included.
PT = potentially present in the tanks
PF = potentially present in the facility
PE = potentially present elsewhere in/adjacent to facility
1 The hazards identification for the tank farms were obtained from RPP-13033
2 The hazards identification for the BV facility was obtained from RPP-23429

Table 11. Hazard Identification Checklist and Energy Designators.

A Electrical
- 1 Battery banks
- 2 Cable runs
- 3 Diesel generators
- 4 Transformers
- 5 High voltage
- 6 HVAC heaters
- 7. Motors
- 8 Pumps
- 9 Power tools
- 10 Switch gear
- 11 Service outlets, fittings
- 12 Electrical equipment
- 13 Transmission lines
- 14 Underground wires
- 15 Facility wiring
- 16 Other _____

B Thermal
- 1 Bunsen burner/hot plates
- 2 Electrical equipment
- 3 Furnaces/boilers/heater
- 4 Steam lines
- 5 Welding torch/arc
- 6 Diesel units/fire box/exhaust line
- 7 Radioactive decay heat
- 8 Exposed hot components
- 9 Power tools
- 10 Convective
- 11 Solar
- 12 Cryogenic
- 13 Lighting
- 14 LASER equipment
- 15 Other _____

C Friction
- 1 Belts
- 2 Bearings
- 3 Fans
- 4 Gears
- 5 Motors
- 6 Power tools
- 7 Other _____

D Corrosives
- 1 Acids
- 2 Caustics
- 3 Natural chemicals
- 4 Decontamination solution
- 5 High temperature waste
- 6 Other _____

E Kinetic – Rotational
- 1 Centrifuges
- 2 Motors
- 3 Turbines
- 4 Pumps
- 5 Cooling tower fans
- 6 Laundry equipment
- 7 Shop equipment
- 8 Power tools
- 9 Other _____

F Kinetic – Linear
- 1 Cars, trucks, buses
- 2 Forklifts, dollies, carts
- 3 Railroad
- 4 Obstructions
- 5 Crane loads
- 6 Pressure vessel blowdown
- 7. Other _____

G Mass, Gravity, Height
- 1 Human effort
- 2 Stairs
- 3 Lifts and cranes
- 4 Bucket and ladder
- 5 Trucks
- 6 Slings
- 7. Hoists
- 8 Elevators
- 9 Jacks
- 10 Scaffold and ladders
- 11 Pits and excavations
- 12 Elevated doors
- 13 Vessels/tanks
- 14 Other _____

H Pressure – Volume
- 1. Boilers
- 2 Surge tanks
- 3 Autoclaves
- 4 Test loops
- 5 Compressed gas bottles
- 6 Pressure vessels
- 7. Stressed members
- 8 Compressors
- 9 Compressed gas receivers
- 10 Negative pressure collapse
- 11 Steam headers and lines
- 12 Positive displacement pumps
- 13 Hydraulic systems
- 14 Other _____

I Explosives/Pyrophorics
- 1. Caps
- 2 Primer cord
- 3 Dynamite/high explosives
- 4 Scrub chemicals
- 5 Dusts
- 6 hydrogen
- 7. Gases, other flammable
- 8 Nitrates/nitrites
- 9 Peroxides/hydrides
- 10 Pu and U metal
- 11 Sodium/phosphorus
- 12 Combustible vapors
- 13 Other _____

J Nuclear Criticality (fissile material present)
- 1. Vaults
- 2 Temporary storage area
- 3 Shipping and receiving area
- 4 Filters
- 5 Vessels/tanks
- 6 Casks
- 7. Burial ground
- 8 Storage racks
- 9 Canals and basins
- 10 Decontamination solution
- 11 Trucks, forklifts, dollies
- 12 Hand carry
- 13 Cranes/lifts
- 14 Hot cells, assembly, inspection
- 15 Laboratories
- 16 Other _____

K Flammable Materials
- 1. Packing materials
- 2 Rags
- 3 Gasoline
- 4 Lube Oil
- 5 Coolant oil
- 6 Paint solvent
- 7 Diesel fuel
- 8 Hydraulic fluids
- 9 Buildings and contents
- 10 Trailers and contents
- 11 Grease
- 12 Hydrogen
- 13 Nitric acid
- 14 Organics
- 15 Gases-others
- 16 Liquids-others
- 17. Other _____

L. Hazardous Materials
- 1 Alkali metals
- 2 Asphyxiants
- 3 Biologicals
- 4 Carcinogens
- 5 Corrosives
- 6 Oxidizers
- 7 Toxics
- 8 Heavy metals
- 9 Other _____

M Ionizing Radiation Sources
- 1 Fissile material
- 2 Radiography equipment
- 3 Radioactive material
- 4 Radioactive sources
- 5 Other _____

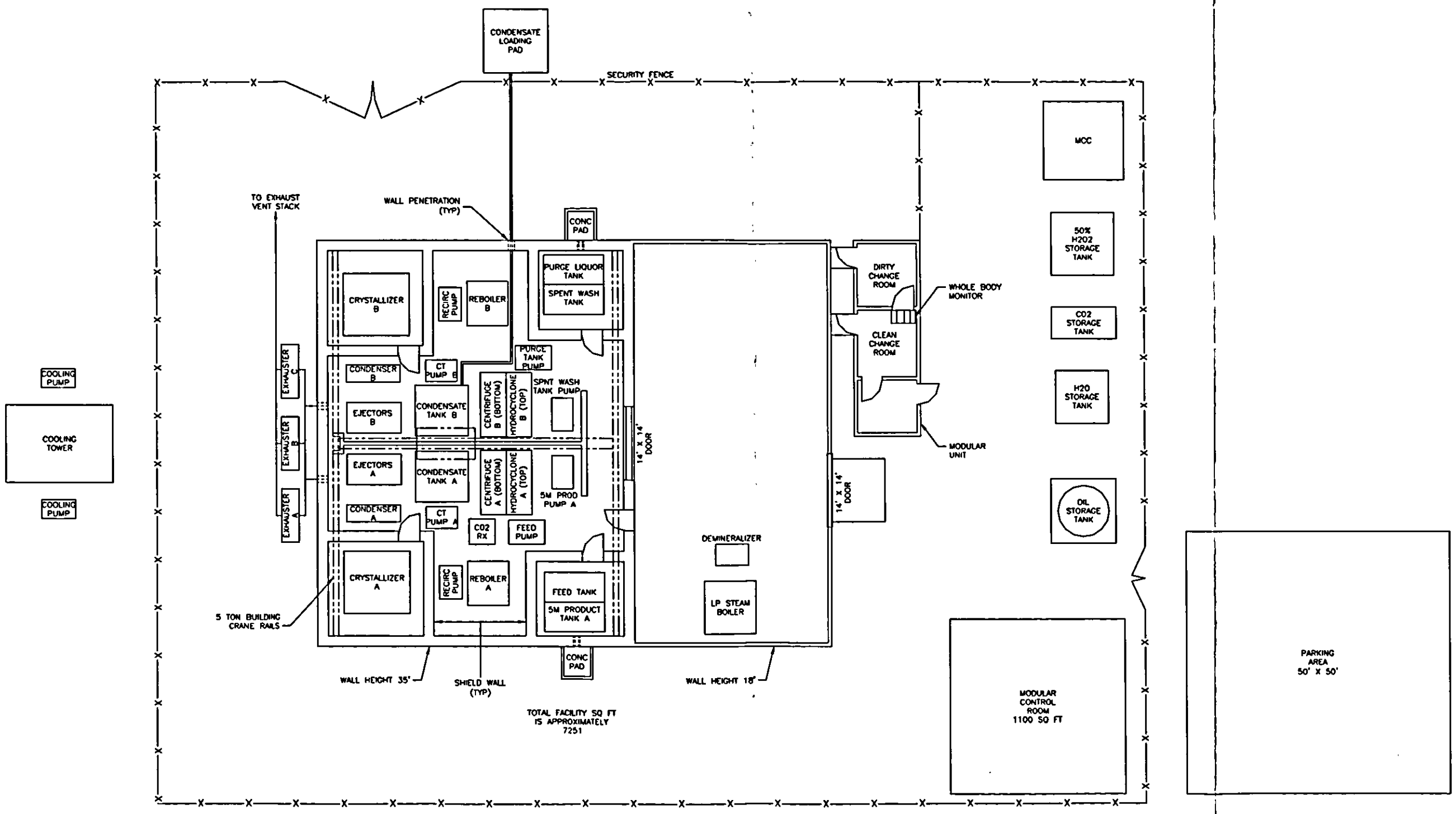
N Chemical Reactions
- 1 Uncontrolled chemical reactions
- 2 Other _____

O External Events
- 1 Explosion
- 2 Fire
- 3 Other sites (interactions)
- 3 01 Toxic materials
- 3 02 Flammable liquids/gasses
- 3 3 Explosive materials
- 3 04 Large water sources
- 3 05 Large quantities of asphyxiants
- 3 06 Other _____

P Vehicles in Motion
- 1 Airplane
- 2 Helicopter
- 3 Train
- 4 Truck/bus/car
- 5 Cranes
- 6 Other _____

Q Natural Events
- 1. Earthquake
- 2 Flood
- 3 Lightning
- 4 Rain
- 5 Snow, freezing weather
- 6 Straight wind
- 7. Dust devil
- 8 Tornado
- 9 Ashfall
- 10 Range fire
- 11. Other _____

Figure 20. FCS Facility Plan



Spills or leaks releasing contaminated liquids from the process systems are other sources of radiological hazards. To minimize this potential, process fluids will be double contained when external to the facility. Inside the facility the normal single wall piping systems will depend on building containment and local catch basins to prevent releases to the environment. During the design phase, stainless steel liners or impervious coatings, e.g. Ameron™ should be considered for additional leak protection and fluid barrier during water wash-down.

The process systems will be provided with flush and drain connections to minimize exposure during maintenance. The contaminated liquids will be routed back to the process to minimize waste generation. Another concept to be explored during the design phase (Phase III) is to include equipment with "cartridge" type replacement to minimize maintenance stay time in process areas. Building HVAC will be zoned to allow air flow from the "least" to potentially "most" contaminated area and will include vents from some of the process tanks/vessels. The HVAC system will be based on configurations currently used for tank farms local exhausters and will consist of redundant units as required to provide minimum ventilation in the event of failure of one unit. The need for redundant capability will be established during Nuclear Safety and Hazards Analyses. The exhaust stack will be equipped with continuous emissions monitoring equipment and will comply with the requirements of the Hanford Site Air Operating Permit.

7.2 OCCUPATIONAL AND NON-RADIOLOGICAL HAZARDS

7.2.1 *Flammable Gas Deflagration*

The potential for a flammable gas hazard exists at all tank farm facilities where wastes are present. The generation of flammable gas, primarily hydrogen, in tank farms wastes has been well documented and is the result of radiolysis of water and organics, thermolytic decomposition of organic compounds, and corrosion of steel tank walls. Additional flammable gases may consist of ammonia, methane, or other organic compounds contained in the waste. The quantity of gas available depends on the composition of waste in a tank, the quantity of waste present in a tank, and the ventilation/ambient pressure in a tank. Since the FCS will be receiving only clear (no particulate) filtered liquids from the tank farms, the concentrations of dissolved gasses will be limited to their solubilities in the tank liquids at the pumping temperature. Inside the FCS facility, where the gasses will be stripped from solution during the evaporation process, the gasses in vessels/components will be removed by an exhaust system that is vented to the atmosphere via the HVAC system.

7.2.2 Hazardous Chemical Exposure

Tank Waste may present a toxicity hazard due to the presence of toxic metals or the presence of toxic organic compounds. Exposures to the waste, aside from the radiological hazard, should be avoided to prevent toxic effects.

The waste solutions handled at the FCS are caustic due to the concentration of sodium hydroxide. Ingestion may cause severe burns of mouth, throat, and stomach, and severe scarring

of tissue may result. Skin contact can cause irritation or severe burns and scarring with greater exposures. Eye contact can cause irritation, and with greater exposures it can cause burns that may result in permanent impairment of vision, or even blindness.

Carbon dioxide may be used at the FCS to carbonate tank wastes for hydroxide neutralization. The gaseous carbon dioxide, as used in the process, presents a suffocation hazard if the gas is released in a confined space and inhalation of high concentrations may cause hyperventilation and unconsciousness. The liquefied gas will be provided with outdoor storage and presents hazards common to liquefied gases under pressure.

Hydrogen peroxide (50% liquid solution) may be used, pending further evaluation, at the FCS to oxidize tank wastes. Inhalation of gaseous hydrogen peroxide can cause chemical burns to the respiratory tract in addition to ulceration of nasal tissue, insomnia, nervous tremors with numb extremities, and in extreme exposure cases, chemical pneumonia or unconsciousness. Ingestion of hydrogen peroxide may cause gastrointestinal irritation with nausea, vomiting and diarrhea. Direct contact may cause severe skin irritation and possible burns. If liquid is splashed in the eyes, it may cause severe burns and corneal damage.

7.2.3 Pressurized Equipment

Pressurized equipment is necessary for routine operation of the FCS. Typical pressure sources will include process steam (saturated at approximately 125 psig), instrument or plant compressed air (at approximately 100 psig), and various water lines at about 30 to 50 psig. The crystallizers will operate under vacuum conditions, but will receive the pressurized discharge of pumping equipment. An additional hazard to consider will be a fire hazard resulting from pressurized fuel oil used to fire the process steam boiler. Fuel oil storage tanks and piping will comply with the applicable portions of WAC 173-180 *Facility Oil Handling Operations and Design Standards.*

7.2.4 High Temperature Exposure

There is the potential for worker exposure to high temperature surfaces (> 135° F) and equipment due to routine operations using process steam.

7.2.5 Human Hazards

The most likely human related hazard is operator error. Operator error is possible when workers are responsible for monitoring system parameters, adjusting operating parameters, responding to system alarms, or responding to out-of-limit parameters. The consequences of human error will depend on the sub-system that is affected and the nature of the materials present in the sub-system. The FCS will be designed to minimize the potential for human error through automatic monitoring of selected parameters and computer controlled actions or reactions to abnormal process conditions.

7.2.6 Environmental Hazards

The FCS will be designed and constructed to prevent damage by potential environmental hazards that may occur such as high wind loads, freezing temperatures, earthquakes, lightning, rain, snow, ashfall, and rangefires. The potential impact that these hazards may have will be addressed by the system design criteria.

7.2.7 Facility Industrial Hazards

In addition to the unique hazards of a nuclear facility, there are a variety of typical industrial hazards present at the FCS. There are electrical shock hazards, hazards from moving equipment, fall hazards, confined space hazards, power tool hazards, welding hazards, vehicle hazards, and others. These hazards are present when workers are involved with normal operations or performing maintenance on the process systems/facility. Once the FCS facility is operational, a comprehensive Conduct of Operations program will be implemented in concert with an Integrated Safety and Management System.

7.2.8 Flammable Liquid Storge

Fuel oil to supply the auxiliary boiler will be stored inside the FCS fenced area and represents a potential fire hazard. To ensure the hazards related to fuel oil storage are minimized, the entire system, including equipment and all operating procedures, will comply with the requirements of WAC 173-180 *Facility Oil Handling Operations and Design Standards Rule.*

7.3 SUMMARY

The above discussions present a cursory review of the potential hazards associated with operating the FCS. The operation of the FCS has also been compared to near-by facilities and is summarized by Table 10. While the occupational and non-radiological hazards are no more severe than typical chemical plant operations, the added dimension of radioactive materials increases risks of exposure to both on and off-site individuals. For preliminary planning purposes, and until more rigorous analyses can be performed, the FCS will be conservatively assumed to be a Category 2, non-reactor nuclear facility. This preliminary designation is based on assuming all proposed fluid systems are filled to operating levels (approximately 7000 gallons) with the DST feed previously cited. Using these values and also assuming no concentration of feed in the evaporators or other decay isotopes, the total ^{137}Cs inventory is about 1.3E +04 curies. This value falls between ^{137}Cs inventories for a Category 2 facility (8.9E +04) and Category 3 facility (6.0E +01) as noted in DOE-STD-1027-92, Attachment 1.

SECTION 8.0

8.0 LIFE CYCLE COST ESTIMATE AND SCHEDULE

8.1 INTRODUCTION

This section presents the basis for the life cycle cost estimates for design, construction and operational cost estimates for a conceptual facility and support systems for the FCS – hereafter referred to as the Fractional Crystallization Facility or FCF. It describes the methodology, assumption and background used to develop the estimates. Details of the estimate are contained in Appendix G.

8.2 OVERALL APPROACH AND METHODOLOGY

The following sections demonstrate the methodology and basis for the life cycle cost estimate provided within this document. The technical basis for the estimated costs contained within are based upon the preliminary process description/flowsheets and preliminary hazard assessment. It does not reflect the impact of operational decisions, e.g. tank farm piping interfaces, additional tanks for storage, process analytical requirements, etc. that have been deferred until Phase III of the project. Previously obtained information from the DBVS and the WTP were incorporated where practical. The costs inserted were for similar or like equipment that could be used for the FCF. Estimated values for engineering effort and equipment costs are partially based upon Framatome-ANP's current experiences with the Hanford evaporator project that supports the Hanford Waste Treatment Plant as well as the Depleted Uranium Hexafluoride (DUF6) projects for the Department of Energy at both Paducah, Kentucky and Portsmouth, Ohio. Costs for DOE-ORP and the Tank Farm Operator (TFO) management/engineering costs have not been estimated or included. To develop the total life cycle cost of the facility, these costs should be included.

8.2.1 Estimate Scope

The FCF life cycle cost estimate was developed with the following Work Breakdown Structure (WBS) elements:

- Project Management
- Engineering
  - Title I (Preliminary / Conceptual Design)
  - Title II (Detailed Design; reviews at 30%, 60%, 90%, and final)
  - Title III (Design Support for Procurement and Fabrication and Construction / Installation)
- Operations (Two Years Trial / 17 Years Full Scale)
- Decommissioning

For this estimate, the overall assumed basis of the plant operation is twofold. The first phase is a demonstration period of two years which the plant would operate at a reduced capacity. The second phase would be to operate at full capacity for a 17 year period. Plant equipment would remain the same under both scenarios; utilizing variable speed drives on pumps and same sizing of pipelines would minimize any equipment change outs between the two operating scenarios. Therefore no capital improvement costs were included in this estimate for moving from the first scenario to the second.

8.2.2 Contingency

Contingencies for the portions of the life cycle cost estimate are shown on the summary page of Appendix G and in Table 12 below. Each segment of the life cycle WBS is represented with its separate contingency. In accordance with DOE 430.1-1, contingency is the amount budgeted to cover costs that may result from incomplete design, unforeseen and unpredictable conditions, or uncertainties. The amount of the contingency will depend on the status of design, procurement, and construction and the complexity and uncertainty of the component parts of the project. Contingency is not to be used to avoid making an accurate assessment of expected cost. For this life cycle cost estimate, with the unforeseen and uncertainties at this stage of the project (pre-planning), a conservative percentage of contingency allowed by the DOE 430.1-1 for each segment in Table 12 was used. Under DOE 430.1-1, during the Planning Stage, the Experimental/Special conditions allow for contingencies of up to and including 50%. Contingencies of less than 50% were used as shown below.

Table 12. Life Cycle Cost Estimate Contingencies (2 Sheets).

WBS Item	Percent Contingency
SUPPORT	
Project Management	10%
QA	5%
ES&H	5%
Information Management	5%
Regulatory and Licensing	10%
ENGINEERING	
Title I Design	20%
Title II Design	35%
Title III Design	10%

Table 12. Life Cycle Cost Estimate Contingencies (2 Sheets).

WBS Item	Percent Contingency
CONSTRUCTION	
Site Work	25%
Building	45%
Process Equipment	40%
Piping and Fittings	30%
Valves	25%
Instrumentation	45%
Off Gas System	30%
Steam Supply	30%
Process Water	30%
Chiller/Condenser System	30%
OPERATIONS (BASED ON 2/17 YEAR LIFE SPAN)	
Operations Labor	10%
Material	15%
Equipment	30%
DECOMMISSIONING	
Characterization	35%
Decommissioning Plan	10%
Field Operations	35%
Final Survey	35%
Final Report	10%

8.2.3 Escalation

The FCF life cycle cost estimate is based upon 2005 dollars. For simplification purposes, the estimate excludes escalations of future costs. In general, unless otherwise noted or described,

any obtained past costs used in this estimate were escalated at 3% per year to bring the costs to present 2005 dollars. Special escalation costs for materials, specifically stainless steel, were not included at this time. The Phased Costs for out years shall be based on the percentage increase or decrease in accordance with a mutually agreeable economic price adjustment index such as the Employment Cost Index for Wages and Salaries and the Engineering News Record (ENR) Construction Cost Index. Local costs for materials and deliveries were included when possible.

8.2.4 Estimate Assumptions

For the purposes of this Phase I estimate, the following assumptions were made:

- The site/facility will be a Category II facility with no Category I equipment required. A full Final Hazards Analysis (FHA) will need to be performed to verify requirements for the facility and equipment.
- Preliminary Documented Safety Analysis (PDSA) has not been performed and will likely impact this estimate.
- Chemical storage and secondary containments are assumed to meet local building code requirements only.
- A temporary (modular) control room for the two year trial period will be acceptable to the DOE.
- Costs of transferring permanent operational control to a permanent control room are not addressed.
- Tank wastes treated by the FCS are accepted by the facilities when they are completed and as described in the scoping documentation.
- Costs of transporting secondary wastes and treated product will be provided by others.
- Costing data assumes the facility location will be no more than 1 mile from existing roads and utilities.
- Engineering/operating labor rates are presented as average rates as of August, 2005 based upon average Framtome-ANP rates or 2004 HAMTC and other Hanford employees' rates. Actual construction labor costs will be governed by the Hanford Site Stabilization Agreement rates in effect at the time of construction.
- Adequate funding is available with no funding gaps throughout life cycle of the project.
- No employee relocation costs are included in the estimate.
- Minimal earth movement and site development is required.
- No extended storage of treated or to be treated material or product is required.

- Decommissioning costs assume only minimal contamination and equipment disposal costs.
- All contaminated material can be disposed of at the Hanford ERDF.
- Installation costs are based on a Hanford crew at 50% efficiency; lift equipment, storage, inspections, and final transport – all approximated by 10% or more of the value of the component.
- Piping installation costs equals material costs.
- BV Plant component costs are applicable as applied.
- Operations take place 24 hours a day 7 days a week.
- Disposal costs for materials during decommissioning do not vary above the amounts found on the estimate.
- The estimate assumes decommissioning surveys would be performed in accordance with specifically developed plans and procedures.

8.3 PROJECT MANAGEMENT COSTS

8.3.1 Project Management

Project management costs are built up using the basis that a project manager and supporting staff will be used from 2006 through 2010. This estimated time frame begins during the initial design phase Title I effort, and continues through startup operations of the FCF. This total effort includes the following level of effort labor:

- Project Manager
- Procurement Management
- Project Controls
- Scheduler
- Configuration Management

A project manager would serve as lead for the project as defined by DOE documentation. Depending upon the final schedule, building and engineering complexities, a deputy project manager may be required during the final design and construction phases of the project. Costs for a deputy project manager were included in this estimate.

A configuration manager would track and process all documents, drawings and calculations associated with the project. As with the project manager, depending upon the FHA, PDSA, final

design and construction complexities, a deputy configuration manager may be required. Costs for a deputy configuration manager were not included in this estimate.

8.3.2 *Construction Management*

Construction management provides necessary resources and direction to ensure that the FCF construction project meets its quality, cost and schedule objectives in a safe manner. Primary areas of responsibility include review of design drawings and specifications for constructability, developing construction contracts, establishing policies and procedures, obtaining necessary permits and licenses, managing contracts, evaluating proposal, procuring equipment and services, negotiating and awarding orders and providing change control.

Construction management costs are based upon level of staffing, construction shifts, applied labor rates and burdens, and construction schedule duration.

These costs are shown in the Title III section of the engineering costs, construction costs and in the project management sections.

8.3.3 Supporting Functions

Supporting functions such as Environmental, Safety and Health (ES&H), Information Management (IM) and Nuclear Safety/Environmental Permitting support are represented in this section. Initial efforts for the EH&S plan and licensing support are scaled back after the start of the demonstration portion of the project. Once the production phase begins, larger efforts for these support functions will be required to during the initial restart and testing of the FCF.

The total estimated cost for the Project management function is $7.66 million dollars and includes over $689,000 in contingency dollars.

8.4 ENGINEERING COSTS

This section describes the estimate for the design engineering effort required for FCF through the three Title phases.

8.4.1 Method of Estimate

The FCF life cycle cost estimate was developed based upon the preliminary process descriptions, conceptual equipment drawing, and the preliminary process flowsheet. From those descriptions and drawings, an assumed preconceptual facility size was created based on anticipated equipment sizes and the estimated supporting infrastructure needed for the facility to operate. A preliminary ALARA review (Appendix F) produced values of radiation doses during operations that were utilized in the conceptual facility layout (Figure 20). Title I, II, and III engineering estimates were built utilizing the estimated number of systems, the facility layout and the estimated number of design products. Past and current Framatome-ANP (FANP) projects and

experiences provided the guidance on the expected number of systems and drawings that could be required to complete a facility such as the FCF. Preliminary information for a System Design Description (SDD) or Documented Safety Analysis (DSA) would be needed to provide a more accurate estimate of the Title I, II and III engineering effort required. An SDD and DSA would also provide the impact to the engineering effort required for the procurement and construction support phases. Work hours for Title III effort were based upon a level of effort workforce appropriate for the size of the construction workforce. A level of effort workforce for engineering support in estimating the labor required for the life span of the facility is included in the Operations section of this document.

8.4.2 Title I Engineering

Title I Engineering begins with a preliminary design of the systems and facility. It includes a Preliminary Hazards Analysis (PHA) and developing an SDD that will assist in identifying component classifications and operating conditions. The effort also includes a PDSA. During Title I, systems will be described, component sizing will be denoted, general operating plans and methods are described. The buildings/facilities needs will be known. Supporting infrastructure and requirements are developed. Fire protection requirements are described.

Total effort is estimated at over 23,000 labor hours for development of the required information needed for Title II start.

8.4.3 Title II Engineering

Title II Support includes design for the facility and systems; establishing operational requirements; equipment documentation; system and component calculations; building and structural designs; fabrication and building specifications; thirty, sixty and ninety percent design reviews; Operational Readiness Review preparations; final design for the facility and systems; procurement specifications; testing procedures; start up procedures; and Operations and Maintenance manuals.

Total labor effort for Title II Engineering is over 63,000 hours.

8.4.4 Title III Engineering

Title III engineering support covers the level of effort required for the construction phase of the project. This effort includes problem/interference resolution, system acceptance reviews, ORR support; start up support; and systems turn over and check out. All documentation would be turned over and project closeout for engineering would occur during this phase.

Total labor effort for Title III Engineering is over 7,000 hours.

Total Engineering Costs are estimated to be $10.49 million dollars with an included contingency of over $2.3 million dollars.

8.5 CONSTRUCTION COSTS

8.5.1 Method of Estimate

Equipment costs were estimated using similar types of equipment found in the WTP, equipment used at the DBVS and actual quotes for components, material and labor. The costs for the evaporator or crystallization systems and similar controls were utilized in this estimate. The facility costs were estimated using *RSMEANS Building Construction Cost Data* (63rd Edition), and facility estimating tools for material and construction labor where applicable.

8.5.2 Construction Site Services

Construction site services costs include construction facility rental costs, costs for construction power and telephone services, costs for temporary roads and parking areas, and construction security costs. Allowances are included for survey crews and for maintenance of permanent equipment prior to turnover to operations.

8.5.3 Construction of Facilities

The estimated costs to construct facilities include all direct and indirect costs. Direct costs include all construction materials, labor, capital equipment and subcontracts. Indirect costs include all equipment rentals, tools, consumables, supervision, insurance, taxes, general and administrative expenses, and contractors overhead and profit.

8.5.4 Facility Description

The facility estimate was based upon a cast in place, reinforced concrete facility. To put an initial bound on the facility, the overall size was estimated to be approximately 7,700 square feet. For a preliminary general arrangement sketch of the facility refer to Figure 20. The crystallizers would be contained in silo like extensions that would rise approximately 15 feet above the roof line of the facility with the remaining roof line limited to 35 feet. A partial shield wall between the first stage process equipment and the second stage equipment will stop just below the ceiling to allow for crane passage. Another smaller partial shield wall will minimize direct "shine" on the equipment door. Other major components such as tanks, pump skids, centrifuges, etc. were arbitrarily located for accessibility. A 5-ton overhead crane and rail system for equipment movement was included in the estimate. A small lay-down area and equipment room is included in the estimate. Fencing surrounds the facility to prevent random access to limit personnel exposure to radiation. The temporary control room would be situated outside the main facility but within the fence line. Supporting equipment and systems such as the CO_2 and H_2O_2 (as a "place holder") storage tanks are outside of the main building.

No facility changes would be required to step up to full scale production from trial production. The equipment, pumps piping etc. would be sized to operate within both parameters. Variable

speed drive mechanisms would control pumps; instrumentation would be initially installed that would be able to read the full scale information as well as the trial production rates.

8.5.5 Component Fabrication

Component fabrication costs included in this estimate include all direct and indirect costs, overheads and profits; shipping insurances; shipping costs and permits, materials, testing and quality assurance costs.

Total facility and equipment costs, as currently scoped, are estimated to be $23.8 million dollars which includes over $6.3 million dollars in contingency dollars.

8.6 *OPERATION COSTS*

8.6.1 Method of Estimate

Operation costs include operations labor (level of effort), facility costs for utilities and upkeep, materials for crystallization processing, maintenance and replacement parts, and personal protection equipment.

Operating costs are stated in 2005 dollars not escalated for each year of operation.

Operational costs for the two-year trial cycle and the costs for full scale operations are assumed the same. Flow rate changes going to full scale operations require additional and/or revised operating procedures whose costs are included in the Title II and Title III engineering and in the operational sections of the estimate. Minimal changes in supporting system costs would be incurred as full scale operations. Due to the small incremental change, the costs for these supporting systems were included at full scale operations rates for the 19 year duration.

Material and equipment were estimated from the process throughputs in the process description. Items such as utilities, personal protective equipment, consumables, and anti-contamination clothing were based on a percentage of the total labor hours. The cost of the large quantity chemicals were based on prices received from vendors supplying other Richland, WA area facilities.

8.6.2 ALARA

A basic review of the anticipated cesium inventory (assumed to be contained only in the crystallizer for the preliminary shielding analysis) indicates high dose rates in the process areas during operations. To avoid excessive exposure, operations would cease for maintenance purposes and liquid systems would be drained and flushed. Minimal costs for this operational change are anticipated and are not included in this estimate.

Normal operational expenses for dosimetry and other radiological environment needs are included in the operations section of the estimate.

8.6.3 Operation Labor

To bound operating costs, the operations estimate was based on running the facility 24 hours a day, 7 days a week, for 19 years. This type operation will require four shifts of operating personnel plus day staff personnel to support them. Each shift is assumed to consist of three operators, one shift manager and one health physics technician. This is considered the minimum staffing for around the clock operation. All rates for personnel are averaged and were based on available data from the Hanford facilities during 2004. The multiplier of 1.65 includes a 1.03% increase that raises expected 2004 rates to 2005 dollars.

The day staff support personnel consists of three operators, one health physics technician and one manager. The dayshift personnel also provide vacation and holiday relief for the rotating shift personnel. The majority maintenance craft are assumed to be ready available labor from a central pool. Only a maintenance supervisor, planner and instrument tech are estimated as full time. Other support personnel for dayshift include ES&H, quality, engineering, procurement, and operational support, some of which are considered to only be needed part time.

Plant Engineering support consists of one mechanical engineer, one process engineer, one instrumentation/controls engineer and one engineering manager. The engineering support would be located in a facility outside of the fence.

8.6.4 Maintenance

Due to radiation exposure limitations, no maintenance would occur on the crystallizer system(s) while they are operating. All maintenance would be performed with the crystallizer system(s) drained of cesium laden liquid and flushed. The material would be pumped from one side of the facility to the other or would be transferred back to the storage tank from where it came until it can be received in the facility again. Costs for any transfer back to its original underground storage tank is not included in this estimate. Labor costs for transferring material from one side of the facility to the other are included in the operations sections of this estimate.

8.6.5 Process Materials

Carbon Dioxide and 50% Hydrogen Peroxide, as noted in Section 7.2.2, would be used during operations in amounts described in the system description. The estimated costs for these consumables were obtained through quotes as shown in Appendix G.

8.6.6 Replacement Equipment

It is assumed that during the total 19 year lifecycle of the facility, components will be replaced periodically. While major components such as the crystallizer and reboiler should be designed to last the life span of the facility; pumps valves and similar pieces of equipment will require replacement over the life span of the facility. These costs are included in the section of the estimate called Operations Summary found in Appendix G.

The total operating costs of $140.4 million dollars includes over $14.0 million dollars in contingency.

8.7 DECOMMISSIONING COSTS

Disposal costs may vary towards the end of life period for this facility due to availability, licensing issues etc. Costs for this estimate are generalized on this basis.

8.7.1 Criteria for Commissioning

Requirements for decommissioning are stated in DOE Order 430.1A, Life Cycle Asset Management (LCAM), which identifies the minimum requirements for disposition of an excess DOE facility. This Guide defines activities or actions that provide a sequenced risk reduction to the selected disposition path. It is part of the DOE Directives System, and is consistent with the principles and core functions of P 450.4, Safety Management System.

Other documents consulted to support the planning and conduct of transition and disposition activities include:

- DOE-STD-1120-98, Integration Of Environment, Safety And Health Into Facility Disposition Activities, and the Good Practice Guides associated with LCAM.
- DOE G 430.1-4, Decommissioning Implementation Guide
- DOE G 430.1-2, Implementation Guide For Surveillance And Maintenance During Facility Transition And Disposition;
- DOE G 430.1-3, Deactivation Implementation Guide;
- DOE G 430.1-5, Transition Implementation Guide.

The Decommissioning Implementation Guide, *Decommissioning Handbook* (Draft -DOE/EM-0383, January 1999), and *Decommissioning Preferred Alternatives Matrix* (June 30, 1997) replace the previously issued *Decommissioning Resource Manual* (DOE/EM-0246, August 1995) and *Decommissioning Handbook* (DOE/EM-EM-0142P, March 1994).

The present DOE G 430.1-4, Decommissioning Implementation Guide differs from the *Decommissioning Resource Manual* (DOE/EM-0246, August 1995), which included a variety of information of interest or potential use to decommissioning project managers and staff. Material from the Resource Manual that directly relates to implementation of these policies and directives has been incorporated in this Guide. Material from the Resource Manual and former Handbook that does not directly relate to acceptable methods for meeting program requirements is being compiled in the present *Decommissioning Handbook* as an information resource for decommissioning project personnel. Material from the former Handbook dealing with decommissioning technologies has been incorporated into the *Decommissioning Preferred Alternatives Matrix*.

8.7.2 Method of Estimate

The estimated cost to decommission the FCF is $4.595 million dollars which includes over $1.1 million in contingency dollars. This section of the cost estimate report provides an overview of the considerations and factors that influenced the decommissioning cost estimate. Table 13 provides a summary of the costs associated with each area of the facility. These estimates are based upon past Framatome-ANP experiences and actual costs where available.

Table 13. Decommissioning Cost Summary - FCF.

Decommissioning Task	Man-hours	Labor Cost	Living & Travel Cost	Equipment, Contracts & Supplies	Radwaste Packaging & Shipping	Total Cost
Characterization	1,144	$93,550	$19,609	$28,902	$0	$142,061
Decommissioning Plan	626	$68,592	$0	$0	$0	$68,592
Field Operations	20,773	$1,647,623	$575,114	$746,740	$64,004	$3,033,481
Final Survey	928	$76,072	$21,035	$19,609	$0	$116,716
Final Report-Closeout	693	$50,353	$17,576	$0	$0	$67,929
Totals	24,164	$1,936,190	$633,333	$795,251	$64,004	$3,428,778

8.7.3 Cost Modifying Factors

There are modifying factors that significantly affect the overall cost for remediation. One of these factors is an adjustment for productivity related to personnel protection requirements and working environment. The degree of protection required depends upon the extent of contamination and specific activities to be performed in a given area. As the level of personnel protection increases, so does the impact on individual productivity and task duration. Adjustments were made to account for the implementation of personnel protective measures where applicable. This estimate used the standardized levels of personnel protection described in Table 14.

8.7.4 Radioactive Waste Volume Estimate

The volume of radioactive waste requiring treatment and disposal can be a very significant modifying factor due to the high cost for radwaste disposal. For the FCF decommissioning, the cost for radioactive waste processing, shipping, and disposal is anticipated to be about 40% of the total decommissioning cost. This is a normal fraction for radioactive facilities. Radioactive waste volume estimates are discussed in the following section. Table 15 provides a volume summary for each area of the FCF.

Table 14. Personnel Protective Equipment Protection Summary.

Level	Description
Level A:	The highest available level of respiratory, skin, and eye protection
Level B:	The highest level of respiratory protection, but less skin protection than Level A. Level B is the minimum level recommended for initial site entries, or for other entry conditions dealing with unknown
Level C:	The same level of skin protection as Level B, but a lower level of respiratory protection.
Level D Modified:	Skin protection similar to or the same as Level C, without respiratory protection.
Level D:	Standard work uniform suitable for construction work: no respiratory protection and minimal skin protection.

Table 15. FCF Unprocessed Radioactive Waste Summary.

Area Description	Total Disposal Volume (ft^3)
DFCS Utility Equipment	149
DFCS Process Equipment	3,347
Process Equipment Building	1,159
Utility Equipment Building	59
TOTALS	4,714

8.7.5 Radioactive Waste Volume Reduction Costs

The volume reduction processes analyzed for use are summarized in Table 16. For each volume reduction method, this table shows application information, transportation container type, and the total process cost per unit weight. These unit factors are applied to specific items of equipment requiring disposal to determine the most cost-effective process. The radioactive waste generated at this facility will include contaminated hardware, contaminated concrete, HEPA ventilation systems, fume hoods, steel, etc., and secondary waste generated during the decontamination work such as protective clothing and materials used during manual decontamination work.

