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RESEARCH and DEVELOPMENT STUDY

EFFLUENT CONTAINMENT SYSTEM for SPACE THERMAL NUCLEAR PROPULSION GROUND TEST FACILITIES

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Technical Package Prepared for the
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Prepared by:
Fluor Daniel
3333 Michelson
Irvine, California 92714
Government Services Operating Company

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1.0 SUMMARY

The summary section of the Research and Development Study of an Effluent Containment System (ECS) Technical Package includes a report introduction, summary of results, a block flow diagram of the proposed ECS process, and recommendations for subsequent design phases for a ground test facility of a space nuclear thermal rocket engine.

1.1 Introduction

This report presents the research and development study work performed for the Space Reactor Power Systems Division of the U.S. Department of Energy on an innovative ECS that would be used during ground testing of a space nuclear thermal rocket engine. A significant portion of the ground test facilities for a space nuclear thermal propulsion engine are the effluent treatment and containment systems. The proposed ECS configuration developed recycles all engine coolant media and does not impact the environment by venting radioactive material. All coolant media, hydrogen and water, are collected, treated for removal of radioactive particulates, and recycled for use in subsequent tests until the end of the facility life. Radioactive materials removed by the treatment systems are recovered, stored for decay of short-lived isotopes, or packaged for disposal as waste. At the end of the useful life, the facility will be decontaminated and dismantled for disposal.

The proposed ECS ground test facility consists of the nuclear thermal propulsion rocket engine, exhaust gas cooling, and cleanup systems. Hot hydrogen effluent from the rocket engine is cooled to near ambient temperature by direct contact with sprayed chilled water in the quench chamber/debris trap. The water is collected in the quench chamber/debris trap and recycled by a bank of pumps. The debris trap is designed to remove large particulates, which are generated by a rocket engine catastrophic failure, from the water. The cooled hydrogen effluent stream accumulates in a large storage sphere during the test run. Following the test run, the treatment of accumulated hydrogen effluent in the storage sphere and the water in the quench chamber/debris trap are delayed for one week to allow radioactive materials in the gas and water to decay before treatment/recycle commences.

During treatment, the effluent gas is compressed and flows to the desiccant dryers to remove the water from the wet hydrogen gas. Radiologically contaminated particulates are removed from the effluent gas using a particle bed filter. The effluent gas is then cooled to cryogenic temperatures in a shell and tube heat exchanger using liquid nitrogen as the cooling media to facilitate removal of iodine and noble gas contaminants using activated charcoal adsorbers. The liquid nitrogen is supplied to the cooler at a pressure level above the maximum system operating pressure to reduce the probability of process gas contaminating the coolant media in the event of exchanger leak. The treated hydrogen gas flows to the liquefaction and purification unit where it is liquefied, purified by distillation, and sent to storage vessels to await the next test run.

The quench water accumulated in the quench chamber/debris trap is pumped through filtration and deionization units for removal of radioactive components. The treated water is sent through a refrigeration unit to cool the water to pre-test conditions and then to a storage tank to await the next test run.

A radiation contamination model of the proposed ECS configuration has been developed to estimate radiation levels on and adjacent to the ECS components during a destructive test run. The model establishes integrated dose rates at various ECS components, providing a basis for shielding, remote operations, and maintenance requirements.

1.2 Summary of Results

A proposed ECS design configuration for a ground test facility of a space nuclear thermal rocket engine has been developed that contains the effluent and any radioactive debris that could potentially escape into the environment. The design configuration allows the facility to operate in three separate and independent modes: exhaust gas cooling, hydrogen treatment and recycle, and water treatment and recycle. This innovative design approach allows a test run to be completed and the coolants stored with a minimum of the system equipment operating during the test run. Various operating modes were investigated which included two different design scenarios. A radiation contamination model of the proposed ECS design concept was also developed to estimate radiation levels on and adjacent to the ECS components during a catastrophic engine failure (i.e., worst case failure scenario).

The block flow diagram depicting the proposed ECS design configuration is included as Figure 1-1 at the end of the following sub-section. The process flow diagram is included as Figure 2-1 in Section 2.2 of this report. Four operating modes were investigated as follows:

(1) 2000 MW Reactor/1000 Second Test Duration

(2) 550 MW Reactor/500 Second Test Duration

(3) 11.5 MW Reactor/5 Hour Test Duration

(4) 0.6 MW Reactor/200 Hour Test Duration

Case 3, 11.5 MW Reactor/5 Hour Test Duration, was used as the baseline design case in determining preliminary equipment sizes and number of equipment required as shown on the process flow diagram. The other three cases were then compared to the baseline design case for two different design scenarios. One design scenario involved revising the baseline design case to reflect the operating mode conditions for all three cases to determine the impact to the baseline design case equipment. The other design scenario involved revising the test run duration times for the other three operating modes to correspond to the baseline design case hydrogen and water usages and determine the impact to the baseline design case equipment. As shown on Table 1-1, Case Summary, both design scenarios impact the baseline design configuration. The design scenario of revising the test run duration times for the three alternate modes has the least impact because the two batch operations for hydrogen and water treatment and recycle are not impacted. The exhaust gas cooling batch mode operation would require some equipment modifications to accommodate the different quench water requirements of the operating modes. Additional information is provided in Section 2.9, Alternate Operating Modes, of this report.

1.3 Block Flow Diagram

The block flow diagram of the proposed ECS concept design depicts normal operation at a gas temperature of 2500°K(4040°F) exiting the nuclear thermal rocket engine. Injection of liquid hydrogen is shown into the rocket engine. Chilled water is shown as the coolant supplied to the quench chamber/debris trap. Liquid nitrogen is the media used to cool the effluent gas to cryogenic temperatures.

1.4 Recommendations

In subsequent design phases for a ground test facility of a space nuclear thermal rocket engine, recommend further investigations and studies to advance the design of the proposed concept. Among those are as follows:

- Investigate the placement of the facility below ground.

- Determine particle size distribution for destructive testing.

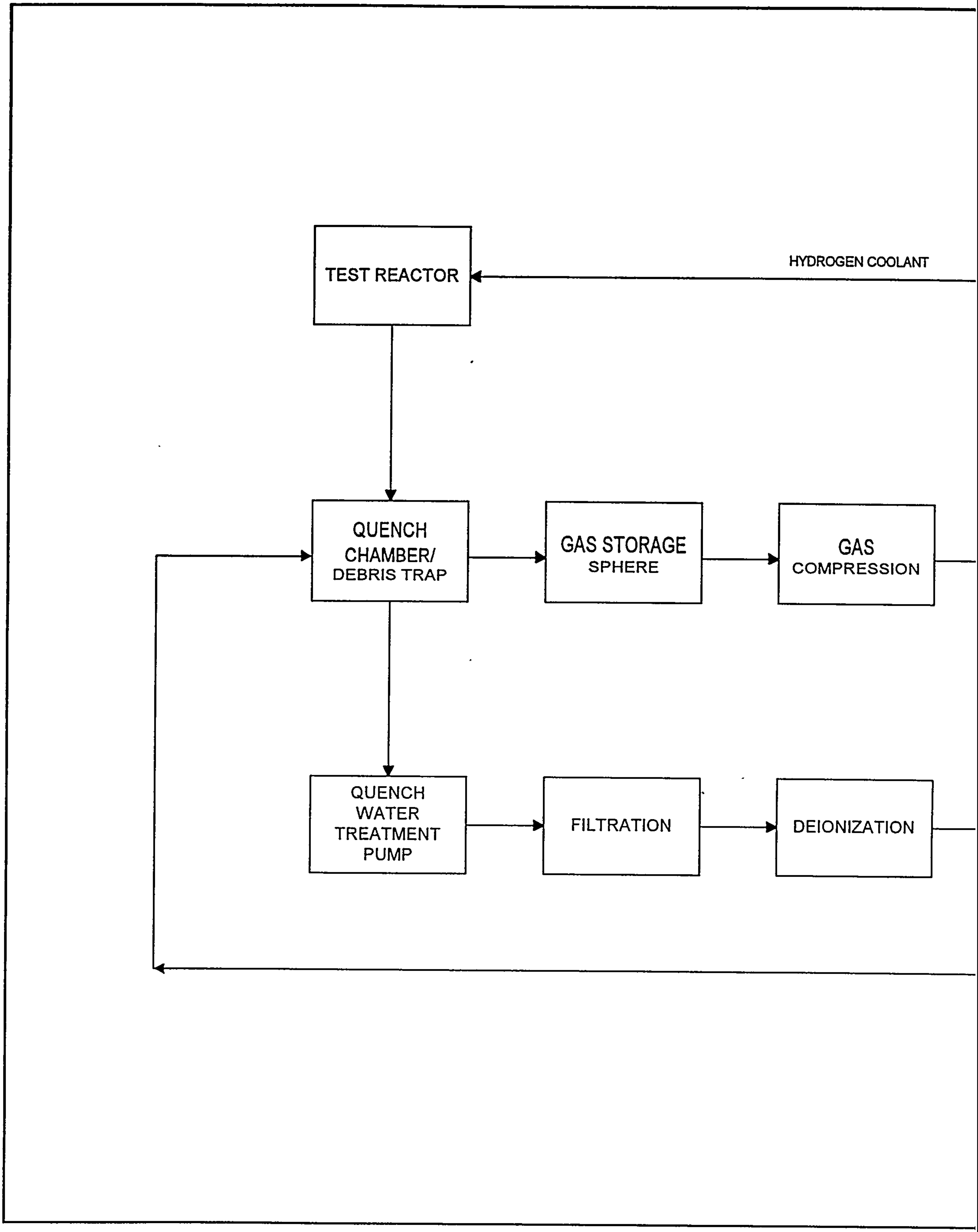
- Maximize equipment design flexibility to accommodate various modes of operation.

- Perform various trade-off studies to achieve the most efficient, operable, cost effective, environmentally benign, and safe design.

Additional information is provided in Section 2.10, Future Design Studies/Optimizations, of this report.

		1 (Case 3) Base Case	2	3	4	5 (Case 1)	6 (Case 2)	7 (Case 4)
Reactor Size	MW	11.5	2000	550	0.6	2000	550	0.6
Test Duration	s or (hr)	(5)	105	384	(97.63)	1000	500	(200)
Hydrogen Rate	kg/s	0.28	47.78	13.14	0.01434	47.78	13.14	0.01434
Total Hydrogen	kg	5040	5040	5040	5040	47780	6570	10325
Quench Water	gpm	1799	307005	84430	92.1	307005	84430	92.1
Water Treatment	gpm	90	90	90	90	853	117	184
Gas Treatment (dry	scfm	291	291	291	291	2754	379	595
Spray Chamber	height, ft	114	114	114	114	242	125	145
	diam, ft	38	38	38	38	81	42	48
	velocity, ft/s	0.061	10.33	2.84	0.003	2.31	2.38	0.002
Hydrogen Storage	diam, ft	100	100	100	100	100	100	100
	pressure, psia	81	81	81	81	81	81	81
	number	1	1	1	1	9	2	2
Chilled Water Tank	Volume, gal	6.48E+05	6.48E+05	6.48E+05	6.48E+05	6.14E+06	8.44E+05	1.33E+06

Table 1-1 Case Summary


HYDROGEN COOLANT
TEST REACTOR
QUENCH CHAMBER/ DEBRIS TRAP
GAS STORAGE SPHERE
GAS COMPRESSION
QUENCH WATER TREATMENT PUMP
FILTRATION
DEIONIZATION

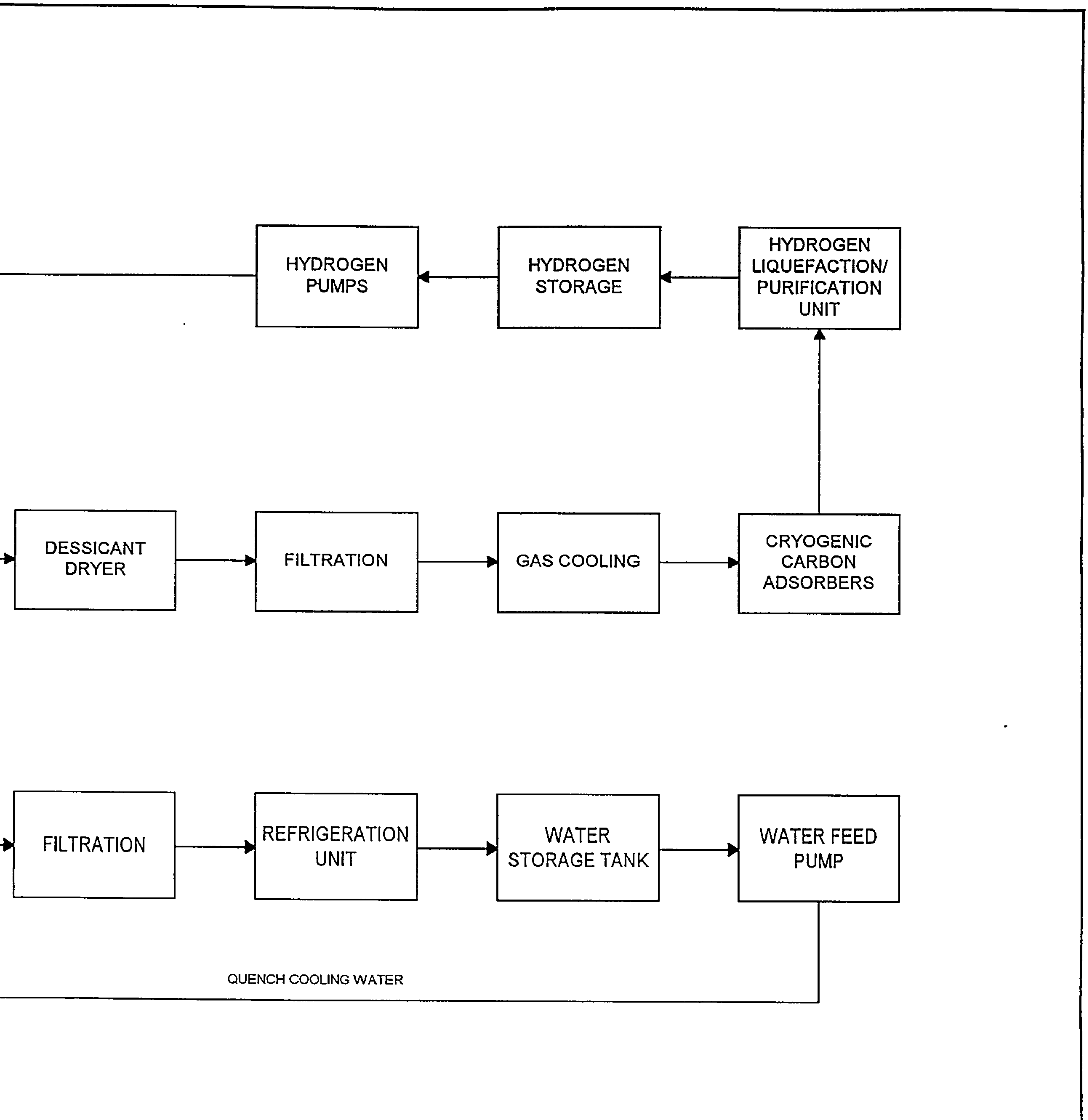


FIGURE 1-1
BLOCK FLOW DIAGRAM
EFFLUENT CONTAINMENT SYSTEM

2.0 TECHNICAL PROCESS PACKAGE

2.1 Process Description

2.1.1 Introduction

This section describes the Effluent Containment System (ECS) as configured for the proposed design. Functional requirements, design capacity, interfaces, equipment design requirements, and material requirements are discussed.

The proposed ECS ground test facility design configuration consists of the following three areas: the test reactor (nuclear thermal rocket engine), exhaust gas cooling, and cleanup systems. The configuration allows the facility to operate in three separate and independent modes. Initially upon start-up, liquid hydrogen at 25°K(-414°F) is used for removal of the heat generated from the nuclear thermal rocket engine. The exhaust gas exiting the rocket engine at 2500°K(4040°F) enters the quench chamber/debris trap and is quenched to 311°K(100°F) by direct contact mixing of 277°K(40°F) sprayed chilled water with the hydrogen exhaust gas in the top portion of the quench chamber/debris trap. The water is collected in the bottom portion of the quench chamber/debris trap and the cooled hydrogen gas flows to a gas storage sphere. The design of the quench chamber/debris trap and the gas storage sphere allows the entire inventory of hydrogen and water used in a test run to be stored for several days prior to treatment for recycle. The gas storage sphere operates between less than one psig at the start of the test run and 60 to 70 psig at the end of the test run. Pressure in the quench chamber/debris trap operates between less than one psig at the start of the test run and controlled to a maximum of 200 psig at the end of the test run. This innovative design approach allows a test run to be completed and the coolants stored to provide time for radioactive decay prior to batch treatment of the water and effluent gas between test runs. No radioactive particulates or noble gases are expected with cermet reactor fuel during normal operation.

The capacity of the hydrogen treatment/recycle system is only a small percent of the test hydrogen flow rate since the test is five hours duration and hydrogen is recovered over a five day period. The hydrogen treatment/recycle system consists of the following equipment/treatment steps:

- Drying-Desiccant dryers with regeneration
- Filtration-Granular filters
- Cooling-Refrigerant cooling
- Adsorption-Cryogenic carbon adsorbers for noble gas removal
- Hydrogen Recovery-Hydrogen liquefaction and purification unit

After one week's storage at ambient temperature, moderate pressure hydrogen is allowed to flow from the gas storage sphere to the desiccant dryers where the water-saturated gas is dried to a minimum 233°K(-40°F) dewpoint. The hydrogen gas stream is then filtered to remove 99.9 weight percent or more of the particulates in the stream. The dried and filtered gas is cooled to 172°K(-150°F) in a heat exchanger using liquid nitrogen as the refrigerant. The cold process gas flows through the noble gas adsorbers where 99.5 weight percent or more of the iodine, krypton and xenon are removed by adsorption on activated carbon. The hydrogen gas exiting the adsorbers flows to the liquefaction and purification unit where it is liquefied, purified by distillation, and sent to storage to await the next test run.

The capacity of the water treatment/recycle system is similar to the hydrogen treatment/recycle system in that the treatment and recovery of the water is also over a five day period. The water/treatment system consists of the following equipment/treatment steps:

- Filtration-Cartridge filters
- Deionization Unit-Ion exchange
- Filtration-Cartridge filters

After one week's storage at ambient temperature, the 300°K(80°F) water in the quench chamber/debris trap is pumped through a roughing filter to remove 99.9 weight percent or more of the particulates in the stream. The majority of the large particulates are removed in the debris trap and should only be present during failure or destructive testing of the nuclear thermal rocket engine. The filtered water flows to a deionization unit where 99.9 weight percent or more of the dissolved radioisotopes of cesium and strontium are removed. The deionized water is then sent to a polishing filter where 99 weight percent or more of the remaining particulates are removed. The treated water flows to the air-cooled refrigeration unit where it is cooled to 277°K(40°F) and sent to storage to await the next test run.

The ECS configuration is described in more detail below and is shown in the Baseline Design Case process flow diagram.

The ECS configuration consists of the following major equipment:

- Quench Chamber/Debris Trap
- Hydrogen Effluent Storage Sphere
- Hydrogen Compressor
- Hydrogen Dryer
- Hydrogen Cryocooler
- Noble Gas Adsorber
- Hydrogen Liquefaction Unit
- Chilled Water Storage Tank
- Chilled Water Feed Pump
- Quench Chamber Recirculating Pump
- Quench Water Feed Pump
- Quench Water Filter
- Quench Water Deionization Unit
- Quench Water Polishing Filter
- Quench Water Chiller

2.1.2 Functional Requirements

The primary function of the ECS is to remove radioactive contaminants from the nuclear thermal rocket engine effluent stream (ECS feed) so that all cooling media is collected and recycled for use in subsequent test runs. Radioactive materials removed by the treatment systems are recovered, stored for decay, or packaged for disposal as waste, eliminating the potential of releasing radioactive contaminants to the environment. An additional function is to cool the hot feed gas to allow treatment using conventional methods and materials. The ECS is designed to remove a minimum of 99.9 weight percent of the most penetrating particulates (0.3 microns), 99.9 weight percent of the radioisotopes of cesium and strontium dissolved in the water, 99.5 weight percent of iodine and other halogens, and 99.5 weight percent of the noble gases (krypton and xenon) from the effluent stream.

The system is designed to operate in a safe and efficient manner.

2.1.3 Design/Capacity Requirements

The ECS is designed to meet the following criteria:

- Avoid a criticality in the ECS

- Nuclear thermal rocket engine design cases:

  - Case I: 2000 MW for 1000 seconds
  - Case II: 550 MW for 500 seconds
  - Case III: 11.5 MW for 5 hours
  - Case IV: 0.6 MW for 200 hours

- Process configuration (i.e., number and size of equipment) developed for Case III (Base Case)

- Other design cases are compared to base case sizes by determining the additional number of equipment required

- Liquid hydrogen temperature to the nuclear thermal rocket engine is 25°K(-414°F)

- Maximum allowable temperature of hydrogen flowing to the quench chamber/debris trap is 2500°K(4040°F)

- Design Basis of Reactor:

  - Total reactor weight is 587 kg
  - 93% enriched U-235
  - 108.04 kg U-235
  - Composition of reactor fuel material (Cermet)
    - 0.595 weight percent UO_2
    - 0.405 weight percent tungsten
  - Balance is stainless steel

This fuel configuration is compatible for Case III and IV. A different fuel and reactor configuration would be expected for Case I and II.

- Remove radioactive contaminates from the feed gas as indicated below:
  - 99.9 weight percent of the most penetrating particles (approx. 0.3 microns)

- 99.9 weight percent of the dissolved cesium and strontium
- 99.5 weight percent of iodine and other halogens
- 99.5 weight percent noble gases (krypton and xenon)

- Cool the feed to allow the use of conventional process methods and materials

- Allow safe destructive testing of nuclear thermal rocket engine

- Allow five test runs of the base case design with the final run as a planned destructive test. No radiation is expected to be released during first four test runs with the cermet fuel.

The base case design capacity sets the inventories of the cooling systems and establishes the design requirements for equipment sizes. The other cases are reviewed by comparing to the base case and determining the necessary design changes in order for those cases to functionally meet the respective design requirements.

The quench chamber/debris trap is designed to cool 0.28 kg/sec(2,200 lb/hr) of feed gas, essentially 100 volume percent hydrogen, at 2500°K(4040°F) to 311°K(100°F) by quenching with 110 kg/sec(900,000 lb/hr) of chilled water at 278°K(40°F). The debris trap in the quench chamber/debris trap removes large particles from the quenched water. The water-saturated quench gas, on pressure control, exits the quench chamber/debris trap and accumulates in the storage sphere and pressurizes the sphere from 103 kPa (15 psia) to 560 kPa (81 psia) during the test run.

Between test runs, the cooled process gas in the storage sphere is allowed to decay for seven days before processing and treatment of the gas begins. The process gas at moderate pressure is batch fed to the downstream equipment over a five day period. The process gas is dried to a minimum dewpoint of 233°K(-40°F) resulting in a 99.5 weight percent reduction in water. The dried process gas is filtered through a bed of 0.1 millimeter (0.004 inch) diameter alumina removing 99.9 weight percent of the most penetrating particulates (approximately 0.3 micron size) in the gas stream. The filtered gas is cooled from 311°K(100°F) to 172°K(-150°F) in a shell and tube exchanger using liquid nitrogen as the cooling media. The nitrogen exits the exchanger and is flared. The cold gas at 172°K(-150°F) flows through a bed of activated charcoal in the noble gas adsorbers where a minimum of 99.5 weight percent of the iodine and other halogens in the feed and a minimum of 99.5 weight percent of the noble gases (krypton and xenon) in the feed are adsorbed. The hydrogen gas exiting the adsorbers flows to the hydrogen liquefaction unit where it is liquefied, purified by distillation and sent to storage for reuse in subsequent test runs.

As with the effluent gas, the quench water is allowed to remain in the quench chamber/debris trap between test runs to allow the radioactive content of the water to decay before processing and treating of the water commences. The quench water is batch fed to the treatment equipment over a five day period. The quench water is filtered through a cartridge-type filter to remove a minimum of 99.9 weight percent of the particulates in the water. The filtered quench water is then passed through a deionization unit to remove a minimum of 99.9 weight percent of the dissolved cesium and strontium radionuclides from the water. The quench water exiting the deionization unit flows to a polishing cartridge-type filter to remove a minimum of 99 weight percent of the remaining particulates in the water. After the polishing filtration, the treated water flows to an air-cooled refrigeration unit where it is cooled from 300°K(80°F) to 278°K(40°F) and sent to storage for reuse in subsequent test runs.

2.1.4 System Interfaces

The ECS interfaces with the following plant systems:

- Nuclear Rocket Engine - which provides feed to the ECS
- Hydrogen Storage - which provides liquid hydrogen as the coolant for the nuclear rocket engine
- Nitrogen Storage - which provides liquid nitrogen for cooling the filtered process gas to cryogenic temperatures in the cryocooler for subsequent removal of noble gases and iodine and provides nitrogen gas for use as plant/instrument air
- Plant/Instrument Air (Nitrogen) - which provides gaseous nitrogen for pneumatic instrumentation, purging hydrogen or air from the process equipment and other services
- Chilled Water Storage - which provides chilled water for quenching the hot hydrogen feed gas
- Electrical - which provides power for equipment, instrumentation and lighting
- Emergency Diesel Generator - which provides emergency power to key equipment items necessary to maintain test run operations during a power failure

2.1.5 Equipment Requirements

Brief descriptions of ECS major equipment and primary design parameters are given below:

100-V-001 Quench Chamber/Debris Trap

The quench chamber/debris trap is used to quench the hot hydrogen feed gas with chilled water and to capture the debris from destructive testing of the nuclear thermal rocket engine. The capture of debris in a geometric safe manner prevents unnecessary contamination of the ECS downstream equipment and allows removal of the trapped radioactive material. The design is based on lowering feed gas temperature, trapping radioactive material in a media with a neutron poison (boron rings and Raschig rings) to prevent the possibility of criticality, and on providing a means of access to inspect the debris trap.

Spray nozzles in the top portion of the quench chamber/debris trap are designed to cool 0.28 kg/sec (2,200 lb/hr) of feed gas at 1480 kPa (200 psig) and 2500°K (4040°F) to 311°K (100°F) by sparging 110 kg/sec (900,000 lb/hr) of water at 278°K (40°F) into the hot feed gas stream. A second set of spray nozzles is used to spray 630 kg/sec (5,000,000 lb/hr) of recirculating water from the quench chamber/debris trap to further enhance the cooling of the hot feed gas stream.

Dimensions - 38'-0" ID x 114'-0" T-T cylindrical section. The debris trap has a removable basket to catch a 4'-0" diameter x 3'-0" high pile of debris. The basket contains 1" diameter boron rods and 1" long boron Raschig rings.

Materials - 304SS inner shell, 304SS external jacket, silicon nitride or silicon carbide for removable basket.

Design - 250 psig,-425°F/650°F inner shell
250 psig,-425°F outer shell

Shielding - The vessel is shielded as required to prevent worker exposure to ionizing radiation above acceptable levels. See section 4.7 for shielding thickness.

100-P-001A/B Quench Chamber Recirculating Pump

The quench chamber recirculating pump is used to provide additional heat transfer of the hot feed gas stream by recirculating 630 kg/sec (5,000,000 lb/hr) of water from the quench chamber/debris trap bottom portion through a second set of spray nozzles.

Quantity - 2

Design - 10,000 GPM

Differential Pressure - 50 psi

Materials - 304SS

Shielding - The pumps are shielded as required to prevent worker exposure to ionizing radiation above acceptable levels. See section 4.7 for shielding thickness.

100-V-002 Hydrogen Effluent Storage Sphere

The hydrogen effluent storage sphere is designed to accumulate and hold the cooled process gas from the quench chamber/debris trap for an entire test run.

Dimensions - 100'-0" with Support Legs

Design - 80 psig, 650°F

Materials - Carbon steel, painted inside and outside

Shielding - The sphere is shielded as required to prevent worker exposure to ionizing radiation above acceptable levels. See section 4.7 for shielding thickness.

100-C-001A/B Hydrogen Compressor

The hydrogen compressor is designed to withdraw the accumulated cooled process gas in the hydrogen effluent storage sphere at about 70 ACFM to process, treat, and recycle the contaminated effluent gas for subsequent test runs.

Quantity - 2

Design - 70 ACFM

Materials - 304SS

Shielding - The compressors are shielded as required to prevent worker exposure to ionizing radiation above acceptable levels. See section 4.7 for shielding thickness.

100-DR-001A/B Hydrogen Dryer

The hydrogen dryer is designed to dry the water-saturated effluent gas to a 233°K(-40°F) or lower dewpoint. Two dryers are used in series with the second dryer acting as a guard bed in the event of breakthrough occurring from the upstream dryer.

Quantity - 2

Dimensions - 5'-0" ID x14'-6" T-T

Packed Bed - 5'-0" ID x 12'-6" High

Media - Silica Gel/Molecular Sieves

Materials - 304SS

Design - 80 psig, 150°F

Flow Pattern - Downflow

Shielding- The dryers are shielded as required to prevent worker exposure to ionizing radiation above acceptable levels. See section 4.7 for shielding thickness.

100-F-004A/B Hydrogen Gas Filter

The hydrogen gas filter removes a minimum of 99.9 weight percent of the most penetrating particulate (approximately 0.3 micron size) contamination from the effluent stream. Two filters are used in series with the second filter acting as a guard bed in the event of breakthrough occurring from the upstream filter.

Quantity - 2

Dimensions - 3'-0" ID x 6'-0" T-T

Bed Dimensions - 3'-0" ID x 4'-0" High

Media - Alumina with 0.1 millimeter (0.004 inch) diameter particles and 40% void fraction

Flow Pattern - Downflow

Materials - 304SS shell, 304SS internals

Design - 80 psig, 150°F

Shielding- The vessels are shielded as required to prevent worker exposure to ionizing radiation above acceptable levels. See section 4.7 for shielding thickness.

100-E-001 Hydrogen Cryocooler

The hydrogen cryocooler is used to cool the process effluent gas stream at 311°K (100°F) in a shell and tube exchanger using liquid nitrogen as the cooling media before flowing into the noble gas adsorber. The outlet temperature from the cryocooler is controlled to achieve a temperature of 172°K (-150°F) at the noble gas adsorber discharge.

Design Duty - 100,000 BTU/hr

Materials - 304SS

Shielding - The exchanger is shielded as required to prevent worker exposure to ionizing radiation above acceptable levels. See section 4.7 for shielding thickness.

100-V-003A/B Noble Gas Adsorber

The noble gas adsorber removes a minimum of 99.5 weight percent of iodine (and other halogens) and noble gases (krypton and xenon) from the cold process effluent gas stream using activated carbon as an adsorbent. Two adsorbers are used in series with the second adsorber acting as a guard bed in the event of breakthrough occurring from the upstream adsorber.

Quantity - 2

Dimensions - 20" ID x 3'-0" T-T

Bed Dimensions - 20" ID x 2'-0" High

Flow Pattern - Downflow

Media - Activated carbon "-12 mesh+30 mesh" particles

Materials - 304SS shell, 304SS internals

Design - 80 psig, -200°F

Shielding- The vessels are shielded as required to prevent worker exposure to ionizing radiation above acceptable levels. See section 4.7 for shielding thickness.

<u>100-ME-001 Hydrogen Liquefaction Unit</u>

The hydrogen liquefaction unit is a package unit designed to liquefy 0.015 kg/sec (120 lb/hr) of the treated effluent gas stream.

<u>100-P-002A/B Quench Water Feed Pump</u>

The quench water feed pump is designed to pump the accumulated water in the quench chamber/debris trap to the treatment units for subsequent test runs.

Quantity - 2

Design - 90 GPM

Differential Pressure - 55 psi

Materials - 304SS

Shielding - The pumps are shielded as required to prevent worker exposure to ionizing radiation above acceptable levels. See section 4.7 for shielding thickness.

<u>100-F-001A/B Quench Water Filter</u>

The quench water filter removes a minimum of 99.9 weight percent of the most penetrating particulate (approximately 0.3 micron size) contamination from the water that had accumulated in the quench chamber/debris trap during a test run.

Quantity - 2

Design - 90 GPM

Media - Cartridge type

Materials - 304SS shell, 304SS internals

Design - 100 psig, 125°F

Shielding - The filters are shielded as required to prevent worker exposure to ionizing radiation above acceptable levels. See section 4.7 for shielding thickness.

100-DI-001 Quench Water Deionization Unit

The quench water deionization unit removes a minimum of 99.9 weight percent of dissolved radionuclides (cesium and strontium) contamination from the water using ion exchange resins.

Quantity - 1

Design - 90 GPM

Media - Ion Exchange Resin

Materials - 304SS shell, 304SS internals

Design - 100 psig, 125°F

Shielding - The deionization unit is shielded as required to prevent worker exposure to ionizing radiation above acceptable levels. See section 4.7 for shielding thickness.

100-F-002A/B Quench Water Polishing Filter

The quench water polishing filter removes a minimum of 99 weight percent of the most penetrating particulate (approximately 0.3 micron size) contamination from the treated water exiting the quench water deionization unit.

Quantity - 2

Design - 90 GPM

Media - Cartridge type

Materials - 304SS shell, 304SS internals

Design - 100 psig, 125°F

Shielding- The filters are shielded as required to prevent worker exposure to ionizing radiation above acceptable levels. See section 4.7 for shielding thickness.

100-RE-001 Quench Water Chiller

The quench water chiller is a packaged air-cooled refrigeration unit designed to cool 90 GPM of water exiting the quench water polishing filter from 300°K (80°F) to 278°K (40°F).

Quantity - 1

Design - 200 tons

Materials - 304SS tubeside, CS shellside

Shielding - The chiller is shielded as required to prevent worker exposure to ionizing radiation above acceptable levels. See section 4.7 for shielding thickness.

100-TK-001 Chilled Water Storage Tank

The chilled water storage tank is designed to hold the entire inventory of the water requirements of the base case test run.

Quantity - 1

Dimensions - 48′-0" ID x 48′-0" High

Materials - 304SS

Shielding - The tank is shielded as required to prevent worker exposure to ionizing radiation above acceptable levels. See section 4.7 for shielding exposure.

100-P-003A/B Chilled Water Feed Pump

The chilled water feed pump is designed to supply an adequate flow of chilled water to cool the hot feed gas exiting the nuclear thermal rocket engine from 2500°K (4040°F) to 311°K (100°F) by direct contact mixing of 278°K (40°F) sprayed chilled water in the top portion of the quench chamber/debris trap.

Quantity - 2

Design - 2160 GPM

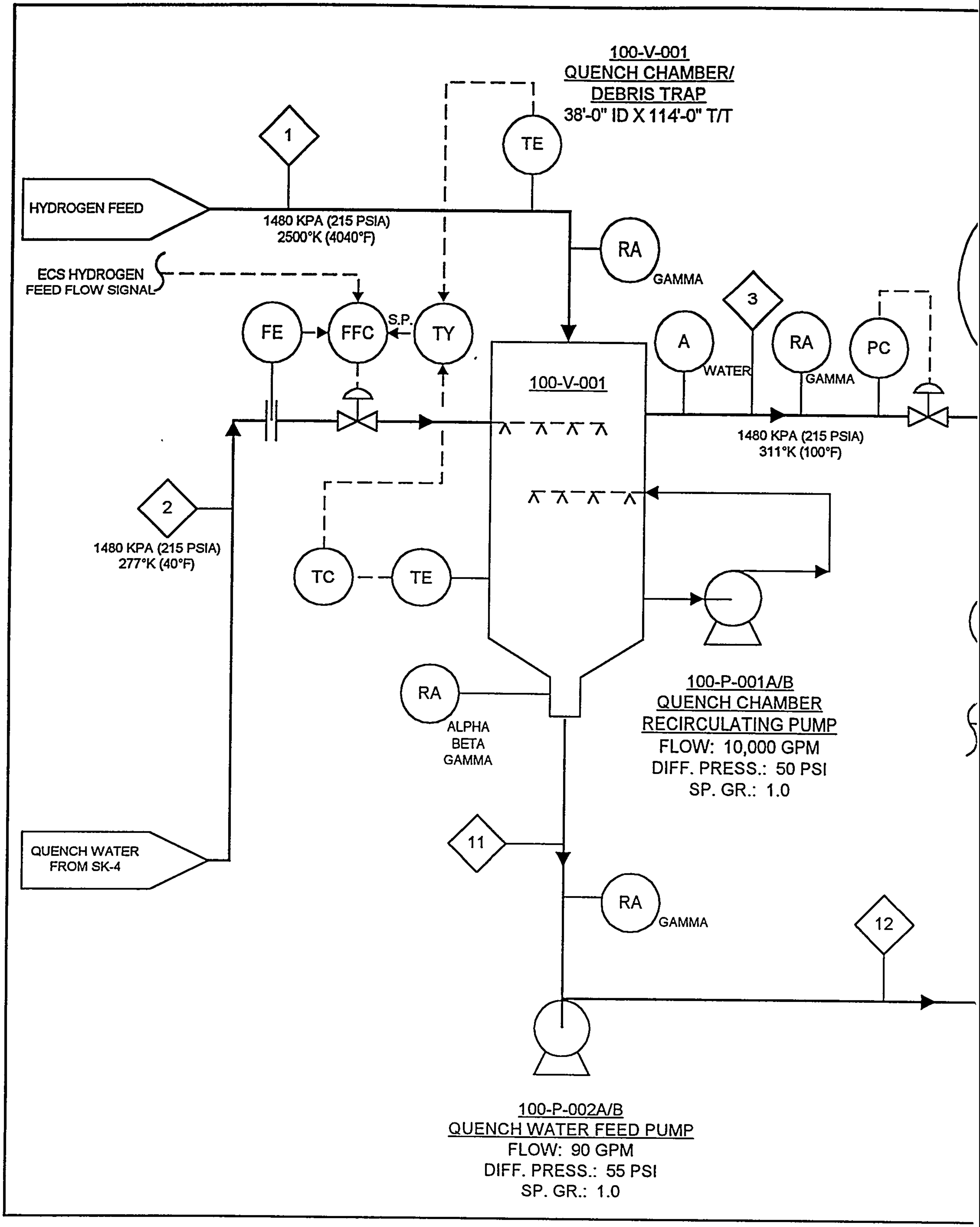
Differential Pressure - 250 psi

Materials - 304SS

Shielding - The pumps are shielded as required to prevent worker exposure to ionizing radiation above acceptable levels. See section 4.7 for shielding thickness.

2.2 Process Flow Diagram

This section presents preliminary sketches (Figures 2-1a, 2-1b, 2-1c, and 2-1d) of the process flow diagram for the proposed ECS process configuration of the ground testing facilities for a space nuclear thermal rocket engine. The number of equipment and equipment sizes shown on the process flow diagram are preliminary in nature and are based on the baseline design case (i.e., 11.5 MW Reactor Output/5 Hour Test Run Duration).



100-V-001
QUENCH CHAMBER/
DEBRIS TRAP
38'-0" ID X 114'-0" T/T
1
TE
HYDROGEN FEED
1480 KPA (215 PSIA)
2500°K (4040°F)
RA
GAMMA
ECS HYDROGEN
FEED FLOW SIGNAL
3
A
WATER
RA
GAMMA
PC
FE
FFC
S.P.
TY
100-V-001
1480 KPA (215 PSIA)
311°K (100°F)
2
1480 KPA (215 PSIA)
277°K (40°F)
TC
TE
RA
ALPHA
BETA
GAMMA
100-P-001A/B
QUENCH CHAMBER
RECIRCULATING PUMP
FLOW: 10,000 GPM
DIFF. PRESS.: 50 PSI
SP. GR.: 1.0
11
QUENCH WATER
FROM SK-4
RA
GAMMA
12
100-P-002A/B
QUENCH WATER FEED PUMP
FLOW: 90 GPM
DIFF. PRESS.: 55 PSI
SP. GR.: 1.0

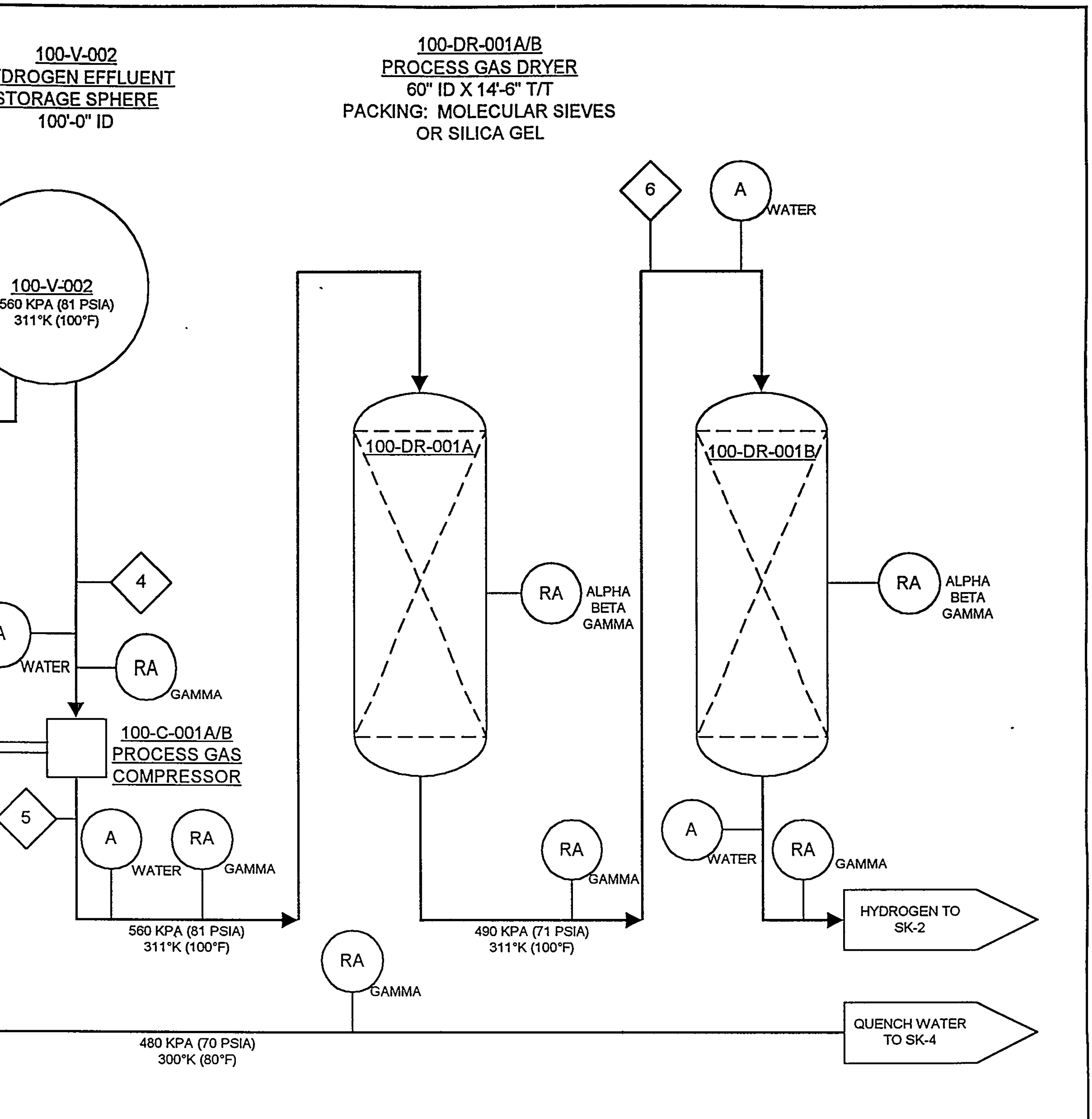
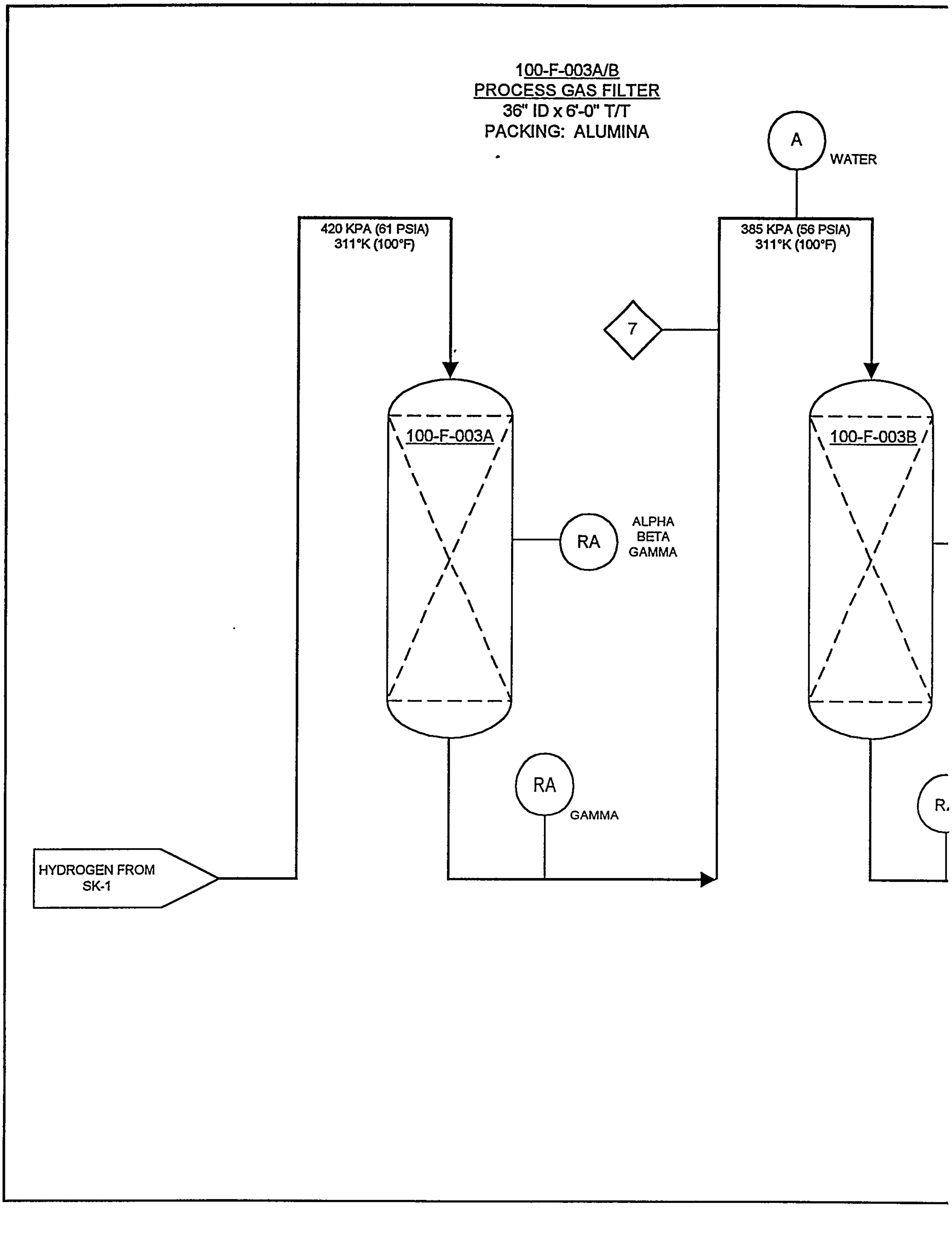