Table 16. *Volume Reduction Methodology Costs.*

VR Methodology	Applicability	Transport Container Type	Total VR Cost ($/lb)
Super Compaction	Dry Active Waste 20 lb/ft	B-25	$5.59
Incidental Lead Decontamination	Bricks and Sheet	Custom Box	$7.25
Survey and Release Low Density Drums	Low Density Waste	55 Gal Drum	$1.45
Survey and Release Medium Density Boxes	Waste At Greater Than 207<60 lb/ft^3	B-25 Box	$0.66
Survey and Release High Density Boxes	Waste At Greater Than 60 lbs/ft	B-25 Boxes	$0.52

8.7.6 Final Surveys

Final survey costs are estimated based on the facility radiation survey information presented in U.S. Nuclear Regulatory Commission Regulating Guides NUREG-1757, MNSS Decommissioning Standard Review Plan. The number of sample points for the various areas being surveyed and the type of survey being performed were determined. The time to perform each of these surveys is estimated, and the product of these two items is the labor time to perform the surveys. Equipment and material cost to perform the surveys is added along with staff support costs to determine a total cost. The survey requirements are based on NUREG-1575, Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM) Ref. 6-10). A spreadsheet was developed which incorporates facility dimensions, labor rates and support cost ratios to estimate the final survey cost. The facility survey labor estimate is summarized in Appendix F as well as the open land and miscellaneous area survey labor estimate.

Decommissioning of the FCF requires that residual radioactive materials be removed from the site to allow removal of the decommissioned facilities. For the purposes of this cost estimate, the end of the decommissioning project occurs when the FCF has been remediated to release limits; the Final Status Survey has been performed, documented and submitted to the DOE.

8.7.7 Remediation Summary

While remediation will be required for the FCF, it is not anticipated that remediation in outdoor areas will be required. Table 17 is a brief summary of the anticipated remediation activities, with applicable assumptions and bases.

Table 17. FCF Planned Remediation Activities.

Building or Area	Remediation Activities
General Area	Perform a general facility cleanup to remove all incidental equipment and materials; both radioactive and non-radioactive.
FCF Process Equipment	Empty water from tanks. Remove tanks and vessels internals. Cut out contaminated concrete from surrounding process tank and disposal as radioactive waste.
FCF Utility Equipment	Remove contaminated FCF Utility Equipment. Cut out contaminated concrete surrounding FCF Utility Equipment.
Process Equipment Building	Remove contaminated portions of HEPA and HVAC systems. Remove demineralizer system and heat exchanger. Remove contaminated portions of systems and fume hoods.
Utility Equipment Building	Perform a general area cleanup and remove all contaminated equipment and materials.
Office Areas	Perform a general area cleanup and remove all contaminated equipment and materials.

8.7.8 Final Facility Status Surveys

The final status survey will be conducted in accordance with a plan and implementing procedures derived from regulatory guidance, specifically NUREG-1575 "Multi-Agency Radiation Survey and Site Investigation Manual" (MARSSIM) and DOE Order 5400.5. The approach to data collection will place the greatest survey efforts on areas that have, or had, the highest potential for residual radioactivity and demonstrates that all radiological parameters do not exceed the established release criteria

8.7.9 Final Decommissioning Costs

Estimated final decommissioning costs are shown in Table 18.

Table 18. Estimated Final Decommissioning Costs.

WBS	Decommissioning Task	Man-Hours	Labor Cost	Living & Travel Cost	Equipment, Contracts & Supplies	Radwaste Packaging & Shipping	Total Cost
3.01.01	Characterization Decommissioning	1144	$93,549	$19,609	$28,902	$--	$142,060
3.01.02	Plan	630	$69,237	$--	$--	$--	$69,237
3.01.03	Field Operations	20773	$1,647,623	$575,114	$746,740	$64,004	$3,033,481
3.01.04	Final Survey Final Report	928	$76,072	$19,609	$21,035	$--	$116,716
3.01.05	Closeout	460	$50,353	$--	$17,576	$--	$67,929
Totals		23934	$1,936,834	$614,331	$814,254	$64,004	$3,429,422

The total decommissioning costs of $4.5 million dollars includes over $1.1 million dollars in contingency.

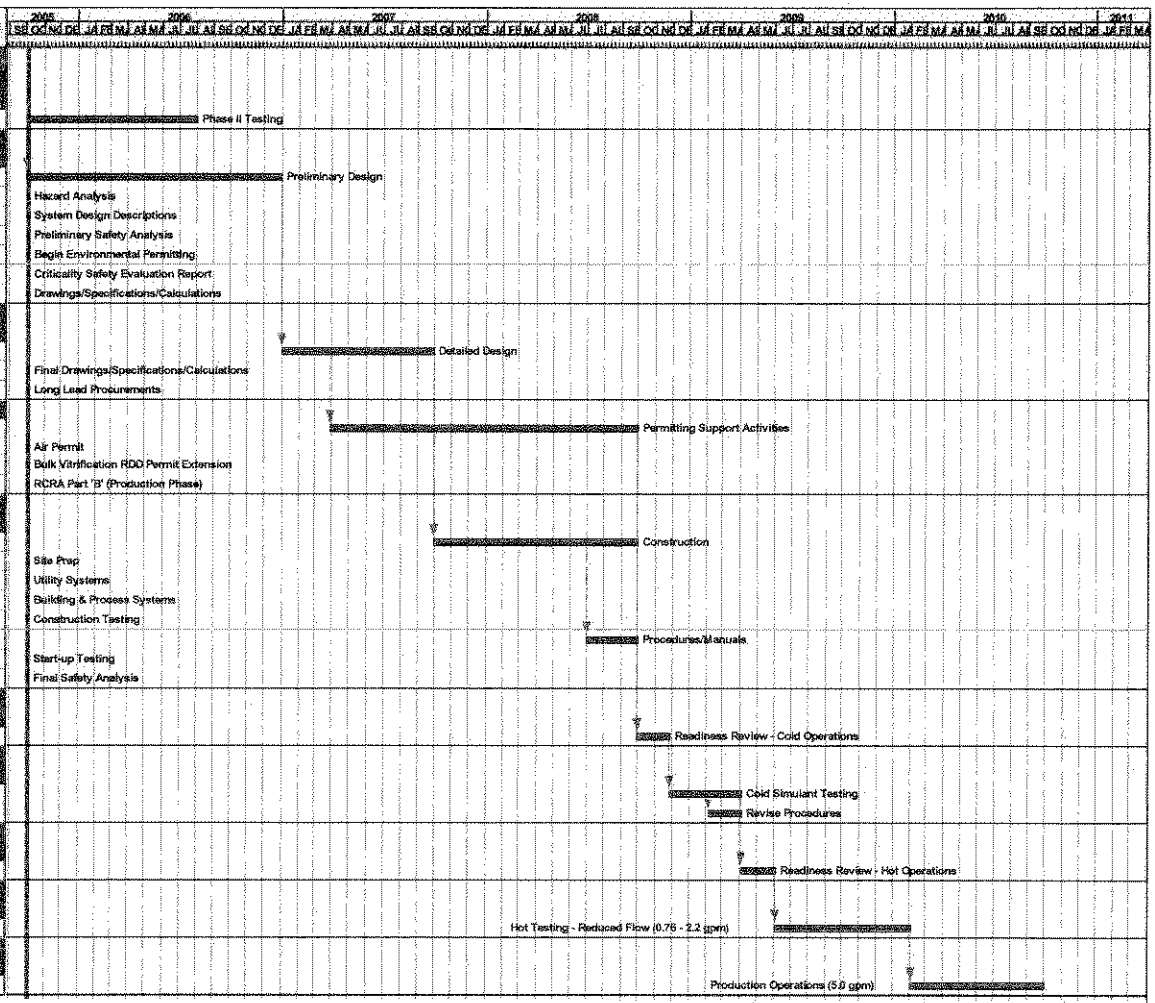
8.8 PROPOSED PROJECT SCHEDULE

To keep the escalation basis as noted previously and without a defined start date for Phase III (beginning with preliminary design), the project estimate and schedule were developed with project design activities being initiated in FY 2006 (October, 2005). This start date is in parallel with Phase II testing of actual tank waste which should be complete by about June or July, 2006. Once the starting time for Phase III is established, all of the design (and subsequent activities) can be adjusted accordingly. Information gained from testing the actual tank waste and future site/project planning will be factored into a revised schedule contained within the Phase II Process Plan update.

A basic assumption for this deployment path is that the equipment and controls selected for a single facility will be able to accommodate the wide ranging flow rates (0.76 gpm through 5.0 gpm) required for BV demonstration and production scale facilities. No costs have been estimated for changeout/modification of equipment as a result of pilot plant operations. Fractional crystallization demonstration scale operations will be performed on simulant, then actual tank waste, for two years to establish operating parameters for the remaining 17 years of facility production use. The schedule terminates at the point the fractional crystallization system begins production scale operation. Activities for decontamination and decommissioning are not shown.

8.9 SCHEDULE

Activity ID	Activity Description	Orig Dur	Early Start
Fractional Crystallization			
Phase II Testing			
1000	Phase II Testing	20	03OCT05
Preliminary Design			
3000	Preliminary Design	31	03OCT05
3100	Hazard Analysis	1	03OCT05
3200	System Design Descriptions	1	03OCT05
3300	Preliminary Safety Analysis	1	03OCT05
3400	Begin Environmental Permitting	1	03OCT05
3500	Criticality Safety Evaluation Report	1	03OCT05
3600	Drawings/Specifications/Calculations	1	03OCT05
Detailed Design			
5000	Detailed Design	19	02JAN07
5200	Final Drawings/Specifications/Calculations	1	03OCT05
5300	Long Lead Procurements	1	03OCT05
5100	Permitting Support Activities	38	28MAR07
5110	Air Permit	1	03OCT05
5120	Bulk Vitrification RDD Permit Extension	1	03OCT05
5130	RCRA Part 'B' (Production Phase)	1	03OCT05
Construction			
7000	Construction	25	01OCT07
7100	Site Prep	1	03OCT05
7200	Utility Systems	1	03OCT05
7300	Building & Process Systems	1	03OCT05
7400	Construction Testing	1	03OCT05
7500	Procedures/Manuals	6	02JUL08
7600	Start-up Testing	1	03OCT05
7700	Final Safety Analysis	1	03OCT05
Readiness Review - Cold Operations			
9000	Readiness Review - Cold Operations	4	01OCT08
Cold Simulant Testing			
10000	Cold Simulant Testing	8	28NOV08
10100	Revise Procedures	4	05FEB09
Readiness Review - Hot Operations			
11000	Readiness Review - Hot Operations	4	03APR09
Hot Testing - Reduced Flow (0.76 - 2.2 gpm)			
13000	Hot Testing - Reduced Flow (0.76 - 2.2 gpm)	16	04JUN09
Production Operations (5.0 gpm)			
15000	Production Operations (5.0 gpm)	16	03FEB10



Start Date	03OCT05
Finish Date	29SEP10
Data Date	03OCT05
Run Date	31AUG05 14:55

Early Bar
Progress Bar
Critical Activity

MLW1 Sheet 1 of 1

Fractional Crystallization of Hanford Tank Waste

"DRAFT"

Date	Revision	Checked	Approved

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SECTION 9.0

9.0 REFERENCES

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Appendix A

APPENDIX A

SST EARLY FEED FLOWSHEET IN SI UNITS

SST Early Feed Flowsheet in SI Units (Sheet 1 of 9)

SST EARLY FEED

MASS BALANCE	BASIS = 1,000 gm FEED									
STREAM			SST FEED		CO2	RECYCLE		STEAM1	SLURRY	
PHASE			Aqueous	Solid	Vapor	Aqueous	Solid	Vapor	Aqueous	Solid
TEMPERATURE, C			25.00	25.00	25.00	40.54	40.54	40.00	40.00	40.00
PRESSURE, atm			1.00	1.00	1.00	1.00	1.00	0.03	0.03	0.03
pH			15.30	-	-	15.35	-	-	15.73	-
		MW								
COMPONENT	FORMULA	gm/gmol	gm	gm	gm	gm	gm	gm	gm	gm
Water	H2O	18.02	529.94	-	-	398.71	-	674.61	236.70	-
Carbon Dioxide	CO2	44.01	0.00	-	33.88	0.00	-	0.00	0.00	-
Aluminum Hydroxide	Al(OH)3	78.00	32.03	-	-	194.70	-	-	226.73	-
Potassium Hydroxide	KOH	56.11	1.37	-	-	8.32	-	-	9.69	-
Sodium Hydroxide	NaOH	40.00	70.35	-	-	103.95	-	-	112.60	-
Sodium Nitrite	NaNO2	69.00	41.61	-	-	226.21	-	-	147.23	120.63
Sodium Nitrate	NaNO3	84.99	234.31	9.88	-	243.84	-	-	148.64	339.47
Sodium Carbonate	Na2CO3	105.99	38.96	-	-	22.12	-	-	13.26	-
Sodium Sulfate	Na2SO4	142.04	14.66	-	-	6.43	-	-	2.92	-
Sodium Chloride	NaCl	58.44	3.56	-	-	21.63	-	-	25.19	-
Sodium Fluoride	NaF	41.99	0.40	-	-	1.02	-	-	0.98	-
Sodium Orthophosphate	Na3PO4	163.94	4.93	-	-	29.95	-	-	34.88	-
Sodium Bicarbonate	NaHCO3	84.01	0.00	-	-	0.00	-	-	0.00	-
Sodium Chromate	Na2CrO4	161.97	9.58	-	-	65.44	-	-	51.79	-
Sodium Chromate Tetrahydrate	Na2CrO4.4H2O	234.03	-	-	-	-	2.53	-	-	36.03
Sodium Carbonate Monohydrate	Na2CO3.1H2O	124.00	-	7.34	-	-	-	-	-	151.49
Trisodium Fluoride Sulfate	Na3FSO4	184.03	-	-	-	-	0.21	-	-	2.13
Burkeite	Na6(SO4)2CO3	390.08	-	-	-	-	-	-	-	22.91
Sodium Oxalate	Na2C2O4	134.00	0.00	1.09	-	0.00	0.00	-	0.00	1.10
Cesium Hydroxide	CsOH	149.91	1.984E-03	-	-	1.206E-02	-	-	1.404E-02	-
Total, gm			981.69	18.31	33.88	1,322.36	2.73	674.61	1,010.63	673.75
Volume, L			0.69	0.01	0.11	0.74	0.00	0.00	0.52	0.28
Enthalpy, cal			-2.860E+06	-3.581E+04	-7.242E+04	-3.478E+06	-7.007E+03	-2.160E+06	-2.762E+06	-1.164E+06
Density, g/L			1,421.83	2,258.96	1.81	1,776.24	35,715.00	0.02	1,931.48	2,376.47
Cs Activity*, Ci/L			0.11	-	-	0.62	-	-	1.03	-
Cs Activity*, Ci/5M Na			0.06	-	-	0.21	-	-	0.31	-

*Assumes 50% is Cs-137

SST Early Feed Flowsheet in SI Units (Sheet 2 of 9)

SST EARLY FEED

MASS BALANCE	BASIS = 1,000 gm FEED								
STREAM			OVERFLOW		UNDERFLOW	LIQUOR	DELIQUORED		WASH1
PHASE			Aqueous	Aqueous	Solid	Aqueous	Aqueous	Solid	Aqueous
TEMPERATURE, C			40.00	40.00	40.00	40.00	40.00	40.00	40.00
PRESSURE, atm			1.00	1.00	1.00	1.00	1.00	1.00	1.00
pH			15.73	15.73	-	15.73	15.73	-	13.93
		MW							
COMPONENT	FORMULA	gm/gmol	gm	gm	gm	gm	gm	gm	gm
Water	H2O	18.02	78.92	157.78	-	140.25	17.53	-	67.37
Carbon Dioxide	CO2	44.01	0.00	0.00	-	0.00	0.00	-	-
Aluminum Hydroxide	Al(OH)3	78.00	75.59	151.14	-	134.34	16.79	-	-
Potassium Hydroxide	KOH	56.11	3.23	6.46	-	5.74	0.72	-	-
Sodium Hydroxide	NaOH	40.00	37.54	75.06	-	66.72	8.34	-	7.49
Sodium Nitrite	NaNO2	69.00	49.09	98.14	120.63	87.24	10.90	120.63	-
Sodium Nitrate	NaNO3	84.99	49.56	99.09	339.45	88.08	11.01	339.45	-
Sodium Carbonate	Na2CO3	105.99	4.43	8.85	-	7.87	0.98	-	-
Sodium Sulfate	Na2SO4	142.04	0.98	1.95	-	1.73	0.22	-	-
Sodium Chloride	NaCl	58.44	8.40	16.79	-	14.93	1.87	-	-
Sodium Fluoride	NaF	41.99	0.33	0.65	-	0.58	0.07	-	-
Sodium Orthophosphate	Na3PO4	163.94	11.63	23.25	-	20.67	2.58	-	-
Sodium Bicarbonate	NaHCO3	84.01	0.00	0.00	-	0.00	0.00	-	-
Sodium Chromate	Na2CrO4	161.97	17.27	34.53	-	30.69	3.84	-	-
Sodium Chromate Tetrahydrate	Na2CrO4.4H2O	234.03	-	-	36.03	-	-	36.03	-
Sodium Carbonate Monohydrate	Na2CO3.1H2O	124.00	-	-	151.47	-	-	151.47	-
Trisodium Fluoride Sulfate	Na3FSO4	184.03	-	-	2.14	-	-	2.14	-
Burkeite	Na6(SO4)2CO3	390.08	-	-	22.90	-	-	22.90	-
Sodium Oxalate	Na2C2O4	134.00	0.00	0.00	1.10	0.00	0.00	1.10	-
Cesium Hydroxide	CsOH	149.91	0.00	9.361E-03	-	8.321E-03	1.040E-03	-	-
Total, gm			336.97	673.70	673.71	598.85	74.86	673.71	74.86
Volume, L			0.17	0.35	0.28	0.31	0.04	0.28	0.07
Enthalpy, cal			-9.209E+05	-1.841E+06	-1.164E+06	-1.637E+06	-2.046E+05	-1.164E+06	-2.756E+05
Density, g/L			1,933.98	1,933.98	2,376.45	1,933.98	1,933.98	2,376.45	1,103.18
Cs Activity*, Ci/L			1.03	1.03	-	1.03	1.03	-	-
Cs Activity*, Ci/5M Na			0.31	0.31	-	0.31	0.31	-	-

*Assumes 50% is Cs-137

SST Early Feed Flowsheet in SI Units (Sheet 3 of 9)

SST EARLY FEED

MASS BALANCE	BASIS = 1,000 gm FEED								
STREAM			SPENT WASH1	WASHED1		WASH2	SPENT WASH2	WASHED2	
PHASE			Aqueous	Aqueous	Solid	Aqueous	Aqueous	Aqueous	Solid
TEMPERATURE, C			40.00	40.00	40.00	40.00	40.00	40.00	40.00
PRESSURE, atm			1.00	1.00	1.00	1.00	1.00	1.00	1.00
pH			15.37	15.37	-	6.77	14.38	14.38	-
		MW							
COMPONENT	FORMULA	gm/gmol	gm	gm	gm	gm	gm	gm	gm
Water	H2O	18.02	61.64	25.77	-	132.90	151.58	17.43	-
Carbon Dioxide	CO2	44.01	0.00	0.00	-	-	0.00	0.00	-
Aluminum Hydroxide	Al(OH)3	78.00	11.84	4.95	-	-	4.44	0.51	-
Potassium Hydroxide	KOH	56.11	0.51	0.21	-	-	0.19	0.02	-
Sodium Hydroxide	NaOH	40.00	11.16	4.67	-	-	4.18	0.48	-
Sodium Nitrite	NaNO2	69.00	27.83	11.64	92.06	-	82.52	9.49	11.68
Sodium Nitrate	NaNO3	84.99	33.03	13.81	303.61	-	93.83	10.79	212.80
Sodium Carbonate	Na2CO3	105.99	2.57	1.07	-	-	9.11	1.05	-
Sodium Sulfate	Na2SO4	142.04	1.04	0.44	-	-	3.25	0.37	-
Sodium Chloride	NaCl	58.44	1.32	0.55	-	-	0.49	0.06	-
Sodium Fluoride	NaF	41.99	0.08	0.03	-	-	0.22	0.02	-
Sodium Orthophosphate	Na3PO4	163.94	1.82	0.76	-	-	0.68	0.08	-
Sodium Bicarbonate	NaHCO3	84.01	0.00	0.00	-	-	0.00	0.00	-
Sodium Chromate	Na2CrO4	161.97	6.08	2.54	-	-	20.35	2.34	-
Sodium Chromate Tetrahydrate	Na2CrO4.4H2O	234.03	-	-	29.11	-	-	-	-
Sodium Carbonate Monohydrate	Na2CO3.1H2O	124.00	-	-	148.84	-	-	-	139.30
Trisodium Fluoride Sulfate	Na3FSO4	184.03	-	-	1.94	-	-	-	1.04
Burkeite	Na6(SO4)2CO3	390.08	-	-	21.38	-	-	-	17.96
Sodium Oxalate	Na2C2O4	134.00	0.00	0.00	1.10	-	0.00	0.00	1.09
Cesium Hydroxide	CsOH	149.91	7.335E-04	3.067E-04	-	-	2.750E-04	3.163E-05	-
Total, gm			158.93	66.45	598.04	132.90	370.85	42.65	383.88
Volume, L			0.10	0.04	0.25	0.13	0.24	0.03	0.17
Enthalpy, cal			-4.151E+05	-1.736E+05	-1.053E+06	-5.020E+05	-8.963E+05	-1.031E+05	-7.251E+05
Density, g/L			1,623.86	1,623.86	2,367.47	992.22	1,570.23	1,570.23	2,266.10
Cs Activity*, Ci/L			0.29	0.29	-	-	0.04	0.04	-
Cs Activity*, Ci/5M Na			0.11	0.11	-	-	0.02	0.02	-

*Assumes 50% is Cs-137

SST Early Feed Flowsheet in SI Units (Sheet 4 of 9)

SST EARLY FEED

MASS BALANCE	BASIS = 1,000 gm FEED									
STREAM			O/F RECYCLE	PURGE	RECYC LIQ	DIL_H2O	5M_PROD		BYPASS	
PHASE			Aqueous	Aqueous	Aqueous	Aqueous	Aqueous	Solid	Aqueous	Solid
TEMPERATURE, C			40.00	40.00	40.00	40.00	38.88	38.88	25.00	25.00
PRESSURE, atm			1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
pH			15.73	15.73	15.73	6.77	11.95	-	15.30	-
		MW								
COMPONENT	FORMULA	gm/gmol	gm	gm	gm	gm	gm	gm	gm	gm
Water	H2O	18.02	78.92	32.91	107.35	942.29	979.87	-	4.78	-
Carbon Dioxide	CO2	44.01	0.00	0.00	0.00	-	0.00	-	0.00	-
Aluminum Hydroxide	Al(OH)3	78.00	75.59	31.52	102.82	-	0.30	0.21	0.29	-
Potassium Hydroxide	KOH	56.11	3.23	1.35	4.39	-	0.02	-	0.01	-
Sodium Hydroxide	NaOH	40.00	37.54	15.65	51.07	-	0.70	-	0.63	-
Sodium Nitrite	NaNO2	69.00	49.09	20.47	66.77	-	21.18	-	0.38	-
Sodium Nitrate	NaNO3	84.99	49.56	20.67	67.42	-	223.59	-	2.11	0.09
Sodium Carbonate	Na2CO3	105.99	4.43	1.85	6.02	-	124.41	-	0.35	-
Sodium Sulfate	Na2SO4	142.04	0.98	0.41	1.33	-	14.26	-	0.13	-
Sodium Chloride	NaCl	58.44	8.40	3.50	11.42	-	0.06	-	0.03	-
Sodium Fluoride	NaF	41.99	0.33	0.14	0.44	-	0.26	-	0.00	-
Sodium Orthophosphate	Na3PO4	163.94	11.63	4.85	15.82	-	0.08	-	0.04	-
Sodium Bicarbonate	NaHCO3	84.01	0.00	0.00	0.00	-	0.46	-	0.00	-
Sodium Chromate	Na2CrO4	161.97	17.27	7.20	23.49	-	2.34	-	0.09	-
Sodium Chromate Tetrahydrate	Na2CrO4.4H2O	234.03	-	-	-	-	-	-	-	-
Sodium Carbonate Monohydrate	Na2CO3.1H2O	124.00	-	-	-	-	-	-	-	0.07
Trisodium Fluoride Sulfate	Na3FSO4	184.03	-	-	-	-	-	-	-	-
Burkeite	Na6(SO4)2CO3	390.08	-	-	-	-	-	-	-	-
Sodium Oxalate	Na2C2O4	134.00	0.00	0.00	0.00	-	0.30	0.80	0.00	0.01
Cesium Hydroxide	CsOH	149.91	4.682E-03	1.952E-03	6.369E-03	-	3.163E-05	-	1.788E-05	-
Total, gm			336.97	140.50	458.35	942.29	1,367.82	1.01	8.85	0.16
Volume, L			0.17	0.07	0.24	0.95	1.11	0.00	0.01	0.00
Enthalpy, cal			-9.209E+05	-3.840E+05	-1.253E+06	-3.559E+06	-4.385E+06	-2.715E+03	-2.578E+04	-3.227E+02
Density, g/L			1,933.98	1,933.98	1,933.98	992.22	1,232.08	2,360.26	1,421.83	2,258.96
Cs Activity*, Ci/L			1.03	1.03	1.03	-	0.00	-	0.11	-
Cs Activity*, Ci/5M Na			0.31	0.31	0.31	-	0.00	-	0.06	-

*Assumes 50% is Cs-137

SST Early Feed Flowsheet in SI Units (Sheet 5 of 9)

SST EARLY FEED

MASS BALANCE	BASIS = 1,000 gm FEED			
STREAM			MIXED PURGE	
PHASE			Aqueous	Solid
TEMPERATURE, C			40.00	40.00
PRESSURE, atm			1.00	1.00
pH			15.82	-
		MW		
COMPONENT	FORMULA	gm/gmol	gm	gm
Water	H2O	18.02	37.67	-
Carbon Dioxide	CO2	44.01	0.00	-
Aluminum Hydroxide	Al(OH)3	78.00	31.81	-
Potassium Hydroxide	KOH	56.11	1.36	-
Sodium Hydroxide	NaOH	40.00	16.29	-
Sodium Nitrite	NaNO2	69.00	20.84	-
Sodium Nitrate	NaNO3	84.99	22.87	-
Sodium Carbonate	Na2CO3	105.99	2.11	-
Sodium Sulfate	Na2SO4	142.04	0.51	-
Sodium Chloride	NaCl	58.44	3.53	-
Sodium Fluoride	NaF	41.99	0.13	-
Sodium Orthophosphate	Na3PO4	163.94	4.89	-
Sodium Bicarbonate	NaHCO3	84.01	0.00	-
Sodium Chromate	Na2CrO4	161.97	7.29	-
Sodium Chromate Tetrahydrate	Na2CrO4.4H2O	234.03	-	-
Sodium Carbonate Monohydrate	Na2CO3.1H2O	124.00	-	0.16
Trisodium Fluoride Sulfate	Na3FSO4	184.03	-	0.03
Burkeite	Na6(SO4)2CO3	390.08	-	0.01
Sodium Oxalate	Na2C2O4	134.00	0.00	0.01
Cesium Hydroxide	CsOH	149.91	1.970E-03	-
Total, gm			149.31	0.21
Volume, L			0.08	0.00
Enthalpy, cal			-4.094E+05	-5.562E+02
Density, g/L			1,891.51	2,320.35
Cs Activity*, Ci/L			0.96	-
Cs Activity*, Ci/5M Na			0.30	-

*Assumes 50% is Cs-137

SST Early Feed Flowsheet (Sheet 6 of 9)

SST EARLY FEED

MOLE BALANCE	BASIS = 1,000 gm FEED										
STREAM			SST FEED		CO2	RECYCLE		STEAM1	SLURRY		OVERFLOW
PHASE			Aqueous	Solid	Vapor	Aqueous	Solid	Vapor	Aqueous	Solid	Aqueous
TEMPERATURE, C			25.00	25.00	25.00	40.54	40.54	40.00	40.00	40.00	40.00
PRESSURE, atm			1.00	1.00	1.00	1.00	1.00	0.03	0.03	0.03	1.00
pH			15.30	-	-	15.35	-	-	15.73	-	15.73
		MW									
COMPONENT	FORMULA	gm/gmol	gmole	gmole	gmole	gmole	gmole	gmole	gmole	gmole	gmole
Water	H2O	18.02	29.42	-	-	22.13	-	37.45	13.14	-	4.38
Carbon Dioxide	CO2	44.01	0.00	-	0.77	0.00	-	0.00	0.00	-	0.00
Aluminum Hydroxide	Al(OH)3	78.00	0.41	-	-	2.50	-	-	2.91	-	0.97
Potassium Hydroxide	KOH	56.11	0.02	-	-	0.15	-	-	0.17	-	0.06
Sodium Hydroxide	NaOH	40.00	1.76	-	-	2.60	-	-	2.82	-	0.94
Sodium Nitrite	NaNO2	69.00	0.60	-	-	3.28	-	-	2.13	1.75	0.71
Sodium Nitrate	NaNO3	84.99	2.76	0.12	-	2.87	-	-	1.75	3.99	0.58
Sodium Carbonate	Na2CO3	105.99	0.37	-	-	0.21	-	-	0.13	-	0.04
Sodium Sulfate	Na2SO4	142.04	0.10	-	-	0.05	-	-	0.02	-	0.01
Sodium Chloride	NaCl	58.44	0.06	-	-	0.37	-	-	0.43	-	0.14
Sodium Fluoride	NaF	41.99	0.01	-	-	0.02	-	-	0.02	-	0.01
Sodium Orthophosphate	Na3PO4	163.94	0.03	-	-	0.18	-	-	0.21	-	0.07
Sodium Bicarbonate	NaHCO3	84.01	0.00	-	-	0.00	-	-	0.00	-	0.00
Sodium Chromate	Na2CrO4	161.97	0.06	-	-	0.40	-	-	0.32	-	0.11
Sodium Chromate Tetrahydrate	Na2CrO4.4H2O	234.03	-	-	-	-	0.01	-	-	0.15	-
Sodium Carbonate Monohydrate	Na2CO3.1H2O	124.00	-	0.06	-	-	-	-	-	1.22	-
Trisodium Fluoride Sulfate	Na3FSO4	184.03	-	-	-	-	0.00	-	-	0.01	-
Burkeite	Na6(SO4)2CO3	390.08	-	-	-	-	-	-	-	0.06	-
Sodium Oxalate	Na2C2O4	134.00	0.00	0.01	-	0.00	0.00	-	0.00	0.01	0.00
Cesium Hydroxide	CsOH	149.91	1.323E-05	-	-	8.044E-05	-	-	9.368E-05	-	3.123E-05
Total, gm mole			35.60	0.18	0.77	34.76	0.01	37.45	24.05	7.20	8.02
Total, gm			981.69	18.31	33.88	1,322.36	2.73	674.61	1,010.62	673.75	336.97
Volume, L			0.69	0.01	0.11	0.74	0.00	0.00	0.52	0.28	0.17
Enthalpy, cal			-2.860E+06	-3.581E+04	-7.242E+04	-3.478E+06	-7.007E+03	-2.160E+06	-2.762E+06	-1.164E+06	-9.209E+05
Density, g/L			1,421.83	2,258.96	1.81	1,776.24	35,715.00	0.02	1,931.48	2,376.47	1,933.98
Cs Activity*, Ci/L			0.11	-	-	0.62	-	-	1.03	-	1.03
Cs Activity*, Ci/5M Na			0.06	-	-	0.21	-	-	0.31	-	0.31

*Assumes 50% is Cs-137

SST Early Feed Flowsheet in SI Units (Sheet 7 of 9)

SST EARLY FEED

MOLE BALANCE	BASIS = 1,000 gm FEED								
STREAM			UNDERFLOW		LIQUOR	DELIQUORED		WASH1	SPENT WASH1
PHASE			Aqueous	Solid	Aqueous	Aqueous	Solid	Aqueous	Aqueous
TEMPERATURE, C			40.00	40.00	40.00	40.00	40.00	40.00	40.00
PRESSURE, atm			1.00	1.00	1.00	1.00	1.00	1.00	1.00
pH			15.73	-	15.73	15.73	-	13.93	15.37
		MW							
COMPONENT	FORMULA	gm/gmol	gmole	gmole	gmole	gmole	gmole	gmole	gmole
Water	H2O	18.02	8.76	-	7.79	0.97	-	3.74	3.42
Carbon Dioxide	CO2	44.01	0.00	-	0.00	0.00	-	-	0.00
Aluminum Hydroxide	Al(OH)3	78.00	1.94	-	1.72	0.22	-	-	0.15
Potassium Hydroxide	KOH	56.11	0.12	-	0.10	0.01	-	-	0.01
Sodium Hydroxide	NaOH	40.00	1.88	-	1.67	0.21	-	0.19	0.28
Sodium Nitrite	NaNO2	69.00	1.42	1.75	1.26	0.16	1.75	-	0.40
Sodium Nitrate	NaNO3	84.99	1.17	3.99	1.04	0.13	3.99	-	0.39
Sodium Carbonate	Na2CO3	105.99	0.08	-	0.07	0.01	-	-	0.02
Sodium Sulfate	Na2SO4	142.04	0.01	-	0.01	0.00	-	-	0.01
Sodium Chloride	NaCl	58.44	0.29	-	0.26	0.03	-	-	0.02
Sodium Fluoride	NaF	41.99	0.02	-	0.01	0.00	-	-	0.00
Sodium Orthophosphate	Na3PO4	163.94	0.14	-	0.13	0.02	-	-	0.01
Sodium Bicarbonate	NaHCO3	84.01	0.00	-	0.00	0.00	-	-	0.00
Sodium Chromate	Na2CrO4	161.97	0.21	-	0.19	0.02	-	-	0.04
Sodium Chromate Tetrahydrate	Na2CrO4.4H2O	234.03	-	0.15	-	-	0.15	-	-
Sodium Carbonate Monohydrate	Na2CO3.1H2O	124.00	-	1.22	-	-	1.22	-	-
Trisodium Fluoride Sulfate	Na3FSO4	184.03	-	0.01	-	-	0.01	-	-
Burkeite	Na6(SO4)2CO3	390.08	-	0.06	-	-	0.06	-	-
Sodium Oxalate	Na2C2O4	134.00	0.00	0.01	0.00	0.00	0.01	-	0.00
Cesium Hydroxide	CsOH	149.91	6.245E-05	-	5.551E-05	6.938E-06	-	-	4.893E-06
Total, gm mole			16.03	7.20	14.25	1.78	7.20	3.93	4.76
Total, gm			673.70	673.70	598.85	74.86	673.70	74.86	158.93
Volume, L			0.35	0.28	0.31	0.04	0.28	0.07	0.10
Enthalpy, cal			-1.841E+06	-1.164E+06	-1.637E+06	-2.046E+05	-1.164E+06	-2.756E+05	-4.151E+05
Density, g/L			1,933.98	2,376.45	1,933.98	1,933.98	2,376.45	1,103.18	1,623.86
Cs Activity*, Ci/L			1.03	-	1.03	1.03	-	-	0.29
Cs Activity*, Ci/5M Na			0.31	-	0.31	0.31	-	-	0.11

*Assumes 50% is Cs-137

SST Early Feed Flowsheet in SI Units (Sheet 8 of 9)

SST EARLY FEED

MOLE BALANCE	BASIS = 1,000 gm FEED									
STREAM			WASHED1		WASH2	SPENT WASH2	WASHED2		O/F RECYCLE	PURGE
PHASE			Aqueous	Solid	Aqueous	Aqueous	Aqueous	Solid	Aqueous	Aqueous
TEMPERATURE, C			40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00
PRESSURE, atm			1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
pH			15.37	-	6.77	14.38	14.38	-	15.73	15.73
		MW								
COMPONENT	FORMULA	gm/gmol	gmole	gmole	gmole	gmole	gmole	gmole	gmole	gmole
Water	H2O	18.02	1.43	-	7.38	8.41	0.97	-	4.38	1.83
Carbon Dioxide	CO2	44.01	0.00	-	-	0.00	0.00	-	0.00	0.00
Aluminum Hydroxide	Al(OH)3	78.00	0.06	-	-	0.06	0.01	-	0.97	0.40
Potassium Hydroxide	KOH	56.11	0.00	-	-	0.00	0.00	-	0.06	0.02
Sodium Hydroxide	NaOH	40.00	0.12	-	-	0.10	0.01	-	0.94	0.39
Sodium Nitrite	NaNO2	69.00	0.17	1.33	-	1.20	0.14	0.17	0.71	0.30
Sodium Nitrate	NaNO3	84.99	0.16	3.57	-	1.10	0.13	2.50	0.58	0.24
Sodium Carbonate	Na2CO3	105.99	0.01	-	-	0.09	0.01	-	0.04	0.02
Sodium Sulfate	Na2SO4	142.04	0.00	-	-	0.02	0.00	-	0.01	0.00
Sodium Chloride	NaCl	58.44	0.01	-	-	0.01	0.00	-	0.14	0.06
Sodium Fluoride	NaF	41.99	0.00	-	-	0.01	0.00	-	0.01	0.00
Sodium Orthophosphate	Na3PO4	163.94	0.00	-	-	0.00	0.00	-	0.07	0.03
Sodium Bicarbonate	NaHCO3	84.01	0.00	-	-	0.00	0.00	-	0.00	0.00
Sodium Chromate	Na2CrO4	161.97	0.02	-	-	0.13	0.01	-	0.11	0.04
Sodium Chromate Tetrahydrate	Na2CrO4.4H2O	234.03	-	0.12	-	-	-	-	-	-
Sodium Carbonate Monohydrate	Na2CO3.1H2O	124.00	-	1.20	-	-	-	1.12	-	-
Trisodium Fluoride Sulfate	Na3FSO4	184.03	-	0.01	-	-	-	0.01	-	-
Burkeite	Na6(SO4)2CO3	390.08	-	0.05	-	-	-	0.05	-	-
Sodium Oxalate	Na2C2O4	134.00	0.00	0.01	-	0.00	0.00	0.01	0.00	0.00
Cesium Hydroxide	CsOH	149.91	2.046E-06	-	-	1.835E-06	2.110E-07	-	3.123E-05	1.302E-05
Total, gm mole			1.99	6.30	7.38	11.13	1.28	3.86	8.02	3.34
Total, gm			66.45	598.04	132.90	370.85	42.65	383.88	336.97	140.50
Volume, L			0.04	0.25	0.13	0.24	0.03	0.17	0.17	0.07
Enthalpy, cal			-1.736E+05	-1.053E+06	-5.020E+05	-8.963E+05	-1.031E+05	-7.251E+05	-9.209E+05	-3.840E+05
Density, g/L			1,623.86	2,367.47	992.22	1,570.23	1,570.23	2,266.10	1,933.98	1,933.98
Cs Activity*, Ci/L			0.29	-	-	0.04	0.04	-	1.03	1.03
Cs Activity*, Ci/5M Na			0.11	-	-	0.02	0.02	-	0.31	0.31