FIGURE 2-1A
PROCESS FLOW DIAGRAM
EFFLUENT CONTAINMENT SYSTEM
DRAWING: SK-1


100-F-003A/B
PROCESS GAS FILTER
36" ID x 6'-0" T/T
PACKING: ALUMINA
A
WATER
420 KPA (61 PSIA)
311°K (100°F)
385 KPA (56 PSIA)
311°K (100°F)
7
100-F-003A
100-F-003B
RA
ALPHA
BETA
GAMMA
RA
GAMMA
HYDROGEN FROM
SK-1

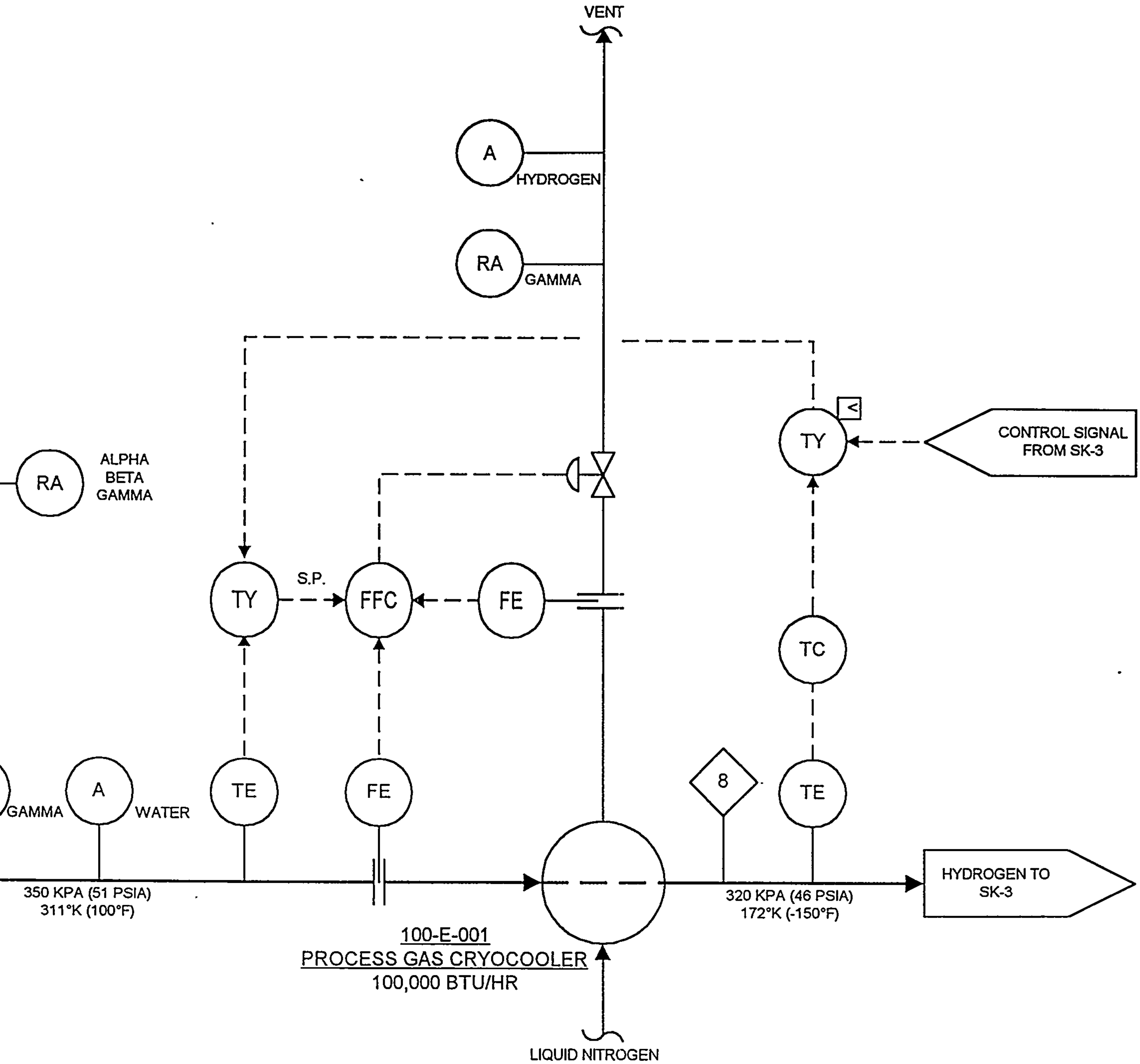
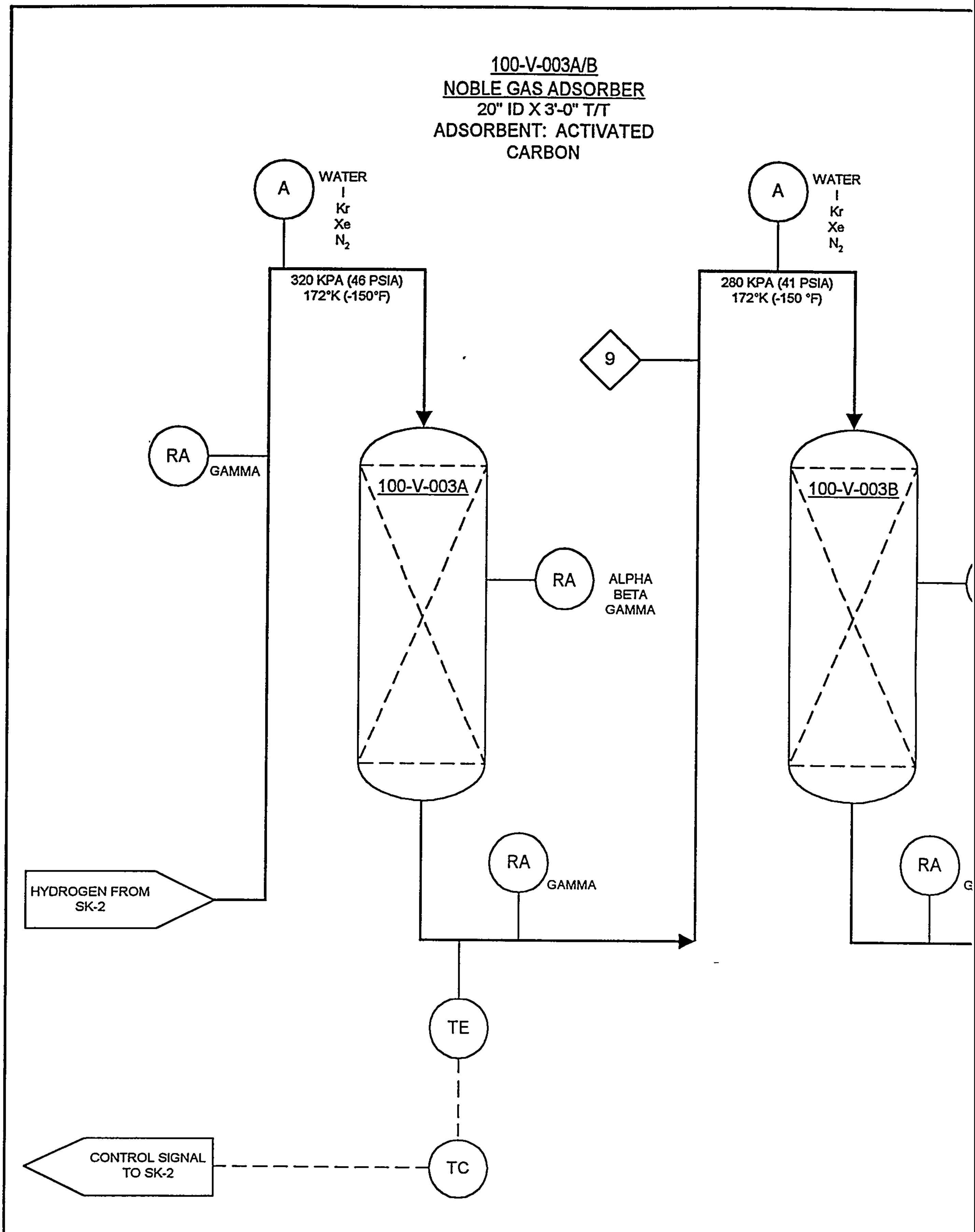


FIGURE 2-1B
PROCESS FLOW DIAGRAM
EFFLUENT CONTAINMENT SYSTEM
DRAWING: SK-2



100-V-003A/B
NOBLE GAS ADSORBER
20" ID X 3'-0" T/T
ADSORBENT: ACTIVATED CARBON
A
WATER
I
Kr
Xe
N2
320 KPA (46 PSIA)
172°K (-150°F)
RA
GAMMA
100-V-003A
RA
ALPHA
BETA
GAMMA
RA
GAMMA
HYDROGEN FROM SK-2
TE
TC
CONTROL SIGNAL TO SK-2
9
A
WATER
I
Kr
Xe
N2
280 KPA (41 PSIA)
172°K (-150 °F)
100-V-003B
RA

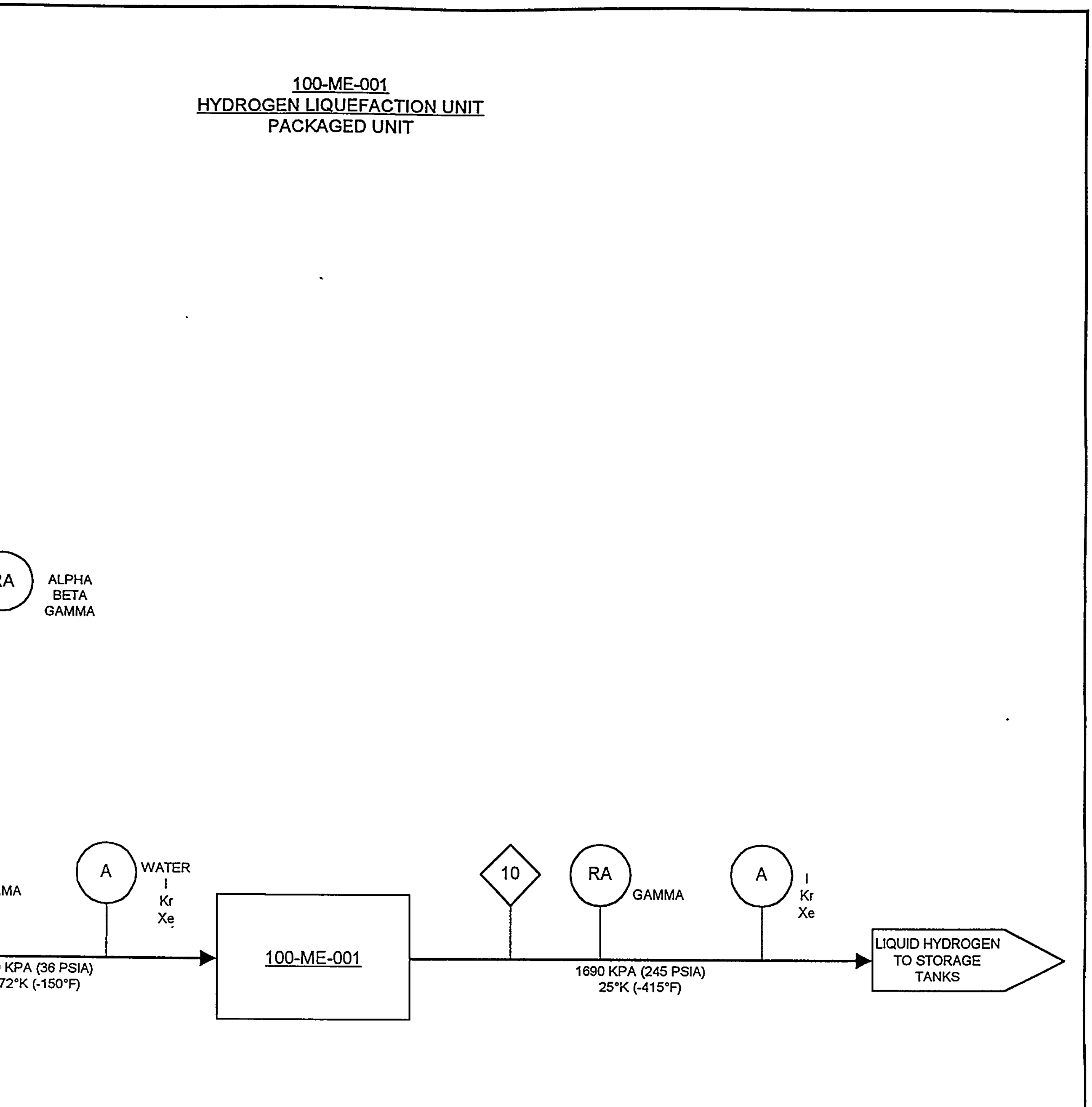
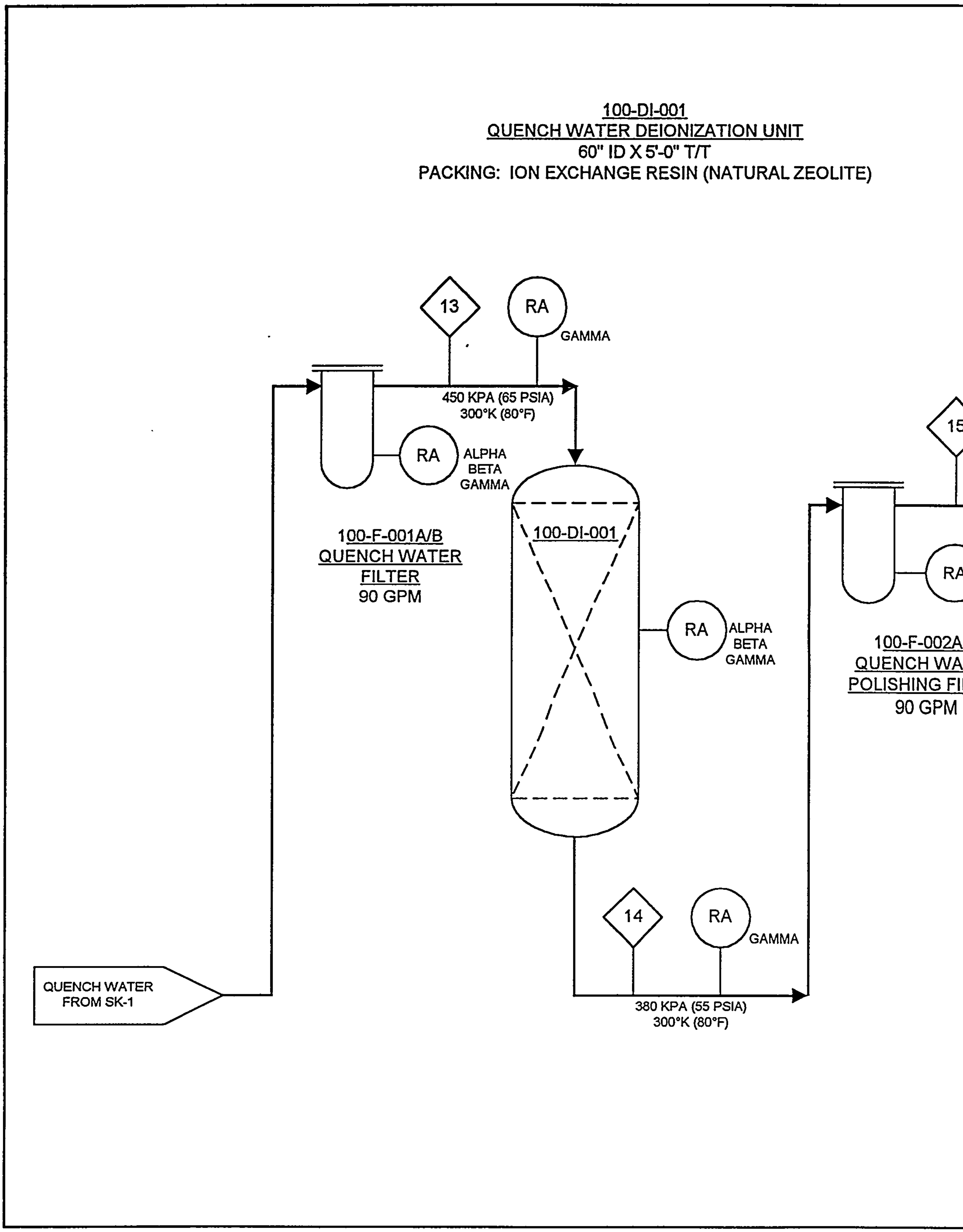


FIGURE 2-1C
PROCESS FLOW DIAGRAM
EFFLUENT CONTAINMENT SYSTEM
DRAWING: SK-3



100-DI-001
QUENCH WATER DEIONIZATION UNIT
60" ID X 5'-0" T/T
PACKING: ION EXCHANGE RESIN (NATURAL ZEOLITE)
13
RA
GAMMA
450 KPA (65 PSIA)
300°K (80°F)
RA
ALPHA
BETA
GAMMA
100-F-001A/B
QUENCH WATER
FILTER
90 GPM
100-DI-001
RA
ALPHA
BETA
GAMMA
15
RA
100-F-002A/
QUENCH WA
POLISHING FIL
90 GPM
14
RA
GAMMA
QUENCH WATER
FROM SK-1
380 KPA (55 PSIA)
300°K (80°F)

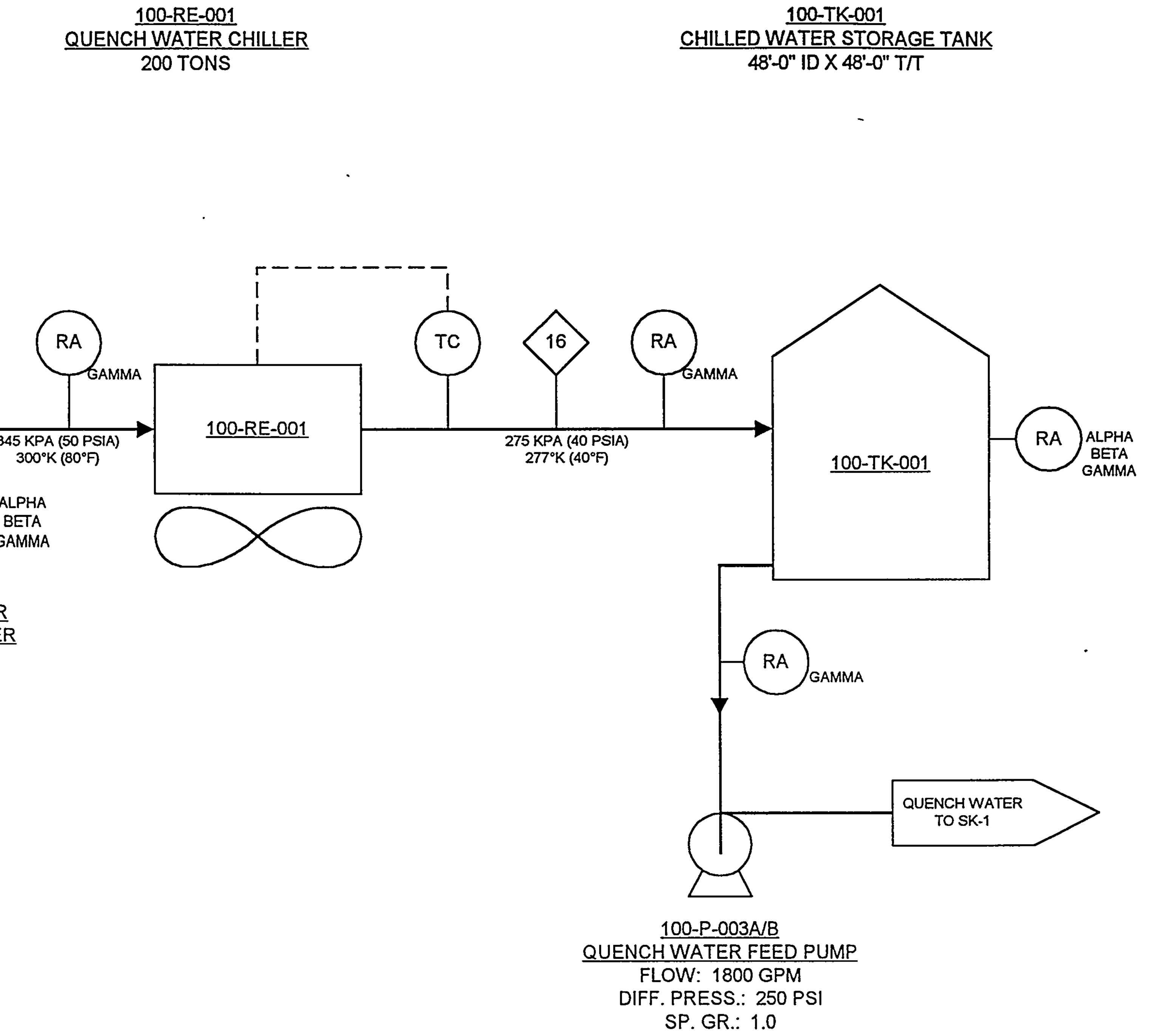


FIGURE 2-1D
PROCESS FLOW DIAGRAM
EFFLUENT CONTAINMENT SYSTEM
DRAWING: SK-4

2.3 Material Balance

This section shows the material balance for the Effluent Containment System (ECS) baseline design case (i.e., 11.5 MW for five hour test run duration) configuration (Table 2-1). The material balance stream numbers indicate the streams shown on the ECS Process Flow Diagram in Section 2.2 of this report. The equipment sizes shown on the process flow diagram (Figures 2-1a through 2-1d) are preliminary in nature and are based on the baseline design case.

Other material balances for the alternate reactor operating cases are shown in Section 2.9, Alternate Operating Modes.