*Assumes 50% is Cs-137

SST Early Feed Flowsheet in SI Units (Sheet 9 of 9)

SST EARLY FEED

MOLE BALANCE	BASIS = 1,000 gm FEED									
STREAM			RECYC LIQ	DIL H2O	5M PROD		BYPASS		MIXED PURGE	
PHASE			Aqueous	Aqueous	Aqueous	Solid	Aqueous	Solid	Aqueous	Solid
TEMPERATURE, C			40.00	40.00	38.88	38.88	25.00	25.00	40.00	40.00
PRESSURE, atm			1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
pH			15.73	6.77	11.95	-	15.30	-	15.82	-
		MW								
COMPONENT	FORMULA	gm/gmol	gmole	gmole	gmole	gmole	gmole	gmole	gmole	gmole
Water	H2O	18.02	5.96	52.30	54.39	-	0.27	-	2.09	-
Carbon Dioxide	CO2	44.01	0.00	-	0.00	-	0.00	-	0.00	-
Aluminum Hydroxide	Al(OH)3	78.00	1.32	-	0.00	0.00	0.00	-	0.41	-
Potassium Hydroxide	KOH	56.11	0.08	-	0.00	-	0.00	-	0.02	-
Sodium Hydroxide	NaOH	40.00	1.28	-	0.02	-	0.02	-	0.41	-
Sodium Nitrite	NaNO2	69.00	0.97	-	0.31	-	0.01	-	0.30	-
Sodium Nitrate	NaNO3	84.99	0.79	-	2.63	-	0.02	0.00	0.27	-
Sodium Carbonate	Na2CO3	105.99	0.06	-	1.17	-	0.00	-	0.02	-
Sodium Sulfate	Na2SO4	142.04	0.01	-	0.10	-	0.00	-	0.00	-
Sodium Chloride	NaCl	58.44	0.20	-	0.00	-	0.00	-	0.06	-
Sodium Fluoride	NaF	41.99	0.01	-	0.01	-	0.00	-	0.00	-
Sodium Orthophosphate	Na3PO4	163.94	0.10	-	0.00	-	0.00	-	0.03	-
Sodium Bicarbonate	NaHCO3	84.01	0.00	-	0.01	-	0.00	-	0.00	-
Sodium Chromate	Na2CrO4	161.97	0.15	-	0.01	-	0.00	-	0.04	-
Sodium Chromate Tetrahydrate	Na2CrO4.4H2O	234.03	-	-	-	-	-	-	-	-
Sodium Carbonate Monohydrate	Na2CO3.1H2O	124.00	-	-	-	-	-	0.00	-	0.00
Trisodium Fluoride Sulfate	Na3FSO4	184.03	-	-	-	-	-	-	-	0.00
Burkeite	Na6(SO4)2CO3	390.08	-	-	-	-	-	-	-	0.00
Sodium Oxalate	Na2C2O4	134.00	0.00	-	0.00	0.01	0.00	0.00	0.00	0.00
Cesium Hydroxide	CsOH	149.91	4.248E-05	-	2.110E-07	-	1.193E-07	-	1.314E-05	-
Total, gm mole			10.91	52.30	58.65	0.01	0.32	0.00	3.66	0.00
Total, gm			458.35	942.29	1,367.82	1.01	8.85	0.16	149.31	0.21
Volume, L			0.24	0.95	1.11	0.00	0.01	0.00	0.08	0.00
Enthalpy, cal			-1.253E+06	-3.559E+06	-4.385E+06	-2.715E+03	-2.578E+04	-3.227E+02	-4.094E+05	-5.562E+02
Density, g/L			1,933.98	992.22	1,232.08	2,360.26	1,421.83	2,258.96	1,891.51	2,320.35
Cs Activity*, Ci/L			1.03	-	0.00	-	0.11	-	0.96	-
Cs Activity*, Ci/5M Na			0.31	-	0.00	-	0.06	-	0.30	-

*Assumes 50% is Cs-137

Appendix B

APPENDIX B

SST LATE FEED FLOWSHEET IN SI UNITS

SST LATE FEED FLOWSHEET IN SI UNITS (Sheet 1 of 10)

SST LATE FEED

MASS BALANCE	BASIS: 1,000 gm FEED									
STREAM			SST2 FEED		CO2	RECYCLE		STEAM1	SLURRY	
PHASE			Aqueous	Solid	Vapor	Aqueous	Solid	Vapor	Aqueous	Solid
TEMPERATURE, C			25.00	25.00	25.00	39.74	39.74	40.00	40.00	40.00
PRESSURE, atm			1.00	1.00	1.00	1.00	1.00	0.03	0.03	0.03
pH			12.60	-	-	15.00	-	-	15.68	-
TOTAL, gmmoles		MW	49.62	0.03	0.00	15.91	0.08	48.19	11.45	2.48
COMPONENT	FORMULA	gm/gmol	gm	gm	gm	gm	gm	gm	gm	gm
Water	H2O	18.02	811.76	-	-	152.50	-	868.23	90.27	-
Aluminum Hydroxide	Al(OH)3	78.00	0.28	2.48	-	27.05	0.11	-	29.92	-
Potassium Hydroxide	KOH	56.11	0.50	-	-	5.99	-	-	6.49	-
Sodium Hydroxide	NaOH	40.00	1.24	-	-	9.95	-	-	10.79	-
Sodium Nitrite	NaNO2	69.00	4.28	-	-	51.26	-	-	55.54	-
Sodium Nitrate	NaNO3	84.99	120.31	-	-	98.53	5.48	-	45.68	178.64
Sodium Carbonate	Na2CO3	105.99	22.51	-	-	4.57	-	-	2.22	-
Sodium Sulfate	Na2SO4	142.04	21.38	-	-	1.47	-	-	0.38	-
Sodium Chloride	NaCl	58.44	0.52	-	-	6.23	-	-	6.75	-
Sodium Fluoride	NaF	41.99	3.71	-	-	0.50	-	-	0.64	-
Sodium Orthophosphate	Na3PO4	163.94	7.25	-	-	86.84	-	-	94.09	-
Sodium Bicarbonate	NaHCO3	84.01	0.02	-	-	0.00	-	-	0.00	-
Sodium Chromate	Na2CrO4	161.97	2.58	-	-	27.86	-	-	25.49	-
Sodium Chromate Tetrahydrate	Na2CrO4.4H2O	234.03	-	-	-	-	2.76	-	-	9.91
Sodium Carbonate Monohydrate	Na2CO3.1H2O	124.00	-	-	-	-	-	-	-	25.20
Trisodium Fluoride Sulfate	Na3FSO4	184.03	-	-	-	-	0.67	-	-	16.30
Burkeite	Na6(SO4)2CO3	390.08	-	-	-	-	-	-	-	14.27
Sodium Oxalate	Na2C2O4	134.00	0.79	0.39	-	0.00	0.00	-	0.00	1.18
Cesium Hydroxide	CsOH	149.91	2.379E-04	-	-	2.849E-03	-	-	3.087E-03	-
Total, gm			997.13	2.87	0.22	472.75	9.02	868.23	368.26	245.51
Total, kg			1.00	0.00	0.00	0.47	0.01	0.87	0.37	0.25
Volume, L			0.87	0.00	1.81	0.19	0.00	0.02	0.05	0.10
Enthalpy, cal			-3.392E+06	-1.073E+04	-4.702E+02	-1.245E+06	-1.640E+04	-2.780E+06	-9.712E+05	-4.073E+05
Density, g/L			1,149.36	2,426.42	1.81	2,497.92	3,314.95	0.02	7,570.33	2,396.39
Cs Activity*, Ci/L			0.01	-	-	0.58	-	-	2.43	-
Cs Activity*, Ci/5M Na			0.02	-	-	0.13	-	-	0.15	-

*Assumes 50% is Cs-137

SST LATE FEED FLOWSHEET IN SI UNITS (Sheet 2 of 10)

SST LATE FEED

MASS BALANCE	BASIS: 1,000 gm FEED								
STREAM			OVERFLOW	UNDERFLOW		LIQUOR	DELIQUORED		WASH1
PHASE			Aqueous	Aqueous	Solid	Aqueous	Aqueous	Solid	Aqueous
TEMPERATURE, C			40.00	40.00	40.00	40.00	40.00	40.00	40.00
PRESSURE, atm			1.00	1.00	1.00	1.00	1.00	1.00	1.00
pH			15.68	15.68	-	15.68	15.68	-	6.77
TOTAL, gmmoles		MW	3.82	7.63	2.48	6.79	0.85	2.48	1.51
COMPONENT	FORMULA	gm/gmol	gm	gm	gm	gm	gm	gm	gm
Water	H2O	18.02	30.10	60.17	-	53.49	6.69	-	27.28
Aluminum Hydroxide	Al(OH)3	78.00	9.97	19.94	-	17.73	2.22	-	-
Potassium Hydroxide	KOH	56.11	2.16	4.33	-	3.84	0.48	-	-
Sodium Hydroxide	NaOH	40.00	3.60	7.19	-	6.39	0.80	-	-
Sodium Nitrite	NaNO2	69.00	18.52	37.03	-	32.91	4.11	-	-
Sodium Nitrate	NaNO3	84.99	15.23	30.46	178.63	27.07	3.38	178.63	-
Sodium Carbonate	Na2CO3	105.99	0.74	1.48	-	1.31	0.16	-	-
Sodium Sulfate	Na2SO4	142.04	0.13	0.26	-	0.23	0.03	-	-
Sodium Chloride	NaCl	58.44	2.25	4.50	-	4.00	0.50	-	-
Sodium Fluoride	NaF	41.99	0.21	0.43	-	0.38	0.05	-	-
Sodium Orthophosphate	Na3PO4	163.94	31.37	62.72	-	55.75	6.97	-	-
Sodium Bicarbonate	NaHCO3	84.01	0.00	0.00	-	0.00	0.00	-	-
Sodium Chromate	Na2CrO4	161.97	8.50	16.99	-	15.11	1.89	-	-
Sodium Chromate Tetrahydrate	Na2CrO4.4H2O	234.03	-	-	9.91	-	-	9.91	-
Sodium Carbonate Monohydrate	Na2CO3.1H2O	124.00	-	-	25.20	-	-	25.20	-
Trisodium Fluoride Sulfate	Na3FSO4	184.03	-	-	16.31	-	-	16.31	-
Burkeite	Na6(SO4)2CO3	390.08	-	-	14.27	-	-	14.27	-
Sodium Oxalate	Na2C2O4	134.00	0.00	0.00	1.18	0.00	0.00	1.18	-
Cesium Hydroxide	CsOH	149.91	1.029E-03	2.058E-03	-	1.829E-03	2.287E-04	-	-
Total, gm			122.78	245.49	245.49	218.21	27.28	245.49	27.28
Total, kg			0.12	0.25	0.25	0.22	0.03	0.25	0.03
Volume, L			0.02	0.03	0.10	0.03	0.00	0.10	0.03
Enthalpy, cal			-3.238E+05	-6.474E+05	-4.073E+05	-5.755E+05	-7.193E+04	-4.073E+05	-1.030E+05
Density, g/L			7,570.34	7,570.34	2,396.36	7,570.34	7,570.34	2,396.36	992.22
Cs Activity*, Ci/L			2.43	2.43	-	2.43	2.43	-	-
Cs Activity*, Ci/5M Na			0.15	0.15	-	0.15	0.15	-	-

*Assumes 50% is Cs-137

SST LATE FEED FLOWSHEET IN SI UNITS (Sheet 3 of 10)

SST LATE FEED

MASS BALANCE	BASIS: 1,000 gm FEED								
STREAM			SPENT WASH1	WASHED1		WASH2	SPENT WASH2	WASHED2	
PHASE			Aqueous	Aqueous	Solid	Aqueous	Aqueous	Aqueous	Solid
TEMPERATURE, C			40.00	40.00	40.00	40.00	40.00	40.00	40.00
PRESSURE, atm			1.00	1.00	1.00	1.00	1.00	1.00	1.00
pH			14.18	14.18	-	6.77	13.22	13.22	-
TOTAL, gmmoles		MW	2.27	0.87	2.17	2.64	4.11	0.70	1.60
COMPONENT	FORMULA	gm/gmol	gm	gm	gm	gm	gm	gm	gm
Water	H2O	18.02	25.79	9.93	-	47.64	50.67	8.57	-
Aluminum Hydroxide	Al(OH)3	78.00	1.36	0.52	0.33	-	0.31	0.05	0.49
Potassium Hydroxide	KOH	56.11	0.35	0.13	-	-	0.11	0.02	-
Sodium Hydroxide	NaOH	40.00	0.58	0.22	-	-	0.19	0.03	-
Sodium Nitrite	NaNO2	69.00	2.97	1.14	-	-	0.98	0.17	-
Sodium Nitrate	NaNO3	84.99	19.98	7.70	154.33	-	45.10	7.63	109.30
Sodium Carbonate	Na2CO3	105.99	1.01	0.39	-	-	1.67	0.28	-
Sodium Sulfate	Na2SO4	142.04	0.44	0.17	-	-	1.22	0.21	-
Sodium Chloride	NaCl	58.44	0.36	0.14	-	-	0.12	0.02	-
Sodium Fluoride	NaF	41.99	0.04	0.02	-	-	0.06	0.01	-
Sodium Orthophosphate	Na3PO4	163.94	5.03	1.94	-	-	1.66	0.28	-
Sodium Bicarbonate	NaHCO3	84.01	0.00	0.00	-	-	0.00	0.00	-
Sodium Chromate	Na2CrO4	161.97	3.93	1.52	-	-	4.12	0.70	-
Sodium Chromate Tetrahydrate	Na2CrO4.4H2O	234.03	-	-	4.76	-	-	-	-
Sodium Carbonate Monohydrate	Na2CO3.1H2O	124.00	-	-	23.98	-	-	-	22.62
Trisodium Fluoride Sulfate	Na3FSO4	184.03	-	-	16.24	-	-	-	16.01
Burkeite	Na6(SO4)2CO3	390.08	-	-	13.55	-	-	-	12.07
Sodium Oxalate	Na2C2O4	134.00	0.00	0.00	1.18	-	0.00	0.00	1.18
Cesium Hydroxide	CsOH	149.91	1.651E-04	6.358E-05	-	-	5.438E-05	9.198E-06	-
Total, gm			61.85	23.82	214.38	47.64	106.21	17.96	161.67
Total, kg			0.06	0.02	0.21	0.05	0.11	0.02	0.16
Volume, L			0.04	0.01	0.09	0.05	0.07	0.01	0.07
Enthalpy, cal			-1.611E+05	-6.204E+04	-3.583E+05	-1.799E+05	-2.729E+05	-4.615E+04	-2.799E+05
Density, g/L			1,652.93	1,652.93	2,356.60	992.22	1,445.82	1,445.82	2,315.60
Cs Activity*, Ci/L			0.17	0.17	-	-	0.03	0.03	-
Cs Activity*, Ci/5M Na			0.07	0.07	-	-	0.02	0.02	-

*Assumes 50% is Cs-137

SST LATE FEED FLOWSHEET IN SI UNITS (Sheet 4 of 10)

SST LATE FEED

MASS BALANCE	BASIS: 1,000 gm FEED									
STREAM			O/F RECYCLE	PURGE	RECYC LIQ	DIL H2O	5M PROD		BYPASS	
PHASE			Aqueous	Aqueous	Aqueous	Aqueous	Aqueous	Solid	Aqueous	Solid
TEMPERATURE, C			40.00	40.00	40.00	40.00	33.52	33.52	25.00	25.00
PRESSURE, atm			1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
pH			15.68	15.68	15.68	6.77	11.78	-	12.60	-
TOTAL, gmmoles		MW	3.82	0.85	5.94	19.22	23.70	0.06	1.35	0.00
COMPONENT	FORMULA	gm/gmol	gm	gm	gm	gm	gm	gm	gm	gm
Water	H2O	18.02	30.10	6.69	46.80	346.24	358.06	-	22.16	-
Aluminum Hydroxide	Al(OH)3	78.00	9.97	2.22	15.51	-	0.04	0.50	0.01	0.07
Potassium Hydroxide	KOH	56.11	2.16	0.48	3.36	-	0.02	-	0.01	-
Sodium Hydroxide	NaOH	40.00	3.60	0.80	5.59	-	0.11	-	0.03	-
Sodium Nitrite	NaNO2	69.00	18.52	4.11	28.80	-	0.17	-	0.12	-
Sodium Nitrate	NaNO3	84.99	15.23	3.38	23.69	-	116.93	-	3.28	-
Sodium Carbonate	Na2CO3	105.99	0.74	0.16	1.15	-	22.70	-	0.61	-
Sodium Sulfate	Na2SO4	142.04	0.13	0.03	0.20	-	14.73	-	0.58	-
Sodium Chloride	NaCl	58.44	2.25	0.50	3.50	-	0.02	-	0.01	-
Sodium Fluoride	NaF	41.99	0.21	0.05	0.33	-	1.71	-	0.10	-
Sodium Orthophosphate	Na3PO4	163.94	31.37	6.97	48.78	-	0.28	-	0.20	-
Sodium Bicarbonate	NaHCO3	84.01	0.00	0.00	0.00	-	0.16	-	0.00	-
Sodium Chromate	Na2CrO4	161.97	8.50	1.89	13.22	-	0.70	-	0.07	-
Sodium Chromate Tetrahydrate	Na2CrO4.4H2O	234.03	-	-	-	-	-	-	-	-
Sodium Carbonate Monohydrate	Na2CO3.1H2O	124.00	-	-	-	-	-	-	-	-
Trisodium Fluoride Sulfate	Na3FSO4	184.03	-	-	-	-	-	8.58	-	-
Burkeite	Na6(SO4)2CO3	390.08	-	-	-	-	-	-	-	-
Sodium Oxalate	Na2C2O4	134.00	0.00	0.00	0.00	-	0.09	1.09	0.02	0.01
Cesium Hydroxide	CsOH	149.91	1.029E-03	2.287E-04	1.601E-03	-	9.198E-06	-	6.495E-06	-
Total, gm			122.78	27.28	190.93	346.24	515.70	10.17	27.22	0.08
Total, kg			0.12	0.03	0.19	0.35	0.52	0.01	0.03	0.00
Volume, L			0.02	0.00	0.03	0.35	0.41	0.00	0.02	0.00
Enthalpy, cal			-3.238E+05	-7.194E+04	-5.035E+05	-1.308E+06	-1.607E+06	-2.643E+04	-9.261E+04	-2.930E+02
Density, g/L			7,570.34	7,570.34	7,570.34	992.22	1,243.01	2,634.39	1,149.36	2,426.42
Cs Activity*, Ci/L			2.43	2.43	2.43	-	0.00	-	0.01	-
Cs Activity*, Ci/5M Na			0.15	0.15	0.15	-	0.00	-	0.02	-

*Assumes 50% is Cs-137

SST LATE FEED FLOWSHEET IN SI UNITS (Sheet 5 of 10)

SST LATE FEED

MASS BALANCE	BASIS: 1,000 gm FEED			
STREAM			MIXED PURGE	
PHASE			Aqueous	Solid
TEMPERATURE, C			31.23	31.23
PRESSURE, atm			1.00	1.00
pH			14.51	-
TOTAL, gmmoles		MW	2.20	0.01
COMPONENT	FORMULA	gm/gmol	gm	gm
Water	H2O	18.02	28.85	-
Aluminum Hydroxide	Al(OH)3	78.00	1.51	0.78
Potassium Hydroxide	KOH	56.11	0.49	-
Sodium Hydroxide	NaOH	40.00	0.83	-
Sodium Nitrite	NaNO2	69.00	4.23	-
Sodium Nitrate	NaNO3	84.99	6.67	-
Sodium Carbonate	Na2CO3	105.99	0.78	-
Sodium Sulfate	Na2SO4	142.04	0.61	-
Sodium Chloride	NaCl	58.44	0.51	-
Sodium Fluoride	NaF	41.99	0.15	-
Sodium Orthophosphate	Na3PO4	163.94	7.17	-
Sodium Bicarbonate	NaHCO3	84.01	0.00	-
Sodium Chromate	Na2CrO4	161.97	1.96	-
Sodium Chromate Tetrahydrate	Na2CrO4.4H2O	234.03	-	-
Sodium Carbonate Monohydrate	Na2CO3.1H2O	124.00	-	-
Trisodium Fluoride Sulfate	Na3FSO4	184.03	-	-
Burkeite	Na6(SO4)2CO3	390.08	-	-
Sodium Oxalate	Na2C2O4	134.00	0.00	0.03
Cesium Hydroxide	CsOH	149.91	2.352E-04	-
Total, gm			53.77	0.81
Total, kg			0.05	0.00
Volume, L			0.03	0.00
Enthalpy, cal			-1.617E+05	-3.148E+03
Density, g/L			1,578.66	2,436.73
Cs Activity*, Ci/L			0.26	-
Cs Activity*, Ci/5M Na			0.13	-

*Assumes 50% is Cs-137

SST LATE FEED FLOWSHEET IN SI UNITS (Sheet 6 of 10)

SST LATE FEED

MOLE BALANCE	BASIS 1,000 gm FEED									
STREAM			SST2 FEED		CO2	RECYCLE		STEAM1	SLURRY	
PHASE			Aqueous	Solid	Vapor	Aqueous	Solid	Vapor	Aqueous	Solid
TEMPERATURE, C			25.00	25.00	25.00	39.74	39.74	40.00	40.00	40.00
PRESSURE, atm			1.00	1.00	1.00	1.00	1.00	0.03	0.03	0.03
pH			12.60	-	-	15.00	-	-	15.68	-
TOTAL, gmmoles		MW	50	0	0	16	0	48	11.45	2
COMPONENT	FORMULA	gm/gmol	gmol	gmol	gmol	gmol	gmol	gmol	gmol	gmol
Water	H2O	18.02	45.06	-	-	8.47	-	48.19	5.01	-
Aluminum Hydroxide	Al(OH)3	78.00	0.00	0.03	-	0.35	0.00	-	0.38	-
Potassium Hydroxide	KOH	56.11	0.01	-	-	0.11	-	-	0.12	-
Sodium Hydroxide	NaOH	40.00	0.03	-	-	0.25	-	-	0.27	-
Sodium Nitrite	NaNO2	69.00	0.06	-	-	0.74	-	-	0.81	-
Sodium Nitrate	NaNO3	84.99	1.42	-	-	1.16	0.06	-	0.54	2.10
Sodium Carbonate	Na2CO3	105.99	0.21	-	-	0.04	-	-	0.02	-
Sodium Sulfate	Na2SO4	142.04	0.15	-	-	0.01	-	-	0.00	-
Sodium Chloride	NaCl	58.44	0.01	-	-	0.11	-	-	0.12	-
Sodium Fluoride	NaF	41.99	0.09	-	-	0.01	-	-	0.02	-
Sodium Orthophosphate	Na3PO4	163.94	0.04	-	-	0.53	-	-	0.57	-
Sodium Bicarbonate	NaHCO3	84.01	0.00	-	-	0.00	-	-	0.00	-
Sodium Chromate (VI)	Na2CrO4	161.97	0.02	-	-	0.17	-	-	0.16	-
Sodium Chromate Tetrahydrate	Na2CrO4.4H2O	234.03	-	-	-	-	0.01	-	-	0.04
Sodium Carbonate Monohydrate	Na2CO3.1H2O	124.00	-	-	-	-	-	-	-	0.20
Trisodium Fluoride Sulfate	Na3FSO4	184.03	-	-	-	-	0.00	-	-	0.09
Burkeite	Na6(SO4)2CO3	390.08	-	-	-	-	-	-	-	0.04
Sodium Oxalate	Na2C2O4	134.00	0.01	0.00	-	0.00	0.00	-	0.00	0.01
Cesium Hydroxide	CsOH	149.91	1.587E-06	-	-	1.901E-05	-	-	2.059E-05	-
Total, gm mole			49.63	0.14	0.00	17.40	0.24	48.19	13.10	6.11
Total, kg			997.13	2.87	0.22	472.75	9.02	868.23	368.26	245.51
Volume, L			0.87	0.00	1.81	0.19	0.00	0.02	0.05	0.10
Enthalpy, cal			-3.392E+06	-1.073E+04	-4.702E+02	-1.245E+06	-1.640E+04	-2.780E+06	-9.712E+05	-4.073E+05
Density, g/L			1,149.36	2,426.42	1.81	2,497.92	3,314.95	0.02	7,570.33	2,396.39
Cs Activity*, Ci/L			0.01			0.58			2.43	
Cs Activity*, Ci/5M Na			0.02			0.13			0.15	

*Assumes 50% is Cs-137

SST LATE FEED FLOWSHEET IN SI UNITS (Sheet 7 of 10)

SST LATE FEED

MOLE BALANCE	BASIS 1,000 gm FEED								
STREAM			OVERFLOW	UNDERFLOW		LIQUOR	DELIQUORED		WASHI
PHASE			Aqueous	Aqueous	Solid	Aqueous	Aqueous	Solid	Aqueous
TEMPERATURE, C			40.00	40.00	40.00	40.00	40.00	40.00	40.00
PRESSURE, atm			1.00	1.00	1.00	1.00	1.00	1.00	1.00
pH			15.68	15.68	-	15.68	15.68	-	6.77
TOTAL, gmmoles		MW	4	7.63	2	7	0.85	2	2
COMPONENT	FORMULA	gm/gmol	gmol	gmol	gmol	gmol	gmol	gmol	gmol
Water	H2O	18.02	1.67	3.34	-	2.97	0.37	-	1.51
Aluminum Hydroxide	Al(OH)3	78.00	0.13	0.26	-	0.23	0.03	-	-
Potassium Hydroxide	KOH	56.11	0.04	0.08	-	0.07	0.01	-	-
Sodium Hydroxide	NaOH	40.00	0.09	0.18	-	0.16	0.02	-	-
Sodium Nitrite	NaNO2	69.00	0.27	0.54	-	0.48	0.06	-	-
Sodium Nitrate	NaNO3	84.99	0.18	0.36	2.10	0.32	0.04	2.10	-
Sodium Carbonate	Na2CO3	105.99	0.01	0.01	-	0.01	0.00	-	-
Sodium Sulfate	Na2SO4	142.04	0.00	0.00	-	0.00	0.00	-	-
Sodium Chloride	NaCl	58.44	0.04	0.08	-	0.07	0.01	-	-
Sodium Fluoride	NaF	41.99	0.01	0.01	-	0.01	0.00	-	-
Sodium Orthophosphate	Na3PO4	163.94	0.19	0.38	-	0.34	0.04	-	-
Sodium Bicarbonate	NaHCO3	84.01	0.00	0.00	-	0.00	0.00	-	-
Sodium Chromate (VI)	Na2CrO4	161.97	0.05	0.10	-	0.09	0.01	-	-
Sodium Chromate Tetrahydrate	Na2CrO4.4H2O	234.03	-	-	0.04	-	-	0.04	-
Sodium Carbonate Monohydrate	Na2CO3.1H2O	124.00	-	-	0.20	-	-	0.20	-
Trisodium Fluoride Sulfate	Na3FSO4	184.03	-	-	0.09	-	-	0.09	-
Burkeite	Na6(SO4)2CO3	390.08	-	-	0.04	-	-	0.04	-
Sodium Oxalate	Na2C2O4	134.00	0.00	0.00	0.01	0.00	0.00	0.01	-
Cesium Hydroxide	CsOH	149.91	6.866E-06	1.373E-05	-	1.220E-05	1.525E-06	-	-
Total, gm mole			4.37	8.73	6.11	7.76	0.97	6.11	1.51
Total, kg			122.78	245.49	245.49	218.21	27.28	245.49	27.28
Volume, L			0.02	0.03	0.10	0.03	0.00	0.10	0.03
Enthalpy, cal			-3.238E+05	-6.474E+05	-4.073E+05	-5.755E+05	-7.193E+04	-4.073E+05	-1.030E+05
Density, g/L			7,570.34	7,570.34	2,396.36	7,570.34	7,570.34	2,396.36	992.22
Cs Activity*, Ci/L			2.43	2.43		2.43	2.43		-
Cs Activity*, Ci/5M Na			0.15	0.15		0.15	0.15		-

*Assumes 50% is Cs-137

SST LATE FEED FLOWSHEET IN SI UNITS (Sheet 8 of 10)

SST LATE FEED

MOLE BALANCE	BASIS 1,000 gm FEED								
STREAM			SPENT WASH1	WASHED1		WASH2	SPENT WASH2	WASHED2	
PHASE			Aqueous	Aqueous	Solid	Aqueous	Aqueous	Aqueous	Solid
TEMPERATURE, C			40.00	40.00	40.00	40.00	40.00	40.00	40.00
PRESSURE, atm			1.00	1.00	1.00	1.00	1.00	1.00	1.00
pH			14.18	14.18	-	6.77	13.22	13.22	-
TOTAL, gmmoles		MW	2	1	2	2.64	4	1	1.60
COMPONENT	FORMULA	gm/gmol	gmol	gmol	gmol	gmol	gmol	gmol	gmol
Water	H2O	18.02	1.43	0.55	-	2.64	2.81	0.48	-
Aluminum Hydroxide	Al(OH)3	78.00	0.02	0.01	0.00	-	0.00	0.00	0.01
Potassium Hydroxide	KOH	56.11	0.01	0.00	-	-	0.00	0.00	-
Sodium Hydroxide	NaOH	40.00	0.01	0.01	-	-	0.00	0.00	-
Sodium Nitrite	NaNO2	69.00	0.04	0.02	-	-	0.01	0.00	-
Sodium Nitrate	NaNO3	84.99	0.24	0.09	1.82	-	0.53	0.09	1.29
Sodium Carbonate	Na2CO3	105.99	0.01	0.00	-	-	0.02	0.00	-
Sodium Sulfate	Na2SO4	142.04	0.00	0.00	-	-	0.01	0.00	-
Sodium Chloride	NaCl	58.44	0.01	0.00	-	-	0.00	0.00	-
Sodium Fluoride	NaF	41.99	0.00	0.00	-	-	0.00	0.00	-
Sodium Orthophosphate	Na3PO4	163.94	0.03	0.01	-	-	0.01	0.00	-
Sodium Bicarbonate	NaHCO3	84.01	0.00	0.00	-	-	0.00	0.00	-
Sodium Chromate (VI)	Na2CrO4	161.97	0.02	0.01	-	-	0.03	0.00	-
Sodium Chromate Tetrahydrate	Na2CrO4.4H2O	234.03	-	-	0.02	-	-	-	-
Sodium Carbonate Monohydrate	Na2CO3.1H2O	124.00	-	-	0.19	-	-	-	0.18
Trisodium Fluoride Sulfate	Na3FSO4	184.03	-	-	0.09	-	-	-	0.09
Burkeite	Na6(SO4)2CO3	390.08	-	-	0.03	-	-	-	0.03
Sodium Oxalate	Na2C2O4	134.00	0.00	0.00	0.01	-	0.00	0.00	0.01
Cesium Hydroxide	CsOH	149.91	1.101E-06	4.241E-07	-	-	3.628E-07	6.135E-08	-
Total, gm mole			2.35	0.90	5.34	2.64	4.13	0.70	4.07
Total, kg			61.85	23.82	214.38	47.64	106.21	17.96	161.67
Volume, L			0.04	0.01	0.09	0.05	0.07	0.01	0.07
Enthalpy, cal			-1.611E+05	-6.204E+04	-3.583E+05	-1.799E+05	-2.729E+05	-4.615E+04	-2.799E+05
Density, g/L			1,652.93	1,652.93	2,356.60	992.22	1,445.82	1,445.82	2,315.60
Cs Activity*, Ci/L			0.17	0.17		-	0.03	0.03	
Cs Activity*, Ci/5M Na			0.07	0.07		-	0.02	0.02	

*Assumes 50% is Cs-137

SST LATE FEED FLOWSHEET IN SI UNITS (Sheet 9 of 10)

SST LATE FEED

MOLE BALANCE	BASIS 1,000 gm FEED									
STREAM			O/F RECYCLE	PURGE	RECYC LIQ	DIL H2O	5M PROD		BYPASS	
PHASE			Aqueous	Aqueous	Aqueous	Aqueous	Aqueous	Solid	Aqueous	Solid
TEMPERATURE, C			40.00	40.00	40.00	40.00	33.52	33.52	25.00	25.00
PRESSURE, atm			1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
pH			15.68	15.68	15.68	6.77	11.78	-	12.60	-
TOTAL, gmmoles		MW	4	1	5.94	19	24	0.06	1	0
COMPONENT	FORMULA	gm/gmol	gmol	gmol	gmol	gmol	gmol	gmol	gmol	gmol
Water	H2O	18.02	1.67	0.37	2.60	19.22	19.88	-	1.23	-
Aluminum Hydroxide	Al(OH)3	78.00	0.13	0.03	0.20	-	0.00	0.01	0.00	0.00
Potassium Hydroxide	KOH	56.11	0.04	0.01	0.06	-	0.00	-	0.00	-
Sodium Hydroxide	NaOH	40.00	0.09	0.02	0.14	-	0.00	-	0.00	-
Sodium Nitrite	NaNO2	69.00	0.27	0.06	0.42	-	0.00	-	0.00	-
Sodium Nitrate	NaNO3	84.99	0.18	0.04	0.28	-	1.38	-	0.04	-
Sodium Carbonate	Na2CO3	105.99	0.01	0.00	0.01	-	0.21	-	0.01	-
Sodium Sulfate	Na2SO4	142.04	0.00	0.00	0.00	-	0.10	-	0.00	-
Sodium Chloride	NaCl	58.44	0.04	0.01	0.06	-	0.00	-	0.00	-
Sodium Fluoride	NaF	41.99	0.01	0.00	0.01	-	0.04	-	0.00	-
Sodium Orthophosphate	Na3PO4	163.94	0.19	0.04	0.30	-	0.00	-	0.00	-
Sodium Bicarbonate	NaHCO3	84.01	0.00	0.00	0.00	-	0.00	-	0.00	-
Sodium Chromate (VI)	Na2CrO4	161.97	0.05	0.01	0.08	-	0.00	-	0.00	-
Sodium Chromate Tetrahydrate	Na2CrO4.4H2O	234.03	-	-	-	-	-	-	-	-
Sodium Carbonate Monohydrate	Na2CO3.1H2O	124.00	-	-	-	-	-	-	-	-
Trisodium Fluoride Sulfate	Na3FSO4	184.03	-	-	-	-	-	0.05	-	-
Burkeite	Na6(SO4)2CO3	390.08	-	-	-	-	-	-	-	-
Sodium Oxalate	Na2C2O4	134.00	0.00	0.00	0.00	-	0.00	0.01	0.00	0.00
Cesium Hydroxide	CsOH	149.91	6.866E-06	1.526E-06	1.068E-05	-	6.135E-08	-	4.333E-08	-
Total, gm mole			4.37	0.97	6.79	19.22	23.70	0.28	1.36	0.00
Total, kg			122.78	27.28	190.93	346.24	515.70	10.17	27.22	0.08
Volume, L			0.02	0.00	0.03	0.35	0.41	0.00	0.02	0.00
Enthalpy, cal			-3.238E+05	-7.194E+04	-5.035E+05	-1.308E+06	-1.607E+06	-2.643E+04	-9.261E+04	-2.930E+02
Density, g/L			7,570.34	7,570.34	7,570.34	992.22	1,243.01	2,634.39	1,149.36	2,426.42
Cs Activity*, Ci/L			2.43	2.43	2.43	-	0.00		0.01	
Cs Activity*, Ci/5M Na			0.15	0.15	0.15	-	0.00		0.02	

*Assumes 50% is Cs-137

SST LATE FEED FLOWSHEET IN SI UNITS (Sheet 10 of 10)

SST LATE FEED

MOLE BALANCE	BASIS 1,000 gm FEED			
STREAM			MIXED PURGE	
PHASE			Aqueous	Solid
TEMPERATURE, C			31.23	31.23
PRESSURE, atm			1.00	1.00
pH			14.51	-
TOTAL, gmmoles		MW	2.20	0
COMPONENT	FORMULA	gm/gmol	gmol	gmol
Water	H2O	18.02	1.60	-
Aluminum Hydroxide	Al(OH)3	78.00	0.02	0.01
Potassium Hydroxide	KOH	56.11	0.01	-
Sodium Hydroxide	NaOH	40.00	0.02	-
Sodium Nitrite	NaNO2	69.00	0.06	-
Sodium Nitrate	NaNO3	84.99	0.08	-
Sodium Carbonate	Na2CO3	105.99	0.01	-
Sodium Sulfate	Na2SO4	142.04	0.00	-
Sodium Chloride	NaCl	58.44	0.01	-
Sodium Fluoride	NaF	41.99	0.00	-
Sodium Orthophosphate	Na3PO4	163.94	0.04	-
Sodium Bicarbonate	NaHCO3	84.01	0.00	-
Sodium Chromate (VI)	Na2CrO4	161.97	0.01	-
Sodium Chromate Tetrahydrate	Na2CrO4.4H2O	234.03	-	-
Sodium Carbonate Monohydrate	Na2CO3.1H2O	124.00	-	-
Trisodium Fluoride Sulfate	Na3FSO4	184.03	-	-
Burkeite	Na6(SO4)2CO3	390.08	-	-
Sodium Oxalate	Na2C2O4	134.00	0.00	0.00
Cesium Hydroxide	CsOH	149.91	1.569E-06	-
Total, gm mole			2.29	0.04
Total, kg			53.77	0.81
Volume, L			0.03	0.00
Enthalpy, cal			-1.617E+05	-3.148E+03
Density, g/L			1,578.66	2,436.73
Cs Activity*, Ci/L			0.26	
Cs Activity*, Ci/5M Na			0.13	

*Assumes 50% is Cs-137

Appendix C

APPENDIX C

DST FLOWSHEET IN SI UNITS

DST FLOWSHEET IN SI UNITS (Sheet 1 of 10)

DST MASS BALANCE

STREAM #	BASIS 1,000 gm FEED									
STREAM			DST FEED		CO2	RECYCLE		STEAM1	SLURRY	
PHASE			Aqueous	Solid	Vapor	Aqueous	Solid	Vapor	Aqueous	Solid
TEMPERATURE, C			25.00	25.00	25.00	41.95	41.95	40.00	40.00	40.00
PRESSURE, atm			1.00	1.00	1.00	1.00	1.00	0.03	0.03	0.03
pH			15.10	-	-	15.44	-	-	15.85	-
TOTAL, gmmoles		MW	45.69	0.00	1.18	38.78	0.20	42.52	25.83	6.94
COMPONENT	FORMULA	gm/gmol	gm	gm	gm	gm	gm	gm	gm	gm
Water	H2O	18.02	621.42	-	-	332.83	-	766.01	186.91	-
Carbon Dioxide	CO2	44.01	0.00	-	51.95	0.00	-	0.00	0.00	-
Nitric Acid	HNO3	63.01	0.00	-	-	0.00	-	0.00	0.00	-
Aluminum Hydroxide	Al(OH)3	78.00	49.19	-	-	184.27	-	-	233.45	-
Potassium Hydroxide	KOH	56.11	11.96	-	-	66.12	-	-	30.79	-
Potassium Nitrate	KNO3	101.10	-	-	-	-	20.44	-	-	105.74
Sodium Hydroxide	NaOH	40.00	104.91	-	-	56.25	-	-	100.45	-
Sodium Nitrite	NaNO2	69.00	86.97	-	-	215.75	-	-	140.85	161.83
Sodium Nitrate	NaNO3	84.99	103.24	-	-	322.92	-	-	160.65	193.79
Sodium Carbonate	Na2CO3	105.99	7.51	-	-	12.28	-	-	12.00	-
Sodium Sulfate	Na2SO4	142.04	1.12	-	-	2.59	-	-	2.00	-
Sodium Chloride	NaCl	58.44	7.37	-	-	27.61	-	-	34.98	-
Sodium Fluoride	NaF	41.99	0.50	-	-	1.40	-	-	1.39	-
Sodium Orthophosphate	Na3PO4	163.94	1.29	-	-	4.83	-	-	6.12	-
Sodium Bicarbonate	NaHCO3	84.01	0.00	-	-	0.00	-	-	0.00	-
Sodium Chromate	Na2CrO4	161.97	0.51	-	-	1.91	-	-	2.42	-
Sodium Carbonate Monohydrate	Na2CO3.1H2O	124.00	-	-	-	-	-	-	-	155.50
Trisodium Fluoride Sulfate	Na3FSO4	184.03	-	-	-	-	-	-	-	2.22
Sodium Acetate	Na(C2H3O2)	82.03	3.62	-	-	13.56	-	-	17.18	-
Sodium Oxalate	Na2C2O4	134.00	0.01	0.41	-	0.00	-	-	0.00	0.42
Cesium Hydroxide	CsOH	149.91	1.018E-02	-	-	3.814E-02	-	-	4.831E-02	-
Total, gm			999.62	0.41	51.95	1,242.37	20.44	766.01	929.26	619.51
Volume, L			0.74	0.00	1.81	0.72	0.01	0.02	0.50	0.28
Enthalpy, cal			-3.150E+06	-9.791E+02	-1.110E+05	-3.066E+06	-2.380E+04	-2.452E+06	-2.482E+06	-1.009E+06
Density, g/L			1,343.49	2,339.99	1.81	1,736.59	2,108.95	0.02	1,875.62	2,206.58
Cs Activity*, Ci/L			0.52	-	-	2.04	-	-	3.73	-
Cs Activity*, Ci/5M Na			0.36	-	-	0.78	-	-	1.20	-

*Assumes 50% is Cs-137

DST FLOWSHEET IN SI UNITS (Sheet 2 of 10)

DST MASS BALANCE

STREAM #	BASIS 1,000 gm FEED						
STREAM			OVERFLOW	UNDERFLOW		O/F RECYCLE	LIQUOR
PHASE			Aqueous	Aqueous	Solid	Aqueous	Aqueous
TEMPERATURE, C			40.00	40.00	40.00	40.00	40.00
PRESSURE, atm			1.00	1.00	1.00	1.00	1.00
pH			15.85	15.85	-	15.85	15.85
TOTAL, gmmoles		MW	8.61	17.22	6.94	8.61	15.31
COMPONENT	FORMULA	gm/gmol	gm	gm	gm	gm	gm
Water	H2O	18.02	62.32	124.60	-	62.32	110.75
Carbon Dioxide	CO2	44.01	0.00	0.00	-	0.00	0.00
Nitric Acid	HNO3	63.01	0.00	0.00	-	0.00	0.00
Aluminum Hydroxide	Al(OH)3	78.00	77.83	155.61	-	77.83	138.32
Potassium Hydroxide	KOH	56.11	10.27	20.52	-	10.27	18.24
Potassium Nitrate	KNO3	101.10	-	-	105.74	-	-
Sodium Hydroxide	NaOH	40.00	33.49	66.96	-	33.49	59.52
Sodium Nitrite	NaNO2	69.00	46.96	93.89	161.83	46.96	83.46
Sodium Nitrate	NaNO3	84.99	53.57	107.11	193.77	53.57	95.21
Sodium Carbonate	Na2CO3	105.99	4.01	8.01	-	4.01	7.12
Sodium Sulfate	Na2SO4	142.04	0.67	1.34	-	0.67	1.19
Sodium Chloride	NaCl	58.44	11.66	23.32	-	11.66	20.72
Sodium Fluoride	NaF	41.99	0.47	0.93	-	0.47	0.83
Sodium Orthophosphate	Na3PO4	163.94	2.04	4.08	-	2.04	3.63
Sodium Bicarbonate	NaHCO3	84.01	0.00	0.00	-	0.00	0.00
Sodium Chromate	Na2CrO4	161.97	0.81	1.61	-	0.81	1.43
Sodium Carbonate Monohydrate	Na2CO3.1H2O	124.00	-	-	155.48	-	-
Trisodium Fluoride Sulfate	Na3FSO4	184.03	-	-	2.22	-	-
Sodium Acetate	Na(C2H3O2)	82.03	5.73	11.45	-	5.73	10.18
Sodium Oxalate	Na2C2O4	134.00	0.00	0.00	0.42	0.00	0.00
Cesium Hydroxide	CsOH	149.91	1.611E-02	3.220E-02	-	1.611E-02	2.863E-02
Total, gm			309.84	619.46	619.46	309.84	550.63
Volume, L			0.17	0.33	0.28	0.17	0.29
Enthalpy, cal			-8.276E+05	-1.655E+06	-1.009E+06	-8.276E+05	-1.471E+06
Density, g/L			1,877.78	1,877.78	2,206.58	1,877.78	1,877.78
Cs Activity*, Ci/L			3.74	3.74	-	3.74	3.74
Cs Activity*, Ci/5M Na			1.20	1.20	-	1.20	1.20

*Assumes 50% is Cs-137

DST FLOWSHEET IN SI UNITS (Sheet 3 of 10)

DST MASS BALANCE

STREAM #	BASIS 1,000 gm FEED								
STREAM			DELIQUORED		WASH1	SPENT WASH1	WASHED1		WASH2
PHASE			Aqueous	Solid	Aqueous	Aqueous	Aqueous	Solid	Aqueous
TEMPERATURE, C			40.00	40.00	40.00	40.00	40.00	40.00	40.00
PRESSURE, atm			1.00	1.00	1.00	1.00	1.00	1.00	1.00
pH			15.85	-	13.93	15.60	15.60	-	6.77
TOTAL, gmmoles		MW	1.91	6.94	3.78	5.68	2.09	5.92	7.34
COMPONENT	FORMULA	gm/gmol	gm	gm	gm	gm	gm	gm	gm
Water	H2O	18.02	13.84	-	61.95	55.57	20.42	-	132.25
Carbon Dioxide	CO2	44.01	0.00	-	-	0.00	0.00	-	-
Nitric Acid	HNO3	63.01	0.00	-	-	0.00	0.00	-	-
Aluminum Hydroxide	Al(OH)3	78.00	17.29	-	-	12.64	4.65	-	-
Potassium Hydroxide	KOH	56.11	2.28	-	-	9.34	3.43	-	-
Potassium Nitrate	KNO3	101.10	-	105.74	-	-	-	86.83	-
Sodium Hydroxide	NaOH	40.00	7.44	-	6.88	5.00	1.84	-	-
Sodium Nitrite	NaNO2	69.00	10.43	161.83	-	28.59	10.51	133.17	-
Sodium Nitrate	NaNO3	84.99	11.90	193.77	-	45.52	16.72	159.32	-
Sodium Carbonate	Na2CO3	105.99	0.89	-	-	1.51	0.55	-	-
Sodium Sulfate	Na2SO4	142.04	0.15	-	-	0.36	0.13	-	-
Sodium Chloride	NaCl	58.44	2.59	-	-	1.89	0.70	-	-
Sodium Fluoride	NaF	41.99	0.10	-	-	0.15	0.06	-	-
Sodium Orthophosphate	Na3PO4	163.94	0.45	-	-	0.33	0.12	-	-
Sodium Bicarbonate	NaHCO3	84.01	0.00	-	-	0.00	0.00	-	-
Sodium Chromate	Na2CrO4	161.97	0.18	-	-	0.13	0.05	-	-
Sodium Carbonate Monohydrate	Na2CO3.1H2O	124.00	-	155.48	-	-	-	154.11	-
Trisodium Fluoride Sulfate	Na3FSO4	184.03	-	2.22	-	-	-	1.77	-
Sodium Acetate	Na(C2H3O2)	82.03	1.27	-	-	0.93	0.34	-	-
Sodium Oxalate	Na2C2O4	134.00	0.00	0.42	-	0.00	0.00	0.42	-
Cesium Hydroxide	CsOH	149.91	3.578E-03	-	-	2.617E-03	9.614E-04	-	-
Total, gm			68.83	619.46	68.83	161.99	59.51	535.61	132.25
Volume, L			0.04	0.28	0.06	0.10	0.04	0.24	0.13
Enthalpy, cal			-1.839E+05	-1.009E+06	-2.534E+05	-3.956E+05	-1.453E+05	-9.023E+05	-4.995E+05
Density, g/L			1,877.78	2,206.58	1,103.18	1,624.80	1,624.80	2,208.67	992.22
Cs Activity*, Ci/L			3.74	-	-	1.01	1.01	-	-
Cs Activity*, Ci/5M Na			1.20	-	-	0.43	0.43	-	-

*Assumes 50% is Cs-137

DST FLOWSHEET IN SI UNITS (Sheet 4 of 10)

DST MASS BALANCE

STREAM #	BASIS 1,000 gm FEED									
STREAM			SPENT WASH2	WASHED2		PURGE	RECYC LIQ	DIL_H2O	5M_PROD	
PHASE			Aqueous	Aqueous	Solid	Aqueous	Aqueous	Aqueous	Aqueous	Solid
TEMPERATURE, C			40.00	40.00	40.00	40.00	40.00	40.00	42.08	42.08
PRESSURE, atm			1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
pH			14.78	14.78	-	15.85	15.85	6.77	11.83	-
TOTAL, gmmoles		MW	14.99	1.01	2.66	5.41	9.90	38.67	47.46	0.00
COMPONENT	FORMULA	gm/gmol	gm	gm	gm	gm	gm	gm	gm	gm
Water	H2O	18.02	130.35	8.76	-	39.14	71.61	696.69	726.75	-
Carbon Dioxide	CO2	44.01	0.00	0.00	-	0.00	0.00	-	0.00	-
Nitric Acid	HNO3	63.01	45.41	3.05	-	0.00	0.00	-	5.49	-
Aluminum Hydroxide	Al(OH)3	78.00	4.35	0.29	-	48.88	89.44	-	0.23	0.07
Potassium Hydroxide	KOH	56.11	46.06	3.10	-	6.45	11.80	-	5.55	-
Potassium Nitrate	KNO3	101.10	-	-	4.43	-	-	-	-	-
Sodium Hydroxide	NaOH	40.00	-	-	-	21.03	38.48	-	-	-
Sodium Nitrite	NaNO2	69.00	86.23	5.80	51.64	29.50	53.96	-	57.44	-
Sodium Nitrate	NaNO3	84.99	118.20	7.95	53.80	33.65	61.56	-	62.19	-
Sodium Carbonate	Na2CO3	105.99	2.16	0.15	-	2.52	4.60	-	129.56	-
Sodium Sulfate	Na2SO4	142.04	0.79	0.05	-	0.42	0.77	-	0.70	-
Sodium Chloride	NaCl	58.44	0.65	0.04	-	7.32	13.40	-	0.04	-
Sodium Fluoride	NaF	41.99	0.25	0.02	-	0.29	0.53	-	0.21	-
Sodium Orthophosphate	Na3PO4	163.94	0.11	0.01	-	1.28	2.35	-	0.01	-
Sodium Bicarbonate	NaHCO3	84.01	0.00	0.00	-	0.00	0.00	-	0.44	-
Sodium Chromate	Na2CrO4	161.97	0.05	0.00	-	0.51	0.93	-	0.00	-
Sodium Carbonate Monohydrate	Na2CO3.1H2O	124.00	-	-	152.06	-	-	-	-	-
Trisodium Fluoride Sulfate	Na3FSO4	184.03	-	-	0.84	-	-	-	-	-
Sodium Acetate	Na(C2H3O2)	82.03	0.32	0.02	-	3.60	6.58	-	0.02	-
Sodium Oxalate	Na2C2O4	134.00	0.00	0.00	0.42	0.00	0.00	-	0.23	0.19
Cesium Hydroxide	CsOH	149.91	9.008E-04	6.056E-05	-	1.012E-02	1.851E-02	-	6.056E-05	0.000E+00
Total, gm			434.95	29.24	263.18	194.60	356.03	696.69	988.86	0.26
Volume, L			0.28	0.02	0.12	0.10	0.19	0.70	0.81	0.00
Enthalpy, cal			-9.159E+05	-6.158E+04	-5.609E+05	-5.198E+05	-9.510E+05	-2.631E+06	-3.253E+06	-7.093E+02
Density, g/L			1,567.38	1,567.38	2,233.75	1,877.78	1,877.78	992.22	1,225.77	2,365.35
Cs Activity*, Ci/L			0.12	0.12	-	3.74	3.74	-	0.00	-
Cs Activity*, Ci/5M Na			0.06	0.06	-	1.20	1.20	-	0.00	-

*Assumes 50% is Cs-137

DST FLOWSHEET IN SI UNITS (Sheet 5 of 10)

DST MASS BALANCE

STREAM #	BASIS 1,000 gm FEED					
STREAM			BYPASS		MIXED PURGE	
PHASE			Aqueous	Solid	Aqueous	Solid
TEMPERATURE, C			25.00	25.00	38.26	38.26
PRESSURE, atm			1.00	1.00	1.00	1.00
pH			15.10	-	16.06	-
TOTAL, gmmoles		MW	0.39	0.00	5.80	0.00
COMPONENT	FORMULA	gm/gmol	gm	gm	gm	gm
Water	H2O	18.02	5.26	-	44.40	-
Carbon Dioxide	CO2	44.01	0.00	-	0.00	-
Nitric Acid	HNO3	63.01	0.00	-	0.00	-
Aluminum Hydroxide	Al(OH)3	78.00	0.42	-	49.30	-
Potassium Hydroxide	KOH	56.11	0.10	-	6.55	-
Potassium Nitrate	KNO3	101.10	-	-	-	-
Sodium Hydroxide	NaOH	40.00	0.89	-	21.92	-
Sodium Nitrite	NaNO2	69.00	0.74	-	30.23	-
Sodium Nitrate	NaNO3	84.99	0.87	-	34.52	-
Sodium Carbonate	Na2CO3	105.99	0.06	-	2.58	-
Sodium Sulfate	Na2SO4	142.04	0.01	-	0.43	-
Sodium Chloride	NaCl	58.44	0.06	-	7.39	-
Sodium Fluoride	NaF	41.99	0.00	-	0.30	-
Sodium Orthophosphate	Na3PO4	163.94	0.01	-	1.29	-
Sodium Bicarbonate	NaHCO3	84.01	0.00	-	0.00	-
Sodium Chromate	Na2CrO4	161.97	0.00	-	0.51	-
Sodium Carbonate Monohydrate	Na2CO3.1H2O	124.00	-	-	-	-
Trisodium Fluoride Sulfate	Na3FSO4	184.03	-	-	-	-
Sodium Acetate	Na(C2H3O2)	82.03	0.03	-	3.63	-
Sodium Oxalate	Na2C2O4	134.00	0.00	0.00	0.00	0.00
Cesium Hydroxide	CsOH	149.91	8.615E-05	-	1.020E-02	-
Total, gm			8.46	0.00	203.06	0.00
Volume, L			0.01	0.00	0.11	0.00
Enthalpy, cal			-2.666E+04	-8.285E+00	-5.465E+05	-8.305E+00
Density, g/L			1,343.49	2,339.99	1,854.36	2,339.99
Cs Activity*, Ci/L			0.52	-	3.57	-
Cs Activity*, Ci/5M Na			0.36	-	1.18	-

*Assumes 50% is Cs-137

DST FLOWSHEET IN SI UNITS (Sheet 6 of 10)

DST MOLE BALANCE

STREAM #	BASIS: 1,000 gm FEED									
STREAM			DST FEED		CO2	RECYCLE		STEAM1	SLURRY	
PHASE			Aqueous	Solid	Vapor	Aqueous	Solid	Vapor	Aqueous	Solid
TEMPERATURE, C			25.00	25.00	25.00	41.95	41.95	40.00	40.00	40.00
PRESSURE, atm			1.00	1.00	1.00	1.00	1.00	0.03	0.03	0.03
pH			15.10	-	-	15.44	-	-	15.85	-
TOTAL, gmmoles		MW	46	0	1	39	0	43	25.83	7
COMPONENT	FORMULA	gm/gmol	gmol	gmol	gmol	gmol	gmol	gmol	gmol	gmol
Water	H2O	18.02	34.49	-	-	18.48	-	42.52	10.38	-
Carbon Dioxide	CO2	44.01	0.00	-	1.18	0.00	-	0.00	0.00	-
Nitric Acid	HNO3	63.01	0.00	-	-	0.00	-	0.00	0.00	-
Aluminum Hydroxide	Al(OH)3	78.00	0.63	-	-	2.36	-	-	2.99	-
Potassium Hydroxide	KOH	56.11	0.21	-	-	1.18	-	-	0.55	-
Potassium Nitrate	KNO3	101.10	-	-	-	-	0.20	-	-	1.05
Sodium Hydroxide	NaOH	40.00	2.62	-	-	1.41	-	-	2.51	-
Sodium Nitrite	NaNO2	69.00	1.26	-	-	3.13	-	-	2.04	2.35
Sodium Nitrate	NaNO3	84.99	1.21	-	-	3.80	-	-	1.89	2.28
Sodium Carbonate	Na2CO3	105.99	0.07	-	-	0.12	-	-	0.11	-
Sodium Sulfate	Na2SO4	142.04	0.01	-	-	0.02	-	-	0.01	-
Sodium Chloride	NaCl	58.44	0.13	-	-	0.47	-	-	0.60	-
Sodium Fluoride	NaF	41.99	0.01	-	-	0.03	-	-	0.03	-
Sodium Orthophosphate	Na3PO4	163.94	0.01	-	-	0.03	-	-	0.04	-
Sodium Bicarbonate	NaHCO3	84.01	0.00	-	-	0.00	-	-	0.00	-
Sodium Chromate (VI)	Na2CrO4	161.97	0.00	-	-	0.01	-	-	0.01	-
Sodium Carbonate Monohydrate	Na2CO3.1H2O	124.00	-	-	-	-	-	-	-	1.25
Trisodium Fluoride Sulfate	Na3FSO4	184.03	-	-	-	-	-	-	-	0.01
Sodium Acetate	Na(C2H3O2)	82.03	0.04	-	-	0.17	-	-	0.21	-
Sodium Oxalate	Na2C2O4	134.00	0.00	0.00	-	0.00	-	-	0.00	0.00
Cesium Hydroxide	CsOH	149.91	6.791E-05	-	-	2.544E-04	-	-	3.223E-04	-
Total, gm mole			48.28	0.01	1.18	48.84	0.40	42.52	38.59	16.43
Total, kg			999.62	0.41	51.95	1,242.37	20.44	766.01	929.26	619.51
Volume, L			0.74	0.00	1.81	0.72	0.01	0.02	0.50	0.28
Enthalpy, cal			-3.150E+06	-9.791E+02	-1.110E+05	-3.066E+06	-2.380E+04	-2.452E+06	-2.482E+06	-1.009E+06
Density, g/L			1,343.49	2,339.99	1.81	1,736.59	2,108.95	0.02	1,875.62	2,206.58
Cs Activity*, Ci/L			0.52			2.04			3.73	
Cs Activity*, Ci/5M Na			0.36			0.78			1.20	

*Assumes 50% is Cs-137

DST FLOWSHEET IN SI UNITS (Sheet 7 of 10)

DST MOLE BALANCE

STREAM #	BASIS: 1,000 gm FEED						
STREAM			OVERFLOW	UNDERFLOW	UNDERFLOW	O/F RECYCLE	LIQUOR
PHASE			Aqueous	Aqueous	Solid	Aqueous	Aqueous
TEMPERATURE, C			40.00	40.00	40.00	40.00	40.00
PRESSURE, atm			1.00	1.00	1.00	1.00	1.00
pH			15.85	15.85	-	15.85	15.85
TOTAL, gmmoles		MW	9	17.22	7	9	15.31
COMPONENT	FORMULA	gm/gmol	gmol	gmol	gmol	gmol	gmol
Water	H2O	18.02	3.46	6.92	-	3.46	6.15
Carbon Dioxide	CO2	44.01	0.00	0.00	-	0.00	0.00
Nitric Acid	HNO3	63.01	0.00	0.00	-	0.00	0.00
Aluminum Hydroxide	Al(OH)3	78.00	1.00	1.99	-	1.00	1.77
Potassium Hydroxide	KOH	56.11	0.18	0.37	-	0.18	0.33
Potassium Nitrate	KNO3	101.10	-	-	1.05	-	-
Sodium Hydroxide	NaOH	40.00	0.84	1.67	-	0.84	1.49
Sodium Nitrite	NaNO2	69.00	0.68	1.36	2.35	0.68	1.21
Sodium Nitrate	NaNO3	84.99	0.63	1.26	2.28	0.63	1.12
Sodium Carbonate	Na2CO3	105.99	0.04	0.08	-	0.04	0.07
Sodium Sulfate	Na2SO4	142.04	0.00	0.01	-	0.00	0.01
Sodium Chloride	NaCl	58.44	0.20	0.40	-	0.20	0.35
Sodium Fluoride	NaF	41.99	0.01	0.02	-	0.01	0.02
Sodium Orthophosphate	Na3PO4	163.94	0.01	0.02	-	0.01	0.02
Sodium Bicarbonate	NaHCO3	84.01	0.00	0.00	-	0.00	0.00
Sodium Chromate (VI)	Na2CrO4	161.97	0.00	0.01	-	0.00	0.01
Sodium Carbonate Monohydrate	Na2CO3.1H2O	124.00	-	-	1.25	-	-
Trisodium Fluoride Sulfate	Na3FSO4	184.03	-	-	0.01	-	-
Sodium Acetate	Na(C2H3O2)	82.03	0.07	0.14	-	0.07	0.12
Sodium Oxalate	Na2C2O4	134.00	0.00	0.00	0.00	0.00	0.00
Cesium Hydroxide	CsOH	149.91	1.074E-04	2.148E-04	-	1.074E-04	1.910E-04
Total, gm mole			12.87	25.72	16.43	12.87	22.87
Total, kg			309.84	619.46	619.46	309.84	550.63
Volume, L			0.17	0.33	0.28	0.17	0.29
Enthalpy, cal			-8.276E+05	-1.655E+06	-1.009E+06	-8.276E+05	-1.471E+06
Density, g/L			1,877.78	1,877.78	2,206.58	1,877.78	1,877.78
Cs Activity*, Ci/L			3.74	3.74		3.74	3.74
Cs Activity*, Ci/5M Na			1.20	1.20		1.20	1.20

*Assumes 50% is Cs-137

DST FLOWSHEET IN SI UNITS (Sheet 8 of 10)

DST MOLE BALANCE

STREAM #	BASIS: 1,000 gm FEED								
STREAM			DELIQUORED		WASH1	SPENT WASH1	WASHED1		WASH2
PHASE			Aqueous	Solid	Aqueous	Aqueous	Aqueous	Solid	Aqueous
TEMPERATURE, C			40.00	40.00	40.00	40.00	40.00	40.00	40.00
PRESSURE, atm			1.00	1.00	1.00	1.00	1.00	1.00	1.00
pH			15.85	-	13.93	15.60	15.60	-	6.77
TOTAL, gmmoles		MW	2	7	4	6	2	5.92	7
COMPONENT	FORMULA	gm/gmol	gmol	gmol	gmol	gmol	gmol	gmol	gmol
Water	H2O	18.02	0.77	-	3.44	3.08	1.13	-	7.34
Carbon Dioxide	CO2	44.01	0.00	-	-	0.00	0.00	-	-
Nitric Acid	HNO3	63.01	0.00	-	-	0.00	0.00	-	-
Aluminum Hydroxide	Al(OH)3	78.00	0.22	-	-	0.16	0.06	-	-
Potassium Hydroxide	KOH	56.11	0.04	-	-	0.17	0.06	-	-
Potassium Nitrate	KNO3	101.10	-	1.05	-	-	-	0.86	-
Sodium Hydroxide	NaOH	40.00	0.19	-	0.17	0.13	0.05	-	-
Sodium Nitrite	NaNO2	69.00	0.15	2.35	-	0.41	0.15	1.93	-
Sodium Nitrate	NaNO3	84.99	0.14	2.28	-	0.54	0.20	1.87	-
Sodium Carbonate	Na2CO3	105.99	0.01	-	-	0.01	0.01	-	-
Sodium Sulfate	Na2SO4	142.04	0.00	-	-	0.00	0.00	-	-
Sodium Chloride	NaCl	58.44	0.04	-	-	0.03	0.01	-	-
Sodium Fluoride	NaF	41.99	0.00	-	-	0.00	0.00	-	-
Sodium Orthophosphate	Na3PO4	163.94	0.00	-	-	0.00	0.00	-	-
Sodium Bicarbonate	NaHCO3	84.01	0.00	-	-	0.00	0.00	-	-
Sodium Chromate (VI)	Na2CrO4	161.97	0.00	-	-	0.00	0.00	-	-
Sodium Carbonate Monohydrate	Na2CO3.1H2O	124.00	-	1.25	-	-	-	1.24	-
Trisodium Fluoride Sulfate	Na3FSO4	184.03	-	0.01	-	-	-	0.01	-
Sodium Acetate	Na(C2H3O2)	82.03	0.02	-	-	0.01	0.00	-	-
Sodium Oxalate	Na2C2O4	134.00	0.00	0.00	-	0.00	0.00	0.00	-
Cesium Hydroxide	CsOH	149.91	2.387E-05	-	-	1.746E-05	6.413E-06	-	-
Total, gm mole			2.86	16.43	3.78	6.37	2.34	14.36	7.34
Total, kg			68.83	619.46	68.83	161.99	59.51	535.61	132.25
Volume, L			0.04	0.28	0.06	0.10	0.04	0.24	0.13
Enthalpy, cal			-1.839E+05	-1.009E+06	-2.534E+05	-3.956E+05	-1.453E+05	-9.023E+05	-4.995E+05
Density, g/L			1,877.78	2,206.58	1,103.18	1,624.80	1,624.80	2,208.67	992.22
Cs Activity*, Ci/L			3.74		-	1.01	1.01		-
Cs Activity*, Ci/5M Na			1.20		-	0.43	0.43		-

*Assumes 50% is Cs-137

DST FLOWSHEET IN SI UNITS (Sheet 9 of 10)

DST MOLE BALANCE

STREAM #	BASIS: 1,000 gm FEED									
STREAM			SPENT WASH2	WASHED2		PURGE	RECYC LIQ	DIL H2O	5M PROD	
PHASE			Aqueous	Aqueous	Solid	Aqueous	Aqueous	Aqueous	Aqueous	Solid
TEMPERATURE, C			40.00	40.00	40.00	40.00	40.00	40.00	42.08	42.08
PRESSURE, atm			1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
pH			14.78	14.78	-	15.85	15.85	6.77	11.83	-
TOTAL, gmmoles		MW	15	1.01	3	5	9.90	39	47	0.00
COMPONENT	FORMULA	gm/gmol	gmol	gmol	gmol	gmol	gmol	gmol	gmol	gmol
Water	H2O	18.02	7.24	0.49	-	2.17	3.98	38.67	40.34	-
Carbon Dioxide	CO2	44.01	0.00	0.00	-	0.00	0.00	-	0.00	-
Nitric Acid	HNO3	63.01	0.72	0.05	-	0.00	0.00	-	0.09	-
Aluminum Hydroxide	Al(OH)3	78.00	0.06	0.00	-	0.63	1.15	-	0.00	0.00
Potassium Hydroxide	KOH	56.11	0.82	0.06	-	0.11	0.21	-	0.10	-
Potassium Nitrate	KNO3	101.10	-	-	0.04	-	-	-	-	-
Sodium Hydroxide	NaOH	40.00	-	-	-	0.53	0.96	-	-	-
Sodium Nitrite	NaNO2	69.00	1.25	0.08	0.75	0.43	0.78	-	0.83	-
Sodium Nitrate	NaNO3	84.99	1.39	0.09	0.63	0.40	0.72	-	0.73	-
Sodium Carbonate	Na2CO3	105.99	0.02	0.00	-	0.02	0.04	-	1.22	-
Sodium Sulfate	Na2SO4	142.04	0.01	0.00	-	0.00	0.01	-	0.00	-
Sodium Chloride	NaCl	58.44	0.01	0.00	-	0.13	0.23	-	0.00	-
Sodium Fluoride	NaF	41.99	0.01	0.00	-	0.01	0.01	-	0.00	-
Sodium Orthophosphate	Na3PO4	163.94	0.00	0.00	-	0.01	0.01	-	0.00	-
Sodium Bicarbonate	NaHCO3	84.01	0.00	0.00	-	0.00	0.00	-	0.01	-
Sodium Chromate (VI)	Na2CrO4	161.97	0.00	0.00	-	0.00	0.01	-	0.00	-
Sodium Carbonate Monohydrate	Na2CO3.1H2O	124.00	-	-	1.23	-	-	-	-	-
Trisodium Fluoride Sulfate	Na3FSO4	184.03	-	-	0.00	-	-	-	-	-
Sodium Acetate	Na(C2H3O2)	82.03	0.00	0.00	-	0.04	0.08	-	0.00	-
Sodium Oxalate	Na2C2O4	134.00	0.00	0.00	0.00	0.00	0.00	-	0.00	0.00
Cesium Hydroxide	CsOH	149.91	6.009E-06	4.040E-07	-	6.748E-05	1.235E-04	-	4.040E-07	-
Total, gm mole			15.23	1.02	7.79	8.08	14.78	38.67	47.48	0.01
Total, kg			434.95	29.24	263.18	194.60	356.03	696.69	988.86	0.26
Volume, L			0.28	0.02	0.12	0.10	0.19	0.70	0.81	0.00
Enthalpy, cal			-9.159E+05	-6.158E+04	-5.609E+05	-5.198E+05	-9.510E+05	-2.631E+06	-3.253E+06	-7.093E+02
Density, g/L			1,567.38	1,567.38	2,233.75	1,877.78	1,877.78	992.22	1,225.77	2,365.35
Cs Activity*, Ci/L			0.12	0.12		3.74	3.74	-	0.00	
Cs Activity*, Ci/5M Na			0.06	0.06		1.20	1.20	-	0.00	

*Assumes 50% is Cs-137

DST FLOWSHEET IN SI UNITS (Sheet 10 of 10)

DST MOLE BALANCE

STREAM #	BASIS: 1,000 gm FEED					
STREAM			BYPASS		MIXED PURGE	
PHASE			Aqueous	Solid	Aqueous	Solid
TEMPERATURE, C			25.00	25.00	38.26	38.26
PRESSURE, atm			1.00	1.00	1.00	1.00
pH			15.10	-	16.06	-
TOTAL, gmmoles		MW	0	0	5.80	0
COMPONENT	FORMULA	gm/gmol	gmol	gmol	gmol	gmol
Water	H2O	18.02	0.29	-	2.46	-
Carbon Dioxide	CO2	44.01	0.00	-	0.00	-
Nitric Acid	HNO3	63.01	0.00	-	0.00	-
Aluminum Hydroxide	Al(OH)3	78.00	0.01	-	0.63	-
Potassium Hydroxide	KOH	56.11	0.00	-	0.12	-
Potassium Nitrate	KNO3	101.10	-	-	-	-
Sodium Hydroxide	NaOH	40.00	0.02	-	0.55	-
Sodium Nitrite	NaNO2	69.00	0.01	-	0.44	-
Sodium Nitrate	NaNO3	84.99	0.01	-	0.41	-
Sodium Carbonate	Na2CO3	105.99	0.00	-	0.02	-
Sodium Sulfate	Na2SO4	142.04	0.00	-	0.00	-
Sodium Chloride	NaCl	58.44	0.00	-	0.13	-
Sodium Fluoride	NaF	41.99	0.00	-	0.01	-
Sodium Orthophosphate	Na3PO4	163.94	0.00	-	0.01	-
Sodium Bicarbonate	NaHCO3	84.01	0.00	-	0.00	-
Sodium Chromate (VI)	Na2CrO4	161.97	0.00	-	0.00	-
Sodium Carbonate Monohydrate	Na2CO3.1H2O	124.00	-	-	-	-
Trisodium Fluoride Sulfate	Na3FSO4	184.03	-	-	-	-
Sodium Acetate	Na(C2H3O2)	82.03	0.00	-	0.04	-
Sodium Oxalate	Na2C2O4	134.00	0.00	0.00	0.00	0.00
Cesium Hydroxide	CsOH	149.91	5.747E-07	-	6.806E-05	-
Total, gm mole			0.41	0.00	8.49	0.00
Total, kg			8.46	0.00	203.06	0.00
Volume, L			0.01	0.00	0.11	0.00
Enthalpy, cal			-2.666E+04	-8.285E+00	-5.465E+05	-8.305E+00
Density, g/L			1,343.49	2,339.99	1,854.36	2,339.99
Cs Activity*, Ci/L			0.52		3.57	
Cs Activity*, Ci/5M Na			0.36		1.18	

*Assumes 50% is Cs-137

Appendix D

APPENDIX D

PROCESS ENHANCEMENT MODELLING INVESTIGATION

D1.0 INTRODUCTION

The presence of high solubility sodium hydroxide, sodium aluminate, and sodium nitrite makes the fractional crystallization and decontamination of low and medium solubility sodium salts more difficult. The high solubility salts increase ionic strength, density, and viscosity of the solution and hinder diffusion, crystallization, and separation. Although low sodium yields (25-50%) may be obtained in wastes containing high concentrations of high solubility salts, crystallization yield and salt decontamination can be enhanced by prior removal alumina and sodium nitrite.

Crystallization of alumina allows increased concentration of other salts without risking formation of alumina gel that would make separation of mother liquor from the precipitated solids essentially impractical. As noted earlier, precipitation of alumina as gibbsite is very slow and the additionally precipitated particle size is problematic for filtration.

Alumina crystallization (as gibbsite) is currently practiced on an industrial scale in the aluminum industry. Alumina is leached from bauxite ore at elevated temperature (250°F) and pressure (50 psig), then gibbsite is crystallized from a seeded solution at 150°F in a four-stage crystallization circuit with a 24-hour residence time.

Due to the slow growth rate of gibbsite, the solution is seeded with recycled coarse-grained gibbsite crystals to promote crystal growth and separation of large (approximately 500 micron) particles. The cooling is done in stages to avoid gel formation on rapid cooling.

This process may be adapted to Hanford waste containing high soluble alumina. Cooling and/or partial neutralization of the waste with an acid (i.e. CO_2, HNO_3) may be done in stages to avoid gel formation. Recycled gibbsite crystals may be used as seed for crystal growth.

By removing soluble alumina and neutralizing sodium hydroxide prior to fractional crystallization, pH, ionic strength, viscosity, and density of the solution are lowered thereby making the crystallization and separation of sodium salts easier. As shown in Table D-1, alumina removal dramatically reduces pH, ionic strength, density, and viscosity and increases theoretical sodium yield of the DST sample.

Table D-1. Alumina Removal Effects.

	DST Base Case	DST w/$Al(OH)_3$ Removal	DST w/$Al(OH)_3$ and $NaNO_2$ Removal
pH	15.85	11.55	11.56
Ionic Strength	15.5	9.86	7.48
Density (SpG)	1.88	1.58	1.47
Viscosity (cP)	7.66	3.39	2.66
Sodium Yield	71.5%	91.3%	94.1%

Lithium carbonate may improve the crystallization rate and stability of alumina by forming lithium aluminum carbonate hydrate salts (LAHCS). LAHCS is a more stable (less soluble) form of alumina which is thermodynamically favored over gibbsite. However, this material is not currently produced on an industrial scale and the viability of LAHCS must be proven experimentally.

The complementary solubility of $NaNO_2$ and $NaNO_3$ increases the total solubility of these sodium salts in solution. This phenomenon is detrimental to crystallization because increased solubility increases the ionic strength of the solution at saturation. Increased ionic strength increases liquid density and viscosity, thereby increasing mass transfer resistance to crystallization and increasing difficulty in crystal separation from the mother liquor.

To improve sodium salt yield and reduce saturation ionic strength, liquid density and viscosity, oxidation of sodium nitrite to sodium nitrate is proposed as a future development. By using nitrite oxidation, a ternary H_2O-$NaNO_3$-$NaNO_2$ is reduced to a binary H_2O-$NaNO_3$ system. By this method, the eutectic is removed, total solubility is reduced, and ionic strength at saturation is reduced.

As shown in Table D-1, oxidation of $NaNO_2$ to $NaNO_3$ reduces ionic strength, liquid density, viscosity, and increases sodium salt theoretical yield during fractional crystallization.

D2.0 LITHIUM ALUMINATE COMPLEX HYDROXIDE CARBONATE SALT (LAHCS) "LITHIUM DAWSONITE"

A low solubility lithium carbonate - aluminum hydroxide salt has been identified that is thermodynamically favored over all basic forms ($Al(OH)_3$, $NaAlO_2$, $Al(OH)_4^{-1}$, $NaAlCO_3(OH)_2$) of alumina. In its pure form, the compound is dilithium carbonate tetra (aluminum trihydroxide) trihydrate (LAHCS) with the formula $Li_2CO_3 \cdot 4Al(OH)_3 \cdot 3H_2O$, or simply "lithium dawsonite".