MATERIAL BALANCE:		EFFLUENT CONTAINMENT SYSTEM RESEARCH AND DEVELOPMENT STUDY - BASE CASE						
Stream Number		1	2	3	4	5	6	
Stream Description		Hydrogen Feed	Quench Water	Quenched Gas to Storage	Quenched Gas to Compressor	Hydrogen Gas to Dryer	Hydrogen Gas from Upstream Dryer	Hydr from Gas
Components								
H2	mol %	100.00	0.00	99.56	99.56	99.56	100.00	
H2O	mol %	0.00	100.00	0.44	0.44	0.44	0.00	
MW		2.016	18.016	2.087	2.087	2.087	2.016	
Flow	LB/HR	2,222	900,790	2,310	96	96	93	
Flow	KG/SEC	0.28	113	0.29	0.012	0.012	0.012	
Flow	ACFM (GPM)	4,130	(1799)	516	57	57	65	
Flow	SCFM	6,972		7,003	292	292	290	
Flow	MMSCFD	10.0		10.1	0.4	0.4	0.4	
Flow	M³/HR	7,016	409	877	97	97	110	
Flow	NM³/HR	11,205		11,255	469	469	467	
Pressure	PSIA	215	215	215	81	81	71	
Pressure	KPA	1,480	1,480	1,480	558	558	490	
Temperature	°F	4,040	40	100	100	100	100	
Temperature	°K	2,500	277	311	311	311	311	
Density	LB/FT³	0.01	62.43	0.07	0.03	0.03	0.02	
Density (liquid)	LB/GAL		8.345					
Density	KG/M³	0.14	1000.00	1.19	0.45	0.45	0.38	
Particulates	MG/SEC	18556		76	2.84	2.81	2.53	
Particulates	Ci/SEC	5.55		5.73E-02	2.15E-03	2.13E-03	1.91E-03	
Noble Gas	MG/SEC	9.47E-02		9.47E-02	3.95E-03	3.95E-03	3.95E-03	
Noble Gas	Ci/SEC	7.91E-01		7.91E-01	3.29E-02	3.29E-02	3.29E-02	
Iodine	MG/SEC	5.60E-02		5.60E-02	2.33E-03	2.33E-03	2.33E-03	
Iodine	Ci/SEC	6.42E-01		6.42E-01	2.67E-02	2.67E-02	2.67E-02	
Cs-137	MG/SEC							
Cs-137	Ci/SEC							
Sr-90	MG/SEC							
Sr-90	Ci/SEC							
Hydrogen	LB/BATCH	11,111		11,111	11,111	11,111	11,111	
Hydrogen	KG/BATCH	5,040		5,040	5,040	5,040	5,040	
Water	LB/BATCH		4.50E+06	4.41E+02	4.41E+02	4.41E+02		
Water	KG/BATCH		2.04E+06	2.00E+02	2.00E+02	2.00E+02		
Particulates	MG/BATCH	3.34E+08		1.36E+06	1.22E+06	1.21E+06	1.09E+06	
Particulates	Ci/BATCH	99943		1031	927.5	918.2	826.4	
Noble Gas	MG/BATCH	1705		1705	1705	1705	1705	
Noble Gas	Ci/BATCH	14230		14230	14230	14230	14230	
Iodine	MG/BATCH	1008		1008	1008	1008	1008	
Iodine	Ci/BATCH	11550		11550	11550	11550	11550	
Cs-137	MG/BATCH							
Cs-137	Ci/BATCH							
Sr-90	MG/BATCH							
Sr-90	Ci/BATCH							

MATERIAL BALANCE NOTES:

(1) All temperatures, pressures, flow quantities, and compositions are for process design purposes only. No guarantee of these conditions is expressed or implied. Supplementar

(2) The process operations consist of three separate batch modes of operation. All equipment upstream of the hydrogen effluent storage sphere are operated in a batch mode firs quench chamber/debris trap in the third batch mode of operation.

(3) Flows for streams 1 through 3 are based on a base case test run operation over a five hour period. The remaining streams for either hydrogen or quench water are processec

ble 2-1

7	8	9	10	11	12	13	14	15	16
en stream er	Hydrogen from Gas Cooler	Hydrogen from Upstream Gas Adsorber	Hydrogen Liquid to Storage	Water from Quench Chamber	Quench Water to Filter	Quench Water to DI Unit	Deionized Water to Polishing	Deionized Water to Chiller	Chilled Water to Storage
100.00	100.00	100.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	100.00	100.00	100.00	100.00	100.00	100.00
2.016	2.016	2.016	2.016	18.016	18.016	18.016	18.016	18.016	18.016
93	93	93	93	37,529	37,529	37,529	37,529	37,529	37,529
0.012	0.012	0.012	0.012	4.7	4.7	4.7	4.7	4.7	4.7
82	55	62	(2.7)	(75)	(75)	(75)	(75)	(75)	(75)
290	290	290							
0.4	0.4	0.4							
139	94	105	0.62	17	17	17	17	17	17
467	467	467							
56	46	41	245	15	70	65	55	50	40
386	317	283	1,689	101	481	448	379	345	276
100	(150)	(150)	(415)	80	80	80	80	80	40
311	172	172	25	300	300	300	300	300	277
0.02	0.03	0.02	4.210	62.22	62.22	62.22	62.22	62.22	62.43
			0.563	8.317	8.317	8.317	8.317	8.317	8.345
0.30	0.45	0.40	67.44	996.6	996.6	996.6	996.6	996.6	1000.0
53E-03	2.50E-03	2.48E-03	2.47E-03	9.45	9.45	9.45E-03	9.45E-03	9.45E-05	9.45E-05
91E-06	1.89E-06	1.87E-06	1.87E-06	7.15E-03	7.15E-03	7.15E-06	7.15E-06	7.15E-08	7.15E-08
95E-03	3.95E-03	1.97E-05	1.97E-05						
29E-02	3.29E-02	1.65E-04	1.65E-04						
33E-03	2.33E-03	1.17E-06	1.17E-06						
67E-02	2.67E-02	1.34E-04	1.34E-04						
				1.03E-03	1.03E-03	1.03E-03	1.03E-06	1.03E-06	1.03E-06
				8.97E-05	8.97E-05	8.97E-05	8.97E-08	8.97E-08	8.97E-08
				6.34E-04	6.34E-04	6.34E-04	6.34E-07	6.34E-07	6.34E-07
				8.65E-05	8.65E-05	8.65E-05	8.65E-08	8.65E-08	8.65E-08
11,111	11,111	11,111	11,111						
5,040	5,040	5,040	5,040						
				4.50E+06	4.50E+06	4.50E+06	4.50E+06	4.50E+06	4.50E+06
				2.04E+06	2.04E+06	2.04E+06	2.04E+06	2.04E+06	2.04E+06
1091	1080	1070	1069	4.08E+06	4.08E+06	4082	4082	40.8	40.8
0.83	0.82	0.81	0.81	3091	3091	3.1	3.1	0.03	0.03
1705	1705	8.5	8.5						
14230	14230	71.2	71.2						
1008	1008	0.5	0.5						
11550	11550	57.8	57.8						
				445.0	445.0	445.0	0.45	0.45	0.45
				38.8	38.8	38.8	0.04	0.04	0.04
				273.9	273.9	273.9	0.27	0.27	0.27
				37.4	37.4	37.4	0.04	0.04	0.04

sign information is contained in the process description and alternate material balances are provided for other operating modes.

The cooled process gas is stored in the sphere and the quench water is stored in the quench chamber/debris trap. The stored gas is then processed in the equipment downstream of the

er a five day period.

2.4 Pressure Profile/Hydrogen Distribution

2.4.1 Introduction

This section describes the Effluent Containment System (ECS) pressure profile/hydrogen distribution during the baseline design case test run. The description applies only to the exhaust gas cooling batch operation which consists of 30 minutes of reactor ramping up, five hours of full reactor power output at 11.5 MW, and 60 minutes of reactor ramping down for a total test run duration time of 390 minutes. The other two batch operations, hydrogen treatment and recycle and water treatment and recycle, process the streams at a constant flow rate and pressure after the test run has been completed. As a starting basis, the description assumes all plant start-up and check-out procedures have been performed and requirements have been met.

The pressure profile/hydrogen distribution figures shown in this section represent, for design purposes, an additional 20 per cent allowance for the quench water flow rate.

2.4.2 Exhaust Gas Cooling Batch Operation

At the start of the test run, the Quench Chamber/Debris Trap and the Hydrogen Effluent Storage Sphere are operating at a few inches water gauge above atmospheric pressure. A back pressure control valve located between the two equipment items is set to maintain a maximum pressure of 200 psig in the Quench Chamber/Debris Trap during the test run. As the reactor ramps up to full power in the initial 30 minutes of operation, liquid hydrogen flows through it to remove the generated heat. Once full reactor power is established, quench water from the storage tank flows into the Quench Chamber/Debris Trap to cool the hot exhaust gas to 311°K (100°F). As shown in Figure 2-2, ECS Pressure Profile, the pressure continues to build up in the Quench Chamber/Debris Trap until about 160 minutes (130 minutes into full reactor power) into the test run when the pressure reaches the control valve setpoint of 200 psig. During the remainder of the test run operation, the pressure controller maintains the pressure in the Quench Chamber/Debris Trap at 200 psig as hydrogen gas begins flowing to the Hydrogen Effluent Storage Sphere. At about 330 minutes (end of full reactor power) into the operation, the pressure in the Hydrogen Effluent Storage Sphere has increased from atmospheric pressure initially to about 50 psig. As the reactor ramps down from full power, liquid hydrogen continues to flow through it for 60 minutes for removal of the residual heat after shutdown. The quench water during this final 60 minute cooldown phase is shut down while the effluent gas flowing from the reactor continues to be cooled by recirculation of the accumulated water in the Quench Chamber/Debris Trap. At the end of the 390 minutes (reactor ramp up, full reactor power, and reactor ramp down), the final pressure in the Hydrogen Effluent Storage Sphere is about 65 psig while the Quench Chamber/Debris Trap is maintained on back pressure control at 200 psig. During the reactor ramp up and ramp down phases, The Quench Chamber Recirculating Pumps are operated.

Figure 2-3, ECS Hydrogen Profile, shows the hydrogen profile during the entire test run (reactor ramp up, full reactor power, and reactor ramp down) for the Quench Chamber/Debris Trap and the Hydrogen Effluent Storage Sphere. Initially, both equipment items indicate hydrogen gas in the units since both are operating at approximately atmospheric pressure in a hydrogen gas environment. As the test run proceeds, the hydrogen in the Quench

Chamber/Debris Trap increases until the pressure controller setpoint of 200 psig is reached at about 160 minutes into the entire test run. For the next 170 minutes of full reactor power, the hydrogen in the Quench Chamber/Debris Trap decreases by about 50 percent. The decrease is contributed to maintaining a 200 psig pressure in the Quench Chamber/Debris Trap when both quench water and hydrogen gas are entering the unit. The continuous rise in water level along with the constant hydrogen flow requires additional hydrogen to be flowing to the Hydrogen Effluent Storage Sphere to maintain a constant back pressure in the Quench Chamber/Debris Trap. During the final 60 minutes when the reactor is ramping down and only hydrogen is flowing into the system, the hydrogen in the Quench Chamber/Debris Trap remains constant while increasing in the Hydrogen Effluent Storage Sphere.

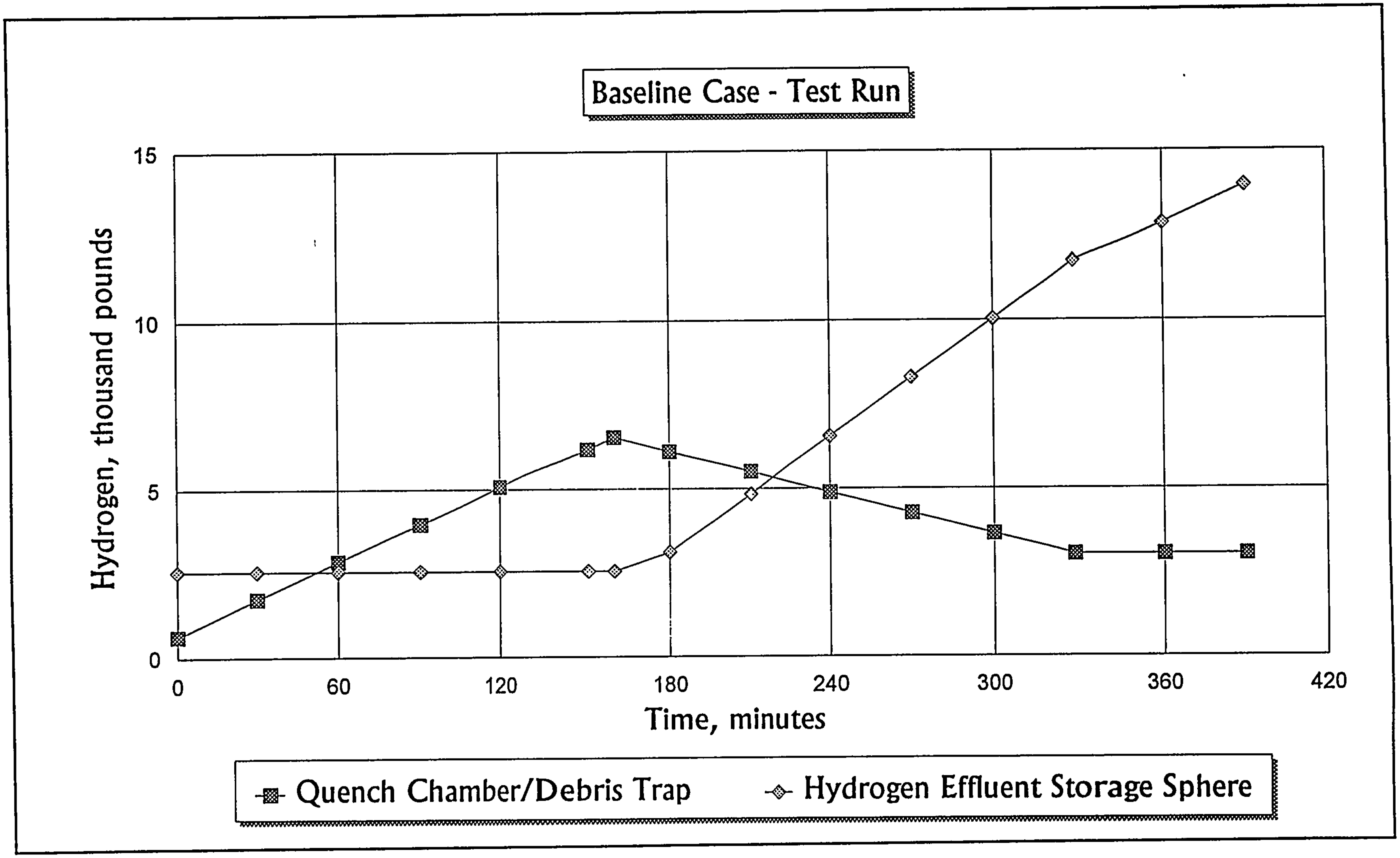


Figure 2-2 ECS Pressure Profile

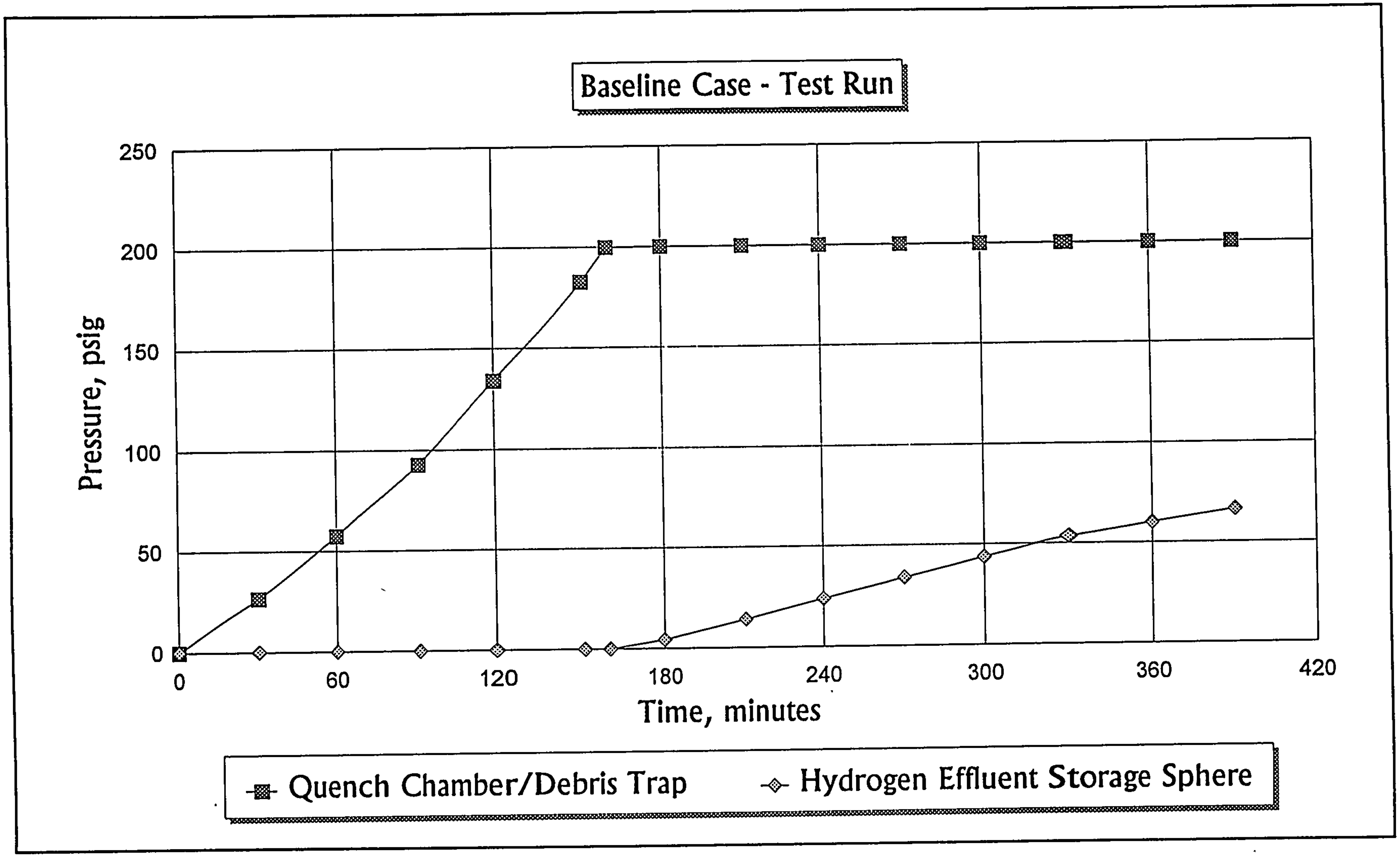


Figure 2-3 ECS Hydrogen Profile

2.5 Systems/Equipment List

2.5.1 Introduction

This section lists the necessary systems and equipment required to support the ECS Ground Test Facility. The quantity listed for equipment is for the baseline design case which is 11.5 MW reactor output for five hours test run duration. The number of equipment required for the other operating cases are discussed in Secton 2.9, Alternate Operating Modes.

SYSTEMS LIST

- Effluent Containment System
- Quench Water Treatment and Recycle System
- Quench Water System
- Hydrogen Treatment and Recycle System
- Liquid Nitrogen Storage System
- Liquid Hydrogen Storage System
- Emergency Diesel Generator System

BASELINE DESIGN EQUIPMENT LIST

ITEM NUMBER	QUANTITY	ITEM DESCRIPTION
100-V-001	1	Quench Chamber/Debris Trap
100-P-001A/B	2	Quench Chamber Recirculating Pump
100-V-002	1	Hydrogen Effluent Storage Sphere
100-P-002A/B	2	Quench Water Feed Pump
100-F-001A/B	2	Quench Water Filter
100-DI-001	1	Quench Water Deionization Unit
100-F-002A/B	2	Quench Water Polishing Filter
100-RE-001	1	Quench Water Chiller
100-TK-001	1	Chilled Water Storage Tank
100-F-003A/B	2	Chilled Water Storage Tank Vent Filter
100-P-003A/B	2	Chilled Water Feed Pump
100-P-004A/B	2	Chilled Water Recirculation Pump
100-C-001A/B	2	Process Gas Compressor
100-DR-001A/B	2	Process Gas Dryer
100-F-004A/B	2	Process Gas Filter
100-E-001	1	Process Gas Cryocooler
100-V-003A/B	2	Noble Gas Adsorber
100-ME-001	1	Hydrogen Liquefaction Unit
200-ME-001	1	Liquid Nitrogen Storage Unit
200-ME-002	1	Liquid Hydrogen Storage Unit
300-G-001A/B	2	Emergency Diesel Generator
300-TK-001	1	Diesel Fuel Storage Tank
300-P-001	1	Diesel Fuel Pump

2.6 Support Systems

2.6.1 Introduction

This section describes the support systems required for supporting the operation of the proposed ECS baseline design case configuration (i.e., 11.5 MW Reactor Output/5 Hour Test Run). The support systems include liquid hydrogen, liquid nitrogen, and emergency power systems. Process descriptions, functional requirements, and design capacity are discussed.

Liquid Hydrogen System

The Liquid Hydrogen System is comprised of a package unit consisting of double-walled storage vessels and other equipment to supply both liquid and gaseous hydrogen to the ECS. Liquid hydrogen is used as the coolant for reactor heat removal during a test run and to provide for quench chamber/debris trap jacket cooling. Gaseous hydrogen is required to purge equipment.

A sufficient quantity of liquid hydrogen is stored in the double-walled storage vessels to meet total plant requirements for one test run. Storage capacity requirements for liquid hydrogen is about 30,000 gallons at 25°K (-415°F) and 690 kPa (100 psia). Liquid hydrogen is pumped at about 75 GPM to remove the reactor heat and provide jacket cooling of the quench chamber/debris trap during the test run. Gaseous hydrogen is supplied at a rate of about 100 SCFM for purging the system.

The Liquid Hydrogen System consists of the following major equipment:

- Liquid Hydrogen Storage Vessel(s)
- Liquid Hydrogen Pumps
- Hydrogen Compressors
- Ambient Air Pressure Building Coil
- Ambient Air Hydrogen Heater
- Electric Pressure Building Coil
- Electric Hydrogen Heater

Liquid Nitrogen System

The Liquid Nitrogen System is comprised of a package unit consisting of double-walled storage vessels and other equipment to supply both liquid and gaseous nitrogen to the ECS. Liquid nitrogen is used to cryogenically cool the filtered process gas in the cryocooler. Gaseous nitrogen is required to purge equipment and to provide for instrumentation needs.

A sufficient quantity of liquid nitrogen is stored in the double-walled storage vessels to meet total plant requirements for one test run. Storage capacity requirements for liquid nitrogen is about 35,000 gallons at 103°K (-275°F) and 1500 kPa (218 psia). Liquid nitrogen is pumped at about 5 GPM to the cryocooler during the hydrogen treatment/recycle batch operation. Gaseous nitrogen is supplied at a rate of about 100 SCFM for instrumentation needs.

The Liquid Nitrogen System consists of the following major equipment:

- Liquid Nitrogen Storage Vessel(s)
- Nitrogen Compressors
- Liquid Nitrogen Pumps
- Ambient Air Pressure Building Coil
- Ambient Air Nitrogen Heater
- Electric Pressure Building Coil
- Electric Nitrogen Heater

Emergency Power Generator System

The Emergency Power Generator System consists of two diesel generators and other supporting equipment to provide standby power to the ECS essential loads during a loss of power. The standby power is used to provide backup power to the essential loads, including the Chilled Water Feed Pumps, Quench Chamber Recirculating Pumps, and the Liquid Hydrogen Pumps in the event of primary power supply interruption during the test run.

The system is to start to provide 1200 kw of power to the essential plant users within 10-20 seconds after loss of power. All three sets of pumps on standby power, including the spare pumps, need to be operating in the event the primary pump fails. The capacity requirements for each diesel fuel storage tank is about 600 gallons which will provide enough fuel to operate the generator system at rated capacity for the entire 5 hour test run.

The Emergency Power Generator System consists of the following major equipment:

- Diesel Generators
- Diesel Fuel Storage Tanks
- Diesel Fuel Day Tanks
- Diesel Fuel Supply Pumps

2.7 Process Control Philosophy

2.7.1 Introduction

The purpose of this section is to develop a process control philosophy for the ECS facility. As a starting basis, this document assumes all plant start-up and check-out procedures have been performed and requirements have been met. Start-up and shutdown requirements will be addressed later.

The ECS is configured to operate in three separate batch operations: exhaust gas cooling, hydrogen treatment and recycle, and water treatment and recycle. The first batch operation consists of quenching the hot hydrogen gas from the nuclear reactor with water and storing the quenched hydrogen gas and water to allow short lived radioisotopes to decay significantly. The next set of batch operations consists of treating and recycling, for subsequent test runs, the hydrogen gas and water through separate treatment systems.

Redundant sensors are provided for important process control loops and all process variables which cause shutdown of either the ECS feed or the operation of the treatment systems. Generally, one of two sensors can activate an alarm or shutdown. In all instances, a high or low signal will alarm and some signals are followed by a high-high or low-low alarm and shutdown of the ECS feed. "Shutdown" of the ECS feed means initiation of reactor shutdown and rapid reduction of feed flow rate. Following reactor "shutdown", hydrogen flow continues for an hour to cool the reactor to ambient conditions. "Shutdown" of the treatment systems means initiation of pump or compressor shutdown resulting in longer processing times.

Each of the three batch operations is discussed separately and based on the base case of 11.5 MW reactor output for five hours of test run duration. The operating conditions, such as flow rates, presented herein represent those conditions encountered for the base case.

See Process Flow Diagram, Effluent Containment System, for flow configuration and stream names.

2.7.2 Exhaust Gas Cooling

Feed gas from the reactor at 2500°K(4040°F) and 1480 kPa(215 psia) and quench water at 278°K(40°F) and 1480 kPa(215 psia) flow into the quench chamber/debris trap. The quench water is heated as the feed gas is cooled. The cooled feed gas, on pressure control, exits the quench chamber/debris trap at 311°K(100°F) and 1480 kPa(215 psia) and flows to the hydrogen effluent storage sphere. The ECS feed gas flow rate is not controlled at the reactor exit. The quench water flow is controlled by maintaining the water temperature in the quench chamber/debris trap at 300°K(80°F). The hot feed gas flow rate and temperature of the gas entering the quench chamber/debris trap are measured and used in a feed forward control scheme to adjust the quench water flow controller. The quench water flow rate is controlled at 113.4 kg/sec (900,000 lb/hr) when the hot feed gas enters the quench chamber/debris trap at 0.28 kg/sec (2200 lb/hr) at 2500°K (4040°F). The quench chamber recirculating pump is manually controlled to recirculate water from the quench chamber through another set of spray nozzles to further enhance the mixing of the water in the quench chamber and the cooling effect on the entering hot feed gas into the quench chamber/debris trap.

Temperature excursions may occur during operation resulting in extremely high feed gas temperatures and exposing the quench chamber/debris trap to these temperatures. One of the purposes of the quench chamber recirculating pumps is to maintain a spray water flow in the event of a temperature excursion and mitigate the effects of the temperature excursion until the reactor can be safety shut down. High feed gas temperature alarms are provided to indicate feed temperature excursions and a high-high feed temperature shutdown is provided to shut down the reactor. Upon pre-operational test run operation, low feed gas temperatures may occur resulting in the quench chamber/debris trap being exposed to temperatures well below the normal operating temperature. Low feed temperature alarms are provided to indicate an abnormally low feed temperature and a low-low temperature alarm shuts down the ECS feed. The ECS feed pressure, flow, and radiation level are also monitored. High and low pressure and flow rate conditions are alarmed. A high radiation (gamma) level is alarmed and high-high levels of radiation initiate shutdown of the reactor.

2.7.2.1 Quench Water

Quench water operating parameters are monitored. High and low quench water flow are monitored and alarmed. Shutdown of ECS feed is initiated under conditions of quench water low-low flow. The quench water flow is shut down after the ECS feed is shut down.

A summary of the instrumentation, alarms, and shutdowns associated with the quench water and ECS feed appears in Table 2-2.

Table 2-2 Quench Water Instrumentation

Stream/Item	Indication	Alarm		Shutdown	
		High	Low	High-High	Low-Low
Feed Gas					
Temperature	X	X	X	X	X
Pressure	X	X	X	X	X
Flow	X	X	X	-	-
Radiation (Gamma)	X	X	-	X	-
Quench Water					
Flow	X	X	X	-	X

2.7.2.2 Quench Chamber/Debris Trap

Process variables are monitored either inside or at the exit of the quench chamber/debris trap. High and low operating temperatures and a high radiation (gamma) level inside the quench chamber/debris trap are alarmed. High pressure in the outlet stream from the quench chamber/debris trap is alarmed. A high radiation (gamma) level or water content of the outlet gas stream is also alarmed. Reactor shutdown is initiated by any of the following conditions: high-high or low-low operating temperatures inside the quench chamber/debris trap, high-high radiation (gamma) levels inside the quench chamber/debris trap or in the outlet stream, or a high-high water content in the outlet stream.

A summary of the instrumentation, alarms, and shutdowns associated with the quench chamber/debris trap appears in Table 2-3.

Table 2-3 Quench Chamber/Debris Trap Instrumentation

Stream/Item	Indication	Alarm		Shutdown	
		High	Low	High-High	Low-Low
Inside Quench Chamber/Debris Trap					
Temperature	X	X	X	X	X
Radiation (gamma)	X	X	-	X	-
Gas Discharge Stream					
Pressure	X	X	-	-	-
Radiation (gamma)	X	X	-	X	-
Water Content	X	X	-	X	-

2.7.2.3 Hydrogen Effluent Storage Sphere

The quenched feed gas exits the quench chamber/debris trap at 311°K(100°F) and accumulates in the hydrogen effluent storage sphere. The gas is held for seven days to allow the decay of short-lived radionuclides prior to treatment commencing. After the seven day decay period, the gas is compressed slightly and flows to the process gas dryers where the water-saturated gas is dried to a minimum dewpoint of 233°K (-40°F). High levels of radiation (gamma) and water content are alarmed. Shutdown of the process gas treatment system is initiated if a high-high radiation (gamma) level is detected.

A summary of the instrumentation, alarms, and shutdowns associated with the hydrogen effluent storage sphere appears in Table 2-4.

Table 2-4 Hydrogen Effluent Storage Sphere Instrumentation

Stream/Item	Indication	Alarm		Shutdown	
		High	Low	High-High	Low-Low
Discharge Stream					
Radiation (gamma)	X	X	-	X	-
Water Content	X	X	-	-	-

2.7.3 Hydrogen Treatment and Recycling System

2.7.3.1 Process Gas Dryers

After the seven day decay period in the hydrogen effluent storage sphere, the process gas is compressed and flows to the process gas dryers where the water-saturated gas is dried to a minimum dewpoint of 233°K (-40°F). Flow through the dryers is controlled to achieve treatment of the contents of the quench chamber/debris trap and hydrogen effluent storage sphere in 120 hours. Two dryers are used in series with the second dryer acting as a guard bed in the event of breakthrough occurring from the upstream dryer.

The compressed gas entering and exiting the dryers is monitored. High levels of radiation (gamma) and water content in the outlet stream are alarmed. Each dryer is monitored for radiation (alpha, beta, and gamma) and pressure drop and alarmed on high radiation level and high pressure drop. Feed shutdown is initiated by high-high radiation (gamma) levels in the inlet and outlet dryer streams, high-high water content in the secondary guard dryer outlet stream, or by high-high radiation (alpha, beta, and gamma) level in either one of the dryers.

A summary of the instrumentation, alarms, and shutdowns associated with the process gas dryers appears in Table 2-5.

Table 2-5 Process Gas Dryer Instrumentation

Stream/Item	Indication	Alarm		Shutdown	
		High	Low	High-High	Low-Low
Dryers Inlet					
Radiation (gamma)	X	X	-	X	-
Water Content (Dewpoint)	X	X	-	-	-
First Dryer Outlet					
Radiation (gamma)	X	X	-	X	-
Water Content (Dewpoint)	X	X	-	-	-
Second Dryer Outlet					
Radiation (gamma)	X	X	-	X	-
Water Content (Dewpoint)	X	X	-	X	-
Dryers					
Pressure Drop	X	X	-	-	-
Radiation	X	X	-	X	-

2.7.3.2 Process Gas Filter

The dried process gas at 311°K (100°F) flows to the particulate filters. Flow through the filters is not controlled. Two filters are used in series with the second filter acting as a guard bed in the event of breakthrough occurring from the upstream filter.

The filtered process gas exiting the filters is monitored. High levels of radiation (gamma) and water content are alarmed. Each filter is monitored for radiation (alpha, beta, and gamma) and pressure drop and alarmed on high radiation level and high pressure drop. Feed shutdown is initiated by high-high radiation (gamma) levels in the outlet streams, high-high water content in the outlet filter streams, or by high-high radiation (alpha, beta, and gamma) level in either one of the filters.

A summary of the instrumentation, alarms, and shutdowns associated with the filters appears in Table 2-6.

Table 2-6 Process Gas Filter Instrumentation

Stream/Item	Indication	Alarm		Shutdown	
		High	Low	High-High	Low-Low
Filter Discharge					
Radiation (gamma)	X	X	-	X	-
Water Content (Dewpoint)	X	X	-	-	-
Filters					
Radiation	X	X	-	X	-
Pressure Drop	X	X	-	X	-

2.7.3.3 Process Gas Cryocooler

The dried filtered process gas exits the filters and flows to the process gas cryocooler where it is cooled from 311°K (100°F) to 172°K (-150°F) using liquid nitrogen as the coolant. The process gas flow is not controlled. Liquid nitrogen flow to the heat exchanger is controlled to maintain the process gas exit temperature. Process gas flow rate and temperature are measured and used in a feed forward control scheme to adjust the nitrogen flow.

The cold process gas exits the cryocooler and is monitored. High and low flow, temperature, and pressure levels are alarmed. High levels of radiation (gamma), krypton,xenon, iodine, nitrogen, and water are alarmed. Feed shutdown is initiated if a high-high temperature, low-low temperature, high-high radiation (gamma) level, high-high nitrogen or high-high water content occurs in the cold process gas.

The nitrogen coolant is also monitored. High or low nitrogen temperature, pressure, and flow rate at the inlet or outlet of the exchanger are alarmed. A high hydrogen content and radiological (gamma) level in the nitrogen vent stream from the exchanger are alarmed. Feed shutdown is initiated by nitrogen coolant high-high temperature, low-low flow, and low-low pressure at the inlet and outlet of the cryocooler. A high-high hydrogen content or high-high radiation (gamma) level in the nitrogen stream exiting the cryocooler also initiates feed shutdown.

A summary of the instrumentation, alarms, and shutdowns associated with the process gas cryocooler appears in Table 2-7.

Table 2-7 Process Gas Cryocooler Instrumentation

Stream/Item	Indication	Alarm		Shutdown	
		High	Low	High-High	Low-Low
Cold Process Gas					
Temperature	X	X	X	X	X
Pressure	X	X	X	-	-
Flow	X	X	X	-	-
Radiation (gamma)	X	X	-	X	-
Krypton Content	X	X	-	-	-
Xenon Content	X	X	-	-	-
Iodine Content	X	X	-	-	-
Nitrogen Content	X	X	-	X	-
Water Content (Dewpoint)	X	X	-	X	-
Inlet Nitrogen					
Temperature	X	X	X	X	-
Pressure	X	X	X	-	X
Flow	X	X	X	-	X
Exit Nitrogen					
Temperature	X	X	X	X	-
Pressure	X	X	X	-	X
Flow	X	X	X	-	X
Radiation (gamma)	X	X	-	X	-
Hydrogen Content	X	X	-	X	-

2.7.3.4 Noble Gas Adsorbers

The cold process gas at 172°K (-150°F) flows to the noble gas adsorbers (cryogenic activated carbon adsorbers). Flow through the adsorbers is not controlled. Two adsorbers are used in series with the second adsorber acting as a guard bed in the event of breakthrough occurring from the upstream adsorber.

The noble gas adsorber exit streams are monitored and conditions of high and low temperature are alarmed. High levels of radiation (gamma), iodine, krypton, xenon, and water in the outlet stream are also alarmed. Each adsorber is monitored for radiation (alpha, beta, and gamma) levels and pressure drop and alarmed on high radiation level and pressure drop. Feed shutdown is initiated by high-high radiation (gamma) levels and high-high/low-low temperature in either of the adsorbers outlet stream, high-high iodine, krypton, xenon, and water content in the secondary guard adsorber outlet stream, or by high-high radiation (alpha, beta, and gamma) level in either one of the adsorbers.

A summary of the instrumentation, alarms, and shutdowns associated with the noble gas adsorbers appears in Table 2-8.

Table 2-8 Noble Gas Adsorbers Instrumentation

Stream/Item	Indication	Alarm		Shutdown	
		High	Low	High-High	Low-Low
First Adsorber Outlet					
Temperature	X	X	X	X	X
Radiation (gamma)	X	X	-	X	-
Iodine Content	X	X	-	-	-
Krypton Content	X	X	-	-	-
Xenon Content	X	X	-	-	-
Water Content (Dewpoint)	X	X	-	-	-
Second Adsorber Outlet					
Temperature	X	X	X	X	X
Radiation (gamma)	X	X	-	X	-
Iodine Content	X	X	-	X	-
Krypton Content	X	X	-	X	-
Xenon Content	X	X	-	X	-
Water Content (Dewpoint)	X	X	-	X	-
Adsorbers					
Pressure Drop	X	X	-	-	-
Radiation	X	X	-	X	-

2.7.3.5 Hydrogen Liquefaction Unit

The cold process gas at 172°K (-150°F) exits the noble gas adsorbers and flows to a package hydrogen liquefaction unit. Flow through the hydrogen liquefaction unit is controlled to maintain a constant feed to the unit.

The hydrogen liquefaction unit exit stream is monitored and conditions of high and low temperature and pressure are alarmed. High levels of radiation (gamma), iodine, krypton, and xenon in the outlet stream are also alarmed. Feed shutdown is initiated under high-high temperature, high-high radiation (gamma) level, and high-high iodine, krypton, and xenon content in the outlet stream.

A summary of the instrumentation, alarms, and shutdowns associated with the hydrogen liquefaction unit appears in Table 2-9.

Table 2-9 Hydrogen Liquefaction Unit Instrumentation

Stream/Item	Indication	Alarm		Shutdown	
		High	Low	High-High	Low-Low
Exit Stream					
Temperature	X	X	X	X	-
Pressure	X	X	X	-	-
Radiation (gamma)	X	X	-	X	-
Iodine Content	X	X	-	X	-
Krypton Content	X	X	-	X	-
Xenon Content	X	X	-	X	-

2.7.4 Quench Water Treatment

2.7.4.1 Quench Water Filter

After the seven day decay period in the quench chamber/debris trap, the quench water is pumped to a cartridge-type filter. Flow through the filter is controlled to achieve treatment of all the water in the quench chamber/debris trap in 120 hours. Two filters are used in parallel with one acting as the primary filter and the other on standby.

The quench water flow and radiation level entering and exiting the filter is monitored. High and low levels of flow are alarmed. High levels of radiation (gamma) are alarmed. Each filter is monitored for radiation (alpha, beta, and gamma) levels and pressure drop and alarmed on high radiation level and high pressure drop. Quench water shutdown is initiated by high-high flow, by high-high radiation (gamma) levels in the inlet and outlet filter streams, by high-high radiation (alpha, beta, and gamma) level in either one of the filters, or by high-high pressure drop in either one of the filters.

A summary of the instrumentation, alarms, and shutdowns associated with the quench water filter appears in Table 2-10.

Table 2-10 Quench Water Filter Instrumentation

Stream/Item	Indication	Alarm		Shutdown	
		High	Low	High-High	Low-Low
Filter Inlet/Outlet Stream					
Flow	X	X	X	X	-
Radiation (gamma)	X	X	-	X	-
Filters					
Radiation	X	X	-	X	-
Pressure Drop	X	X	-	X	-

2.7.4.2 Quench Water Deionization Unit

The filtered quench water at 300°K (80°F) flows to the deionization unit. Flow through the deionization unit is not controlled.

The deionized quench water leaving the deionization unit is monitored. High levels of radiation (gamma) are alarmed. The deionization unit is monitored for radiation (alpha, beta, and gamma) level and pressure drop and alarmed on high radiation level and pressure drop. Quench water shutdown is initiated by high-high radiation (gamma) levels in the outlet deionization unit stream or by high-high radiation (alpha, beta, and gamma) levels in the deionization unit.

A summary of the instrumentation, alarms, and shutdowns associated with the quench water deionization unit appears in Table 2-11.

Table 2-11 Quench Water Deionization Unit Instrumentation

Stream/Item	Indication	Alarm		Shutdown	
		High	Low	High-High	Low-Low
DI Unit Discharge					
Radiation (gamma)	X	X	-	X	-
DI Unit					
Radiation	X	X	-	X	-
Pressure Drop	X	X	-	-	-

2.7.4.3 Quench Water Polishing Filter

The deionized water leaving the deionization unit flows for final filtration to the quench water polishing filter. Flow through the polishing filter is not controlled. Two filters are used in parallel with one acting as the primary filter and the other on standby.

The filtered water leaving the filter is monitored. High levels of radiation (gamma) are alarmed. Each filter is monitored for radiation (alpha, beta, and gamma) levels and pressure drop and alarmed on high radiation level and high pressure drop. Quench water shutdown is initiated by high-high radiation (gamma) levels in the outlet filter stream or by high-high radiation (alpha, beta, and gamma) levels in either one of the filters.

A summary of the instrumentation, alarms, and shutdowns associated with the quench water polishing filter appears in Table 2-12.

Table 2-12 Quench Water Polishing Filter Instrumentation

Stream/Item	Indication	Alarm		Shutdown	
		High	Low	High-High	Low-Low
Filter Discharge					
Radiation (gamma)	X	X	-	X	-
Filters					
Radiation	X	X	-	X	-
Pressure Drop	X	X	-	-	-

2.7.4.4 Quench Water Chiller

The treated quench water leaving the polishing filter flows to the quench water chiller where it is cooled from 300°K (80°F) to 278°K (40°F) in the air-cooled packaged chiller. The quench water flow is not controlled. The refrigeration side of the unit is controlled to maintain the quench water exit temperature. Quench water temperature is measured and used to adjust the refrigerant flow.

The chilled quench water exits the chiller and is monitored. High and low temperature levels are alarmed. High levels of radiation (gamma) are also alarmed. Quench water shutdown is initiated if high-high temperature or radiation (gamma) level occurs in the chilled quench water.

A summary of the instrumentation, alarms, and shutdowns associated with the quench water chiller appears in Table 2-13.

Table 2-13 Quench Water Chiller Instrumentation

Stream/Item	Indication	Alarm		Shutdown	
		High	Low	High-High	Low-Low
Chiller Discharge					
Temperature	X	X	X	X	-
Radiation (gamma)	X	X	-	X	-

2.8 Metallurgy

The extreme conditions encountered during operation requires careful selection of materials for the ECS. The 304SS was selected based on its cost and general excellent resistance to corrosion, low temperature as well as high temperature. The quench chamber/debris trap and hydrogen effluent storage sphere are potentially exposed to hot hydrogen gas, liquid hydrogen, cold hydrogen gas, or radioactive particulates and gases as well as deionized water. All equipment in this area are constructed of 304SS. The hydrogen gas treatment equipment are exposed to wet hydrogen gas containing radioactive particulates and gases as well as cryogenic nitrogen. All equipment in the gas treatment portion of the plant is constructed of 304SS. The quench water contains radioactive particulates, radioactive ions and is deionized in process. All equipment in this area is constructed of 304SS.

2.9 Alternate Operating Modes

2.9.1 Introduction

The purpose of this section is to discuss the alternate operating modes presented in the design criteria in Section 2.1, Process Description, for the Effluent Containment System (ECS). Included in this discussion are material balances for the alternate operating modes based on two different design scenarios:

(1) Revising the baseline case to reflect the alternate operating modes.

(2) No modifications to the baseline design case for the alternate operating modes. Test run duration times for the alternate operating cases were revised such that the total amount of hydrogen and water used during a test run is the same as the baseline design case. Hydrogen flow rate, quench water feed rate and quench chamber water recirculating rate are increased or decreased as appropriate.

2.9.2 Alternate Operating Modes

During this research and development study for a ground base ECS test facility, alternate modes of operation were investigated to determine the effects on the facility when deviating from the baseline design case. The alternate operating modes investigated are as follows:

- 2000 MW Reactor/1000 Second Duration
- 550 MW Reactor/550 Second Duration
- 0.6 MW Reactor/200 Hour Duration

For the above set of operating modes, two different scenarios were investigated. One scenario consisted of developing material balance information and pro-rating equipment sizes from the baseline design case based on the flow rate determined for that particular operating case. The second scenario consisted of modifying the test run duration times such that the amount of hydrogen and water used for all three cases is the same as the baseline design case.

2.9.2.1 Design Scenario 1

Material balances for the following three operating modes are located at the end of this section:

- Table 2-14: 2000 MW Reactor/1000 Second Duration
- Table 2-15: 550 MW Reactor/500 Second Duration
- Table 2-16: 0.6 MW Reactor/200 Hour Duration

By comparing these material balances with the material balance for the baseline design case presented in Section 2.3, either additional equipment or larger equipment sizes will be required to operate the facility properly for any of these cases. In addition, larger pipe sizes and control valves will be required.

2.9.2.2 Design Scenario 2

Material balances for the following three operating modes are located at the end of this section:

- Table 2-17: 2000 MW Reactor/106 Second Duration
- Table 2-18: 550 MW Reactor/384 Second Duration
- Table 2-19: 0.6 MW reactor/98 Hour Duration

This design scenario of no modifications to the baseline design case allows most of the equipment and design configuration of the baseline design case to be utilized for all four operating cases by reducing the test run duration times. However, some equipment items, such as the quench water pumps and quench chamber recirculating pumps, would require larger capacity to properly cool the exhaust stream exiting the reactor. Other items, such as hydrogen feed pumps, pipe sizes and control valves, would also need to be reassessed to accommodate the different flow rates deviating from the baseline design case.

2.9.2.3 Summary

Deviating from the baseline design case for alternate operating modes results in some design configuration changes. Depending on the design scenario, each has its own impacts to the baseline design case. Table 2-20, entitled Case Summary, is a summary table indicating the major effects to equipment sizes, number of required equipment, and flowing quantities for the baseline design case and the alternate operating modes for either of the two design scenarios discussed in this section.