LAHCS is formed by the reaction of lithium carbonate, aluminum trihydroxide gel, and water.

$$Li_2CO_3 + 4Al(OH)_3 + 3H_2O \rightarrow Li_2CO_3 \cdot 4Al(OH)_3 \cdot 3H_2O \qquad \text{(D-1)}$$

This solid form of alumina has an isometric crystal habit which allows separation, deliquoring, and decontamination. A scanning electron photomicrograph of LAHCS is shown in Figure D-1.

Figure D-1. Scanning Electron Photomicrograph of LAHCS (U.S. Patent 5,997,836).

LAHCS also forms solid solutions of the structure $xLi_2O.xCO_2.yAl_2O_3 \cdot zH_2O$, where $0.1 \leq x \leq 1.0$, $1.5 \leq y \leq 2.5$, and $0 \leq z \leq 10$. Thus, the Li/Al ratio can vary from ~0.16 to 1.6.

By the precipitation of alumina from the system, free hydroxide is no longer needed to maintain sodium aluminate in solution. By this method, high-solubility sodium hydroxide may be neutralized and crystallized as a sodium salt thus increasing sodium salt yield.

D2.1 LAHCS CRYSTALLIZATION

Initial Conditions:

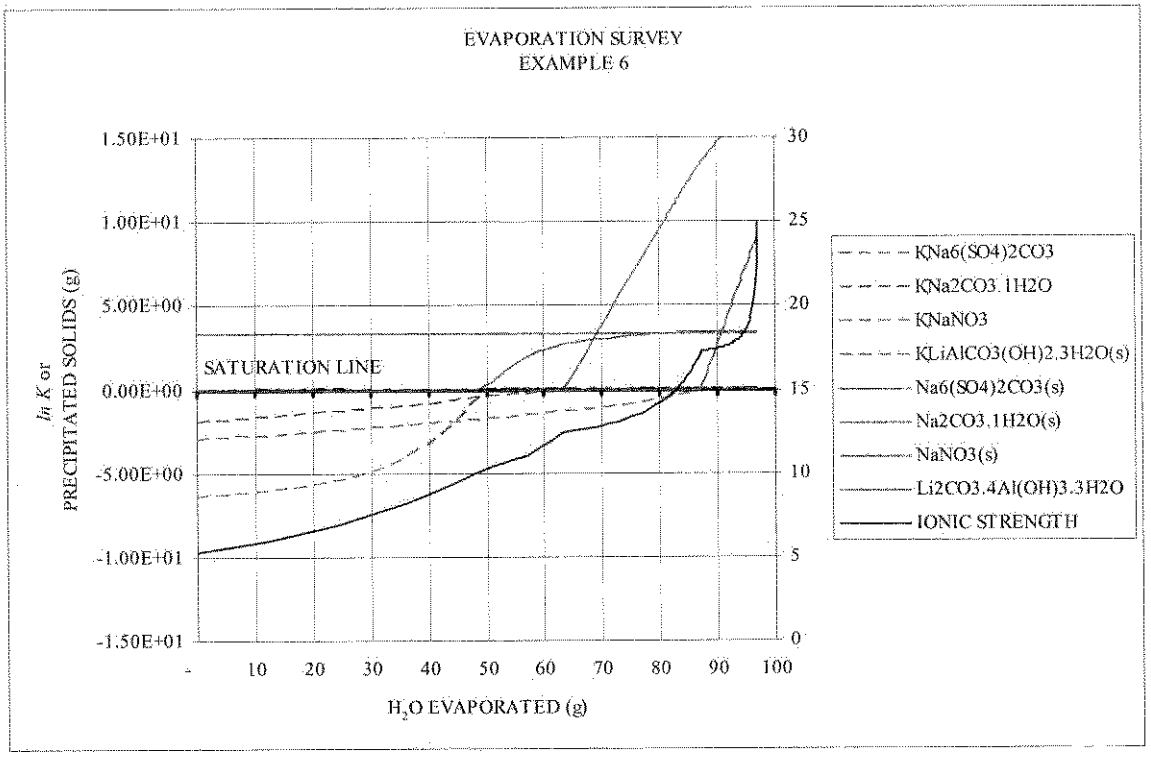
Temperature	40°C
H_2O	101.13 g
Na_2SO_4	2.5
Na_2CO_3	11.62

$NaNO_3$	10.0
NaOH	2.0
$NaAlO_2$	2.5
Li_2CO_3	0.8
CO_2	1.8
Total	132.35 g

In this example, lithium carbonate has been added to crystallize alumina as Dilithium Carbonate Tetra(aluminum trihydroxide) Trihydrate (LAHCS), $Li_2CO_3 \cdot 4Al(OH)_3 \cdot 3H_2O$.

By the crystallization of LAHCS, sodium hydroxide is not needed to maintain alumina solubility. Thus, carbon dioxide or nitric acid can be used to reduce free hydroxide and ionic strength. By this method, highly soluble sodium aluminate and sodium hydroxide are removed from solution, and most of the remaining sodium salts can crystallized from solution.

Figure D-2. Evaporation Survey.



In this case, alumina is initially precipitated as LAHCS (purple line). The initial solubility product for LAHCS[27] is:

$$K_{Li2CO3\cdot4Al(OH)3\cdot3H2O} = \{\alpha_{Li}\}^2\{\alpha_{Al}\}^4\{\alpha_{CO3}\}\{\alpha_{OH}\}^{12}\{\gamma_{H2O}\}^3$$
$$= \{2.971x10^{-2}\}^2\{2.85x10^{-30}\}^4\{0.0369\}\{0.0362\}^{12}\{1\}^3 \qquad \text{(D-3)}$$
$$= 9.93x10^{-153}$$

From the above calculation, because of the small solubility product for LAHCS, increasing the lithium concentration (the limiting reagent) substantially reduces alumina solubility ($\{Al^{+1}\}=10^{-30}$, $[Al(OH)_4^{-1}] = 10^{-6}$). By forming of LAHCS, lithium scavenges alumina from solution.

Saturation points for $Na_6(SO_4)_2CO_3$, $Na_2CO_3 \cdot 1H_2O$, $NaNO_3$ occur at 51.1, 65.1, and 87.3 g of water evaporated. An ionic strength of 20 is reached at 96.4 g of water evaporated.

At an ionic strength of 20, a total of 3.4, 17.2, 8.6, and 3.36 g of $Na_6(SO_4)_2CO_3$, $Na_2CO_3 \cdot 1H_2O$, $NaNO_3$, and $Li_2CO_3 \cdot 4Al(OH)_3 \cdot 3H_2O$ have crystallized. Theoretical yields for sulfate, carbonate, nitrate, and alumina are 99.8, 91.2, 85.6 and 100%. Theoretical sodium yield is 95.0%.

Thus, the addition of Li_2CO_3 and CO_2 has the potential to increase sodium yield by forming LAHCS and Na_2CO_3 and removing high solubility $NaAlO_2$ and NaOH from solution.

D3.0 NITRITE OXIDATION BY HYDROGEN PEROXIDE

Oxidation of nitrite to nitrate using ozone in Hanford waste has been demonstrated in laboratory tests[29,30,31,32]. These tests used a high shear mixing to overcome gas-to-solution mass transfer resistance. At this time, oxidation of Hanford waste to support fractional crystallization has not been developed, however the technique is offered as a potential method to increase sodium salt yield.

Gaseous ozone has been demonstrated to rapidly oxidize sodium nitrite in Hanford waste. However, an aqueous solution of hydrogen peroxide is far safer to handle than ozone gas. The oxidation potential for several common oxidants is shown Table D-2[33].

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[29] RHO-SA-93, "Ozonation of Hanford Nuclear Defense Waste," Rockwell International, Rockwell Hanford Operations, Lutton, T.W., Schulz, W.W, Strachan, d. M., Bollyky, L. J.
[30] RHO-C-47, "Ozone Mass Transfer and Kinetics Experiments," Rockwell International, Rockwell Hanford Operations, L. Joseph Bollyky and Associates and M. M. Beary.
[31] WHC-EP-0701, "Laboratory Testing of Ozone Oxidation of Hanford Site Waste from Tank 241-SY-101," Westinghouse Hanford Company, Delegard, C.H., Stubbs, A. M., Bolling, S. D., December 1993.
[32] *RHO-SA-203-201, "Effect of pH on the Destruction of Complexants with Ozone in Hanford Nuclear Waste,"* Rockwell International, Rockwell Hanford Operations, Winters, W. I.
[33] From "Introduction to Hydrogen Peroxide" http://www.h2o2.com/intro/overview.

Table D-2. Oxidation Potential for Common Oxidants.

Oxidant	Oxidation Potential, V
Fluorine	3.0
Hydroxyl Radical	2.8
Ozone	2.1
Hydrogen Peroxide	1.8
Sodium Permanganate	1.7
Chlorine Dioxide	1.5
Chlorine	1.4
Nitric Acid*	0.9

*Reducing to the nitrite ion.

Hydrogen peroxide is a moderately strong oxidant which decomposes to oxygen and water. Therefore, it does not introduce (or increase the amount of) undesirable components such as fluoride, potassium, manganese, or chlorine in the waste[34]. Thus, hydrogen peroxide solutions are safer and simpler to handle than ozone/oxygen gas blends.

The reaction of nitrite and hydrogen peroxide to form nitrate is shown below:

$$NO_2^{-1} + H_2O_2 \rightarrow NO_3^{-1} + H_2O \qquad \text{(D-2)}$$

By this using hydrogen peroxide oxidation of sodium nitrite, the ternary H_2O-$NaNO_3$-$NaNO_2$ system can be reduced to a binary H_2O-$NaNO_3$ system which eliminates the $NaNO_2$-$NaNO_3$ eutectic and reduces the total solubility of the sodium salts in the system.

Using the same example from Section 3.4 and Figure 9, when 10 g of $NaNO_2$ are oxidized with 4.9 g H_2O_2 to 13.2 g $NaNO_3$ and crystallized by evaporation, the system follows operating line D-E. Upon evaporation of 90 g H_2O, the net yield of $NaNO_3$ is 40.8 g $NaNO_3$, for a net sodium yield of 76.6%. At the end of evaporation, the ionic strength is 13 M Na. Thus, oxidation of $NaNO_2$ to $NaNO_3$ reduces total sodium solubility, ionic strength, and increases sodium yield at fixed ionic strength.

Used in combination with alumina removal and NaOH neutralization, nitrite oxidation can further lower ionic strength, liquid density, viscosity, and increase theoretical sodium salt yield. In the case in Table D-1, theoretical sodium yield is increased to 94.1%.

Oxidation has the potential to produce soluble transuranic compounds, such as plutonium +6. The formation of soluble transuranic compounds is highly undesirable because precipitation (due to pH, oxidation-reduction potential, or temperature) may form sufficient mass to cause nuclear criticality. If oxidation were to be used to support fractional crystallization, several methods must be used to prevent oxidation of TRU. These methods include using an oxidant with lower

[34] Transition metals (i.e. Fe, Cu, Mn) are known to catalyze the reaction of hydrogen peroxide to the hydroxyl radical, thereby increasing its oxidation potential. However, the catalysis reactions typically require acidic pH.

oxidizing potential less than +2.4 volts. From the table above, hydrogen peroxide has an oxidation potential of +1.8 volts. In this example, hydrogen peroxide does not have the oxidation potential to oxidize Pu(+4) to Pu(+6).

Other preventative measures include filtration and separation of TRU prior to oxidation and control of oxidation by measuring oxidation-reduction potential to maintain the system to below the potential to oxidize TRU compounds.

Once oxidation and crystallization is complete, the system is returned to redox neutral by the addition of sodium nitrite or blending with raw waste, as required by the tank farms acceptance criteria. The benefit of oxidation for the improvement of sodium yield occurs only when the initial sodium nitrite substantially exceeds the amount needed to meet the tank farms acceptance criteria.

APPENDIX E

APPENDIX E

BATCH EVAPORATION MODELS

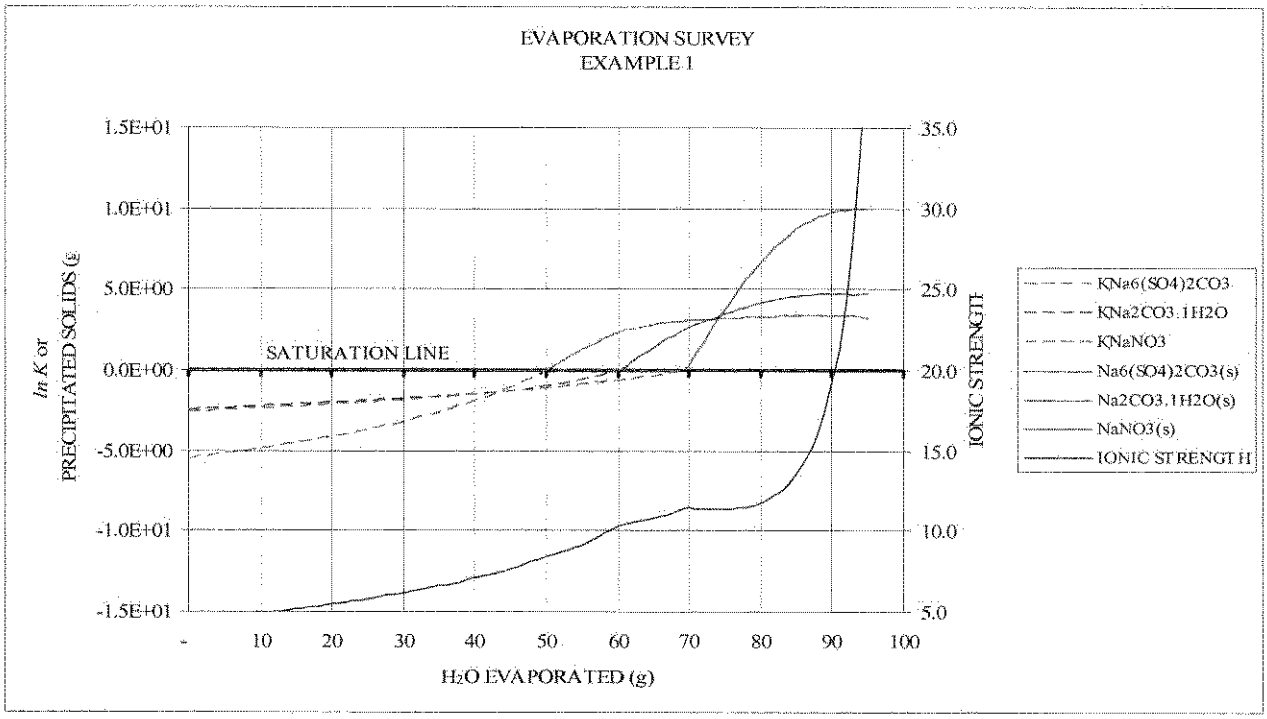
E1.0 BASE CASE

Initial Conditions:

Temperature	40°C
H_2O	100.0 g
Na_2SO_4	2.5
Na_2CO_3	5.0
$NaNO_3$	10.0
NaOH	7.0
Total	124.5 g

Figure E-1 illustrates changes in ionic strength, ionic activities, solubility products, and the type and amount of crystals that form during batch evaporative crystallization of the sample. Because of the large span in the numbers, solubility products are shown on a natural logarithmic scale.

Figure E-1. Evaporation Survey



The initial ionic strength is 4.4. Ionic activities of Na^+, SO_4^{-2}, CO_3^{-2}, NO_3^{-1}, OH^{-1} and H_2O are 2.56, 0.00378, 0.01048, 0.4625, 1.699, and 0.8855 respectively. Using the calculations shown above, the initial saturation ratios for $Na_6(SO_4)_2CO_3(s)$, $Na_2CO_3 \cdot 1H_2O(s)$, and $NaNO_3(s)$ are 0.00425, 0.0861, and 0.0752 respectively; the salts are undersaturated at the initial conditions.

Upon evaporation of 50 g H_2O and an ionic strength of 8.5, $Na_6(SO_4)_2CO_3$ becomes saturated. That is, the calculated solubility product equals the saturated solubility product of 1.007×10^{-2}.

$$K_{Na6(SO4)2CO3} = \{\alpha_{Na}\}^6\{\alpha_{SO4}\}^2\{\alpha_{CO3}\} = \{6.638\}^6\{0.00377\}^2\{0.00806\} = 1.007x10^{-2} \quad \text{(E-1)}$$

$$S_{Na6(SO4)2CO3} = K_{CALC} / K_{SAT} = 1 \quad \text{(E-2)}$$

$$\ln S_{Na6(SO4)2CO3} = 0 \quad \text{(E-3)}$$

This is shown by the red dashed line in the diagram. As the system becomes concentrated, the solubility product increases in proportion to the sixth power of the sodium activity to the saturation line. Beyond saturation, $Na_6(SO_4)_2CO_3$ begins to crystallize at a rate to maintain the solubility product equal to 1.007×10^{-2}. This is shown by the solid red line in the diagram. Although sodium sulfate is removed from solution at twice the rate of sodium carbonate, the solubility product for $Na_6(SO_4)_2CO_3$ remains constant after saturation.

Upon evaporation of a total of 61 g of water and an ionic strength of 10.4, 2.5 g of $Na_6(SO_4)_2CO_3$ has crystallized; $Na_2CO_3 \cdot 1H_2O$ becomes saturated when its solubility product equals 7.108×10^{-1}. This is shown by the blue dashed line in the diagram.

At $Na_2CO_3 \cdot 1H_2O$ saturation:

$$K_{Na2CO3 \cdot 1H2O} = \{\alpha_{Na}\}^2\{\alpha_{CO3}\}\{\alpha_{H2O}\} = \{8.952\}^2\{0.01292\}\{0.6868\} = 7.108x10^{-1} \quad \text{(E-4)}$$

and

$$K_{Na6(SO4)2CO3} = \{\alpha_{Na}\}^6\{\alpha_{SO4}\}^2\{\alpha_{CO3}\} = \{8.952\}^6\{0.00123\}^2\{0.01292\} = 1.007x10^{-2} \quad \text{(E-5)}$$

Beyond this point, $Na_2CO_3 \cdot 1H_2O$ co-crystallizes with $Na_6(SO_4)_2CO_3$ at rates to maintain both solubility products constant.

Upon evaporation of 70 g H_2O, 3.1 g of $Na_6(SO_4)_2CO_3$ and 2.7 g $Na_2CO_3 \cdot 1H_2O$ have crystallized, $NaNO_3$ becomes saturated at an ionic strength of 11.4. This is shown by the green dashed line. At this point, the solubility products for three salts are equal to the saturated values.

$$K_{NaNO3} = \{\alpha_{Na}\}\{\alpha_{NO3}\} = \{12.867\}\{1.2267\} = 1.579x10^{1} \tag{E-6}$$

and

$$K_{Na2CO3 \cdot 1H2O} = \{\alpha_{Na}{}^{2}\}\{\alpha_{CO3}\}\{\alpha_{H2O}\} = \{12.867\}^{2}\{0.00711\}\{0.60435\} = 7.108x10^{-1} \tag{E-7}$$

and

$$K_{Na6(SO4)2CO3} = \{\alpha_{Na}\}^{6}\{\alpha_{SO4}\}^{2}\{\alpha_{CO3}\} = \{12.867\}^{6}\{0.00056\}^{2}\{0.00711\} = 1.007x10^{-2} \tag{E-8}$$

Beyond this point, the three salts co-crystallize. The remaining salt NaOH is highly soluble (128 g NaOH/100 g H_2O @ 40°C). Further evaporation causes a dramatic increase in ionic strength because of increasing sodium ion activity due to the concentration of unsaturated NaOH.

For this study, an ionic strength of 20 M will be used as an endpoint of evaporation. The actual practical limit for evaporation may be more or less than 20 due to the density and/or viscosity of the solution.

After evaporation of 90.4 g H_2O, at an ionic strength of 20, sodium activity has increased to 200. At this point, total of 3.4, 4.2, and 9.7 g of $Na_6(SO_4)_2CO_3$, $Na_2CO_3 \cdot 1H_2O$, and $NaNO_3$ have crystallized. Theoretical yields for sulfate, carbonate and nitrate are 98.5, 99.6, and 97.9%. Theoretical sodium yield is 57.9%.

To improve the yield of sodium salts by evaporative crystallization, carbon dioxide (CO_2) may be used to convert sodium hydroxide to sodium carbonate (Na_2CO_3) which may be removed as $Na_2CO_3 \cdot 1H_2O_{(s)}$ by evaporative crystallization.

$$2NaOH + CO_2(g) \rightarrow Na_2CO_3 + H_2O \rightarrow Na_2CO_3 \cdot 1H_2O(s) \tag{E-9}$$

To illustrate the effects of carbonation on ionic activities and solubility products, the sample in Example 1 is reacted with 2.75 g of CO_2 prior to evaporation. The resulting composition is as follows:

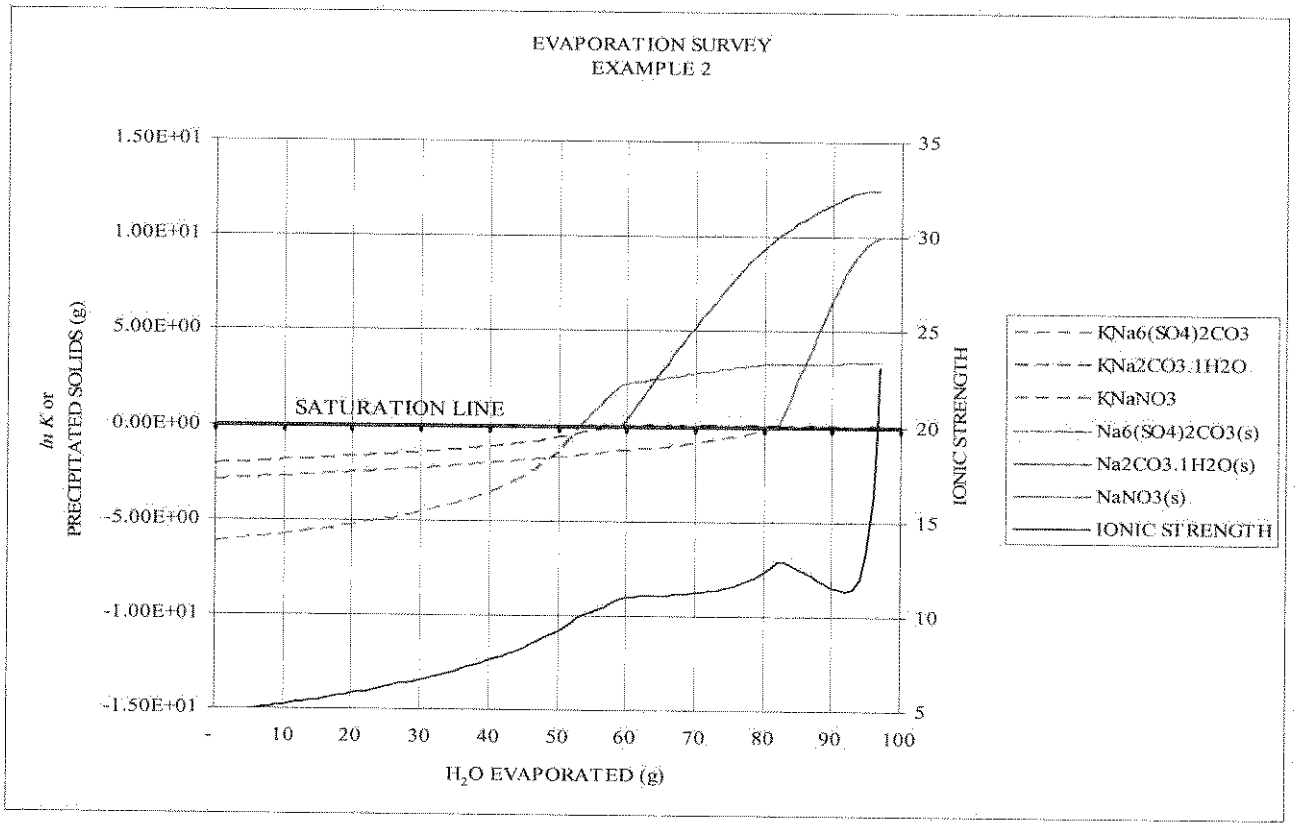
E2.0 CARBONATION OF NAOH

Initial Conditions:

Temperature	40°C
H_2O	101.13 g
Na_2SO_4	2.50
Na_2CO_3	11.62
$NaNO_3$	10.00
NaOH	2.00
Total	127.25 g

As in the previous example, the salts are undersaturated at the initial conditions. A survey of the evaporation is shown in Figure E-2.

Figure E-2. Evaporation Survey.



As indicated in the diagram, more $Na_2CO_3 \cdot 1H_2O$ crystallizes and ionic strength is reduced over the base case above 80 g H_2O evaporated. The carbonate activity has increased due to the higher initial Na_2CO_3 concentration. However, sodium activity is reduced (due a lower sodium activity coefficient γ_{Na}). These effects partially offset in the calculation of solubility products.

Upon evaporation of 55 g of water and an ionic strength of 10.2, $Na_6(SO_4)_2CO_3$ becomes saturated.

$$\begin{aligned} K_{Na6(SO4)2CO3} &= \{\alpha_{Na}\}^6\{\alpha_{SO4}\}^2\{\alpha_{CO3}\} \\ &= \{4.06497\}^6\{0.00777\}^2\{0.03697\} = 1.007x10^{-2} \end{aligned} \tag{E-10}$$

$Na_6(SO_4)_2CO_3$ saturation occurs slightly later than the previous example due to the effects noted above - (higher α_{CO3} but lower α_{Na}).

After evaporation of 60 g of water and an ionic strength of 11.0, 2.23 g of $Na_6(SO_4)_2CO_3$ crystallizes and $Na_2CO_3 \cdot 1H_2O$ becomes saturated. This is slightly lower (1 g) than Example 1, again because the higher carbonate activity is offset by the lower sodium activity. The solubility products are:

$$\begin{aligned} K_{Na2CO3 \cdot 1H2O} &= \{\alpha_{Na}\}^2\{\alpha_{CO_3}\}\{\alpha_{H_2O}\} \\ &= \{4.31987\}^2\{0.04515\}\{0.85736\} = 7.108x10^{-1} \end{aligned} \tag{E-11}$$

and

$$\begin{aligned} K_{Na6(SO4)2CO3} &= \{\alpha_{Na}\}^6\{\alpha_{SO4}\}^2\{\alpha_{CO3}\} \\ &= \{4.31987\}^6\{0.00586\}^2\{0.04515\} = 15.79 \end{aligned} \tag{E-12}$$

$Na_6(SO_4)_2CO_3$ and $Na_2CO_3 \cdot 1H_2O$ co-crystallize to maintain both solubility products constant. The increasing sodium activity (due to $NaNO_3$) during evaporation drives the crystallization reactions "to the right".

Upon evaporation of 84.5 g H_2O, 3.3 g of $Na_6(SO_4)_2CO_3$ and 10.2 g $Na_2CO_3 \cdot 1H_2O$ have crystallized, $NaNO_3$ becomes saturated at an ionic strength of 12.9. This is a significantly higher evaporation amount (14 g) than Example 1, because much of the sodium has been depleted from the aqueous phase by precipitating $Na_2CO_3 \cdot 1H_2O$. At this point, the solubility products for three salts are equal to the saturated values.

$$K_{NaNO3} = \{\alpha_{Na}\}\{\alpha_{NO3}\} = \{7.4262\}\{2.1260\} = 1.579x10^{-1} \tag{E-13}$$

and

$$\begin{aligned} K_{Na2CO3 \cdot 1H2O} &= \{\alpha_{Na}\}^2\{\alpha_{CO3}\}\{\alpha_{H2O}\} \\ &= \{7.4262\}^2\{0.0190\}\{0.67841\} = 7.108x10^{-1} \end{aligned} \tag{E-14}$$

and

$$K_{Na6(SO4)2CO3} = \{\alpha_{Na}\}^6\{\alpha_{SO4}\}^2\{\alpha_{CO3}\} = \{7.4262\}^6\{0.00178\}^2\{0.0190\} = 1.007x10^{-2} \quad \text{(E-15)}$$

Beyond this point, the three salts co-crystallize. The remaining 2 g of NaOH is highly soluble and stays in solution. However, with the amount of NaOH reduced by carbonation, ionic strength does not increase as dramatically as in Example 1.

At an ionic strength of 20 M, a total of 3.4, 12.5, and 9.9 g of $Na_6(SO_4)_2CO_3$, $Na_2CO_3 \cdot 1H_2O$, and $NaNO_3$ have crystallized. Theoretical yields for sulfate, carbonate and nitrate are 98.3, 99.9, and 99.4%. Theoretical sodium yield is 88.0%.

Thus, carbonation can increase sodium yield by converting highly soluble NaOH to less soluble Na_2CO_3 which can be crystallized as $Na_2CO_3 \cdot 1H_2O$. In this case, the sodium yield increased 57.9 from to 88.0% at an ionic strength of 20 M.

The effects of the complementary solubility of $NaNO_2$-$NaNO_3$ will de demonstrated in the next example. If the initial composition of sodium nitrate was split (on a mole basis) between sodium nitrite and sodium nitrate, the initial conditions would be:

E3.0 NANO$_2$/NANO3 EUTECTIC

Initial Conditions:

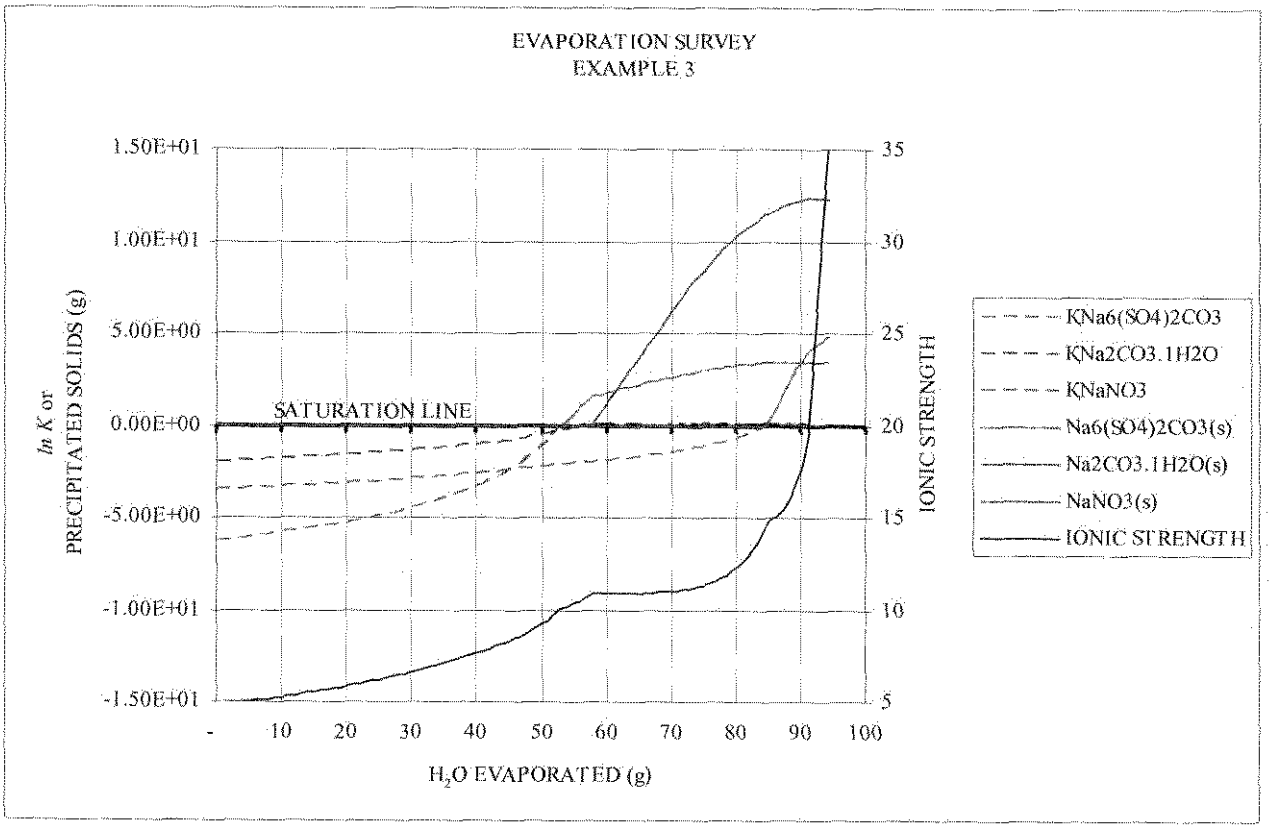
Temperature	40°C
H_2O	101.13 g
Na_2SO_4	2.50
Na_2CO_3	11.62
$NaNO_2$	4.06
$NaNO_3$	5.00
NaOH	2.00
Total	126.31 g

As shown in Figure E-3, $Na_6(SO_4)_2CO_3$ and 10.2 g $Na_2CO_3 \cdot 1H_2O$ have similar saturation points and yields as in Example 2. However, the saturation point of $NaNO_3$ has shifted to the right because of the lower initial concentration of $NaNO_3$.

$$K_{NaNO3} = \{\alpha_{Na}\}\{\alpha_{NO3}\} = \{11.6588\}\{1.3545\} = 15.79 \quad \text{(E-16)}$$

Saturation of $NaNO_3$ occurs after 85.3 g H_2O evaporated and an ionic strength of 14.88. At this point, ionic strength begins to rise rapidly due to the complementary solubility of $NaNO_2$ and $NaNO_3$.

Figure E-3. Evaporation Survey.



At an ionic strength of 20, sodium nitrite has not reached saturation. A total of 3.4, 12.5, and 4.0 g of $Na_6(SO_4)_2CO_3$, $Na_2CO_3 \cdot 1H_2O$, and $NaNO_3$ have crystallized. Theoretical yields for sulfate, carbonate and nitrate are 97.8, 99.0, and 80.1%. Theoretical sodium yield is 70.9%.

Thus, the presence of sodium nitrite decreases sodium and nitrate yield because of the eutectic it forms with sodium nitrate. To improve the yield of sodium and nitrate, oxidation may be used to convert sodium nitrite to sodium nitrate.

$$NaNO_2 + H_2O_2 \rightarrow NaNO_3 + H_2O \qquad \text{(E-17)}$$

By this method, the composition of Example 3 would be converted to the composition of Example 2 (with slightly more H_2O), and the theoretical sodium and nitrate yield would improve to 88.0 and 94.4% at an ionic strength of 20 M.

E4.0 SODIUM ALUMINATE

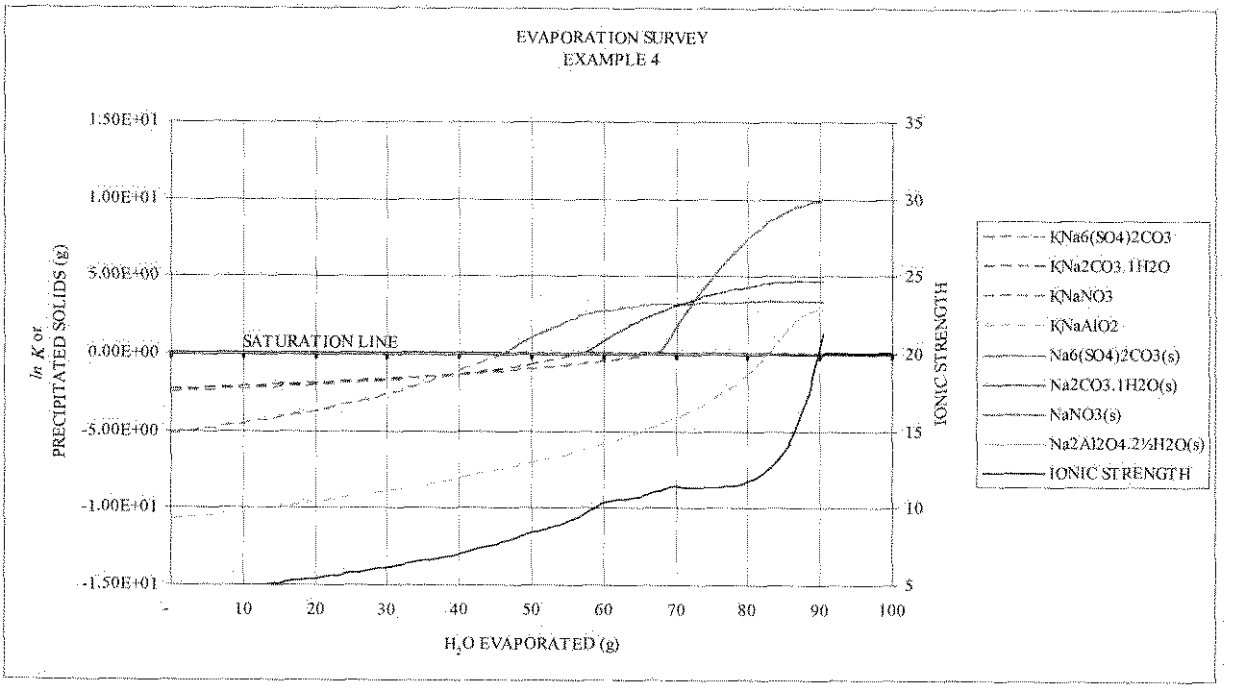
Initial Conditions:

Temperature	40°C
H_2O	100.0 g
Na_2SO_4	2.5

Na_2CO_3	5.0
$NaNO_3$	10.0
NaOH	7.0
$NaAlO_2$	2.5
Total	127.0 g

As shown in Figure E-4, alumina is soluble (as the $Al(OH)_4^{-1}$ ion) during evaporation and crystallization of $Na_6(SO_4)_2CO_3$, $Na_2CO_3 \cdot 1H_2O$, and $NaNO_3$. These salts crystallize at the same saturation points and produce the same yield as in Example 1. During this period, the solubility of alumina increases because the increasing hydroxide activity. The solubility product of gibbsite is:

Figure E-4. Evaporation Survey.



$$K_{Al(OH)3} = \{\alpha_{Al(OH)4-1}\}\{\alpha_{OH-1}\}^{-1} \qquad \text{(E-18)}$$

Initially, the saturation ratio for gibbsite is 0.93. Gibbsite solubility increases during the evaporation because an increasing $Al(OH)_4^{-1}$ activity is offset by a greater increasing OH^{-1} activity. This is shown by the orange dotted line in Figure 12. Thus, gibbsite becomes more soluble during evaporation of this sample because of increasing hydroxide concentration.