MATERIAL BALANCE:		EFFLUENT CONTAINMENT SYSTEM RESEARCH AND DEVELOPMENT STUDY - 2000MW REACTOR/1000 S TEST DURATION						
Stream Number		1	2	3	4	5	6	
Stream Description		Hydrogen Feed	Quench Water	Quenched Gas to Storage	Quenched Gas to Compressor	Hydrogen Gas to Dryer	Hydrogen Gas from Upstream Dryer	Hy fro Ga
Components								
H2	mol %	100.00	0.00	99.56	99.56	99.56	100.00	
H2O	mol %	0.00	100.00	0.44	0.44	0.44	0.00	
MW		2.016	18.016	2.087	2.087	2.087	2.016	
Flow	LB/HR	379,209	153,720,000	394,258	913	913	878	
Flow	KG/SEC	47.78	19369	49.68	0.115	0.115	0.111	
Flow	ACFM (GPM)	704,696	(307005)	88,085	540	540	614	
Flow	SCFM	1,189,667		1,194,951	2,766	2,766	2,754	
Flow	MMSCFD	1,713.1		1,720.7	4.0	4.0	4.0	
Flow	M³/HR	1,197,293	69,728	149,658	918	918	1,043	
Flow	NM³/HR	1,912,053		1,920,544	4,446	4,446	4,426	
Pressure	PSIA	215	215	215	81	81	71	
Pressure	KPA	1,480	1,480	1,480	558	558	490	
Temperature	°F	4,040	40	100	100	100	100	
Temperature	°K	2,500	277	311	311	311	311	
Density	LB/FT³	0.01	62.43	0.07	0.03	0.03	0.02	
Density (liquid)	LB/GAL		8.345					
Density	KG/M³	0.14	1000.00	1.19	0.45	0.45	0.38	
Particulates	MG/SEC	334,000		1,361	2.84	2.81	2.53	
Particulates	Ci/SEC	99.94		1.03E+00	2.15E-03	2.13E-03	1.91E-03	
Noble Gas	MG/SEC	1.71E+00		1.71E+00	3.95E-03	3.95E-03	3.95E-03	
Noble Gas	Ci/SEC	1.42E+01		1.42E+01	3.29E-02	3.29E-02	3.29E-02	
Iodine	MG/SEC	1.01E+00		1.01E+00	2.33E-03	2.33E-03	2.33E-03	
Iodine	Ci/SEC	1.16E+01		1.16E+01	2.67E-02	2.67E-02	2.67E-02	
Cs-137	MG/SEC							
Cs-137	Ci/SEC							
Sr-90	MG/SEC							
Sr-90	Ci/SEC							
Hydrogen	LB/BATCH	105336		105,336	105,336	105,336	105,336	
Hydrogen	KG/BATCH	47780		47,780	47,780	47,780	47,780	
Water	LB/BATCH		4.27E+07	4.18E+03	4.18E+03	4.18E+03		
Water	KG/BATCH		1.94E+07	1.90E+03	1.90E+03	1.90E+03		
Particulates	MG/BATCH	3.34E+08		1.36E+06	1.22E+06	1.21E+06	1.09E+06	
Particulates	Ci/BATCH	99943		1031	927.5	918.2	826.4	
Noble Gas	MG/BATCH	1705		1705	1705	1705	1705	
Noble Gas	Ci/BATCH	14230		14230	14230	14230	14230	
Iodine	MG/BATCH	1008		1008	1008	1008	1008	
Iodine	Ci/BATCH	11550		11550	11550	11550	11550	
Cs-137	MG/BATCH							
Cs-137	Ci/BATCH							
Sr-90	MG/BATCH							
Sr-90	Ci/BATCH							

MATERIAL BALANCE NOTES:

(1) All temperatures, pressures, flow quantities, and compositions are for process design purposes only. No guarantee of these conditions is expressed or implied. Supplementary

(2) The process operations consist of three separate batch modes of operation. All equipment upstream of the hydrogen effluent storage sphere are operated in a batch mode firs quench chamber/debris trap in the third batch mode of operation.

(3) Flows for streams 1 through 3 are based on operation of a 2000MW reactor over a 1000 second period. The remaining streams for either hydrogen or quench water are proc

ble 2-14

7	8	9	10	11	12	13	14	15	16
gen pstream ter	Hydrogen from Gas Cooler	Hydrogen from Upstream Gas Adsorber	Hydrogen Liquid to Storage	Water from Quench Chamber	Quench Water to Filter	Quench Water to DI Unit	Deionized Water to Polishing	Deionized Water to Chiller	Chilled Water to Storage
100.00	100.00	100.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**
2.016	2.016	2.016	2.016	18.016	18.016	18.016	18.016	18.016	18.016
878	878	878	878	355,798	355,798	355,798	355,798	355,798	355,798
0.111	0.111	0.111	0.111	44.8	44.8	44.8	44.8	44.8	44.8
778	524	588	(26.0)	(713)	(713)	(713)	(713)	(713)	(711)
2,754	2,754	2,754							
4.0	4.0	4.0							
1,322	891	1,000	5.90	162	162	162	162	162	161
4,426	4,426	4,426							
56	46	41	245	15	70	65	55	50	40
386	317	283	1,689	101	481	448	379	345	276
100	(150)	(150)	(415)	80	80	80	80	80	40
311	172	172	25	300	300	300	300	300	277
0.02	0.03	0.02	4.210	62.22	62.22	62.22	62.22	62.22	62.43
			0.563	8.317	8.317	8.317	8.317	8.317	8.345
0.30	0.45	0.40	67.44	996.6	996.6	996.6	996.6	996.6	1000.0
.53E-03	2.50E-03	2.48E-03	2.47E-03	9.45	9.45	9.45E-03	9.45E-03	9.45E-05	9.45E-05
.91E-06	1.89E-06	1.87E-06	1.87E-06	7.15E-03	7.15E-03	7.15E-06	7.15E-06	7.15E-08	7.15E-08
.95E-03	3.95E-03	1.97E-05	1.97E-05						
.29E-02	3.29E-02	1.65E-04	1.65E-04						
.33E-03	2.33E-03	1.17E-06	1.17E-06						
.67E-02	2.67E-02	1.34E-04	1.34E-04						
				1.03E-03	1.03E-03	1.03E-03	1.03E-06	1.03E-06	1.03E-06
				8.97E-05	8.97E-05	8.97E-05	8.97E-08	8.97E-08	8.97E-08
				6.34E-04	6.34E-04	6.34E-04	6.34E-07	6.34E-07	6.34E-07
				8.65E-05	8.65E-05	8.65E-05	8.65E-08	8.65E-08	8.65E-08
105,336	105,336	105,336	105,336						
47,780	47,780	47,780	47,780						
				4.27E+07	4.27E+07	4.27E+07	4.27E+07	4.27E+07	4.27E+07
				1.94E+07	1.94E+07	1.94E+07	1.94E+07	1.94E+07	1.94E+07
1091	1080	1070	1069	**4.08E+06**	4.08E+06	4082	4082	40.8	40.8
0.83	0.82	0.81	0.81	3091	3091	3.1	3.1	0.03	0.03
1705	1705	**8.5**	8.5						
14230	14230	**71.2**	71.2						
1008	1008	**0.5**	0.5						
11550	11550	**57.8**	57.8						
				445.0	445.0	445.0	0.45	0.45	0.45
				38.8	38.8	38.8	0.04	0.04	0.04
				273.9	273.9	273.9	0.27	0.27	0.27
				37.4	37.4	37.4	0.04	0.04	0.04

sign information is contained in the process description and alternate material balances are provided for other operating modes.

he cooled process gas is stored in the sphere and the quench water is stored in the quench chamber/debris trap. The stored gas is then processed in the equipment downstream of the

ed over a five day period.

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MATERIAL BALANCE:		EFFLUENT CONTAINMENT SYSTEM RESEARCH AND DEVELOPMENT STUDY - 550MW REACTOR/500 S TEST DURATION						
Stream Number		1	2	3	4	5	6	
Stream Description		Hydrogen Feed	Quench Water	Quenched Gas to Storage	Quenched Gas to Compressor	Hydrogen Gas to Dryer	Hydrogen Gas from Upstream Dryer	Hydr from Gas
Components								
H2	mol %	100.00	0.00	99.56	99.56	99.56	100.00	
H2O	mol %	0.00	100.00	0.44	0.44	0.44	0.00	
MW		2.016	18.016	2.087	2.087	2.087	2.016	
Flow	LB/HR	104,286	42,274,800	108,425	125	125	121	
Flow	KG/SEC	13.14	' 5327	13.66	0.016	0.016	0.015	
Flow	ACFM (GPM)	193,799	(84430)	24,224	74	74	84	
Flow	SCFM	327,171		328,624	380	380	379	
Flow	MMSCFD	471.1		473.2	0.5	0.5	0.5	
Flow	M³/HR	329,268	19,176	41,158	126	126	143	
Flow	NM³/HR	525,835		528,170	611	611	609	
Pressure	PSIA	215	215	215	81	81	71	
Pressure	KPA	1,480	1,480	1,480	558	558	490	
Temperature	°F	4,040	40	100	100	100	100	
Temperature	°K	2,500	277	311	311	311	311	
Density	LB/FT³	0.01	62.43	0.07	0.03	0.03	0.02	
Density (liquid)	LB/GAL		8.345					
Density	KG/M³	0.14	1000.00	1.19	0.45	0.45	0.38	
Particulates	MG/SEC	668,000		2,722	2.84	2.81	2.53	
Particulates	Ci/SEC	199.89		2.06E+00	2.15E-03	2.13E-03	1.91E-03	
Noble Gas	MG/SEC	3.41E+00		3.41E+00	3.95E-03	3.95E-03	3.95E-03	
Noble Gas	Ci/SEC	2.85E+01		2.85E+01	3.29E-02	3.29E-02	3.29E-02	
Iodine	MG/SEC	2.02E+00		2.02E+00	2.33E-03	2.33E-03	2.33E-03	
Iodine	Ci/SEC	2.31E+01		2.31E+01	2.67E-02	2.67E-02	2.67E-02	
Cs-137	MG/SEC							
Cs-137	Ci/SEC							
Sr-90	MG/SEC							
Sr-90	Ci/SEC							
Hydrogen	LB/BATCH	14484		14,484	14,484	14,484	14,484	
Hydrogen	KG/BATCH	6570		6,570	6,570	6,570	6,570	
Water	LB/BATCH		5.87E+06	5.75E+02	5.75E+02	5.75E+02		
Water	KG/BATCH		2.66E+06	2.61E+02	2.61E+02	2.61E+02		
Particulates	MG/BATCH	3.34E+08		1.36E+06	1.22E+06	1.21E+06	1.09E+06	
Particulates	Ci/BATCH	99943		1031	927.5	918.2	826.4	
Noble Gas	MG/BATCH	1705		1705	1705	1705	1705	
Noble Gas	Ci/BATCH	14230		14230	14230	14230	14230	
Iodine	MG/BATCH	1008		1008	1008	1008	1008	
Iodine	Ci/BATCH	11550		11550	11550	11550	11550	
Cs-137	MG/BATCH							
Cs-137	Ci/BATCH							
Sr-90	MG/BATCH							
Sr-90	Ci/BATCH							

MATERIAL BALANCE NOTES:

(1) All temperatures, pressures, flow quantities, and compositions are for process design purposes only. No guarantee of these conditions is expressed or implied. Supplementary d

(2) The process operations consist of three separate batch modes of operation. All equipment upstream of the hydrogen effluent storage sphere are operated in a batch mode first. chamber/debris trap in the third batch mode of operation.

(3) Flows for streams 1 through 3 are based on operation of a 550MW reactor over a 500 second period. The remaining streams for either hydrogen or quench water are processe

le 2-15

	8	9	10	11	12	13	14	15	16
n stream r	Hydrogen from Gas Cooler	Hydrogen from Upstream Gas Adsorber	Hydrogen Liquid to Storage	Water from Quench Chamber	Quench Water to Filter	Quench Water to DI Unit	Deionized Water to Polishing	Deionized Water to Chiller	Chilled Water to Storage
100.00	100.00	100.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**
2.016	2.016	2.016	2.016	18.016	18.016	18.016	18.016	18.016	18.016
121	121	121	121	48,924	48,924	48,924	48,924	48,924	48,924
0.015	0.015	0.015	0.015	6.2	6.2	6.2	6.2	6.2	6.2
107	72	81	(3.6)	(98)	(98)	(98)	(98)	(98)	(98)
379	379	379							
0.5	0.5	0.5							
182	123	137	0.81	22	22	22	22	22	22
609	609	609							
56	**46**	**41**	**245**	**15**	**70**	**65**	**55**	**50**	**40**
386	317	283	1,689	101	481	448	379	345	276
100	**(150)**	**(150)**	**(415)**	**80**	**80**	**80**	**80**	**80**	**40**
311	172	172	25	300	300	300	300	300	277
0.02	0.03	0.02	**4.210**	**62.22**	**62.22**	**62.22**	**62.22**	**62.22**	**62.43**
			0.563	8.317	8.317	8.317	8.317	8.317	8.345
0.30	0.45	0.40	67.44	996.6	996.6	996.6	996.6	996.6	1000.0
3E-03	2.50E-03	2.48E-03	2.47E-03	9.45	9.45	9.45E-03	9.45E-03	9.45E-05	9.45E-05
1E-06	1.89E-06	1.87E-06	1.87E-06	7.15E-03	7.15E-03	7.15E-06	7.15E-06	7.15E-08	7.15E-08
5E-03	3.95E-03	1.97E-05	1.97E-05						
9E-02	3.29E-02	1.65E-04	1.65E-04						
3E-03	2.33E-03	1.17E-06	1.17E-06						
7E-02	2.67E-02	1.34E-04	1.34E-04						
				1.03E-03	1.03E-03	1.03E-03	1.03E-06	1.03E-06	1.03E-06
				8.97E-05	8.97E-05	8.97E-05	8.97E-08	8.97E-08	8.97E-08
				6.34E-04	6.34E-04	6.34E-04	6.34E-07	6.34E-07	6.34E-07
				8.65E-05	8.65E-05	8.65E-05	8.65E-08	8.65E-08	8.65E-08
14,484	14,484	14,484	14,484						
6,570	6,570	6,570	6,570						
				5.87E+06	5.87E+06	5.87E+06	5.87E+06	5.87E+06	5.87E+06
				2.66E+06	2.66E+06	2.66E+06	2.66E+06	2.66E+06	2.66E+06
1091	1080	1070	1069	**4.08E+06**	4.08E+06	4082	4082	40.8	40.8
0.83	0.82	0.81	0.81	3091	3091	3.1	3.1	0.03	0.03
1705	1705	**8.5**	8.5						
14230	14230	**71.2**	71.2						
1008	1008	**0.5**	0.5						
11550	11550	**57.8**	57.8						
				445.0	445.0	445.0	0.45	0.45	0.45
				38.8	38.8	38.8	0.04	0.04	0.04
				273.9	273.9	273.9	0.27	0.27	0.27
				37.4	37.4	37.4	0.04	0.04	0.04

n information is contained in the process description and alternate material balances are provided for other operating modes.

e cooled process gas is stored in the sphere and the quench water is stored in the quench chamber/debris trap. The stored gas is then processed in the equipment downstream of the quench

er a five day period.

MATERIAL BALANCE:		EFFLUENT CONTAINMENT SYSTEM RESEARCH AND DEVELOPMENT STUDY - 0.6MW REACTOR/200 HOUR TEST DURATION						
Stream Number		1	2	3	4	5	6	
Stream Description		Hydrogen Feed	Quench Water	Quenched Gas to Storage	Quenched Gas to Compressor	Hydrogen Gas to Dryer	Hydrogen Gas from Upstream Dryer	Hyd from Gas
Components								
H2	mol %	100.00	0.00	99.56	99.56	99.56	100.00	
H2O	mol %	0.00	**100.00**	0.44	0.44	0.44	0.00	
MW		2.016	18.016	2.087	2.087	2.087	2.016	
Flow	LB/HR	114	46,116	118	197	197	190	
Flow	KG/SEC	**0.01**	6	0.01	0.025	0.025	0.024	
Flow	ACFM (GPM)	211	(92)	26	117	117	133	
Flow	SCFM	357		359	598	598	595	
Flow	MMSCFD	0.5		0.5	0.9	0.9	0.9	
Flow	M³/HR	359	21	45	198	198	225	
Flow	NM³/HR	574		576	961	961	956	
Pressure	PSIA	215	215	215	81	81	71	
Pressure	KPA	1,480	1,480	1,480	558	558	490	
Temperature	°F	4,040	40	100	100	100	100	
Temperature	°K	2,500	277	311	311	311	311	
Density	LB/FT³	0.01	62.43	0.07	0.03	0.03	0.02	
Density (liquid)	LB/GAL		8.345					
Density	KG/M³	0.14	1000.00	1.19	0.45	0.45	0.38	
Particulates	MG/SEC	464		2	2.84	2.81	2.53	
Particulates	Ci/SEC	0.14		1.43E-03	2.15E-03	2.13E-03	1.91E-03	
Noble Gas	MG/SEC	2.37E-03		2.37E-03	3.95E-03	3.95E-03	3.95E-03	
Noble Gas	Ci/SEC	1.98E-02		1.98E-02	3.29E-02	3.29E-02	3.29E-02	
Iodine	MG/SEC	1.40E-03		1.40E-03	2.33E-03	2.33E-03	2.33E-03	
Iodine	Ci/SEC	1.60E-02		1.60E-02	2.67E-02	2.67E-02	2.67E-02	
Cs-137	MG/SEC							
Cs-137	Ci/SEC							
Sr-90	MG/SEC							
Sr-90	Ci/SEC							
Hydrogen	LB/BATCH	22762		22,762	22,762	22,762	22,762	
Hydrogen	KG/BATCH	10325		10,325	10,325	10,325	10,325	
Water	LB/BATCH		9.22E+06	9.03E+02	9.03E+02	9.03E+02		
Water	KG/BATCH		4.18E+06	4.10E+02	4.10E+02	4.10E+02		
Particulates	MG/BATCH	3.34E+08		1.36E+06	1.22E+06	1.21E+06	1.09E+06	
Particulates	Ci/BATCH	**99943**		1031	927.5	918.2	826.4	
Noble Gas	MG/BATCH	1705		1705	1705	1705	1705	
Noble Gas	Ci/BATCH	**14230**		14230	14230	14230	14230	
Iodine	MG/BATCH	1008		1008	1008	1008	1008	
Iodine	Ci/BATCH	**11550**		11550	11550	11550	11550	
Cs-137	MG/BATCH							
Cs-137	Ci/BATCH							
Sr-90	MG/BATCH							
Sr-90	Ci/BATCH							

MATERIAL BALANCE NOTES:

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(2) The process operations consist of three separate batch modes of operation. All equipment upstream of the hydrogen effluent storage sphere are operated in a batch mode first quench chamber/debris trap in the third batch mode of operation.

(3) Flows for streams 1 through 3 are based on operation of a 0.6MW reactor over a 200 hour period. The remaining streams for either hydrogen or quench water are processed

...ble 2-16

7	8	9	10	11	12	13	14	15	16
...en ...stream ...ter	Hydrogen from Gas Cooler	Hydrogen from Upstream Gas Adsorber	Hydrogen Liquid to Storage	Water from Quench Chamber	Quench Water to Filter	Quench Water to DI Unit	Deionized Water to Polishing	Deionized Water to Chiller	Chilled Water to Storage
100.00	100.00	100.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	100.00	100.00	100.00	100.00	100.00	100.00
2.016	2.016	2.016	2.016	18.016	18.016	18.016	18.016	18.016	18.016
190	190	190	190	76,852	76,852	76,852	76,852	76,852	76,852
0.024	0.024	0.024	0.024	9.7	9.7	9.7	9.7	9.7	9.7
168	113	127	(5.6)	(154)	(154)	(154)	(154)	(154)	(153)
595	595	595							
0.9	0.9	0.9							
286	193	216	1.28	35	35	35	35	35	35
956	956	956							
56	46	41	245	15	70	65	55	50	40
386	317	283	1,689	101	481	448	379	345	276
100	(150)	(150)	(415)	80	80	80	80	80	40
311	172	172	25	300	300	300	300	300	277
0.02	0.03	0.02	4.210	62.22	62.22	62.22	62.22	62.22	62.43
			0.563	8.317	8.317	8.317	8.317	8.317	8.345
0.30	0.45	0.40	67.44	996.6	996.6	996.6	996.6	996.6	1000.0
...53E-03	2.50E-03	2.48E-03	2.47E-03	9.45	9.45	9.45E-03	9.45E-03	9.45E-05	9.45E-05
...91E-06	1.89E-06	1.87E-06	1.87E-06	7.15E-03	7.15E-03	7.15E-06	7.15E-06	7.15E-08	7.15E-08
...95E-03	3.95E-03	1.97E-05	1.97E-05						
...29E-02	3.29E-02	1.65E-04	1.65E-04						
...33E-03	2.33E-03	1.17E-06	1.17E-06						
...67E-02	2.67E-02	1.34E-04	1.34E-04						
				1.03E-03	1.03E-03	1.03E-03	1.03E-06	1.03E-06	1.03E-06
				8.97E-05	8.97E-05	8.97E-05	8.97E-08	8.97E-08	8.97E-08
				6.34E-04	6.34E-04	6.34E-04	6.34E-07	6.34E-07	6.34E-07
				8.65E-05	8.65E-05	8.65E-05	8.65E-08	8.65E-08	8.65E-08
22,762	22,762	22,762	22,762						
10,325	10,325	10,325	10,325						
				9.22E+06	9.22E+06	9.22E+06	9.22E+06	9.22E+06	9.22E+06
				4.18E+06	4.18E+06	4.18E+06	4.18E+06	4.18E+06	4.18E+06
1091	1080	1070	1069	4.08E+06	4.08E+06	4082	4082	40.8	40.8
0.83	0.82	0.81	0.81	3091	3091	3.1	3.1	0.03	0.03
1705	1705	8.5	8.5						
14230	14230	71.2	71.2						
1008	1008	0.5	0.5						
11550	11550	57.8	57.8						
				445.0	445.0	445.0	0.45	0.45	0.45
				38.8	38.8	38.8	0.04	0.04	0.04
				273.9	273.9	273.9	0.27	0.27	0.27
				37.4	37.4	37.4	0.04	0.04	0.04

...gn information is contained in the process description and alternate material balances are provided for other operating modes.

...he cooled process gas is stored in the sphere and the quench water is stored in the quench chamber/debris trap. The stored gas is then processed in the equipment downstream of the

...r a five day period.