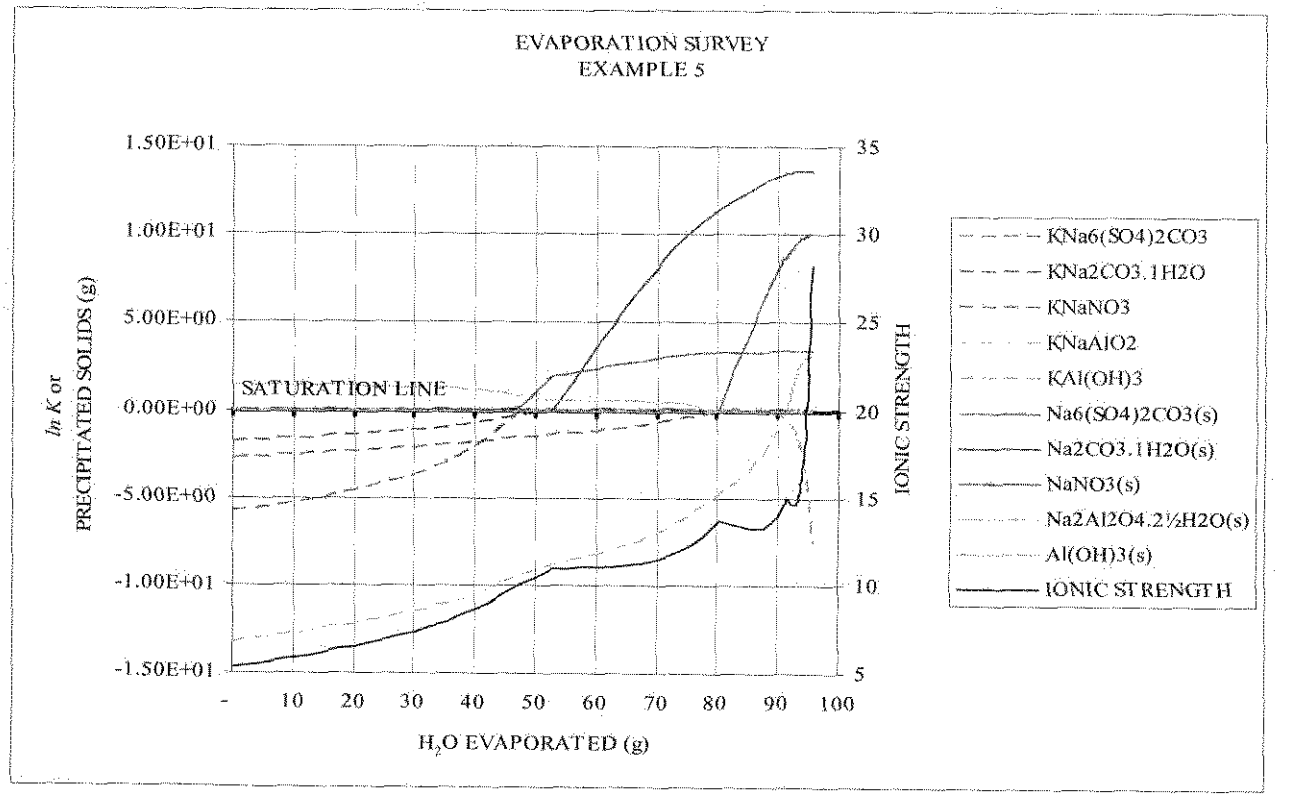
After evaporation of 84 g of water to an ionic strength of 13.0, sodium aluminate 2.5 hydrate ($Na_2Al_2O_4 \cdot 2½H_2O$) reaches saturation and begins to crystallize. At this point, the solubility product for $Na_2Al_2O_4 \cdot 2½H_2O$ is:

$$K_{SAH} = \{\alpha_{Na}\}\{\alpha_{Al(OH)4}\}^2\{\gamma_{H2O}\}^{-1.5}$$
$$= \{54.857\}^2\{0.9141\}^2\{0.3613\}^{-1.5} = 1.156x10^4 \quad \text{(E-19)}$$

As the ionic strength reaches 20 M, a total of 3.4, 4.7, 9.9, and 2.9 g of $Na_6(SO_4)_2CO_3$, $Na_2CO_3 \cdot 1H_2O$, $NaNO_3$, and $Na_2Al_2O_4 \cdot 2½H_2O$ have crystallized. Theoretical yields for sulfate, carbonate, nitrate, and alumina are 98.2. 99.6, 98.9, and 46.1%. Theoretical sodium yield is 56.6%.

As shown in Figure E-5 (as in Example 1), the uncrystallized sodium exists as highly soluble NaOH. To increase sodium yield, the sample is carbonated (as in example 2) to convert NaOH to Na_2CO_3.

Figure E-5. Evaporation Survey.



E5.0 GIBBSITE PRECIPITATION

Initial Conditions:

Temperature	40°C
H_2O	101.13 g
Na_2SO_4	2.5
Na_2CO_3	11.62
$NaNO_3$	10.0
NaOH	2.0
$NaAlO_2$	2.5
Total	129.75 g

In this example, carbon dioxide has been added to convert most of the NaOH to Na_2CO_3, and gibbsite is precipitated.

Gibbsite has very slow crystal growth rates. To fully equilibrate gibbsite at 40°C may require as much as 264 hours.[35] Thus, a fully developed crystalline gibbsite may not form during carbonation. It has been demonstrated that rapid carbonation can cause alumina gel formation.[36] For this example, gibbsite is considered to be initially precipitated.

Upon evaporation, this sample exhibits the same saturation points for $Na_6(SO_4)_2CO_3$ and $Na_2CO_3 \cdot 1H_2O$ as Example 2. The sodium nitrate saturation point is shifted slightly to the left because of the added sodium from $NaAlO_2$ in the starting material.

During this period of evaporation, alumina becomes more soluble because of increasing OH^- activity as in Example 4. The saturation ratio for gibbsite reduces below 1.0 at 77.6 g of H_2O evaporated and an ionic strength of 12.8. Beyond this point, gibbsite is undersaturated and all alumina is in solution until the $Na_2Al_2O_4 \cdot 2\frac{1}{2}H_2O$ saturation point is reached. The $Na_2Al_2O_4 \cdot 2\frac{1}{2}H_2O$ saturation point occurs at 91.5 g H_2O evaporated and an ionic strength of 15.0.

At an ionic strength of 20 M, a total of 3.4, 4.7, 9.9, and 2.9 g of $Na_6(SO_4)_2CO_3$, $Na_2CO_3 \cdot 1H_2O$, $NaNO_3$, and $Na_2Al_2O_4 \cdot 2\frac{1}{2}H_2O$ have crystallized. Theoretical yields for sulfate, carbonate, nitrate, and alumina are 98.3, 99.9, 99.4 and 48.9%. Theoretical sodium yield is 87.0%. As in Example 2, carbonation has increased sodium yield by converting NaOH to Na_2CO_3.

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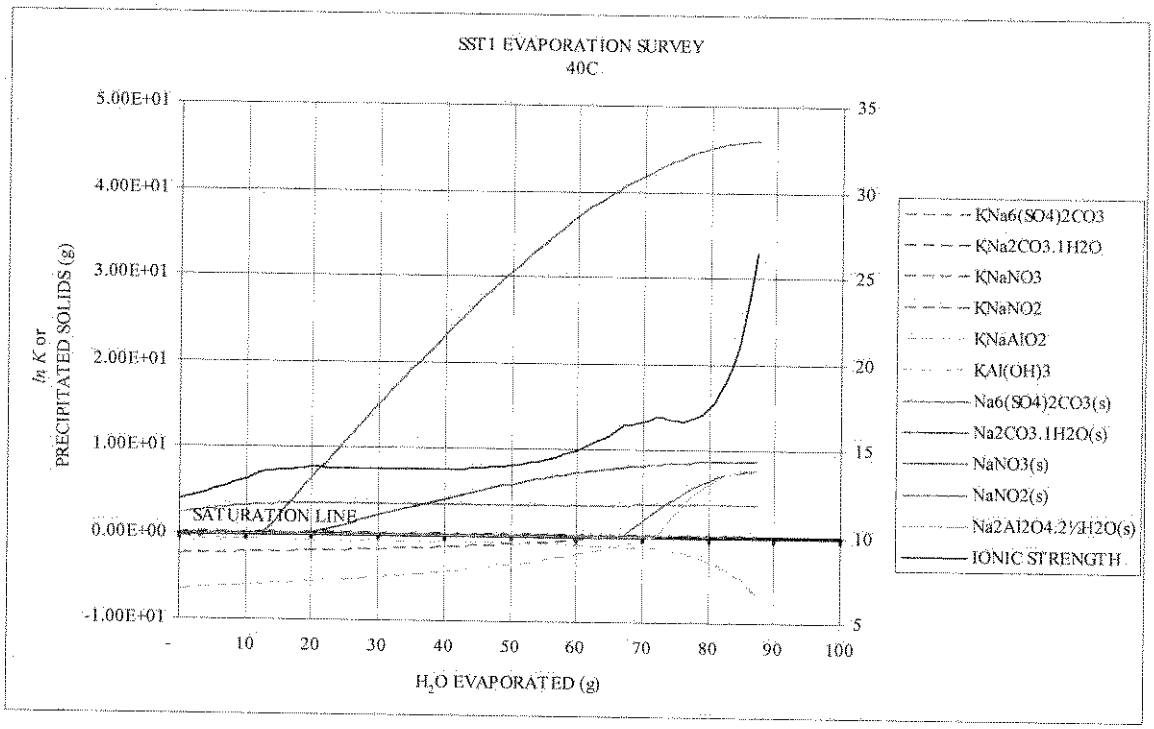
[35] Thermochemical Properties of Gibbsite, Bayerite, Boehmite, Diaspore, and the Aluminate Ion Between 0 and 350C. NUREG/CR-5271, T189 006046 J. A. Apps, J. M. Neil, C.-H. Jun. Lawrence Berkeley Laboratory.
[36] "Aluminum Precipitation from Hanford DSSF," Wiley, J.R., University of Texas – Permian Basin, Contract QW098921, September 30, 1993.

E6.0 SST EARLY FEED

A simplified composition of the SST Early Feed simulant is shown in Figure E-6. These compounds are the dominant sodium salts in the system. Trace components KOH, NaCl, Na_3PO_4, Na_2CrO_4, NaF, $Na_2C_2O_4$, CsOH are included in the thermodynamic model, but not shown in this example for simplicity.

Figure E-6. SST Early Feed Survey 40°C.



Initial Conditions:

Temperature	25°C
H_2O	100 g
Na_2SO_4	2.66
Na_2CO_3	7.38
$NaNO_2$	7.86
$NaNO_3$	46.11
NaOH	13.26
$Al(OH)_3$	6.06
Total	131.21 g

In comparison to the earlier examples, this material is relatively high in $NaNO_3$. An evaporation survey at 40°C (Figure E-6 above) indicates that burkeite is saturated a the initial conditions and $NaNO_3$ reaches saturation and crystallizes between $Na_6(SO_4)_2CO_3$ and $Na_2CO_3 \cdot 1H_2O$.

In this example, the theoretical yields for sodium, sulfate, carbonate, nitrate, nitrite, and alumina evaporated to an ionic strength of 20 are 76.1, 99.6, 99.5, 99.1, 92.5, and 90.2%. The 24% sodium yield loss is largely due to highly soluble sodium hydroxide. The effect of sodium hydroxide on ionic strength can be seen by the inflection of the curve above 80 g of H_2O evaporated.

Because of kinetic limitations, it may not be desirable to co-crystallize sodium nitrate with sodium sulfate and carbonate. Sodium nitrate is a fast growing crystal and has temperature dependent solubility. Burkeite and carbonate monohydrate are slow-growth crystals and have retrograde temperature solubility.

E7.0 SST LATE FEED

A simplified composition of the SST late feed simulant is shown below. As in the early feed example, trace components KOH, NaCl, Na_3PO_4, Na_2CrO_4, NaF, $Na_2C_2O_4$, CsOH are included in the thermodynamic model, but not shown in this study for simplicity.

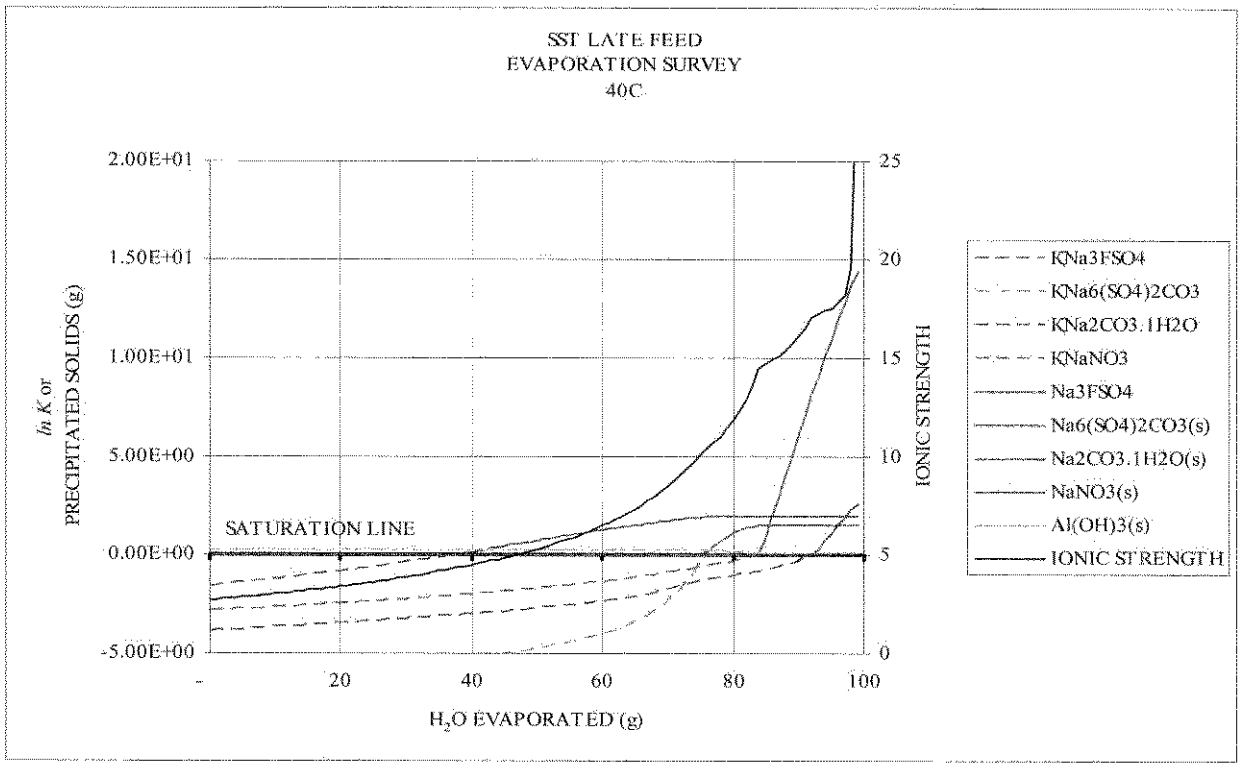
Initial Conditions:

Temperature	25°C
H_2O	100 g
Na_2SO_4	2.63
Na_2CO_3	2.78
$NaNO_2$	0.53
$NaNO_3$	14.82
NaOH	0.15
NaF	0.46
$Al(OH)_3$	0.34
Total	121.71 g

In comparison to the SST Early Feed, this sample has a higher concentration of sodium fluoride, a near equal amount of sodium sulfate, but lower concentrations of sodium carbonate, nitrate, and hydroxide. At the initial conditions, 90% of the alumina would be insoluble at 25°C.

Figure E-7 is an evaporation survey at 40°C.

Figure E-7. SST Late Feed Evaporation Survey 40°C.



The initial ionic strength is 2.7. At the initial conditions, 0.30 g of gibbsite ($Al(OH)_3$) are precipitated. Upon evaporation, gibbsite becomes more soluble due to the increasing free hydroxide and ionic strength.

In this example, the solution salts do not reach saturation until 38 g of water are evaporated. It may be beneficial to pre-evaporate excess water from this material prior to crystallization to increase available waste tank volume.

In this example, schairerite (Na_3FSO_4) is the first sodium salt to reach saturation at 38 g of water evaporated and an ionic strength of 4.4. By forming the double salt schairerite during evaporative crystallization, sodium sulfate scavenges sodium fluoride from the aqueous phase[37]. The solubility product for schairerite at 40°C is:

$$K_{Na_3FSO_4} = \{\alpha_{Na}\}^3\{\alpha_F\}\{\alpha_{SO4}\} = \{1.78683\}^3\{0.06666\}\{0.01132\} = 1.00028 \qquad \text{(E-20)}$$

The next salt to reach saturation is burkeite at 76 g of water evaporated and an ionic strength of 10.4. Sodium nitrate saturates at 85 g of water evaporated and an ionic strength of 17.3. Sodium carbonate monohydrate reaches saturation at 93 g of water evaporated and an ionic strength of 17.2.

[37] The crystallization and separation of schairerite is beneficial to Hanford waste handling; sodium fluoride co-precipitates with sodium phosphate in the waste to form low solubility sodium fluoride phosphate non-decahydrate ($Na_7F(PO_4)_2 \cdot 19H_2O$). This highly-hydrated double salt removes water from solution and has low solubility.

Because of the low initial sodium hydroxide and nitrite, an ionic strength of 20 is not reached until 98 g of water are evaporated. At this point, the theoretical yields of sodium, sulfate, carbonate, nitrate, and fluoride are 88.2, 99.9, 85.0, 92.2, and 99.7%. The remaining sodium yield loss is mainly due to soluble sodium nitrate and carbonate above an ionic strength of 20. Alumina yield has dropped to 13% due to increased solubility.

As in the SST early feed example, it may be beneficial to conduct the SST late feed crystallization in two stages: one higher temperature stage to crystallize sodium sulfates and carbonates and a lower temperature stage to crystallize sodium nitrate. This method may benefit the crystal growth rates of schairerite and burkeite.

However, in this case, because of the low initial sodium carbonate concentration, higher temperatures (60-100°C) do not shift the sodium carbonate monohydrate saturation point ahead of the sodium nitrate saturation point. High temperatures can cause the transition of sodium carbonate monohydrate to anhydrous sodium carbonate. Thus, in this case, it would not be beneficial to crystallize sodium carbonate at higher temperatures.

E8.0 DST FEED

A simplified composition of the DST simulant is shown below.

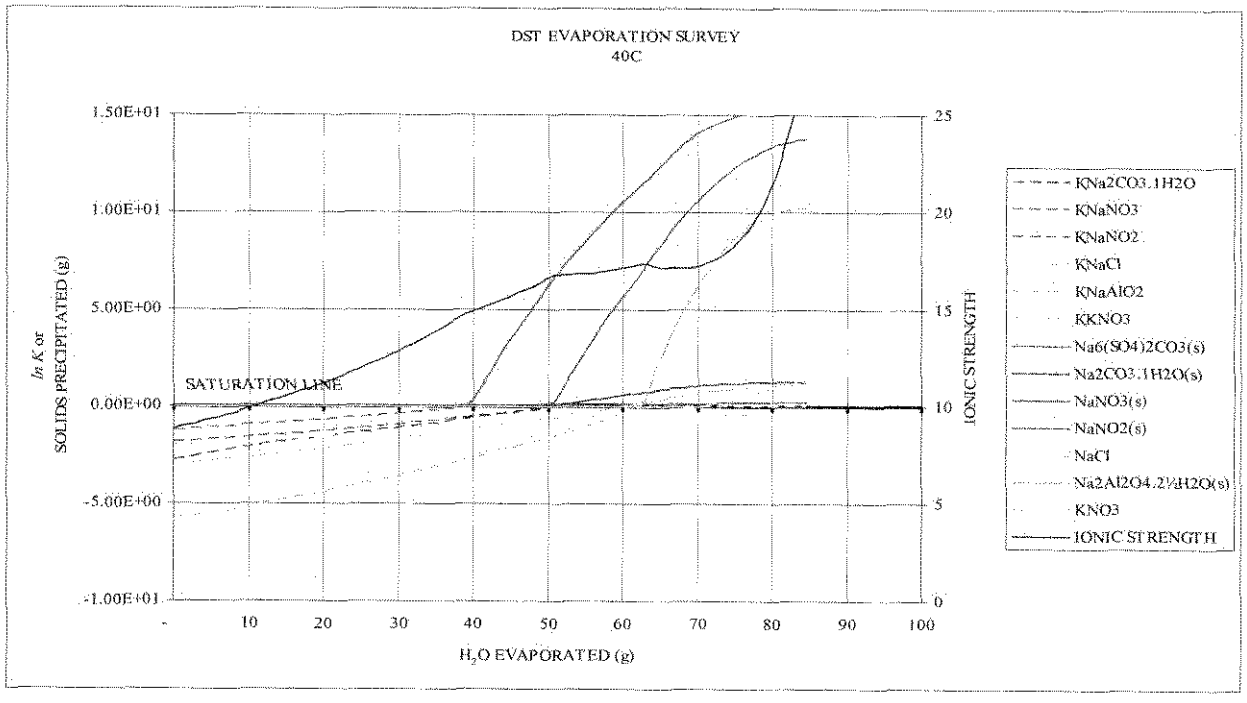
Initial Conditions:

Temperature	25°C
H_2O	100 g
Na_2SO_4	0.18
Na_2CO_3	1.21
$NaNO_2$	13.99
$NaNO_3$	16.61
NaOH	16.88
NaF	0.08
NaCl	1.19
KOH	1.92
$Al(OH)_3$	7.91
Total	159.98 g

Compared to the previous example, the DST simulant has lower concentrations of sodium sulfate, carbonate, and fluoride. It has higher concentrations of sodium nitrate, nitrite, hydroxide, chloride, and aluminum and potassium hydroxide.

Figure E-8 is an evaporation survey at 40°C.

Figure E-8. DST Evaporation Survey.



The initial ionic strength of the system is 8.9 M. At 40°C, no major salts are initially saturated; and there is sufficient free hydroxide to dissolve all of the alumina as sodium aluminate. As the system is evaporated, the ionic strength increases rapidly due to the presence of high solubility sodium hydroxide and aluminate.

During evaporation, major salts $NaNO_3$, $NaNO_2$, $Na_2Al_2O_4 \cdot 2\frac{1}{2}H_2O$, $Na_2CO_3 \cdot 1H_2O$, NaCl, and KNO_3 crystallize; minor double salts schairerite and burkeite co-crystallize. For this study, only the major salts are considered for simplicity of the example.

The first major salt to reach saturation is sodium nitrate at 40 g of H_2O evaporated and an ionic strength of 14.9. Sodium carbonate and sodium nitrite reach saturation at 49 g of H_2O evaporated and an ionic strength of 16.7. At this point, the system reaches the $NaNO_2$-$NaNO_3$ invariant, and the ionic strength begins to level out.

Sodium chloride reaches saturation at 60 g H_2O evaporated and an ionic strength of 17.1. Sodium aluminate reaches saturation at 62 g H_2O evaporated and an ionic strength of 17.3. Potassium nitrate reaches saturation at 70.7 g H_2O evaporated and an ionic strength of 17.3.

The solubility products for NaCl and KNO_3 at 40°C are:

$$K_{NaCl} = \{\alpha_{Na}\}\{\alpha_{Cl}\} = \{32.55502\}\{1.13676\} = 37.003 \quad \text{(E-21)}$$

$$K_{KNO_3} = \{\alpha_{K}\}\{\alpha_{NO_3}\} = \{1.99815\}\{0.43141\} = 1.0958 \quad \text{(E-22)}$$

At an ionic strength of 20, the amounts of sodium carbonate monohydrate, sodium nitrate, sodium nitrite, sodium chloride, sodium aluminate, and potassium nitrate are 1.28, 15.26, 13.14, 1.10, 9.642, and 0.866 g. The theoretical yields of sodium, potassium, sulfate, carbonate, nitrate, nitrite, chloride, and aluminate are 56.0, 25.0, 94.1, 95.7, 91.8, 94.9, 92.6, and 91%. The primary sodium yield loss is due to the high initial concentration of sodium hydroxide.

To increase sodium yield, reduce ionic strength, liquid density, and viscosity the DST sample may be initially treated to remove alumina as gibbsite, free hydroxide neutralized to Na_2CO_3 or $NaNO_3$, and $NaNO_2$ oxidized to $NaNO_3$.

APPENDIX F

APPENDIX F

PRELIMINARY ALARA EVALUATION FOR THE FRACTIONAL CRYSTALLIZATION SYSTEM

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Preliminary ALARA Evaluation of the Fractional Crystallization System

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Preliminary ALARA Evaluation of the Fractional Crystallization System

List of Acronyms and Symbols

ALARA	As Low As Reasonably Achievable
DFCS	Demonstration Fractional Crystallization System
DST	Double Shell Tank
SST	Single Shell Tank
DR	dose rate
cm	centimeter
g	gram
ft^3	cubic feet
cc	cubic centimeter
wt%	weight percent
kg	kilogram
p	photon
l	liter
cm^2	square centimeter
hr	hour
sec	second
mm	millimeter
min	minute

Preliminary ALARA Evaluation of the Fractional Crystallization System

1.0 OBJECTIVE

This evaluation is based on a preliminary conceptual design of the Fractional Crystallization System and as such will be revised as additional detail on design and facility operation emerge. The primary objective of this document is to provide an estimation of the total dose received by the operations and maintenance staff working at the DFCS over a one year period during normal conditions. The secondary objective of this document is to provide recommendations that will reduce the dose below 500 person-mrem per year and achieve appropriate ALARA goals. The design process includes an estimate of the occupational dose assessment for the facility. ALARA evaluations are performed and documented to determine cost-effective design enhancements to reduce exposures. This evaluation does not address airborne containments, radioactive effluent releases or any accident conditions or scenarios.

2.0 METHOD

Dose rates are calculated using the computer code MicroShield. The input and output files are attached. Radiation shielding is selected to minimize personnel occupational exposures based on facility occupancy for normal operations and facility maintenance. Personnel exposures are estimated based on similar facility experience for access requirements, and standard shielding methods are used to estimate radiation fields. The method is iterated to minimize the number of personnel that have the potential of receiving 500 mrem/yr.

3.0 INPUTS

The Dose rates at various distances from the DFCS facility are calculated using MicroShield. The parameters for the computer code calculation are located in the following sections and in Appendix A through Appendix C.

3.1 Geometry

The general arrangement and overall geome try of the various systems and components were considered in this evaluation. Based on the location and the source term contained within the 1st Stage Crystallizer, it was selected as the most limiting component for shielding design considerations. For modeling purposes the following assumptions were used: (1) A cylindrical geometry of 4'h x 6'd was used to approximate the area within the crystallizer that contains the ~830 gallons of liquid as stated in the DFCS System Description. (2) The volume used in the Microshield model was 113ft^3 (844 gal.) which compares favorably to the preliminary design operating capacity of the crystallizer. (3) There are other components, including recirculation piping that will contain radioactive liquids but for the purposes of this limited evaluation they were not included in this evaluation. (4) The Crystallizer will be constructed of 304L stainless steel (0.5" thickness). See attached data sheets for geometries used in dose calculations including crystallizer dimensions, shield thicknesses and configurations.

3.2 Materials

The Crystallizer will be constructed of 304L stainless steel (0.5" thickness). A density of (1) g/cc was used for the source material. Shield walls were based on concrete with a density of 2.4 g/cc. See attached data sheets for specifications on materials used in dose calculations including crystallizer material, shield materials and associated densities.

3.3 Source Description

For the purpose of this preliminary dose estimate and shielding evaluation, the source of the maximum expected dose rate was assumed to be the DFCS crystallizers. There are two (2) possible feeds into the DFCS, the Single Shell Tanks (SSTs) and the Double Shell Tanks (DSTs). They have expected concentrations of up 2.244 Ci/L and 8.53 Ci/L respectively. For the purpose of this evaluation, the higher feed source(DST) was used in the model. The DST PFD, the composition of Stream 8 ("FLASH") in the crystallizer is in three phases: liquid, solid, and vapor. The mass of the liquid phase is 35.26 lb/hr, the solid 31.03 lb/hr, and the vapor 33.55 lb/hr. The total mass is the flow rate times the residence time. So the slurry composition (liquid + solid) is 46.38wt% solids. The solids mainly consist of sodium nitrate (74%), and sodium carbonate. Water (17%) with a density of 19.027 lb/gal. The DFCS crystallizers will contain radioactive liquid with a concentration of up to 8.53 Ci/liter of Cs^{137} mixed into a slurry and introduced into the crystallizer. The resulting concentration will be ~5.11 Ci/L of Cs^{137} activity assuming (8.53 Ci/L)*(2.44 gal liquid) /(2.44 gal liq + 1.63 gal solid) = 5.11 Ci/L (~40 % reduction). Each crystallizer is designed to operate with a minimum liquid volume of 530 gallons, a normal liquid volume of 830 gallons, and a high liquid level of 1140 gallons. This does not include the volume of tank waste that is contained in the recirculation piping. A rough estimate of the quantity of material that is contained in the recirculation piping is 100 gallons. Based on the volume and concentration of Cs^{137}, up to 16,300 Curies may be present with the crystallizer vessel during some evolutions. The DFCS crystallizers produce sodium salt crystals from dissolved salts in tank waste. The crystals are produced by evaporating water from tank waste solutions and growing crystals in the supersaturated solution. The sizes of the crystallizers are based on the required residence time for growing separable crystals. The crystallizers are designed to allow thorough washing and cleaning to remove accumulated deposits.

4.0 ASSUMPTIONS

- The First Stage Crystallizer is assumed to be the highest dose rate component with volume estimated at ~845 gal.
- Personnel entries are limited to designated areas for tours & inspections.
- Prior to entry into the facility high dose rate (DR) material is flushed from components, vessels and piping. Dose rates are verified via remote rad monitoring instrumentation.
- Cs^{137} is the principle nuclide and the maximum concentration of Cs137 does not exceed 8.5 Ci/L and the effective concentration of the slurry is ~5.11Ci/L
- Only occupational workers have access to the facility and fenced surrounding areas.
- The facility is operated remotely.

- 2 Operators/ 8hr shift.
- 2 Maintenance techs/crew
- Working hours/shift = 8.
- Working days/year = 250.
- All materials that contain, may contain, or contact tank waste or treated tank waste are constructed of 304L stainless steel.
- A whole-body dose ACL (administrative control limit <500 mrem/yr) to aid in keeping radiation doses ALARA was established. This ACL is substantially below the DOE ACL of 2000 mrem/yr per person for all DOE activities
- Restricted area fence line is 30' from exterior surface of DFCS.
- Control room is located >30' from DFCS.

5.0 CONFIRMATION REQUIRED

None.

6.0 COMPUTER PROGRAM IDENTIFICATION

MicroShield v5.05 (5.05-00538) has been verified and validated for the use of calculating dose rates.

7.0 RESULTS

The MicroShield calculated dose rates at various distances from the 1st Stage Crystallizer processing feed from the DSTs were used for this estimate. The results can be seen in Summaries provided in Appendix A, B and C. Dose points were selected at various locations to determine the dose rates at locations where facility staff would be expected to perform their duties. The locations and estimated durations are provided in the Table below and serve as the basis for this estimate. A general arrangement sketch, Appendix D, is provided to illustrate the relative locations used and are noted as Zones A, B and C.

The total individual estimated annual exposure for the operations and maintenance staff is approximately 211 mrem per year per for each individual and a total collective dose of 2113 person-mrem annually. It should be noted that this dose only includes direct exposure and does not account for dose received from other potential exposure pathways.

In addition to the dose estimates for processing the DST feed, an evaluation was performed using the expected source term associated with the feed from SSTs. The results of that evaluation were annual exposures to operations and maintenance personnel of approximately 73 mrem per year per for each individual and a total collective dose of 728 person-mrem annually. It should be noted that this dose only includes direct exposure and does not account for dose received from other potential exposure pathways. For comparison purposes the difference between the projected annual exposure to the DFCS personnel at a facility handling SST feed verses DST is directly proportion to Cs^{137}concentration in the feed. The lower source term associated with processing the

feed from the SSTs results in doses that are approximately 35% of those expected from the DST source term.

8.0 CONCLUSION

The following tables are an estimation of expected occupational doses at the DFCS during normal operations. No allowances or design considerations have been incorporated for accident scenarios. Table 1 represents DST doses and Table 2 represents SST doses.

Projected Occupational Doses for DFCS Ops. & Maint. Activities (DST Feed)

					dose (mremTEDE)			
location	Task Description	GA dose rate (mR/hr)	Occu. time hrs.	# staff	indiv daily	collect daily	indiv. annual	Collect annual
A	Operator tours & inspection (1/shift)	6	0.125	6	0.27	1	188	1125
A	Preventive Maintenance (daily)	6	0.125	4	0.27	2	188	750
B	Operator tours & inspection (4/shift)	0.07	0.5	6	0.01	2	9	53
B	Preventive Maintenance (daily)	0.07	0.5	4	0.01	3	9	35
C	Operator tours & inspection (4/shift)	0.008	7.5	6	0.02	0	15	90
C	Preventive Maintenance (daily)	0.008	7.5	4	0.7	1	15	60
					Ops total		211	1268
					Maint. Total		211	845
					Total Crew		423	2113

Table 1

As seen in Table 1 the projected individual doses for the staff is less than 500 mrem/yr TEDE based on the stated dose rates resulting from the DST feed source and occupancy times . These estimates will be revised as more detailed design and operating parameters evolve.

Projected Occupational Doses for DFCS Ops. & Maint. Activities (SST Feed)

					dose (mremTEDE)			
location	Task Description	GA dose rate (mR/hr)	Occu. time hrs.	# staff	indiv daily	collect daily	indiv. annual	Collect annual
A	Operator tours & inspection (1/shift)	2.13	0.125	6	0.27	2	67	399
A	Preventive Maintenance (daily)	2.13	0.125	4	0.27	1	67	266
B	Operator tours & inspection (4/shift)	0.02	0.5	6	0.01	0	3	15
B	Preventive Maintenance (daily)	0.02	0.5	4	0.01	0	3	10
C	Operator tours & inspection (4/shift)	0.002	7.5	6	0.02	0	4	23
C	Preventive Maintenance (daily)	0.002	7.5	4	0.02	0	4	15
					Ops total		73	437
					Maint. Total		73	291
					Total Crew		146	728

Table 2

As seen in Table 2 the projected individual doses for the staff is less than 500 mrem/yr TEDE based on the stated dose rates resulting from the SST feed source and occupancy times. Expected dose rates and expected personnel exposure are approximately 35% of that of the DST feed shown

in Table 1 above. These estimates will be revised as more detailed design and operating parameters evolve.

9.0 RECOMMENDATIONS

- Utilize remote video monitoring equipment to reduce entry occurrences into facility.
- Place valve operators, gauges, etc. in low dose areas to the greatest extent practical to lower personnel exposure.
- Ensure ventilation system design is adequate to maintain DFCS under negative pressure and to provide an acceptable monitored release pathway.
- A more detailed and comprehensive ALARA evaluation should be performed that will account for direct exposure from the source term present in all systems and components.
- An analysis/evaluation of all other potential exposure pathways should be performed to ensure the facility design meets all applicable DOE design requirements.
- A determination must be made as to the accessibility and occupancy factors for the DFCS fence line. For the purpose of this evaluation, it is assumed that only occupational workers have access to that area. However, if a member of the public has access to the DFCS fence line, it may be necessary to extend the fence further from the DFCS facility to ensure that exposure to a member of the public dose not exceed 100 mrem/yr..

10.0 REFERENCES

1) *DST Fractional Crystallization System Conceptual Design, COGEMA-DWG-002*

2) *DFCS General Arrangement Conceptual Sketch, 08/11/05*

3) *DFCS Preliminary Safety Analysis, 05/05/05*

4) *MicroShield User's Manual; version 5, Grove Engineering 1992-1998*

5) *Calculation and Measurement of Direct and Scattered Gamma Radiation from LWR Nuclear Power Plants*, ANSI/ANS-6.6.1 – 1987.

11.0 CALCULATION REVISIONS

None.

Preliminary ALARA Evaluation of the Fractional Crystallization System

Appendix A

MicroShield input and output

1st Stage Crystallizer w 2' shields
FCS#1

Preliminary ALARA Evaluation of the Fractional Crystallization System

Page : 1
DOS File : FCS#1.MS5
Run Date: August 25, 2005
Run Time: 10:15:44 AM
Duration : 00:00:02

MicroShield v6.02 (6.02-00146)

File Ref: _____
Date: _____
By: _____
Checked: _____

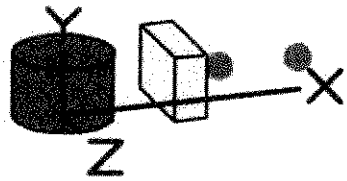
Case Title: FCS Dose Est.
Description: 1st Stage Crystallizer with 2' shield
Geometry: 7 - Cylinder Volume - Side Shields

Source Dimensions

Height	121.92 cm	4 ft
Radius	91.44 cm	3 ft

Dose Points

	X	Y	Z
# 1	252.984 cm	60.96 cm	0 cm
	8 ft 3.6 in	2 ft	0.0 in
# 2	304.8 cm	60.96 cm	0 cm
	10 ft 0.0 in	2 ft	0.0 in
# 3	457.2 cm	60.96 cm	0 cm
	15 ft	2 ft	0.0 in



Shields

Shield Name	Dimension	Material	Density
Source	3.20e+06 cm³	Water	1.95
Transition	91.44 cm	Air	0.00122
Shield 3	60.96 cm	Concrete	2.4
Air Gap		Air	0.00122
Wall Clad	1.27 cm	Iron	7.8
Top Clad	1.27 cm	Iron	7.8

Source Input
Grouping Method : Actual Photon Energies

Nuclide	curies	becquerels	µCi/cm³	Bq/cm³
Ba-137m	1.5401e+004	5.7281e+014	4.8341e+003	1.7886e+008
Cs-137	1.6365e+004	6.0551e+014	5.1100e+003	1.8907e+008

Buildup
The material reference is : Source

Integration Parameters

Radial	10
Circumferential	10
Y Direction (axial)	20

Results - Dose Point # 1 - (252.984,60.96,0) cm

Energy MeV	Activity photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.0318	1.186e+13	2.021e-09	4.138e-19	1.683e-91	3.447e-21
0.0322	2.188e+13	2.484e-06	8.370e-19	1.999e-88	6.736e-21
0.0364	7.962e+12	1.621e-62	7.995e-19	9.212e-65	4.542e-21
0.6616	5.154e+14	7.808e+01	5.762e+03	1.514e-01	1.117e+01
TOTALS:	5.571e+14	7.808e+01	5.762e+03	1.514e-01	1.117e+01

Results - Dose Point # 2 - (304.8,60.96,0) cm

Energy MeV	Activity photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.0318	1.186e+13	1.745e-09	2.810e-19	1.454e-91	2.341e-21
0.0322	2.188e+13	2.136e-06	5.684e-19	1.719e-88	4.574e-21
0.0364	7.962e+12	1.342e-62	5.429e-19	7.624e-65	3.085e-21
0.6616	5.154e+14	5.737e+01	4.186e+03	1.112e-01	8.116e+00
TOTALS:	5.571e+14	5.737e+01	4.186e+03	1.112e-01	8.116e+00

Results - Dose Point # 3 - (457.2,60.96,0) cm

Energy MeV	Activity photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.0318	1.186e+13	1.111e-09	1.227e-19	9.258e-92	1.022e-21
0.0322	2.188e+13	1.352e-06	2.482e-19	1.088e-88	1.998e-21
0.0364	7.962e+12	8.016e-63	2.371e-19	4.554e-65	1.347e-21
0.6616	5.154e+14	2.666e+01	1.925e+03	5.169e-02	3.732e+00
TOTALS:	5.571e+14	2.666e+01	1.925e+03	5.169e-02	3.732e+00

Preliminary ALARA Evaluation of the Fractional Crystallization System

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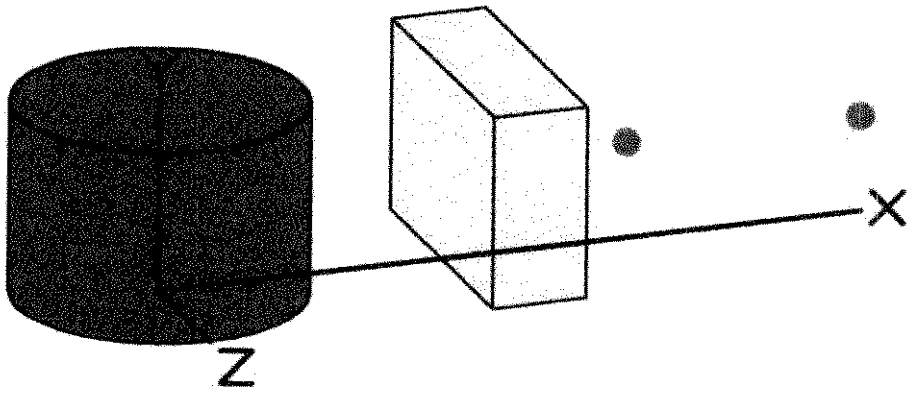


Appendix B

MicroShield input and output

1st Stage Crystallizer w/o shielding
FCS#2

Preliminary ALARA Evaluation of the Fractional Crystallization System

Page : 1
DOS File : FCS#2.MSS
Run Date : August 25, 2005
Run Time : 10:13:14 AM
Duration : 00:00:03

MicroShield v6.02 (6.02-00146)

File Ref:
Date:
By:
Checked:

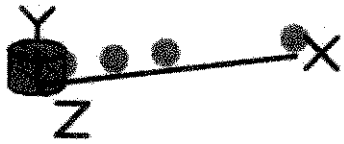
Case Title: FCS dose est
Description: 1st Stage Crystallizer w/o shield
Geometry: 7 - Cylinder Volume - Side Shields

Source Dimensions

Height	121.92 cm	4 ft
Radius	91.44 cm	3 ft

Dose Points

	X	Y	Z
# 1	94.488 cm 3 ft 1.2 in	60.96 cm 2 ft	0 cm 0.0 in
# 2	277.368 cm 9 ft 1.2 in	60.96 cm 2 ft	0 cm 0.0 in
# 3	460.248 cm 15 ft 1.2 in	60.96 cm 2 ft	0 cm 0.0 in
# 4	917.448 cm 30 ft 1.2 in	60.96 cm 2 ft	0 cm 0.0 in



Shields

Shield Name	Dimension	Material	Density
Source	3.20e+06 cm³	Water	1.95
Transition		Air	0.00122
Air Gap		Air	0.00122
Wall Clad	.5 cm	Iron	7.8
Top Clad	.5 cm	Iron	7.8

Source Input
Grouping Method : Actual Photon Energies

Nuclide	curies	becquerels	µCi/cm³	Bq/cm³
Ba-137m	1.5481e+004	5.7281e+014	4.8341e+003	1.7886e+008
Cs-137	1.6365e+004	6.0551e+014	5.1100e+003	1.8907e+008

Buildup
The material reference is : Transition

Integration Parameters

Radial	10
Circumferential	10
Y Direction (axial)	20

Results - Dose Point # 1 - (94.488,60.96,0) cm

Energy MeV	Activity photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.0318	1.186e+13	5.525e-12	2.212e-10	4.602e-14	1.842e-12
0.0322	2.188e+13	3.202e-11	1.327e-09	2.577e-13	1.068e-11
0.0364	7.962e+12	2.628e-07	1.589e-05	1.493e-09	9.030e-08
0.6616	5.154e+14	1.322e+08	5.309e+08	2.563e+05	1.029e+06
TOTALS:	5.571e+14	1.322e+08	5.309e+08	2.563e+05	1.029e+06

Results - Dose Point # 2 - (277.368,60.96,0) cm

Energy MeV	Activity photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.0318	1.186e+13	4.512e-09	1.244e-07	3.758e-11	1.036e-09
0.0322	2.188e+13	2.078e-08	5.917e-07	1.672e-10	4.762e-09
0.0364	7.962e+12	2.138e-05	8.535e-04	1.215e-07	4.849e-06
0.6616	5.154e+14	1.276e+07	4.229e+07	2.475e+04	8.198e+04
TOTALS:	5.571e+14	1.276e+07	4.229e+07	2.475e+04	8.198e+04

Results - Dose Point # 3 - (460.248,60.96,0) cm

Energy MeV	Activity photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.0318	1.186e+13	1.594e-09	4.382e-08	1.327e-11	3.650e-10
0.0322	2.188e+13	7.315e-09	2.080e-07	5.887e-11	1.674e-09
0.0364	7.962e+12	7.443e-06	2.980e-04	4.229e-08	1.693e-06
0.6616	5.154e+14	4.135e+06	1.379e+07	8.016e+03	2.673e+04
TOTALS:	5.571e+14	4.135e+06	1.379e+07	8.016e+03	2.673e+04

Results - Dose Point # 4 - (917.448,60.96,0) cm

Energy MeV	Activity photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.0318	1.186e+13	3.250e-10	9.002e-09	2.707e-12	7.498e-11
0.0322	2.188e+13	1.497e-09	4.287e-08	1.205e-11	3.450e-10
0.0364	7.962e+12	1.571e-06	6.348e-05	8.925e-09	3.607e-07
0.6616	5.154e+14	9.218e+05	3.125e+06	1.787e+03	6.059e+03
TOTALS:	5.571e+14	9.218e+05	3.125e+06	1.787e+03	6.059e+03

Preliminary ALARA Evaluation of the Fractional Crystallization System

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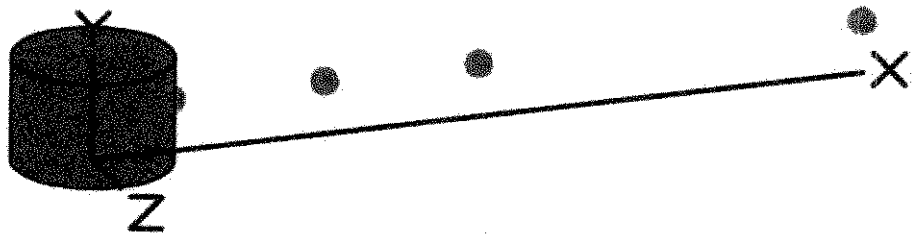

Preliminary ALARA Evaluation of the Fractional Crystallization System

Appendix C

MicroShield input and output

1st Stage Crystallizer w/ shielding at fence line
FCS#3

Preliminary ALARA Evaluation of the Fractional Crystallization System

Page : 1
DOS file : FCS#3.MSS
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Run Time: 10:19:03 AM
Duration : 00:00:02

MicroShield v6.02 (6.02-00146)

File Ref: _____
Date: _____
By: _____
Checked: _____

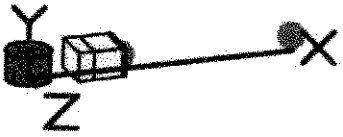
Case Title: FCS Dose Estimate
Description: 1st Stage Crystallizer Dose rate @ ext wall & fence line
Geometry: 7 - Cylinder Volume - Side Shields

Source Dimensions

Height	121.92 cm	4 ft
Radius	91.44 cm	3 ft

Dose Points

	X	Y	Z
# 1	1143 cm 37 ft 6.0 in	60.96 cm 2 ft	0 cm 0.0 in
# 2	399.288 cm 13 ft 1.2 in	60.96 cm 2 ft	0 cm 0.0 in



Shields

Shield Name	Dimension	Material	Density
Source	3.20e+06 cm³	Water	1.95
Transition	91.44 cm	Air	0.00122
Shield 2	68.58 cm	Concrete	2.4
Shield 3	121.92 cm	Air	0.00122
Shield 4	15.24 cm	Concrete	2.4
Air Gap		Air	0.00122
Wall Clad	1.27 cm	Iron	7.8
Top Clad	1.27 cm	Iron	7.8

Source Input
Grouping Method : Actual Photon Energies

Nuclide	curies	becquerels	uCi/cm³	Bq/cm³
Ba-137m	1.5481e+004	5.7281e+014	4.8341e+003	1.7886e+008
Cs-137	1.6365e+004	6.0551e+014	5.1100e+003	1.8907e+008

Buildup
The material reference is : Shield 2

Integration Parameters

Radial	10
Circumferential	10
Y Direction (axial)	20

Results - Dose Point # 1 - (1143,60.96,0) cm

Energy MeV	Activity photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.0045	5.946e+12	0.000e+00	1.577e-23	0.000e+00	1.081e-23
0.0318	1.186e+13	8.401e-114	4.399e-22	6.998e-116	3.665e-24
0.0322	2.188e+13	4.932e-110	8.435e-22	3.985e-112	6.788e-24
0.0364	7.962e+12	2.130e-80	4.701e-22	1.210e-82	2.671e-24
0.6616	5.154e+14	5.729e-02	4.356e+00	1.111e-04	8.444e-03
TOTALS:	5.631e+14	5.729e-02	4.356e+00	1.111e-04	8.444e-03

Results - Dose Point # 2 - (399.288,60.96,0) cm

Energy MeV	Activity photons/sec	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.0045	5.946e+12	0.000e+00	1.314e-22	0.000e+00	9.004e-23
0.0318	1.186e+13	4.877e-113	3.664e-21	4.062e-115	3.052e-23
0.0322	2.188e+13	2.907e-109	7.025e-21	2.340e-111	5.654e-23
0.0364	7.962e+12	1.393e-79	3.915e-21	7.916e-82	2.224e-23
0.6616	5.154e+14	4.786e-01	3.659e+01	9.279e-04	7.094e-02
TOTALS:	5.631e+14	4.786e-01	3.659e+01	9.279e-04	7.094e-02

Preliminary ALARA Evaluation of the Fractional Crystallization System

Page : 2
DOS File : FCS#3.MSS
Run Date: August 25, 2005
Run Time: 10:19:03 AM
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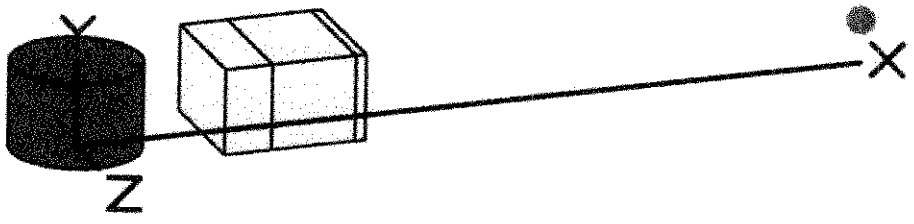
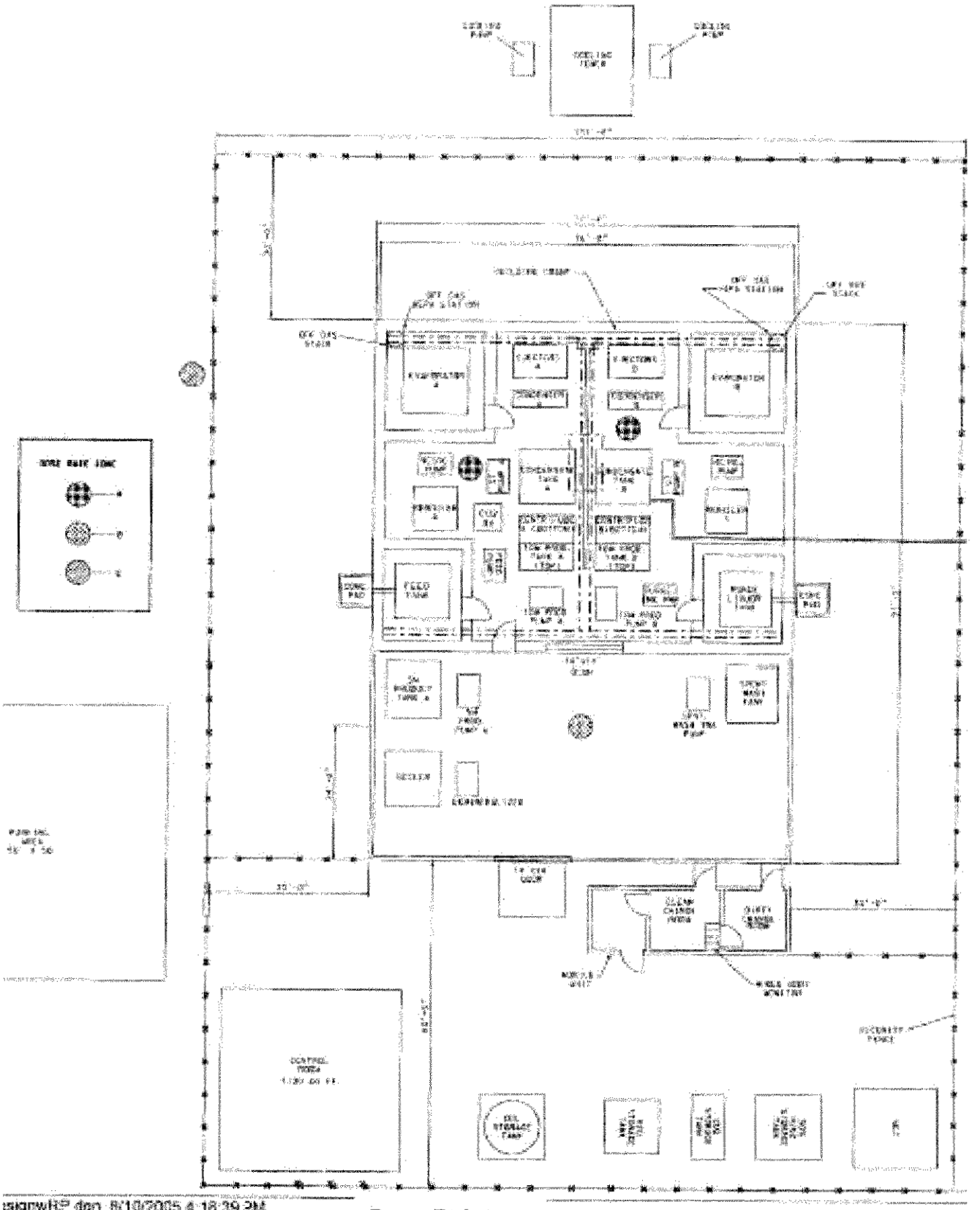


Appendix D

DFCS Facility General Arrangement Drawing

Dose Points

Preliminary ALARA Evaluation of the Fractional Crystallization System



Dose Points

APPENDIX G

APPENDIX G

COST ESTIMATE SUMMARY SHEETS

Summary Costs

Item		Costs	Contingency Amount		Contingency Dollars		Total
Support							
Project Management	$	4,999,424	10%	$	499,942	$	5,499,366
QA	$	881,580	5%	$	44,079	$	925,659
EH&S	$	493,824	5%	$	24,691	$	518,515
Information Management	$	171,418	5%	$	8,571	$	179,989
Regulatory and Licensing	$	1,119,248	10%	$	111,925	$	1,231,173
Subtotal	**$**	**7,665,494**		**$**	**689,208**	**$**	**8,354,702**
Engineering							
Title I Design	$	2,183,019	20%	$	436,604	$	2,619,623
Title II Design	$	5,359,231	35%	$	1,875,731	$	7,234,962
Title III Design	$	581,116	10%	$	58,112	$	639,227
Subtotal	**$**	**8,123,366**		**$**	**2,370,446**	**$**	**10,493,812**
Construction							
Site Work	$	566,401	25%	$	141,600	$	708,001
Building	$	5,078,288	45%	$	2,285,230	$	7,363,518
Process Equipment	$	6,045,396	40%	$	2,418,158	$	8,463,554
Piping and Fittings	$	417,468	30%	$	125,240	$	542,708
Valves	$	192,470	25%	$	48,118	$	240,588
Instrumentation	$	868,351	45%	$	390,758	$	1,259,109
Off Gas System	$	2,316,805	30%	$	695,042	$	3,011,847
Steam Supply	$	211,375	30%	$	63,413	$	274,788
Process Water	$	38,250	30%	$	11,475	$	49,725
Chiller/Condenser System	$	62,276	30%	$	18,683	$	80,959
Construction Mgmt Labor	$	1,680,204	10%	$	168,020	$	1,848,225
Subtotal	**$**	**17,477,283**		**$**	**6,365,736**	**$**	**23,843,019**
Operations (based on 2/17 yr life span)							
Operations Labor	$	99,977,036	10%	$	9,997,704	$	109,974,740
Material	$	26,209,784	15%	$	3,931,468	$	30,141,251
Equipment	$	257,244	30%	$	77,173	$	334,417
Subtotal	**$**	**126,444,064**		**$**	**14,006,344**	**$**	**140,450,408**
Decommissioning							
Characterization	$	142,060	35%	$	49,721	$	191,781
Decomissioning Plan	$	69,237	10%	$	6,924	$	76,161
Field Operations	$	3,033,481	35%	$	1,061,718	$	4,095,199
Final Survey	$	116,716	35%	$	40,850	$	157,566
Final Report	$	67,929	10%	$	6,793	$	74,722
Subtotal	**$**	**3,429,422**		**$**	**1,166,006**	**$**	**4,595,428**
Total Project	**$**	**163,139,629**		**$**	**24,597,741**	**$**	**187,737,370**

WBS	Description	Quantity	Unit	Hours	Rate	FY 2006	FY 2007	FY 2008	FY 2009	FY 2010	Total Dollars	Comments
	Rates are average rates for category shown and are rounded off to nearest dollar											
1.01.01	Project Management & Integration										$ 4,999,424	
	Project Management	1	ea	2080	$ 166	$ 344,968	$344,968	$344,968	$344,968	$344,968	$ 1,724,840	
	Project Controls	0.75	ea	2080	$ 77	$ 120,370	$120,370	$120,370	$120,370	$120,370	$ 601,848	
	Scheduling	0.5	ea	2080	$ 77	$ 80,246	$ 80,246	$ 80,246	$ 80,246	$ 80,246	$ 401,232	
	Purchasing	1	ea	2080	$ 72	$ 149,011	$149,011	$149,011	$149,011	$149,011	$ 745,056	
	Configuration Mgmt	1	ea	2080	$ 108	$ 223,850	$223,850	$223,850	$223,850	$223,850	$ 1,119,248	
	Administration	1	ea	2080	$ 38	$ 79,040	$ 79,040	$ 79,040	$ 79,040	$ 79,040	$ 395,200	
	Travel/Per Diem	1	ea		$ 2,000	$ 2,000	$ 2,000	$ 2,000	$ 2,000	$ 2,000	$ 12,000	
1.01.02	Quality Assurance										$ 881,580	
	Quality Assurance Plan development	1	ea	400	$ 66	$ 26,372		$ 26,372	$ 26,372		$ 79,116	
	QA Manager	1	ea	2080	$ 77	$ 160,493	$160,493	$ 160,493	$ 160,493	$ 160,493	$ 802,464	
1.01.03	EH&S										$ 493,824	
	EH&S Plan development	1	ea	400	$ 77	$ 30,864		$ 30,864	$ 30,864		$ 92,592	
	EH&S Management	0.5	ea	2080	$ 77	$ 80,246	$ 80,246	$ 80,246	$ 80,246	$ 80,246	$ 401,232	
1.01.04	Information Management										$ 171,418	
	IM Support	0.25	ea	2080	$ 66	$ 34,284	$ 34,284	$ 34,284	$ 34,284	$ 34,284	$ 171,418	
1.01.05	Regulatory and Licensing										$ 1,119,248	
	Permitting suport	0.5	ea	2080	$ 108	$ 111,925	$111,925	$ 111,925	$ 111,925	$ 111,925	$ 559,624	
	Licensing Support	0.5	ea	2080	$ 108	$ 111,925	$111,925	$ 111,925	$ 111,925	$ 111,925	$ 559,624	

WBS	Description	Quantity	Unit	Labor Unit Hours	Labor Hours Total	Labor Rate	Labor Dollars	Misc. Cost	Travel Dollars	Sub. Dollars	Total Dollars	Comments
1.02	Engineering, Design and Construction Support						for engineering tasks - averaged rates for Engineer I (60%) Principle Engineer (30%) and Eng. Mgr II (10%) for design tasks - averaged rates for desinger (60%) Tech Spec III (30%) and Engr Mgr II (10%)					
1.02.01	Title I										$ 2,183,019	
	Initial Calculations Mass balance	1		160	160	$ 82.78	$ 13,245		$ 2,000	$ 100,000	$ 115,245	
	Reports	15		20	300	$ 82.78	$ 24,834				$ 24,834	
	Testing/Equipment Outlines	30		60	1800	$ 82.78	$ 149,004				$ 149,004	
	Equipment Outline Specifications	30		40	1200	$ 82.78	$ 99,336				$ 99,336	
	Preliminary Process Design	1		400	400	$ 82.78	$ 33,112		$ 2,000	.	$ 35,112	
	System Description	1		200	200	$ 82.78	$ 16,556			$ 120,000	$ 136,556	
	System Calulations	30		10	300	$ 82.78	$ 24,834				$ 24,834	
	Preliminary Data Sheets	60		10	600	$ 82.78	$ 49,668				$ 49,668	
	Drawings	150		60	9000	$ 82.78	$ 745,020				$ 745,020	
	Building and Utility Pre-Designs	10		40	400	$ 82.78	$ 33,112				$ 33,112	
	Building General Arraingment Dwgs	10		100	1000	$ 82.78	$ 82,780				$ 82,780	
	Permitting/Licensing	1		1000	1000	$ 82.78	$ 82,780		$ 2,000		$ 84,780	
	Engineering Estimate	1		300	300	$ 82.78	$ 24,834				$ 24,834	
	Fire Protection	1		800	800	$ 82.78	$ 66,224				$ 66,224	
	Preliminary Hazards Assessment	1		2000	2000	$ 82.78	$ 165,560		$ 5,000		$ 170,560	
	Preliminary Design Safety Assessment	1		2000	2000	$ 82.78	$ 165,560				$ 165,560	
	Design Management	1		2000	2000	$ 82.78	$ 165,560	$ 5,000	$ 5,000		$ 175,560	Shipping/fedex
	Total				23460							
1.02.02	Title II										$ 5,359,231	
	System Calculations											
	Feed System	1		160	160	$ 82.78	$ 13,245				$ 13,245	
	Primary Steam	1		160	160	$ 82.78	$ 13,245				$ 13,245	
	Recirculation System	2		120	240	$ 82.78	$ 19,867				$ 19,867	
	Primary Loop	1		60	60	$ 82.78	$ 4,967				$ 4,967	
	Condensor System	1		120	120	$ 82.78	$ 9,934				$ 9,934	
	Steam Ejection System	1		120	120	$ 82.78	$ 9,934				$ 9,934	
	Center/Hydro Systems	4		120	480	$ 82.78	$ 39,734				$ 39,734	
	5M & 10M Systems	2		120	240	$ 82.78	$ 19,867				$ 19,867	
	Spent Wash System	2		120	240	$ 82.78	$ 19,867				$ 19,867	
	Purge System	2		120	240	$ 82.78	$ 19,867				$ 19,867	
	Utility Systems	5		120	600	$ 82.78	$ 49,668				$ 49,668	
	System Drains	4		120	480	$ 82.78	$ 39,734				$ 39,734	
	Sump Systems	4		120	480	$ 82.78	$ 39,734				$ 39,734	
	System Drawings	90		80	7200	$ 82.78	$ 596,016				$ 596,016	
	Instrumentation	100		100	10000	$ 82.78	$ 827,800				$ 827,800	
	Controls	3		160	480	$ 82.78	$ 39,734				$ 39,734	
	PLC Drawings	10		40	400	$ 82.78	$ 33,112				$ 33,112	
	Building and Utility Designs											
	Site Layout and Design	1		120	120	$ 82.78	$ 9,934				$ 9,934	
	Facility Layout and Design	1		200	200	$ 82.78	$ 16,556				$ 16,556	
	Structural Design	3		1200	3600	$ 82.78	$ 298,008				$ 298,008	
	Electrical and HVAC	3		300	900	$ 82.78	$ 74,502				$ 74,502	
	Rad Monitoring Systems	3		300	900	$ 82.78	$ 74,502				$ 74,502	
	Fire Protection Systems	3		500	1500	$ 82.78	$ 124,170				$ 124,170	
	Control Room Design	2		250	500	$ 82.78	$ 41,390				$ 41,390	

WBS	Description	Quantity	Unit	Labor Unit Hours	Labor Hours Total	Labor Rate	Labor Dollars	Misc. Cost	Travel Dollars	Sub. Dollars	Total Dollars	Comments
	ALARA	1		400	400	$ 82.78	$ 33,112				$ 33,112	
	Drawings	30		80	2400	$ 82.78	$ 198,672				$ 198,672	
	30&60% Reports											
	Equipment/Component Design	30		40	1200	$ 82.78	$ 99,336				$ 99,336	
	Equipment Specifications	30		40	1200	$ 82.78	$ 99,336				$ 99,336	
	Equipment Fabrication Drawings	90		80	7200	$ 82.78	$ 596,016				$ 596,016	
	Permitting/Licensing Support	3		500	1500	$ 82.78	$ 124,170				$ 124,170	
	Estimates	1		400	400	$ 82.78	$ 33,112				$ 33,112	
	Design Reviews	3		400	1200	$ 82.78	$ 99,336				$ 99,336	
	Design Management	1		2000	2000	$ 122.73	$ 245,460				$ 245,460	
	ORR Prep	1		1200	1200	$ 82.78	$ 99,336				$ 99,336	
	90% Design Review											
	Assume 300 Drawings	300										
	Designer Support											
	Prepare Records Pkg.	10		10	100	$ 78.51	$ 7,851				$ 7,851	
	Review Records Pkg.	10		10	100	$ 107.54	$ 10,754				$ 10,754	
	Approve	10		10	100	$ 122.73	$ 12,273				$ 12,273	
	Assume Vendor Submittals for Documentation, Review, and Processing through Records											
	Assume 300 Submittals											
	Originate	300		1	300	$ 78.51	$ 23,553				$ 23,553	
	Document, Verify and Process	300		1	300	$ 78.51	$ 23,553				$ 23,553	
	Document, Review and Process	300		1	300	$ 107.54	$ 32,262				$ 32,262	
	Approve	300		0.5	150	$ 122.73	$ 18,410				$ 18,410	
	Final Design											
	Assume 300 Drawings											
	Designer Support	300		2	600	$ 78.51	$ 47,106				$ 47,106	
	Prepare Records Pkg.	300		2	600	$ 78.51	$ 47,106				$ 47,106	
	Review Records Pkg.	300		2	600	$ 107.54	$ 64,524				$ 64,524	
	Approve	300		2	600	$ 122.73	$ 73,638				$ 73,638	
	Vendor Submittals (Assume 60)											
	Originate	60		1	60	$ 78.51	$ 4,711				$ 4,711	
	Document, Verify and Process	60		1	60	$ 78.51	$ 4,711				$ 4,711	
	Document, Review and Process	60		1	60	$ 107.54	$ 6,452				$ 6,452	
	Approve	60		0.5	30	$ 122.73	$ 3,682				$ 3,682	
	Final Design Report input	1		10								
	Originate	1		10	10	$ 82.78	$ 828				$ 828	
	Verify	1		3	3	$ 82.78	$ 248				$ 248	
	Review	1		2	2	$ 82.78	$ 166				$ 166	
	Approve	1		1	1	$ 82.78	$ 83				$ 83	
	Drawingsw/Index	300										
	Originate	1		1	1	$ 78.51	$ 79				$ 79	
	Verify	1		1	1	$ 78.51	$ 79				$ 79	
	Testing Procedures											
	Prepare Test Procedures	30		40	1200	$ 82.78	$ 99,336				$ 99,336	
	Review Test Procedures	30		40	1200	$ 82.78	$ 99,336				$ 99,336	

WBS	Description	Quantity	Unit	Labor Unit Hours	Labor Hours Total	Labor Rate	Labor Dollars	Misc. Cost	Travel Dollars	Sub. Dollars	Total Dollars	Comments
	Incorporate comments	30		10	300	$ 82.78	$ 24,834				$ 24,834	
	Approve	30		2	60	$ 82.78	$ 4,967				$ 4,967	
	Startup Procedures											
	Provide Input for Startup Procedure	30		40	1200	$ 82.78	$ 99,336				$ 99,336	
	Review Input for Startup Procedure:	30		40	1200	$ 82.78	$ 99,336				$ 99,336	
	Incorporate comments	30		10	300	$ 82.78	$ 24,834				$ 24,834	
	Approve	30		2	60	$ 82.78	$ 4,967				$ 4,967	
	O&M Mannuals											
	Prepare O&M Packages	60		40	2400	$ 82.78	$ 198,672				$ 198,672	
	Review O&M Packages	60		40	2400	$ 82.78	$ 198,672				$ 198,672	
	Incorporate comments	60		10	600	$ 82.78	$ 49,668				$ 49,668	
	Approve	60		2	120	$ 82.78	$ 9,934				$ 9,934	
			Total Labor		63138							
1.02.03	Title III										$ 581,116	
	System review/acceptance	30		30	900	$ 82.78	$ 74,502				$ 74,502	
	Building and Utility Review & Acceptance	3		120	360	$ 82.78	$ 29,801				$ 29,801	
	Reports	20		20	400	$ 82.78	$ 33,112				$ 33,112	
	Testing/Equipment Verification	30		30	900	$ 82.78	$ 74,502				$ 74,502	
	Equipment Acceptance	90		20	1800	$ 82.78	$ 149,004				$ 149,004	
	Document Management	1		600	600	$ 82.78	$ 49,668				$ 49,668	
	Permitting/Licensing support	1		600	600	$ 82.78	$ 49,668				$ 49,668	
	Design Change Reviews	3		20	60	$ 82.78	$ 4,967				$ 4,967	
	Startup Support	1		600	600	$ 82.78	$ 49,668				$ 49,668	
	ORR Support	1		600	600	$ 82.78	$ 49,668				$ 49,668	
	Turnover to Operations Support	1		200	200	$ 82.78	$ 16,556				$ 16,556	
			Total Labor		7020							

WBS	Item	Quantity	Unit	Material Type	Labor Costs	Material Cost	Total Cost $	Notes
1.03.01	Facility						$ 17,477,283	Facility Subtotal
1.03.01.01	Site work						$ 566,401	Subtotal
	Subsurface Investigation	1	lot		$ 1,000	$ 3,700	$ 4,700	Subsurface investigation with foundation recomndation Means
	Earthwork	1	lot	soil	$ 5,000	$ -	$ 5,000	spoil to be placed within 200 ft includes mob & demob 100cyds Means
	Aggregate	700	ton	0.375		$ 12	$ 8,610	includes delivery 25 miles one way Quote America Rock
	Site Preperation	500	cyds	0.375	$ 5	$ 3	$ 3,760	compaction $5/yd for mob and demob Means
	Utilities Electrical	2	ea		$ 5,990	$ 61,490	$ 134,960	3750 KvA transformer drop with pad/taps 3 phase Means
	Utilities Water (pipeline)	5280	lf	6" PVC	$ 1	$ 13	$ 72,917	process/makeup waterline plus excav and backfill 12"x36" Means
	Utilities Wastewater Holding Tank	2	ea	Fiber		$ 17,400	$ 34,800	12k gallon U/G double walled Means
	Utilities Telephone	1	lot		$ 18,027	$ 11,240	$ 29,267	BVP Basis wired CR for 5 phone/data lines
	Pipeline to ETF	0	lf	NA			$ -	provided by others
	Pipeline to Storage (HLW)	0	lf	NA			$ -	provided by others
	Pipeline to Bulk Vitrification	0	lf	NA			$ -	provided by others
	Fencing	650	lf	steel	$ 4	$ 35	$ 25,064	8 ft chain link with gates
	Concrete Impact Barriers	65	ea	Conc		$ 405	$ 26,325	Barrel type UTMCD Means
	Yard drainage	400	lf		$ 23	$ 18	$ 16,304	4 inlets plus piping and installation Means
	Area Rad Monitoring	2	ea		$ 2,200	$ 43,905	$ 92,210	BVP Basis
	Temporary Power	1	lot			$ 5,000	$ 5,000	temporary power drop and pole Means
	Exterior Security Lighting	8	ea		$ 123	$ 525	$ 5,184	1000 watt pole based Means
	Underground Conduit	500	lf			$ 214	$ 107,000	Means Steel 6@4

1.03.01.02	**Building**								$	5,078,288 Subtotal
	Foundation	500	cyds	conc	$	150	$	99	$	124,500 7,700 sqft with heavy footings 79/cyd + 20/cyd steel american rock and Means and FANP exp
	Floor Coating	7700	sqft	Epoxy			$	2	$	16,632 3 coats epoxy finish (3x.72) Means
	Structure (Building)	935	cyds	conc	$	-	$	593 80	$	555,203 Means 18' high walls 2 times (2x296.90) cast in place concrete walls
	Structure (Columns)	1000	lf	conc	$	20	$	72	$	92,000 Cast in place conc columns
	Interior Cells (walls)	1400	cyds	conc	$	150	$	129	$	390,600 Cast in place conc walls& forms 79/cyd + 50/cyd steel Quote American Rock and Means
	Interior Containment Wall	600	cyds	conc	$	150	$	129	$	167,400 Cast in place conc walls& forms 79/cyd + 50/cyd steel Quote American Rock and Means
	Roof Hatches	2	ea				$	5,000	$	10,000 Estimate
	Roof and supporting concrete Ts	7700	sqft	conc	$	32	$	32	$	490,490 7,700 sqft conc t's - $15.55 plus $16.30 for 60 mil fully adhrd Means
	5 Ton Crane	1	ea	steel			$	850,000	$	850,000 Verbal quote from Whiting Crane Ed Torretta based on WTP cranes
	Catwalks and Maintenance Supports	2	lot	steel	$	1,830	$	6,100	$	15,860 400 sq ft at $7.73/sqft and 100 lf of railing at $30/lf
	Doors and Hatches	1	lot	steel	$	4,110	$	13,700	$	17,810 7 fire rated doors ($400 ea) +2@$5450 hatchways Means
	Misc Sump systems	1	lot	steel			$	10,000	$	10,000 misc pumps and piping FANP exp.
	Misc Pavement	200	cyds	conc	$	79	$	79	$	31,600 3" deep American Rock quote and Means
	Temporary Control Room	1	ea		$	4,900	$	68,140	$	73,040 mobile facility 1440 sqft BVP Basis
	Office Furniture	1	lot				$	3,952	$	3,952 3 desks, 10 chairs, conference table Means
	Restroom Facilities for Control Room	1	ea	sht rck	$	1,500	$	1,500	$	3,000 Sheet rock walled enclosure FANP based Exp
	Plumbing Facilities for Control Room	1	ea				$	1,225	$	1,225 water closet and sink - Means
	Temporary Support Building (change facility)	1	ea		$	4,900	$	68,140	$	73,040 mobile facility 1440 sqft BVP Basis
	Building Systems (Interior Lighting, electrical)	100	ea		$	163	$	500	$	66,300 1000 Watts Means
	Interior Lighting wire and conduit	1	lot				$	15,000	$	15,000 Misc conduit installed FANP exp
	Emergency Exit and Lighting	8	ea		$	82	$	607	$	5,504 NiCad Charged Means
	Emergency Exit and Lighting wire and conduit									
	Building Systems (AC)	1	ea				$	32,900	$	32,900 60 ton Means
	Building Systems (Heating)	1	ea				$	94,500	$	94,500 6970 MBH Means
	Duct Work	5000	lbs	SS			$	8	$	39,000 Means
	CCTV System	8	ea		$	31,600	$	31,600	$	505,600 Quote on camera (tilt zoom rad
	Montiors for CCTV	8	ea				$	479	$	3,832 Dell 19" Flat Panel Monitors
	Fire Detection/Protection	7700	sqft		$	2	$	12	$	107,800 FANP past experience
	Radiation Detection/Monitoring	1	lot		$	70,000	$	140,000	$	210,000 interior area and HVAC, reporting to
	Emergency Generator	1	ea				$	60,000	$	60,000 300Kw with day tank Diesel Generator Means
	Conductors	5000	lf				$	193	$	965,000 1/0 Copper installed Means
	Cable Tray	1500	lf				$	31	$	46,500 4 ft Galv. Means