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MATERIAL BALANCE:		EFFLUENT CONTAINMENT SYSTEM RESEARCH AND DEVELOPMENT STUDY - 2000MW REACTOR/106 S TEST DURATION						
Stream Number		1	2	3	4	5	6	
Stream Description		Hydrogen Feed	Quench Water	Quenched Gas to Storage	Quenched Gas to Compressor	Hydrogen Gas to Dryer	Hydrogen Gas from Upstream Dryer	Hyd from Gas
Components								
H2	mol %	100.00	0.00	99.56	99.56	99.56	100.00	
H2O	mol %	0.00	100.00	0.44	0.44	0.44	0.00	
MW		2.016	18.016	2.087	2.087	2.087	2.016	
Flow	LB/HR	3.792E+05	1.537E+08	3.943E+05	96	96	93	
Flow	KG/SEC	47.78	1.937E+04	49.68	0.012	0.012	0.012	
Flow	ACFM (GPM)	7.047E+05	(3.070E+05)	8.808E+04	57	57	65	
Flow	SCFM	1.190E+06		1.195E+06	292	292	290	
Flow	MMSCFD	1.713E+03		1.721E+03	0.4	0.4	0.4	
Flow	M³/HR	1.197E+06	6.973E+04	1.497E+05	97	97	110	
Flow	NM³/HR	1.912E+06		1.921E+06	469	469	467	
Pressure	PSIA	215	215	215	81	81	71	
Pressure	KPA	1,480	1,480	1,480	558	558	490	
Temperature	°F	4,040	40	100	100	100	100	
Temperature	°K	2,500	277	311	311	311	311	
Density	LB/FT³	0.01	62.43	0.07	0.03	0.03	0.02	
Density (liquid)	LB/GAL		8.345					
Density	KG/M³	0.14	1000.00	1.19	0.45	0.45	0.38	
Particulates	MG/SEC	3,166,477		12,903	2.84	2.81	2.53	
Particulates	Ci/SEC	947.51		9.77E+00	2.15E-03	2.13E-03	1.91E-03	
Noble Gas	MG/SEC	1.62E+01		1.62E+01	3.95E-03	3.95E-03	3.95E-03	
Noble Gas	Ci/SEC	1.35E+02		1.35E+02	3.29E-02	3.29E-02	3.29E-02	
Iodine	MG/SEC	9.56E+00		9.56E+00	2.33E-03	2.33E-03	2.33E-03	
Iodine	Ci/SEC	1.09E+02		1.09E+02	2.67E-02	2.67E-02	2.67E-02	
Cs-137	MG/SEC							
Cs-137	Ci/SEC							
Sr-90	MG/SEC							
Sr-90	Ci/SEC							
Hydrogen	LB/BATCH	11111		11,111	11,111	11,111	11,111	
Hydrogen	KG/BATCH	5040		5,040	5,040	5,040	5,040	
Water	LB/BATCH		4.50E+06	4.41E+02	4.41E+02	4.41E+02		
Water	KG/BATCH		2.04E+06	2.00E+02	2.00E+02	2.00E+02		
Particulates	MG/BATCH	3.34E+08		1.36E+06	1.22E+06	1.21E+06	1.09E+06	
Particulates	Ci/BATCH	99943		1031	927.5	918.2	826.4	
Noble Gas	MG/BATCH	1705		1705	1705	1705	1705	
Noble Gas	Ci/BATCH	14230		14230	14230	14230	14230	
Iodine	MG/BATCH	1008		1008	1008	1008	1008	
Iodine	Ci/BATCH	11550		11550	11550	11550	11550	
Cs-137	MG/BATCH							
Cs-137	Ci/BATCH							
Sr-90	MG/BATCH							
Sr-90	Ci/BATCH							

MATERIAL BALANCE NOTES:

(1) All temperatures, pressures, flow quantities, and compositions are for process design purposes only. No guarantee of these conditions is expressed or implied. Supplementary

(2) The process operations consist of three separate batch modes of operation. All equipment upstream of the hydrogen effluent storage sphere are operated in a batch mode first. quench chamber/debris trap in the third batch mode of operation.

(3) Flows for streams 1 through 3 are based on operation of a 2000MW reactor over a 106 second period. The remaining streams for either hydrogen or quench water are proces

ble 2-17

7	8	9	10	11	12	13	14	15	16
en ostream ter	Hydrogen from Gas Cooler	Hydrogen from Upstream Gas Adsorber	Hydrogen Liquid to Storage	Water from Quench Chamber	Quench Water to Filter	Quench Water to DI Unit	Deionized Water to Polishing	Deionized Water to Chiller	Chilled Water to Storage
100.00	100.00	100.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**
2.016	2.016	2.016	2.016	18.016	18.016	18.016	18.016	18.016	18.016
93	93	93	93	37,530	37,530	37,530	37,530	37,530	37,530
0.012	0.012	0.012	0.012	4.7	4.7	4.7	4.7	4.7	4.7
82	55	62	(2.7)	(75)	(75)	(75)	(75)	(75)	(75)
290	290	290							
0.4	0.4	0.4							
139	94	105	0.62	17	17	17	17	17	17
467	467	467							
56	46	41	245	15	70	65	55	50	40
386	317	283	1,689	101	481	448	379	345	276
100	(150)	(150)	(415)	80	80	80	80	80	40
311	172	172	25	300	300	300	300	300	277
0.02	0.03	0.02	4.210	62.22	62.22	62.22	62.22	62.22	62.43
			0.563	8.317	8.317	8.317	8.317	8.317	8.345
0.30	0.45	0.40	67.44	996.6	996.6	996.6	996.6	996.6	1000.0
53E-03	2.50E-03	2.48E-03	2.47E-03	9.45	9.45	9.45E-03	9.45E-03	9.45E-05	9.45E-05
91E-06	1.89E-06	1.87E-06	1.87E-06	7.15E-03	7.15E-03	7.15E-06	7.15E-06	7.15E-08	7.15E-08
95E-03	3.95E-03	1.97E-05	1.97E-05						
29E-02	3.29E-02	1.65E-04	1.65E-04						
33E-03	2.33E-03	1.17E-06	1.17E-06						
67E-02	2.67E-02	1.34E-04	1.34E-04						
				1.03E-03	1.03E-03	1.03E-03	1.03E-06	1.03E-06	1.03E-06
				8.97E-05	8.97E-05	8.97E-05	8.97E-08	8.97E-08	8.97E-08
				6.34E-04	6.34E-04	6.34E-04	6.34E-07	6.34E-07	6.34E-07
				8.65E-05	8.65E-05	8.65E-05	8.65E-08	8.65E-08	8.65E-08
11,111	11,111	11,111	11,111						
5,040	5,040	5,040	5,040						
				4.50E+06	4.50E+06	4.50E+06	4.50E+06	4.50E+06	4.50E+06
				2.04E+06	2.04E+06	2.04E+06	2.04E+06	2.04E+06	2.04E+06
1091	1080	1070	1069	4.08E+06	4.08E+06	4082	4082	40.8	40.8
0.83	0.82	0.81	0.81	3091	3091	3.1	3.1	0.03	0.03
1705	1705	8.5	8.5						
14230	14230	**71.2**	71.2						
1008	1008	0.5	0.5						
11550	11550	**57.8**	57.8						
				445.0	445.0	445.0	0.45	0.45	0.45
				38.8	38.8	38.8	0.04	0.04	0.04
				273.9	273.9	273.9	0.27	0.27	0.27
				37.4	37.4	37.4	0.04	0.04	0.04

gn information is contained in the process description and alternate material balances are provided for other operating modes.

he cooled process gas is stored in the sphere and the quench water is stored in the quench chamber/debris trap. The stored gas is then processed in the equipment downstream of the

over a five day period.

T

MATERIAL BALANCE:		EFFLUENT CONTAINMENT SYSTEM RESEARCH AND DEVELOPMENT STUDY - 550MW REACTOR/384 S TEST DURATION						
Stream Number		1	2	3	4	5	6	
Stream Description		Hydrogen Feed	Quench Water	Quenched Gas to Storage	Quenched Gas to Compressor	Hydrogen Gas to Dryer	Hydrogen Gas from Upstream Dryer	Hyd from Gas
Components								
H2	mol %	100.00	0.00	99.56	99.56	99.56	100.00	
H2O	mol %	0.00	100.00	0.44	0.44	0.44	0.00	
MW		2.016	18.016	2.087	2.087	2.087	2.016	
Flow	LB/HR	104,286	42,274,800	108,425	96	96	93	
Flow	KG/SEC	13.14	5327	13.66	0.012	0.012	0.012	
Flow	ACFM (GPM)	193,799	(84430)	24,224	57	57	65	
Flow	SCFM	327,171		328,624	292	292	290	
Flow	MMSCFD	471.1		473.2	0.4	0.4	0.4	
Flow	M³/HR	329,268	19,176	41,158	97	97	110	
Flow	NM³/HR	525,835		528,170	469	469	467	
Pressure	PSIA	215	215	215	81	81	71	
Pressure	KPA	1,480	1,480	1,480	558	558	490	
Temperature	°F	4,040	40	100	100	100	100	
Temperature	°K	2,500	277	311	311	311	311	
Density	LB/FT³	0.01	62.43	0.07	0.03	0.03	0.02	
Density (liquid)	LB/GAL		8.345					
Density	KG/M³	0.14	1000.00	1.19	0.45	0.45	0.38	
Particulates	MG/SEC	870,789		3,548	2.84	2.81	2.53	
Particulates	Ci/SEC	260.57		2.69E+00	2.15E-03	2.13E-03	1.91E-03	
Noble Gas	MG/SEC	4.45E+00		4.45E+00	3.95E-03	3.95E-03	3.95E-03	
Noble Gas	Ci/SEC	3.71E+01		3.71E+01	3.29E-02	3.29E-02	3.29E-02	
Iodine	MG/SEC	2.63E+00		2.63E+00	2.33E-03	2.33E-03	2.33E-03	
Iodine	Ci/SEC	3.01E+01		3.01E+01	2.67E-02	2.67E-02	2.67E-02	
Cs-137	MG/SEC							
Cs-137	Ci/SEC							
Sr-90	MG/SEC							
Sr-90	Ci/SEC							
Hydrogen	LB/BATCH	11111		11,111	11,111	11,111	11,111	
Hydrogen	KG/BATCH	5040		5,040	5,040	5,040	5,040	
Water	LB/BATCH		4.50E+06	4.41E+02	4.41E+02	4.41E+02		
Water	KG/BATCH		2.04E+06	2.00E+02	2.00E+02	2.00E+02		
Particulates	MG/BATCH	3.34E+08		1.36E+06	1.22E+06	1.21E+06	1.09E+06	
Particulates	Ci/BATCH	99943		1031	927.5	918.2	826.4	
Noble Gas	MG/BATCH	1705		1705	1705	1705	1705	
Noble Gas	Ci/BATCH	14230		14230	14230	14230	14230	
Iodine	MG/BATCH	1008		1008	1008	1008	1008	
Iodine	Ci/BATCH	11550		11550	11550	11550	11550	
Cs-137	MG/BATCH							
Cs-137	Ci/BATCH							
Sr-90	MG/BATCH							
Sr-90	Ci/BATCH							

MATERIAL BALANCE NOTES:

(1) All temperatures, pressures, flow quantities, and compositions are for process design purposes only. No guarantee of these conditions is expressed or implied. Supplementary

(2) The process operations consist of three separate batch modes of operation. All equipment upstream of the hydrogen effluent storage sphere are operated in a batch mode first quench chamber/debris trap in the third batch mode of operation.

(3) Flows for streams 1 through 3 are based on operation of a 550MW reactor over a 384 second period. The remaining streams for either hydrogen or quench water are process

ble 2-18

7	8	9	10	11	12	13	14	15	16
en pstream ter	Hydrogen from Gas Cooler	Hydrogen from Upstream Gas Adsorber	Hydrogen Liquid to Storage	Water from Quench Chamber	Quench Water to Filter	Quench Water to DI Unit	Deionized Water to Polishing	Deionized Water to Chiller	Chilled Water to Storage
100.00	100.00	100.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	100.00	100.00	100.00	100.00	100.00	100.00
2.016	2.016	2.016	2.016	18.016	18.016	18.016	18.016	18.016	18.016
93	93	93	93	37,531	37,531	37,531	37,531	37,531	37,531
0.012	0.012	0.012	0.012	4.7	4.7	4.7	4.7	4.7	4.7
62	55	62	(2.7)	(75)	(75)	(75)	(75)	(75)	(75)
290	290	290							
0.4	0.4	0.4							
139	94	105	0.62	17	17	17	17	17	17
467	467	467							
56	46	41	245	15	70	65	55	60	40
386	317	283	1,689	101	481	448	379	345	276
100	(150)	(150)	(415)	80	80	80	80	80	40
311	172	172	25	300	300	300	300	300	277
0.02	0.03	0.02	4.210	62.22	62.22	62.22	62.22	62.22	62.43
			0.563	8.317	8.317	8.317	8.317	8.317	8.345
0.30	0.45	0.40	67.44	996.6	996.6	996.6	996.6	996.6	1000.0
53E-03	2.50E-03	2.48E-03	2.47E-03	9.45	9.45	9.45E-03	9.45E-03	9.45E-05	9.45E-05
91E-06	1.89E-06	1.87E-06	1.87E-06	7.15E-03	7.15E-03	7.15E-06	7.15E-06	7.15E-08	7.15E-08
95E-03	3.95E-03	1.97E-05	1.97E-05						
29E-02	3.29E-02	1.65E-04	1.65E-04						
33E-03	2.33E-03	1.17E-06	1.17E-06						
67E-02	2.67E-02	1.34E-04	1.34E-04						
				1.03E-03	1.03E-03	1.03E-03	1.03E-06	1.03E-06	1.03E-06
				8.97E-05	8.97E-05	8.97E-05	8.97E-08	8.97E-08	8.97E-08
				6.34E-04	6.34E-04	6.34E-04	6.34E-07	6.34E-07	6.34E-07
				8.65E-05	8.65E-05	8.65E-05	8.65E-08	8.65E-08	8.65E-08
11,111	11,111	11,111	11,111						
5,040	5,040	5,040	5,040						
				4.50E+06	4.50E+06	4.50E+06	4.50E+06	4.50E+06	4.50E+06
				2.04E+06	2.04E+06	2.04E+06	2.04E+06	2.04E+06	2.04E+06
1091	1080	1070	1069	4.08E+06	4.08E+06	4082	4082	40.8	40.8
0.83	0.82	0.81	0.81	3091	3091	3.1	3.1	0.03	0.03
1705	1705	8.5	8.5						
14230	14230	71.2	71.2						
1008	1008	0.5	0.5						
11550	11550	57.8	57.8						
				445.0	445.0	445.0	0.45	0.45	0.45
				38.8	38.8	38.8	0.04	0.04	0.04
				273.9	273.9	273.9	0.27	0.27	0.27
				37.4	37.4	37.4	0.04	0.04	0.04

gn information is contained in the process description and alternate material balances are provided for other operating modes.

e cooled process gas is stored in the sphere and the quench water is stored in the quench chamber/debris trap. The stored gas is then processed in the equipment downstream of the

ver a five day period.

Table 2-19

7	8	9	10	11	12	13	14	15	16
drogen m Upstream s Filter	Hydrogen from Gas Cooler	Hydrogen from Upstream Gas Adsorber	Hydrogen Liquid to Storage	Water from Quench Chamber	Quench Water to Filter	Quench Water to DI Unit	Deionized Water to Polishing	Deionized Water to Chiller	Chilled Water to Storage
100.00	100.00	100.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**
2.016	2.016	2.016	2.016	18.016	18.016	18.016	18.016	18.016	18.016
93	93	93	93	37.516	37.516	37.516	37.516	37.516	37.516
0.012	0.012	0.012	0.012	4.7	4.7	4.7	4.7	4.7	4.7
82	55	62	(2.7)	(75)	(75)	(75)	(75)	(75)	(75)
290	290	290							
0.4	0.4	0.4							
139	94	105	0.62	17	17	17	17	17	17
467	467	467							
56	46	41	245	15	70	65	55	60	40
386	317	283	1,689	101	481	448	379	345	276
100	(150)	(150)	(415)	80	80	80	80	80	40
311	172	172	25	300	300	300	300	300	277
0.02	0.03	0.02	4.210	62.22	62.22	62.22	62.22	62.22	62.43
			0.563	8.317	8.317	8.317	8.317	8.317	8.345
0.30	0.45	0.40	67.44	996.6	996.6	996.6	996.6	996.6	1000.0
2.53E-03	2.50E-03	2.48E-03	2.47E-03	9.45	9.45	9.45E-03	9.45E-03	9.45E-05	9.45E-05
1.91E-06	1.89E-06	1.87E-06	1.87E-06	7.15E-03	7.15E-03	7.15E-06	7.15E-06	7.15E-08	7.15E-08
3.95E-03	3.95E-03	1.97E-05	1.97E-05						
3.29E-02	3.29E-02	1.65E-04	1.65E-04						
2.33E-03	2.33E-03	1.17E-06	1.17E-06						
2.67E-02	2.67E-02	1.34E-04	1.34E-04						
				1.03E-03	1.03E-03	1.03E-03	1.03E-06	1.03E-06	1.03E-06
				8.97E-05	8.97E-05	8.97E-05	8.97E-08	8.97E-08	8.97E-08
				6.34E-04	6.34E-04	6.34E-04	6.34E-07	6.34E-07	6.34E-07
				8.65E-05	8.65E-05	8.65E-05	8.65E-08	8.65E-08	8.65E-08
11,111	11,111	11,111	11,111						
5,040	5,040	5,040	5,040						
				4.50E+06	4.50E+06	4.50E+06	4.50E+06	4.50E+06	4.50E+06
				2.04E+06	2.04E+06	2.04E+06	2.04E+06	2.04E+06	2.04E+06
1091	1080	1070	1069	**4.08E+06**	4.08E+06	4082	4082	40.8	40.8
0.83	0.82	0.81	0.81	3091	3091	3.1	3.1	0.03	0.03
1705	1705	8.5	8.5						
14230	14230	**71.2**	71.2						
1008	1008	0.5	0.5						
11550	11550	**57.8**	57.8						
				445.0	445.0	445.0	0.45	0.45	0.45
				38.8	38.8	38.8	0.04	0.04	0.04
				273.9	273.9	273.9	0.27	0.27	0.27
				37.4	37.4	37.4	0.04	0.04	0.04

y design information is contained in the process description and alternate material balances are provided for other operating modes.

st. The cooled process gas is stored in the sphere and the quench water is stored in the quench chamber/debris trap. The stored gas is then processed in the equipment downstream of the

over a five day period.

MATERIAL BALANCE:		EFFLUENT CONTAINMENT SYSTEM RESEARCH AND DEVELOPMENT STUDY - 0.6MW REACTOR/98 HOUR TEST DURATION					
Stream Number		1	2	3	4	5	6
Stream Description		Hydrogen Feed	Quench Water	Quenched Gas to Storage	Quenched Gas to Compressor	Hydrogen Gas to Dryer	Hydrogen Gas from Upstream Dryer
Components							
H2	mol %	100.00	0.00	99.56	99.56	99.56	100.00
H2O	mol %	0.00	100.00	0.44	0.44	0.44	0.00
MW		2.016	18.016	2.087	2.087	2.087	2.016
Flow	LB/HR	114	45,116	118	96	96	93
Flow	KG/SEC	0.01	6	0.01	0.012	0.012	0.012
Flow	ACFM (GPM)	211	(92)	26	57	57	65
Flow	SCFM	357		359	292	292	290
Flow	MMSCFD	0.5		0.5	0.4	0.4	0.4
Flow	M³/HR	359	21	45	97	97	110
Flow	NM³/HR	574		576	469	469	467
Pressure	PSIA	215	215	215	81	81	71
Pressure	KPA	1,480	1,480	1,480	558	558	490
Temperature	°F	4,040	40	100	100	100	100
Temperature	°K	2,500	277	311	311	311	311
Density	LB/FT³	0.01	62.43	0.07	0.03	0.03	0.02
Density (liquid)	LB/GAL		8.345				
Density	KG/M³	0.14	1000.00	1.19	0.45	0.45	0.38
Particulates	MG/SEC	950		4	2.84	2.81	2.53
Particulates	Ci/SEC	0.28		2.93E-03	2.15E-03	2.13E-03	1.91E-03
Noble Gas	MG/SEC	4.85E-03		4.85E-03	3.95E-03	3.95E-03	3.95E-03
Noble Gas	Ci/SEC	4.05E-02		4.05E-02	3.29E-02	3.29E-02	3.29E-02
Iodine	MG/SEC	2.87E-03		2.87E-03	2.33E-03	2.33E-03	2.33E-03
Iodine	Ci/SEC	3.29E-02		3.29E-02	2.67E-02	2.67E-02	2.67E-02
Cs-137	MG/SEC						
Cs-137	Ci/SEC						
Sr-90	MG/SEC						
Sr-90	Ci/SEC						
Hydrogen	LB/BATCH	11111		11,111	11,111	11,111	11,111
Hydrogen	KG/BATCH	5040		5,040	5,040	5,040	5,040
Water	LB/BATCH		4.50E+06	4.41E+02	4.41E+02	4.41E+02	
Water	KG/BATCH		2.04E+06	2.00E+02	2.00E+02	2.00E+02	
Particulates	MG/BATCH	3.34E+08		1.36E+06	1.22E+06	1.21E+06	1.09E+06
Particulates	Ci/BATCH	99943		1031	927.5	918.2	826.4
Noble Gas	MG/BATCH	1705		1705	1705	1705	1705
Noble Gas	Ci/BATCH	14230		14230	14230	14230	14230
Iodine	MG/BATCH	1008		1008	1008	1008	1008
Iodine	Ci/BATCH	11550		11550	11550	11550	11550
Cs-137	MG/BATCH						
Cs-137	Ci/BATCH						
Sr-90	MG/BATCH						
Sr-90	Ci/BATCH						

MATERIAL BALANCE NOTES:

(1) All temperatures, pressures, flow quantities, and compositions are for process design purposes only. No guarantee of these conditions is expressed or implied. Supplementa

(2) The process operations consist of three separate batch modes of operation. All equipment upstream of the hydrogen effluent storage sphere are operated in a batch mode fi quench chamber/debris trap in the third batch mode of operation.

(3) Flows for streams 1 through 3 are based on operation of a 0.6MW reactor over a 98 hour period. The remaining streams for either hydrogen or quench water are processe

Table 2-20 Case Summary

		1 (Case 3) Base Case	2	3	4	5 (Case 1)	6 (Case 2)	7 (Case 4)
Reactor Size	MW	11.5	2000	550	0.6	2000	550	0.6
Test Duration	s or (hr)	(5)	105	384	(97.63)	1000	500	(200)
Hydrogen Rate	kg/s	0.28	47.78	13.14	0.01434	47.78	13.14	0.01434
Total Hydrogen	kg	5040	5040	5040	5040	47780	6570	10325
Quench Water	gpm	1799	307005	84430	92.1	307005	84430	92.1
Water Treatment	gpm	90	90	90	90	853	117	184
Gas Treatment (dry	scfm	291	291	291	291	2754	379	595
Spray Chamber	height, ft	114	114	114	114	242	125	145
	diam, ft	38	38	38	38	81	42	48
	velocity, ft/s	0.061	10.33	2.84	0.003	2.31	2.38	0.002
Hydrogen Storage	diam, ft	100	100	100	100	100	100	100
	pressure, psia	81	81	81	81	81	81	81
	number	1	1	1	1	9	2	2
Chilled Water Tank	Volume, gal	6.48E+05	6.48E+05	6.48E+05	6.48E+05	6.14E+06	8.44E+05	1.33E+06

2.10 Future Design Studies/Optimizations

This section presents future design studies/optimizations to be investigated/pursued in the subsequent design phases for a ground test facility of a space nuclear thermal rocket engine.

The following list of items should be evaluated for their impact to the overall design of a space nuclear thermal rocket engine ground test facility:

- Evaluate design modifications to improve flexibility to test a range of rocket power and operating times.
- Evaluate criticality requirements throughout the entire system.
- Evaluate the impact of noise/vibration to equipment and piping.
- Evaluate the impact of Thermal Shock to equipment and piping for normal and failure operation.
- Evaluate metallurgy to be used in the system based on cost, operability, and safety.
- Determine particle size distribution based on failure using nonradioactive system.
- Evaluate the Quench Chamber/Debris Trap design based on cost, operability, criticality, and safety.
- Perform a cost trade-off study for the gas treatment cryocooler between hydrogen quenching in a mixer or a process gas cryogenic cooler utilizing liquid nitrogen.
- Perform a cost trade-off study between hydrogen liquefaction/recycle and hydrogen flaring.
- Perform a cost trade-off study of the storage conditions (pressure and temperature) for liquid hydrogen and nitrogen to establish conditions which minimize the storage volumes of liquid hydrogen and nitrogen consumptions.
- Evaluate types of ion exchange resins based on selective radioisotope partition/immobilization, cost, environmental benefits, and safety.
- Evaluate alternative tritium removal technologies.

3.0 ACCIDENTS/FAILURES ANALYSIS

3.1 Introduction

This section represents the first step in identifying potential accidents/failures inherent in the proposed ECS design configuration. The accidents/failures analysis was initiated in the research and development phase to provide a basis for establishing corrective action to eliminate or minimize catastrophic and critical failure possibilities. The analysis provides a qualitative rather than a quantitative assessment.