	Item	Quantity	Unit	Material Type	Installation Costs	Fabrication Cost/unit	Total Cost $	Notes
1.03.02	**Process Equipment - Includes in vessel**						$ 6,045,396	Subtotal Includes vendor markups
	First Stage Crystallizer with support, mesh and trays	1	ea	304L	$ 82,500	$ 825,000	$ 907,500	WTP Based - installation based on crew of 6 at 50% eff. and includes site storage - equates to 10% of fab
	First Stage Reboiler with support and Inconnel tubing	1	ea	304L	$ 65,000	$ 650,000	$ 715,000	WTP Based - installation based on crew of 6 at 50% eff. and includes site storage - equates to 10% of fab
	First Stage Condenser	1	ea	304L	$ 35,000	$ 350,000	$ 385,000	WTP Based - installation based on crew of 6 at 50% eff. and includes site storage - equates to 10% of fab
	First Stage Vacuum System	1	ea	304L	$ 5,000	$ 50,000	$ 55,000	WTP Based - installation based on crew of 6 at 50% eff. and includes site storage - equates to 10% of fab
	First Stage Hydrocyclone	1	ea	304L	$ 10,000	$ 20,000	$ 30,000	Quote
	First Stage Centerfuge	1	ea	304L	$ 2,000	$ 20,000	$ 22,000	Similar to Hydrocylcone
	Oxidation Carbonation Reactor	1	ea	304L	$ 3,000	$ 30,000	$ 33,000	WTP Based - installation based on crew of 6 at 50% eff. and includes site storage - equates to 10% of fab
	First Stage Reboiler Pump with ASD's	1	ea	304L	$ 68,000	$ 680,000	$ 748,000	WTP Based - installation based on crew of 6 at 50% eff. and includes site storage - equates to 10% of fab
	Second Stage Crystallizer	1	ea	304L	$ 82,500	$ 825,000	$ 907,500	WTP Based - installation based on crew of 6 at 50% eff. and includes site storage - equates to 10% of fab
	Second Stage Reboiler with support and Inconnel tubing	1	ea	304L	$ 65,000	$ 650,000	$ 715,000	WTP Based - installation based on crew of 6 at 50% eff. and includes site storage - equates to 10% of fab
	Second Stage Condenser	1	ea	304L	$ 35,000	$ 350,000	$ 385,000	WTP Based - installation based on crew of 6 at 50% eff. and includes site storage - equates to 10% of fab
	Second Stage Vacuum System	1	ea	304L	$ 5,000	$ 50,000	$ 55,000	WTP Based - installation based on crew of 6 at 50% eff. and includes site storage - equates to 10% of fab
	Second Stage Hydrocyclone				$ -		$ -	
	Second Stage Centerfuge				$ -		$ -	
	Feed Tank	1	ea	304L	$ 8,500	$ 85,000	$ 93,500	2,000 gallon plus support
	CO_2 Storage Tank	1	ea	Steel	$ 4,181	$ 41,806	$ 45,987	BVP estimate 80"x40"
	50% H_2O_2 Storage Tank	1	ea	HDPE	$ 1,650	$ 16,500	$ 18,150	Tolplast Catalog 16500 gallon
	Heat Trace and Insulation for H_2O_2 Tank	4000	sqft		$ -	$ 2	$ 9,400	FANP exp R Meachum with insulation
	Condensate Tank A	1	ea	304L	$ 8,500	$ 85,000	$ 93,500	2,000 gallon plus support WTP based
	10 M Product Tank A	1	ea	304L	$ 8,500	$ 85,000	$ 93,500	2,000 gallon plus support WTP based

	Spent Wash Tank	1	ea	304L	$	8,500	$	85,000	$ 93,500	2,000 gallon plus support WTP based
					$	-				
	Condensate Tank B	1	ea	304L	$	8,500	$	85,000	$ 93,500	2,000 gallon plus support WTP based
	5M Product Tank	1	ea	304L	$	8,500	$	85,000	$ 93,500	2,000 gallon plus support WTP based
	Purge Liquor Tank	1	ea	304L	$	8,500	$	85,000	$ 93,500	2,000 gallon plus support WTP based
					$	-				
	Misc. Pumps	14	ea	SS	$	2,334	$	23,335	$ 359,359	Carotek. Inc
1.03.03	**Piping & Fittings**								**$ 417,468**	**Subtotal**
	<1" Diameter	1000	lf	304L	$	9	$	9	$ 18,000	Freguson Quote
	1"	1000	lf	312	$	14	$	14	$ 27,000	Freguson Quote
	2"	0	lf		$	-			$ -	Freguson Quote
	3"	1000	lf	312	$	40	$	40	$ 79,460	Freguson Quote
	4"	1000	lf	312	$	56	$	56	$ 111,500	Freguson Quote
	6"	1	lf	304L	$	10	$	10	$ 20	Freguson Quote
	16"	200	lf	312	$	267	$	267	$ 106,888	Freguson Quote
	Insulation	2000	lf		$	12	$	12	$ 49,600	Fiberglass with metal jacket average diam. Means
	Misc. Hangers	1	lot	A992			$	25,000	$ 25,000	Includes installation FANP exp

1.03.04	**Valves**							$	192,470	Subtotal
	<1" Diameter	40	ea	316		$	1,013	$	40,520	Flowserve
	1"	40	ea	316		$	1,013	$	40,520	Flowserve
	2"	40	ea	316		$	1,013	$	40,520	
	3"	30	ea	316		$	1,013	$	30,390	Flowserve
	4"	20	ea	316		$	1,013	$	20,260	Flowserve
	6"	20	ea	316		$	1,013	$	20,260	
1.03.05	**Instrumentation**							$	868,351	Subtotal
	Flow Meters	50	ea			$	2,550	$	127,500	Means 6" + meter
	Temperature Instruments	50	ea			$	1,500	$	75,000	Estimate
	Raman Probes	3	ea			$	10,000	$	30,000	Website
	Presure Instruments	70	ea			$	2,500	$	175,000	Estimate
	Pump Instrumentation							$	-	
	Radiation Detection/Instrumentation	1	lot		$ 23,866	$	288,407	$	312,273	BVP Basis 6 Alpha,Beta, 6 fixed and 3 Survey stations
	Rad instrumentation support components	1	lot			$	28,841	$	28,841	BVP Basis 6 Alpha,Beta, 6 fixed and 3 Survey stations
	MCC and Process control panels	1	lot			$	50,000	$	50,000	Estimate
	Instrument Air Compressor	1	ea		$ 2,764	$	27,640	$	30,404	Quote Ingersol Rand
	Instrument Air piping	2500	lf	CS	$ 2	$	8	$	25,625	Fergusen
	Computers	2	ea			$	6,854	$	13,708	Dell XPS
1.03.06	**Off Gas System**							$	2,316,805	Subtotal
	Piping	250	ft			$	267	$	66,805	Freguson Quote
	Tank Farm Exhauster System	3	ea			$	750,000	$	2,250,000	Cogema
1.03.07	**Steam Supply System**							$	211,375	Subtotal
	Oil Fired Boiler	2	ea		$ 8,550	$	57,000	$	131,100	Quote from Industrial Combustion
	Demin System	1	ea		$ 3,000	$	22,950	$	25,950	Quote from Culligan
	DW Oil Storage Tank with containment, pad	1	ea		$ 5,000	$	32,785	$	37,785	20,000 gallon double walled with conc pad BVP
	Oil Piping	100	lf		$ 20	$	20	$	4,000	
	Control Panels	1	ea			$	1,140	$	1,140	BVP Basis
	Misc Support Equipment	1	ea			$	11,400	$	11,400	BVP Basis

1.03.08	**Process Water System**							$ 38,250	**Subtotal**
	Water Storage Tank	1	ea	HDPE	$ 5,000	$ 16,500		$ 21,500	Tolplast Catalog 16500 gallon
	Insulation and heaters	1000	sqft		$ 4	$ 13		$ 16,750	past projects
1.03.09	**Chiller/Condenser System**							$ 62,276	**Subtotal**
	Packaged Cooling Tower	582	ton			$ 68		$ 39,576	Means
	Pumps	2	ea			$ 7,050		$ 14,100	Means
	Piping	200	lf			$ 43		$ 8,600	Means 4" Galv

WBS	Description	Quantity	Unit	Labor Unit Hours	Labor Hours Total	Labor Rate	Labor Dollars	Misc. Cost	Travel Dollars	Sub. Dollars	Total Dollars	Comments
1.03.10	Construction Mgmt Labor										$ 1,680,204	
	Construction Manager	1	ea	5200	$ 5,200.00	$ 166	$ 862,420		$ 5,000		$ 867,586	
	Purchasing Support	3	ea	2080	$ 6,240.00	$ 77	$ 481,478		$ 5,000		$ 486,556	
	QA Support	2	ea	2080	$ 4,160.00	$ 77	$ 320,986		$ 5,000		$ 326,063	

WBS	Description	Quantity	Unit	Labor Unit Hours	Labor Hours Total	Unburdened rate	Labor Rate	Labor Dollars	Material Cost	Equipment Dollars	Total Dollars	Comments
2	Plant Operations							$ 99,977,036	$ 26,209,784	$ 257,244	$ 126,444,064	
2.01	Operations							$ 54,649,521			$ 54,649,521	
	Nuclear Chemical Operators	15	each/yr	39,520	592,800	$ 28.51	$ 47.04	$ 27,886,201				
	Operations Manager	1	each/yr	39,520	39,520	$ 45.00	$ 74.25	$ 2,934,360				
	Plant Manager	1	each/yr	39,520	39,520	$ 50.00	$ 82.50	$ 3,260,400				
	Waste shipper	1	each/yr	39,520	39,520	$ 32.00	$ 52.80	$ 2,086,656				
	Admin	2	each/yr	39,520	79,040	$ 26.64	$ 43.96	$ 3,474,282				
	Procedure writer	0.5	each/yr	39,520	19,760	$ 28.51	$ 47.04	$ 929,540				
	Training	0.5	each/yr	39,520	19,760	$ 28.51	$ 47.04	$ 929,540				
	Document Control	1	each/yr	39,520	39,520	$ 26.64	$ 43.96	$ 1,737,141				
	Shift Managers	5	each/yr	39,520	197,600	$ 35.00	$ 57.75	$ 11,411,400				
2.02	Maintenance							$ 11,296,112			$ 11,296,112	
	Maintenance supervisor	1	each/yr	39,520	39,520	$ 37.00	$ 61.05	$ 2,412,696				
	Electricians	0.5	each/yr	39,520	19,760	$ 28.51	$ 47.04	$ 929,540				
	Millwright	0.25	each/yr	39,520	9,880	$ 28.51	$ 47.04	$ 464,770				
	Pipefitter	0.25	each/yr	39,520	9,880	$ 28.51	$ 47.04	$ 464,770				
	Instrument Technician	1	each/yr	39,520	39,520	$ 28.51	$ 47.04	$ 1,859,080				
	Carpenter	0.1	each/yr	39,520	3,952	$ 28.51	$ 47.04	$ 185,908				
	Ironworker	0.25	each/yr	39,520	9,880	$ 28.51	$ 47.04	$ 464,770				
	Painter	0.1	each/yr	39,520	3,952	$ 28.51	$ 47.04	$ 185,908				
	M&TE	0.25	each/yr	39,520	9,880	$ 28.51	$ 47.04	$ 464,770				
	Spare Parts, tool crib	0.25	each/yr	39,520	9,880	$ 28.51	$ 47.04	$ 464,770				
	Planner	1	each/yr	39,520	39,520	$ 30.00	$ 49.50	$ 1,956,240				
	Scheduler	0.5	each/yr	39,520	19,760	$ 30.00	$ 49.50	$ 978,120				
	Drivers	0.25	each/yr	39,520	9,880	$ 28.51	$ 47.04	$ 464,770				
2.03	ES&H							$ 17,446,400			$ 17,446,400	
	ES&H lead	1	each/yr	39,520	39,520	$ 37.00	$ 61.05	$ 2,412,696				
	Health physicist	1	each/yr	39,520	39,520	$ 32.00	$ 52.80	$ 2,086,656				
	Industrial Safety Tech	1	each/yr	39,520	39,520	$ 32.00	$ 52.80	$ 2,086,656				
	Environmental Engineer	0.5	each/yr	39,520	19,760	$ 32.00	$ 52.80	$ 1,043,328				
	Health physics technicians	5	each/yr	39,520	197,600	$ 28.51	$ 47.04	$ 9,295,400				
	QA	0.25	each/yr	39,520	9,880	$ 32.00	$ 52.80	$ 521,664				
2.04	Support Functions							$ 16,585,003			$ 16,585,003	
	Corrective action management	0.1		39,520	3,952	$ 32.00	$ 52.80	$ 208,666				
	Safety basis	0.5		39,520	19,760	$ 35.00	$ 57.75	$ 1,141,140				
	Engineering	5		39,520	197,600	$ 35.00	$ 57.75	$ 11,411,400				
	Admin	1		39,520	39,520	$ 26.64	$ 43.96	$ 1,737,141				
	Procurements	1		39,520	39,520	$ 32.00	$ 52.80	$ 2,086,656				
2.05	Materials & Equipment								$ 26,209,784	$ 257,244	$ 26,467,028	
	CO_2	24,100.00	lbs/week		per lb	$ 0.09	$ 65.00		$ 2,207,192			Based on Air Liquide to Framatome fuel plant $180/ton + $65 delivery

WBS	Description	Quantity	Unit	Labor Unit Hours	Labor Hours Total	Unburdened rate	Labor Rate	Labor Dollars	Material Cost	Equipment Dollars	Total Dollars	Comments
	H_2O_2	37,500.00	lbs/week		per lb	$ 0.33			$ 12,226,500			Based on Cascade Columbia quote
	Utilities - Electricity, water, sewer								$ 954,818			
	Vehicles for plant operation	2	trucks			$ 199.00				$ 90,744		
	Industrial PPE								$ 636,545			
	Rad measuring equipment									$ 86,500		
	Consumables and Handtools								$ 3,182,727			
	Computers	20				$ 1,000.00				$ 80,000		
	Waste disposal								$ 1,909,636			
	Rad PPE (Anti-Cs, laundry)								$ 5,092,364			

Notes	Burden multiplier	1.65	Includes benefits and escalation to 2005 dollars
	19 years (17 full + 2 test) Operation period	19	
	24/7 operation		
	4 shift operation		
	3 operator, 1 HP, 1 supervisor per shift		
	FTE hours per year	2080	
	Consumables and Handtools is x% of shift labor	5%	
	Rad PPE is x% of shift labor	8%	
	Waste disposal is x% of shift labor	3%	
	Computer life span in years	4	
	Industrial PPE is x% of shift labor	1%	
	No escalation		
	Utilities is x% of shift labor	2%	

Rad measuring equipment	10	High flow BZ pumps	1,000.00	each
	12	A & B hand friskers	1,500.00	each
	4	Dose rate meters	1,500.00	each
	10	low volume air samplers	1,000.00	each
	5	high volume air samplers	1,000.00	each
	3	telletectors	3,000.00	each
	16	Iudium 177s 8 A & 8B	1,500.00	each
	3	uR dose meters	1,500.00	each
	1	annual HP off-site calibration	10,000.00	

WBS	Decommissioning Task	Man-hours	Labor Cost	Living & Travel Cost	Equipment, Contracts & Supplies	Radwaste Packaging & Shipping	Total Cost
3.01.01	Characterization	1144	$ 93,549	$ 19,609	$ 28,902	$ -	$ 142,060
3.01.02	Decomissioning Plan	630	$ 69,237	$ -	$ -	$ -	$ 69,237
3.01.03	Field Operations	20773	$ 1,647,623	$ 575,114	$ 746,740	$ 64,004	$ 3,033,481
3.01.04	Final Survey	928	$ 76,072	$ 19,609	$ 21,035	$ -	$ 116,716
3.01.05	Final Report-Closeout	460	$ 50,353	$ -	$ 17,576	$ -	$ 67,929
	Totals	**23934**	**$ 1,936,834**	**$ 614,331**	**$ 814,254**	**$ 64,004**	**$ 3,429,422**

3.01.01	Characterization	$ 142,060	Characterization Total

3.01.01	WBS Item Description Summary	Man-Hour Total	Labor Total	Subcontacts & Materials	Living & Travel	Total
3.01.01.01	Preparation and Historical Site Assessment (HSA)	98	10,728	$0	1,153	$ 11,880
3.01.01.02	Site Characterization Plan Preparation	99	9,962	$0	0	$ 9,962
3.01.01.03	Conduct Characterization Survey	757	52,979	$28,902	18,456	$ 100,337
3.01.01.04	Develop Site Characterization Report (SCR)	190	19,881	$0	0	$ 19,881
	Characterization Task Totals	1144	93,549	$28,902	19,609	$ 142,060

	WBS Item Description	Personnel and/or Service	Duration (days) or Units (each)	Hours	Labor Rate & Other *	Labor Total	Subs/Mat'l	Travel	Total	Comments
3.01.01.01	Preparation and Historical Site Assessment (HSA)									
	Perform HSA. Includes:	Principle Engineer	5	40	108.84	$ 4,354			$ 4,354	
	Mobilization & Demobilization	Principle Engineer		0	108.84	$ -			$ -	
	Develop HSA Document	Principle Engineer	5	40	108.84	$ 4,354			$ 4,354	
	HSA Document: Internal Review &	Principle Engineer	0.5	4	99.14	$ 397			$ 397	
	Review HSA Document	Rad Protection Manager	0.5	4	161.35	$ 645			$ 645	
	HSA Document Transmittal	Senior Admin Assistant	0.25	2	53.82	$ 108			$ 108	
	Document Review and Approval Period	Principle Engineer	5	8	108.84	$ 871			$ 871	Respond to Client Comments
	Other Direct Cost (ODC)	Instruments and Equipment	0						$ -	TBD
	ODC	Airline one R/T	1		400			$ 400	$ 400	One R/T
	ODC	Travel & Trip Expenses	5		150.50			$ 753	$ 753	5 days onsite
	Subtotal					$ 10,728		$ 1,153	$ 11,880	
3.01.01.02	Site Characterization Plan Preparation									
	Develop SCP Document	Principle Engineer	10	80	99.14	$ 7,931			$ 7,931	Start in parallel with 2.1
	Review SCP Document	Principle Engineer	0.5	4	108.84	$ 435			$ 435	
	Review SCP Document	Rad Protection Manager	0.5	4	161.35	$ 645			$ 645	
	Develop Health and Safety Plan (HASP)	EHS Engineer	0	0	99.14	$ -			$ -	
	Review HASP Document	Principle Engineer	0	0	108.84	$ -			$ -	
	Review HASP Document	Rad Protection Manager	0	0	161.35	$ -			$ -	
	Compile Procedure Manual	Principle Engineer	1	8	99.14	$ 793			$ 793	
	Plan and Procedure Documents Transmittal	Senior Admin Assistant	0.25	2	53.82	$ 108			$ 108	

Document Review and Approval Period	Principle Engineer	10	0.5	99.14	$ 50			$ 50	Respond to Client Comments
Other Direct Cost (ODC)	Instruments and Equipment	0	0					$ -	
ODC	Airline one R/T	0		400			$ -	$ -	
ODC	Travel & Trip Expenses	0		150.50			$ -	$ -	0 days onsite
Subtotal			98.5		$ 9,962	$ -	$ -	$ 9,962	

3.01.01.03 Conduct Characterization Survey

									Assumptions: 5 10hr days/week, 2 crews w/ 1 Eng + 1 Teah
Obtain/Procure Instruments, Equipment and Supplies	Principle Engineer	1	8	99.14	$ 793			$ 793	
	Principle Engineer	0.625	5	108.84	$ 544			$ 544	
Mobilization, Setup and Training	Principle Engineer	1.875	15	99.14	$ 1,487			$ 1,487	
	Principle Engineer	3	24	108.84	$ 2,612			$ 2,612	
	Senior Characterization Tech	3	30	41.30	$ 1,239			$ 1,239	
	Senior Characterization Tech	3	30	41.30	$ 1,239			$ 1,239	
Conduct Survey for: (Survey Area Type Description)									
Impacted Facility Structures	Principle Engineer	5	40	99.14	$ 3,966			$ 3,966	
	Senior Characterization Tech	8	80	41.30	$ 3,304			$ 3,304	
Non-impacted Facility Structures	Principle Engineer	1.875	15	108.84	$ 1,633			$ 1,633	
	Senior Characterization Tech	3	30	41.30	$ 1,239			$ 1,239	
Sytem Components	Principle Engineer	10	100	105.71	$ 10,571			$ 10,571	
	Principle Engineer	0.625	5	108.84	$ 544			$ 544	
	Senior Characterization Tech	1	10	41.30	$ 413			$ 413	
Impacted Systems	Principle Engineer	1.875	15	108.84	$ 1,633			$ 1,633	
	Senior Characterization Tech	3	30	41.30	$ 1,239			$ 1,239	
Non-impacted Systems	Principle Engineer	1	8	108.84	$ 871			$ 871	
	Senior Characterization Tech	1.5	15	41.30	$ 619			$ 619	
Impacted Environs	Principle Engineer	1.25	10	108.84	$ 1,088			$ 1,088	
	Senior Characterization Tech	2.5	25	41.30	$ 1,032			$ 1,032	
Non-impacted Environs	Principle Engineer	1	8	99.14	$ 793			$ 793	
	Senior Characterization Tech	1	10	41.30	$ 413			$ 413	
Background Reference Area - Structures	Principle Engineer	0.625	5	108.84	$ 544			$ 544	
	Senior Characterization Tech	1	10	41.30	$ 413			$ 413	
Background Reference Area - Environs	Principle Engineer	2	16	99.14	$ 1,586			$ 1,586	
	Senior Characterization Tech	2	20	41.30	$ 826			$ 826	
Quality Assurance Reviews & Data Evaluation	Principle Engineer	2	16	99.14	$ 1,586			$ 1,586	
	Senior Characterization Tech	2	20	41.30	$ 826			$ 826	
Ship Remaining Samples to Offsite Lab(s)	Principle Engineer	0.625	5	108.84	$ 544			$ 544	
	Senior Characterization Tech	1	10	41.30	$ 413			$ 413	
Return Site and Facility to Safe Condition	Principle Engineer	0.625	5	108.84	$ 544			$ 544	
	Senior Characterization Tech	1	10	41.30	$ 413			$ 413	

	Instruments and Equipment Return	Principle Engineer	1		8	99.14	$ 793				$ 793	
		Senior Characterization Tech	1		10	41.30	$ 413				$ 413	
	Technician OT Pay	Senior Characterization Tech OT	4		40	60.08	$ 2,403				$ 2,403	Tech OT Pay for 4 weeks
	Technician OT Pay	Senior Characterization Tech OT	4		40	60.08	$ 2,403				$ 2,403	Tech OT Pay for 4 weeks
	Demobilization	Principle Engineer	1		8	99.14	$ 793				$ 793	
		Principle Engineer	0 625		5	108.84	$ 544				$ 544	
		Senior Characterization Tech	1		8	41.30	$ 330				$ 330	
		Senior Characterization Tech	1		8	41.30	$ 330				$ 330	
	Other Direct Cost (ODC)	Instruments and Equipment	1	Months		10,683.00		$ 10,683			$ 10,683	
	ODC	Rental Equipment	1	Lot		1,250.00		$ 1,250			$ 1,250	
	ODC	Consumable Supplies	1	Lot		4,428.60		$ 4,429			$ 4,429	
	ODC	Sample Analysis	1	Lot		10,240.83		$ 10,241			$ 10,241	
	ODC	Sample & Instrument shipping cost	1	Lot		500.00		$ 500			$ 500	
	ODC	Core Drill Contractor w/ Sampling Equip	1	Lot		1,800.00		$ 1,800			$ 1,800	
	ODC	Airline R/T	4	Each		400				$ 1,600	$ 1,600	Mob & Demob
	ODC	Travel & Trip Expenses (per week)	4			1,053.50				$ 4,214	$ 4,214	4 weeks onsite
	ODC	Travel & Trip Expenses (per week)	4			1,053.50				$ 4,214	$ 4,214	4 weeks onsite
	ODC	Travel & Trip Expenses (per week)	4			1,053.50				$ 4,214	$ 4,214	4 weeks onsite
	ODC	Travel & Trip Expenses (per week)	4			1,053.50				$ 4,214	$ 4,214	4 weeks onsite
	Subtotal				757		$ 52,979	$ 28,902		$ 18,456	$ 100,337	
3.01.01.04	**Develop Site Characterization Report (SCR)**											
	Receive Data from Offsite Lab(s)	Principle Engineer	30		8	99.14	$ 793				$ 793	
	Quality Assurance Reviews & Data Evaluation	Principle Engineer	2		16	108.84	$ 1,742				$ 1,742	
	Develop SCR Document	Principle Engineer	20		120	99.14	$ 11,897				$ 11,897	
		Principle Engineer	20		16	108.84	$ 1,742				$ 1,742	
	Review SCR Document	Rad Protection Manager	1		8	161.35	$ 1,291				$ 1,291	
	SCR Document Transmittal	Senior Admin Assistant	0.25		2	53.82	$ 108				$ 108	
	Document Review and Approval Period	Principle Engineer	15		8	99.14	$ 793				$ 793	Respond to Client Comments
		Principle Engineer	1		8	108.84	$ 871				$ 871	
		Rad Protection Manager	1		4	161.35	$ 645				$ 645	
					190		$ 19,881				$ 19,881	

3.01.02	Decommssioning Plan	$ 69,237	Characterization Total

3.01.02	WBS Item Description Summary	Man-Hour Total	Labor Total	Subcontacts & Materials	Living & Travel	Total
3.01.02.01	Environmental Report (ER) Preparation	118	$ 12,510	$ -	$ -	$ 12,510
3.01.02.02	Decommissioning Cost Estimate (DCE) Preparation	158	$ 16,475	$ -	$ -	$ 16,475
3.01.02.03	Decommissioning Plan (DP) Preparation	270	$ 31,287	$ -	$ -	$ 31,287
3.01.02.04	Provide Support During NRC Review and Approval of DP	84	$ 8,965	$ -	$ -	$ 8,965
	Task Totals	630	$ 69,237	$ -	$ -	$ 69,237

	WBS Item Description	Personnel and/or Service	Duration (days) or Units (each)	Hours	Labor Rate & Other *	Labor Total	Subs/Mat'l	Travel	Total	Comments
3.01.02.01	Environmental Report (ER) Preparation									
	Develop ER	Senior Engineer	10	80	$ 99.14	$ 7,931	$ -	$ -	$ 7,931	
	Review ER Document	Senior Engineer	1	8	$ 108.84	$ 871	$ -	$ -	$ 871	
	Review ER Document	Project Manager	1	8	$ 161.35	$ 1,291	$ -	$ -	$ 1,291	
	ER Document Transmittal	Senior Admin Assist	0.25	2	$ 53.82	$ 108	$ -	$ -	$ 108	
	Document Review and Approval Period	Senior Engineer	10	8	$ 99.14	$ 793	$ -	$ -	$ 793	
		Senior Engineer	1	8	$ 108.84	$ 871	$ -	$ -	$ 871	
		Project Manager	1	4	$ 161.35	$ 645	$ -	$ -	$ 645	
	Subtotal			118		$ 12,510	$ -	$ -	$ 12,510	
3.01.02.02	Decommissioning Cost Estimate (DCE) Preparation									
	Develop DCE	Senior Engineer	15	120	$ 99.14	$ 11,897	$ -	$ -	$ 11,897	
	Review DCE Document	Senior Engineer	1	8	$ 108.84	$ 871	$ -	$ -	$ 871	
	Review DCE Document	Project Manager	1	8	$ 161.35	$ 1,291	$ -	$ -	$ 1,291	
	DCE Document Transmittal	Senior Admin Assist	0.25	2	$ 53.82	$ 108	$ -	$ -	$ 108	
	Document Review and Approval Period	Senior Engineer	15	8	$ 99.14	$ 793	$ -	$ -	$ 793	
		Senior Engineer	1	8	$ 108.84	$ 871	$ -	$ -	$ 871	
		Project Manager	1	4	$ 161.35	$ 645	$ -	$ -	$ 645	
	Subtotal			158		$ 16,475	$ -	$ -	$ 16,475	
3.01.02.03	Decommissioning Plan (DP) Preparation									
	Develop DP	Senior Engineer	30	120	$ 108.84	$ 13,061	$ -	$ -	$ 13,061	
		Senior Engineer		80	$ 124.72	$ 9,977	$ -	$ -	$ 9,977	
	Review DP Document	Senior Engineer	2	16	$ 99.14	$ 1,586	$ -	$ -	$ 1,586	
	Review DP Document	Project Manager	2	16	$ 161.35	$ 2,582	$ -	$ -	$ 2,582	
	DP Document Transmittal	Senior Admin Assist	0.25	2	$ 53.82	$ 108	$ -	$ -	$ 108	
	Document Review and Approval Period	Senior Engineer	2	16	$ 108.84	$ 1,742	$ -	$ -	$ 1,742	
		Senior Engineer	2	16	$ 99.14	$ 1,586	$ -	$ -	$ 1,586	
		Project Manager	1	4	$ 161.35	$ 645	$ -	$ -	$ 645	
	Subtotal			270		$ 31,287	$ -	$ -	$ 31,287	
3.01.02.04	Provide Support During NRC Review and Approval of DP									
	Document Review and Approval Period	Senior Engineer		40	$ 108.84	$ 4,354	$ -	$ -	$ 4,354	
		Senior Engineer		40	$ 99.14	$ 3,966	$ -	$ -	$ 3,966	
		Project Manager		4	$ 161.35	$ 645	$ -	$ -	$ 645	
				84		$ 8,965	$ -	$ -	$ 8,965	

3.01.03 Field Operations $ 3,033,481

WBS	Item Description	Labor Unit Hours	Labor Hours Total	Labor Rate & Other *	Labor Dollars	Living and Travel Costs	Equipment Dollars	D&D Waste Pack & Ship Dollars	
3.01.03.01	Training, & Mobilization	272	272	78.57	$ 21,370	$ 7,459	$ -	$ -	$ 28,829
3.01.03.02	DFCS Process Equipment	6264	6264	79.70	$ 499,243	$ 174,264	$ 290,728	$ 19,906	$ 984,141
3.01.03.03	DFCS Process Building	4046	4046	78.60	$ 318,013	$ 111,005	$ 97,446	$ 12,403	$ 538,867
3.01.03.04	DFCS Utility Equipment	5338	5338	79.59	$ 424,827	$ 148,289	$ 273,787	$ 19,599	$ 866,502
3.01.03.05	DFCS Utility Building	3120	3120	78.08	$ 243,597	$ 85,029	$ 80,505	$ 12,096	$ 421,227
3.01.03.06	Remediation Support Surveys	1040	1040	86.75	$ 90,220	$ 31,492	$ 4,274	$ -	$ 125,986
3.01.03.07	Oversight	693	693	72.66	$ 50,353	$ 17,576	$ -	$ -	$ 67,929
	Subtotal		20773		$ 1,647,623	$ 575,114	$ 746,740	$ 64,004	$ 3,033,481

WBS	Description		
3.01.04	Final Survey	$ 116,716	Total

	WBS Item Description	Man-Hour Total	Labor Total $s	Subcontacts & Living	Trav Total $s	
3.01.04.01	FSS Preparation, Review Post-Remediation Survey Data	80	$ 8,708	$ -	$ 1,153	$ 9,860
3.01.04.02	Final Status Survey Plan Preparation	99	$ 9,962	$ -	$ -	$ 9,962
3.01.04.03	Conduct FSS Survey	523	$ 33,720	$ 21,035	$ 18,456	$ 73,211
3.01.04.04	Develop FSS Report	226	$ 23,683	$ -	$ -	$ 23,683
	Task Total	928	$ 76,072	$ 21,035	$ 19,609	$ 116,716

	WBS Item Description	Personnel and/or Service	Duration (days) or Units (each)	Hours	Labor Rate & Other *	Labor Total	Subs/Mat'l	Travel	Total	Comments
3.01.04.01	**FSS Preparation, Review Post-Remediation Survey Data**									
	FSS Preparation, Review Char Data	Senior Engineer	5	40	108.84	$ 4,354			$ 4,354	
	Mobilization & Demobilization	Senior Engineer		0	108.84	$ -			$ -	
	Review Post-Remediation Survey Data	Senior Engineer	5	40	108.84	$ 4,354			$ 4,354	
	ODC	Airline one R/T	1		400.00			$ 400	$ 400	One R/T
	ODC	Travel & Trip Expenses	5		150.50			$ 753	$ 753	5 days onsite
	Subtotal			80		$ 8,708	$ -	$ 1,153	$ 9,860	
3.01.04.02	**Final Status Survey Plan Preparation**									
	Develop FSS Plan Document	Senior Engineer	10	80	99.14	$ 7,931			$ 7,931	Start in parallel with 2.1
	Review FSS Plan Document	Senior Engineer	1	4	108.84	$ 435			$ 435	
	Review FSS Plan Document	Project Manager	1	4	161.35	$ 645			$ 645	
	Update Health and Safety Plan (HASP)	EHS Engineer	0	0	99.14	$ -			$ -	
	Review HASP Document	Senior Engineer	0	0	108.84	$ -			$ -	
	Review HASP Document	Project Manager	0	0	161.35	$ -			$ -	
	Compile Procedure Manual	Senior Engineer	1	8	99.14	$ 793			$ 793	
	Plan and Procedure Documents Transmittal	Senior Admin Assistant	0	2	53.82	$ 108			$ 108	
	Document Review and Approval Period	Senior Engineer	10	0.5	99.14	$ 50			$ 50	Respond to Client Comments
	Other Direct Cost (ODC)	Instruments and Equipment	0	0					$ -	
	ODC	Airline one R/T	0		400.00			$ -	$ -	
	ODC	Travel & Trip Expenses	0		150.50			$ -	$ -	0 days onsite
	Subtotal			98.5		$ 9,962	$ -	$ -	$ 9,962	

		Assumptions: 5 10hr days/week, 2 crews w/ 1 Eng + 1 Teah											
3.01.04.03	Conduct FSS Survey												
	Obtain/Procure Instruments, Equipment a	Senior Engineer	1		8	99.14	$ 793				$ 793		
		Senior Engineer	1		5	108.84	$ 544				$ 544		
	Mobilization, Setup and Training	Senior Engineer	2		15	99.14	$ 1,487				$ 1,487		
		Senior Engineer	3		24	108.84	$ 2,612				$ 2,612		
		Senior Characterization Tech	3		30	41.30	$ 1,239				$ 1,239		
		Senior Characterization Tech	3		30	41.30	$ 1,239				$ 1,239		
	Conduct Survey for: (Survey Area Type Description)												
	Impacted Reactor Facility Structures	Senior Engineer	5		40	99.14	$ 3,966				$ 3,966		
		Senior Characterization Tech	8		80	41.30	$ 3,304				$ 3,304		
	Non-impacted Reactor Facility Structures	Senior Engineer	2		15	108.84	$ 1,633				$ 1,633		
		Senior Characterization Tech	3		30	41.30	$ 1,239				$ 1,239		
	Impacted Environs	Senior Engineer	1		10	108.84	$ 1,088				$ 1,088		
		Senior Characterization Tech	3		25	41.30	$ 1,032				$ 1,032		
	Non-Impacted Environs	Senior Engineer	1		8	99.14	$ 793				$ 793		
		Senior Characterization Tech	1		10	41.30	$ 413				$ 413		
	Quality Assurance Reviews & Data Evaluation	Senior Engineer	2		16	99.14	$ 1,586				$ 1,586		
		Senior Characterization Tech	2		20	41.30	$ 826				$ 826		
	Ship Remaining Samples to Offsite Lab(s)	Senior Engineer	1		5	108.84	$ 544				$ 544		
		Senior Characterization Tech	1		10	41.30	$ 413				$ 413		
	Return Site and Facility to Safe Condition	Senior Engineer	1		5	108.84	$ 544				$ 544		
		Senior Characterization Tech	1		10	41.30	$ 413				$ 413		
	Instruments and Equipment Return	Senior Engineer	1		8	99.14	$ 793				$ 793		
		Senior Characterization Tech	1		10	41.30	$ 413				$ 413		
	Technician OT Pay	Senior Characterization Tech OT	4		40	60.08	$ 2,403				$ 2,403	Tech OT Pay for 4 weeks	
	Technician OT Pay	Senior Characterization Tech OT	4		40	60.08	$ 2,403				$ 2,403	Tech OT Pay for 4 weeks	
	Demobilization	Senior Engineer	1		8	99.14	$ 793				$ 793		
		Senior Engineer	1		5	108.84	$ 544				$ 544		
		Senior Characterization Tech	1		8	41.30	$ 330				$ 330		
		Senior Characterization Tech	1		8	41.30	$ 330				$ 330		
	Other Direct Cost (ODC)	Instruments and Equipment	1	Months		6,830.00		$ 6,830			$ 6,830		
	ODC	Rental Equipment	1	Lot		1,250.00		$ 1,250			$ 1,250		
	ODC	Consumable Supplies	1	Lot		2,214.30		$ 2,214			$ 2,214		
	ODC	Sample Analysis	1	Lot		10,240.83		$ 10,241			$ 10,241		
	ODC	Sample & Instrument shipping cc	1	Lot		500.00		$ 500			$ 500		
	ODC	Airline R/T	4	Each		400.00			$ 1,600		$ 1,600	Mob & Demob	
	ODC	Travel & Trip Expenses (per wee	4			1,053.50			$ 4,214		$ 4,214	4 weeks onsite	
	ODC	Travel & Trip Expenses (per wee	4			1,053.50			$ 4,214		$ 4,214	4 weeks onsite	
	ODC	Travel & Trip Expenses (per wee	4			1,053.50			$ 4,214		$ 4,214	4 weeks onsite	
	ODC	Travel & Trip Expenses (per wee	4			1,053.50			$ 4,214		$ 4,214	4 weeks onsite	
	Subtotal				523		$ 33,720	$ 21,035	$ 18,456		$ 73,211		

3.01.04 04	**Develop FSS Report**										
	Receive Data from Offsite Lab(s)	Senior Engineer	30	20	99.14	$ 1,983			$ 1,983		
	Quality Assurance Reviews & Data Evaluation	Senior Engineer	5	40	108 84	$ 4,354			$ 4,354		
	Develop FSS Report Document	Senior Engineer	20	120	99.14	$ 11,897			$ 11,897		
		Senior Engineer	20	16	108 84	$ 1,742			$ 1,742		
	Review FSS Report Document	Project Manager	1	8	161.35	$ 1,291			$ 1,291		
	FSS Report Document Transmittal	Senior Admin Assistant	0 25	2	53 82	$ 108			$ 108		
	Document Review and Approval Period	Senior Engineer	15	8	99.14	$ 793			$ 793	Respond to Client Comments	
		Senior Engineer	1	8	108.84	$ 871			$ 871		
		Project Manager	1	4	161.35	$ 645			$ 645		
	Subtotal			226		$ 23,683	$ -	$ -	$ 23,683		

$ 67,929 Total

3.01.05 **Final Report/Closeout**

WBS	Description	Quantity	Unit	Labor Unit Hours	Labor Hours Total	Average Labor Rate	Labor Dollars	Living and Travel Costs	Equipment Dollars	Material Costs	Total Dollars	Comments
3.01.05	Document Preparation, Review and Approval Period	1	ea	460	460	$ 108.84	$ 50,353	$ -	$ -	$ 17,576	$ 67,929	
	Subtotal				460		$ 50,353	$ -	$ -	$ 17,576	$ 67,929	