The analysis of the proposed ECS design configuration is based on three separate batch operations: exhaust gas cooling, treatment and recycle of hydrogen, and treatment and recycle of water. For each of the batch operations, potential accidents/failures have been identified and the consequences evaluated.

The documentation utilized for this analysis are the block flow diagram and process description for the ECS design configuration included in this report.

3.2 Assumptions

The accidents/failures analysis on the proposed preliminary ECS design configuration was prepared with the following assumptions:

- The analysis will consider upsets occurring during normal operations that are identified in this report.
- ECS facility pre-test check-out and start-up procedures have been successfully completed.
- External events such as seismic activity, severe weather, airplane crash, and sabotage are not to be considered.
- Utility support systems such as hydrogen, nitrogen, water, electrical power, air, etc. are assumed to include high reliability elements and necessary redundancy and controls to ensure their system reliability and availability.
- Process and facility instrumentation, monitoring and control is assumed to include high reliable elements and necessary redundancy to ensure system functional high reliability and availability.
- The effects of high noise levels and vibration expected to be generated during test flow operations is not to be assessed in this analysis.
- The effects of destructive testing of the nuclear rocket engine is not to be assessed in this analysis.

3.3 Summary

There are numerous initiating upsets/events that must be considered during subsequent detailed design of the ECS. The ECS must be designed to preclude hazardous risk events occurring from as many operating upsets/events as practical. This preliminary analysis on the proposed ECS design focuses on operating upsets/events that are listed below.

3.3.1 Exhaust Gas Cooling

The following list of accidents/failures occurring during normal batch operations has the consequences of aborting the test run:

- Loss of Hydrogen Feed Flow
- Loss of Quench Water Flow
- Low System Flowing Temperature
- High System Flowing Temperature
- Hydrogen Leak/Fire
- Radionuclide Release to ECS Equipment/Elements and Atmosphere

3.3.1.1 Loss of Hydrogen Feed Flow

If hydrogen feed flow is lost, the reactor will be shut down. However, a reactor failure may occur with damage to the fuel. The worst case would be meltdown or vaporization of the core. The quench water flow is designed to remove the heat of reaction from the hydrogen that cools the reactor by increasing in temperature from 40°F to 80°F. The quench water flowing into the system for one minute if heated to 200°F would condense the entire reactor mass even though vaporized and heated to 8500°F.

3.3.1.2 Loss of Quench Water Flow

If the quench water flow is lost, the reactor will be shut down. The recirculating quench water will continue to flow, cooling the hot hydrogen until reactor cooldown is achieved.

3.3.1.3 Low System Flowing Temperature

If a low system (hydrogen) temperature occurs, the reactor will be shut down and the hydrogen flow to the reactor stopped. The condition causing this event would be loss of reaction. The quench water and recirculating quench water contacts the cold hydrogen and cools down while heating and vaporizing the hydrogen.

3.3.1.4 High System Flowing Temperature

A high system (hydrogen) temperature will shut down the reactor. Quench Water and recirculating quench water will cool the hot hydrogen gas.

3.3.1.5 Hydrogen Leak/Fire

If a hydrogen leak or fire is detected, the reactor is shut down. Depending on location of the leak/fire, hydrogen flow will be reduced or shut down. Fire mitigation will depend on the severity and location of the fire.

3.3.1.6 Radionuclide Release

If a radionuclide leak is detected, the reactor will be shut down. Release mitigation efforts will depend on the location and severity of the release.

3.3.2 Hydrogen Treatment and Recycle

The following list of accidents/failures occurring during normal batch operations has the consequences of aborting the hydrogen treatment and recycle phase and requiring a longer clean-up time:

- Loss of Hydrogen Compressor
- Loss of Nitrogen Coolant Flow
- Plugged Hydrogen Dryer
- Hydrogen Dryer Blow-Through
- Plugged Hydrogen Gas Filter
- Hydrogen Gas Filter Blow-Through
- Plugged Noble Gas Adsorber
- Noble Gas Adsorber Blow-Through
- Loss of Hydrogen Liquefaction/Purification Unit
- Hydrogen Leak/Fire
- Radionuclide Release to ECS Equipment/Elements and Atmosphere
- Nitrogen Leak into Hydrogen
- Hydrogen Gas Leak into Nitrogen Cooling System

For all accidents/failures in this area, the system will be shut down and the impacted equipment isolated, repaired and returned to service.

3.3.3 Water Treatment and Recycle

The following list of accidents/failures occurring during normal batch operations has the consequences of aborting the water treatment and recycle phase and requiring a longer clean-up time:

- Loss of Quench Water Recirculation Flow
- Plugged Quench Water Filters
- Quench Water Filters Blow-Through
- Plugged Quench Water DI Unit
- Quench Water DI Unit Blow-Through
- Loss of Quench Water Refrigeration Unit
- Radionuclide Release to ECS Equipment/Elements and Atmosphere

For all accidents/failures in this area, the system will be shut down and the impacted equipment isolated, repaired and returned to service.

4.0 RADIATION MODEL AND SHIELDING REQUIREMENTS

4.1 Introduction

Radiation shielding requirements were evaluated for the Quench Chamber/Debris Trap, the Hydrogen Treatment/Recycling system, and the Quench Water Treatment/Recycling system. The "design basis" scenario was assumed to consist of five rocket reactor burns; each burn was taken to last five hours, and time between burns was taken to be seven days. After the last (fifth) burn, the rocket reactor was assumed destroyed, and the entire core dumped into the Quench Chamber/Debris Trap. The ECS would have to be able to process the results of this scenario, and, in particular, provide adequate radiation shielding for each vessel in the process.

Based on the design basis scenario, quantities of radionuclides in each of the vessels in the ECS process were estimated. Uncertainties in the radionuclide composition were compensated for by conservatism. Since the results of this study are preliminary, only the photon shield was addressed. Included in the source term were gamma emissions from the fission and activation products, and secondary photon radiation produced inside the fuel by beta emissions.

The neutron source was not addressed in this preliminary study. Dumping reactor debris in the Quench Chamber/Debris Trap represents a potential criticality event, which must be adequately shielded against. Even when conditions favorable to criticality are not present, spontaneous fission and the alpha, neutron reaction will generate a neutron source which will have to be addressed in future shielding calculations. The Quench Chamber/Debris Trap will be designed to prevent reactor debris from becoming critical by use of safe geometry and the use of poisons.

4.2 Choice of Computer Models

Radiological inventory in the reactor core material, resulting from the various phases of design basis scenario, were estimated with the ORIGEN2 computer code, Reference 1. This code also produces the photon spectrum resulting from gamma emissions and secondary photons produced in the specified reactor material from beta emissions and their interactions.

The code selected to perform shielding calculations on the various components of the ECS is the MicroShield Version 4.10 (Reference 2).

4.3 Code Verification & Validation

All codes used in shielding and criticality calculations at Fluor Daniel have been verified by running the test problems supplied with the code packages. The test problem results are shown to be in agreement either with the published documentation supplied as part of the code package, or with the sample problem output, if supplied. This information is documented, dated, and retained on file at Fluor Daniel. Any changes, such as upgrades, corrections, modifications, etc., are incorporated into the documentation following rerunning of the verification problems.

The MicroShield code is a commercially available code which is supplied with a verification & validation package. This package includes a test problem set which compares the results of these programs to those from other industry standard, noncommercial programs for both mainframe and personal computers. The test cases used were the ANSI/ANS-6.6.1, (Reference 3) and the ESIS Reference Cases (Reference 4). These test cases were run at Fluor Daniel using the MicroShield codes obtaining agreement with the published results. The results were dated, documented, and retained in the various program documentation files.

The ORIGEN2 code was obtained from the Radiation Shielding Information Center (RSIC) code library, Reference 5. This code, Version 2.1 (8-1-91), came supplied with sample problems and examples. The supplied sample problems and examples were executed and the results compared (favorably) to those supplied with the code.

4.4 Material Properties

The fractional densities for common materials used in these calculations are listed in Table 4-1. The reactor core composition, based on the NEBA1 reactor, Reference 6, was taken to consist of UO_2, mass fraction 0.595, and W, mass fraction 0.405. Uranium was taken to be enriched to 93% U^{235}, with a total U^{235} content of 108.04 kg.

4.5 Radiation Sources

The radiation sources used in shielding calculations were based on a test sequence consisting of five, five hour reactor burns, with a seven day interval between burns. Following the last burn, the reactor core is broken up and its fragments dropped into the quench chamber/debris trap. The vapor phase will contain the hydrogen gas used to cool the test reactor, gas constituents of the fission products and some particulate material entrained in the gas. This entrained material was assumed to contain 1% of the total core activity.

The first vessel in the hydrogen treatment/recycling system is the Hydrogen Effluent Storage Sphere. This vessel will hold the hydrogen gas and entrained particulates for a minimum period of one week. The vessels following the Hydrogen Effluent Storage Sphere will receive radioisotope inventory decayed for at least one week, and with some of the particulates precipitated out in the Storage Sphere (assumed 10% of the total inventory).

The remainder of the hydrogen treatment/recycling system consists of a Compressor, Dryer, Filter, Cooler, and Adsorber, followed by the hydrogen liquefaction and purification unit and other components. At each one of these units, some of the particulates precipitate out. The assumed rate is 1% at the Compressor, 10% at the Dryer, 99.9% at the Filter, 1% at the Cooler, and 1% at the Adsorber. The Adsorber also removes a minimum of 99.9% of the gaseous radioisotopes. The resulting source terms in each one of these vessels is based on the photon spectrum (and intensity) generated by ORIGEN2, for the appropriate time after irradiation and reduced by the amount precipitated out in the preceding vessels. Calculations used to define the source terms for each vessel are illustrated in the spread sheet in Figure 4-1.

In addition to the entrained particulates in the vapor, all of the krypton, xenon and iodine isotopes were included. These isotopes were assumed present in full strength (decayed for seven days before leaving the Hydrogen Effluent Storage Sphere) in all vessels in the vapor process up to, and including the adsorber. These isotopes are the most significant contributions to the photon source term in all vessels past the Hydrogen Effluent Storage Sphere.

A similar approach was used to define the source terms for the various vessels in the water treatment/recycle system. For this system, 3% of the reactor core isotope composition are assumed to contaminate the water, including 100% of the strontium and cesium which are dissolved in the water. The first filter is expected to remove a minimum of 99.9% of the particulates, but none of the dissolved isotopes or their daughters. The De-ionization Unit removes 99.9% of the isotopes in solution. The second filter removes a minimum of 99% of the remaining particulates. Small amounts of radioactivity will remain in those vessels following the second filter. The spread sheet used to define these sources is illustrated in Figure 4-2.

4.6 Fluence Rate to Dose Rate Conversion

Once a gamma or neutron fluence rate (particle/cm^2-sec) has been calculated by the appropriate computer code, the code must convert this fluence rate to an absorbed dose rate in humans in units of rem/h or mrem/h (rem = Roentgen Equivalent Man). The conversion is dependent both on the type of particle (γ or n) and the energy of the particle. The conversion factors for gamma exposure (built into MicroShield) are based on ICRP-51 (Reference 8) and ANSI/ANS-6.1.1-1991 (Reference 9) and are given in Table 4-2.

Table 4-1 Composition of Materials Used in Radiation Shielding Calculations (Given as Fractional Densities in g/cm^3)

Atomic Number	Element	Air	Water	Stainless Steel 304L ASTM A240 (Ref. 4)	Concrete (Ref. 7)
1	H		0.11111		0.01316
5	B^{10}				
5	B^{11}				
6	C	0.00000017		0.0023	
7	N	0.00092132			
8	O	0.00028276	0.88889		1.171
11	Na				0.0402
12	Mg				0.0056
13	Al				0.1072
14	Si			0.0587	0.74213
15	P			0.0035	
16	S			0.0023	0.00282
18	Ar	0.00001575			
19	K				0.04512
20	Ca				0.1941
22	Ti				
24	Cr			1.5660	
25	Mn			0.1566	
26	Fe			5.1009	0.0287
28	Ni			0.9396	
Total		0.00122	1.00	7.8299	2.35

Table 4-2 Fluence Rate to Dose Rate Conversion Factors for Gammas (Reference 9)

PHOTON ENERGY (MeV)	CONVERSION FACTOR (mrem/h) (Ph/cm^2-sec)
1.00E-02	0.00002232
1.50E-02	0.00005652
2.00E-02	0.00008568
3.00E-02	0.0001184
4.00E-02	0.0001314
5.00E-02	0.0001382
6.00E-02	0.0001440
8.00E-02	0.0001624
1.00E-01	0.0001919
1.50E-01	0.0002797
2.00E-01	0.0003708
3.00E-01	0.0005616
4.00E-01	0.0007416
5.00E-01	0.0009144
6.00E-01	0.0010764
8.00E-01	0.001379
1.00E+00	0.001656
1.50E+00	0.002246
2.00E+00	0.002758
3.00E+00	0.003672
4.00E+00	0.004500
5.00E+00	0.005292
6.00E+00	0.006012
8.00E+00	0.007488
1.00E+01	0.008892
1.20E+01	0.010404

4.7 Calculation Results

The ORIGEN2 was used to generate the isotope inventory in the reactor material. Five, five hour burns were assumed, separated by decay periods of seven days. Isotope inventories, and an associated photon spectrum, was generated at the end of each irradiation and each decay period. Additional isotope inventories and photon spectra were obtained for various time periods following the last irradiation. The worst case isotope composition was assumed to be that following the fifth irradiation, with the core destroyed and its contents dumped into the Quench Chamber/Debris Trap. This was the source used to calculate the photon shielding requirements for the Quench Chamber/Debris Trap. This vessel was assumed to be cylindrical in shape, with a 38 foot inside diameter, and a height of 114 feet; the maximum water/isotope level was assumed to be 76 feet high. The MicroShield code was used to evaluate exposure levels behind a steel and a concrete shield, for various shield thicknesses. The results are shown in Figures 4-3 and 4-4. (In all cases which follow, the exposure levels were estimated at the side of the container, at the midpoint of the source region.)

For an assumed maximum acceptable exposure level of 0.2 mrem/h (which would be representative of a full time occupied, controlled access area), the shield for the Quench Chamber/Debris Trap could require about two feet of steel or 78 inches of concrete, or some combination of the two materials. One approach would be to place this vessel below ground level and take advantage of earth to provide some of the shielding.

Exposure levels behind various thicknesses of steel and concrete, for the Hydrogen Effluent Storage Sphere, are shown in Figures 4-5 and 4-6. The sphere was taken to be 100 feet in diameter and filled with vapor, modeled as air. To achieve exposure levels of about 0.2 mrem/hr, a shield of about 19 inches of steel, or 6 feet of concrete would be required.

Since the source terms for the Compressor, Dryer, Filter, Cooler and Adsorber, are dominated by contributions from krypton, xenon, and iodine isotopes, which are assumed present at full intensity in all of these vessels (a worst case assumption), the shielding requirements for these vessels are very similar. Most differences are the result of different geometries of the vessels.

The Compressor was modeled as a 3ft x 3ft x 3ft cube, and the exposure levels behind various shield thicknesses of steel and concrete are shown in Figures 4-7 and 4-8. The Compressor would also require substantial shielding of about 20 inches of steel, or 6 feet of concrete.

The Dryer Unit is modeled as a 5 feet diameter cylinder, 14.5 feet high with the radioactive material extending to a height of 12.5 feet. The exposure levels behind various shield thicknesses of steel and concrete are shown in Figures 4-9 and 4-10. To achieve levels less than 0.2 mrem/hr, the shield requirements are 15 inches of steel, or 46 inches of concrete.

The filter was assumed to be cylindrical, 3ft in diameter and 6ft high. The exposure levels behind various thicknesses of steel and concrete are shown in Figures 4-11 and 4-12. This unit would require shields of 16 inches of steel, or 48 inches of concrete to reduce exposure levels to about 0.2 mrem/hr.

The Cooler and Adsorber were assumed to be approximately the same, as far as the geometry and source composition was concerned, and were modeled as a 3ft diameter cylinder, 6ft high. The exposure levels for these units, behind various thicknesses of steel and concrete are shown in Figures 4-13 and 4-14. Again, about 19 inches of steel, or 5 feet of concrete are required to reduce exposure levels to about 0.2 mrem/hr.

The Quench Water Treatment Pump was modeled as a rectangular unit, 2ft x 2ft x 3ft. The behind various thicknesses of steel and concrete are shown in Figures 4-15 and 4-16. The source for this unit was assumed to consist of particulates in the water and dissolved materials, consisting of cesium, strontium and their decay products (e.g. Y^{91} and Y^{91m}). The particulates were assumed to represent 1/33 the strength of the total activity in the Quench Chamber/Debris Trap.

Both water filter units were modeled as a cylinder, 2ft in diameter and 5ft high. The results for the first filter are shown in Figures 4-17 and 4-18. Figures 4-19 and 4-20 present the results for the De-ionization Unit, modeled as a 5ft diameter cylinder, 5ft high with the source occupying the lower 3ft of the cylinder. The worst case source for both the first water filter and the DI unit, are assumed to contain all the isotopes in solution (the particulate concentrations were discussed in Section 4.5).

Figures 4-21 and 4-22 show the results for the second filter (i.e., the one following the DI Unit in the process).

The source strength for the remaining units is approximately the same and only differences in geometry provide some variation in the exposure rate outside those vessels. Sample results are shown in Figures 4-23 through 4-25. Only minimal, if any, shielding would be required for those units.

4.8 References

1. Croff, A. G., "A User's Manual for the ORIGEN2 Computer Code," ORNL/TM-7175, Dist. Category UC-70, Oak Ridge National Laboratory, July 1980.

2. Negin, C. A. and G. Worku, "MicroShield, Version 4.10, User's Manual," Grove Engineering, Inc, Rockville, Maryland, October 1993.

3. "American National Standard for Calculation and Measurement of Direct and Scattered Radiation from LWR Nuclear Power Plants," ANSI/ANS-6.6.1-1979, January 1979.

4. "Specification for Gamma Ray Shielding Benchmark Applicable to a Nuclear Radwaste Facility," ESIS - European Shielding Information Service, Newsletter #37, ISPRA Establishment, Italy, April 1981.

5. "RSIC COMPUTER CODE COLLECTION, ORIGEN2.1 Isotope Generation and Depletion Code Matrix Exponential Method," Oak Ridge National Laboratory, CCC-371, December 1991.

6. "Conceptual Design Review USAF/DOE Bimodal Power and Propulsion Program, U.S. Air Force/U.S. Department of Energy, February 22-23, 1995.

7. "Guidelines On the Nuclear Analysis and Design of Concrete Radiation Shielding for Nuclear Power Plants," ANSI/ANS-6.4-1985, March 1985.

8. "Data for Use in Protection Against External Radiation," ICRP-51.

9. "Neutron and Gamma-Ray Fluence-to-Dose Factors," ANSI/ANS-6.1.1, 1991 August 1991.

Figure 4-1
Calculations Used to Define Source Terms -Hydrogen Treatment/Recycling System

QUENCH CHAMBER

ENERGY	ACTIV.	ACTIN +	FISSION	TOTALS	x0.01	GAS, 1wk
0.01	2.6E+15	2.6E+14	6.1E+17	6.1E+17	6.1E+15	3.4E+13
0.025	3.4E+14	2.5E+13	1.4E+17	1.4E+17	1.4E+15	0
0.0375	2.2E+14	4.3E+13	1.1E+17	1.1E+17	1.1E+15	2.7E+14
0.0575	3.5E+15	2.3E+13	1.3E+17	1.3E+17	1.3E+15	0
0.085	1.3E+15	2.4E+14	9.2E+16	9.4E+16	9.4E+14	1.9E+14
0.125	1.2E+15	2.6E+13	8.0E+16	8.2E+16	8.2E+14	5.2E+11
0.225	1.4E+14	2.1E+13	2.3E+17	2.3E+17	2.3E+15	2.2E+12
0.375	2.7E+13	4.3E+12	1.5E+17	1.5E+17	1.5E+15	2.0E+14
0.575	7.7E+15	3.0E+12	1.9E+17	1.9E+17	1.9E+15	3.3E+14
0.85	5.4E+14	4.5E+12	2.4E+17	2.4E+17	2.4E+15	1.9E+14
1.25	2.4E+11	5.3E+10	1.7E+17	1.7E+17	1.7E+15	5.8E+13
1.75	3.8E+09	9235000	4.8E+16	4.8E+16	4.8E+14	3.1E+13
2.25	1.1E+09	44.65	3.6E+16	3.6E+16	3.6E+14	6.5E+12
2.75	1.3E+09	26	1.6E+16	1.6E+16	1.6E+14	0
3.5	1.0E+09	22.45	1.0E+16	1.0E+16	1.0E+14	0
5	3.8E+08	9.445	5.7E+15	5.7E+15	5.7E+13	0
7	6.0E+10	1.065	4.6E+13	4.6E+13	4.6E+11	0
9.5	62010000	0.1209	9.1E+09	9.1E+09	91210100	0
TOTALS	1.8E+16	6.6E+14	2.2E+18	2.3E+18	2.3E+16	1.3E+15

ONE WK. DECAY

ENERGy	ACTIV.	ACTIN. +	FISSION	TOTALS	x0.01	F x 0.9	F x 0.89	F x 0.8
0.01	2.1E+13	4.7E+12	9.0E+14	9.2E+14	9.2E+12	8.3E+12	8.2E+12	7.4E+12
0.025	2.9E+12	6.4E+10	4.0E+14	4.0E+14	4.0E+12	3.6E+12	3.5E+12	3.2E+12
0.0375	1.8E+12	4.1E+10	5.2E+14	5.3E+14	5.3E+12	4.7E+12	4.7E+12	4.2E+12
0.0575	2.8E+13	1.4E+11	1.7E+14	2.0E+14	2.0E+12	1.8E+12	1.8E+12	1.6E+12
0.085	1.0E+13	8.4E+11	3.2E+14	3.3E+14	3.3E+12	3.0E+12	2.9E+12	2.6E+12
0.125	9.5E+12	2.4E+12	4.7E+14	4.8E+14	4.8E+12	4.3E+12	4.3E+12	3.9E+12
0.225	1.1E+12	1.7E+12	3.3E+14	3.4E+14	3.4E+12	3.0E+12	3.0E+12	2.7E+12
0.375	2.1E+11	1.6E+11	3.5E+14	3.5E+14	3.5E+12	3.1E+12	3.1E+12	2.8E+12
0.575	5.9E+13	6.8E+08	8.1E+14	8.7E+14	8.7E+12	7.8E+12	7.7E+12	6.9E+12
0.85	4.1E+12	1196000	7.2E+14	7.3E+14	7.3E+12	6.6E+12	6.5E+12	5.8E+12
1.25	1.8E+09	696700	5.1E+13	5.1E+13	5.1E+11	4.6E+11	4.5E+11	4.1E+11
1.75	25010000	63000	4.5E+14	4.5E+14	4.5E+12	4.0E+12	4.0E+12	3.6E+12
2.25	203700	44.69	8.7E+12	8.7E+12	8.7E+10	7.9E+10	7.8E+10	7.0E+10
2.75	0	26.76	1.7E+13	1.7E+13	1.7E+11	1.5E+11	1.5E+11	1.4E+11
3.5	0	22.45	1.4E+11	1.4E+11	1.4E+09	1.3E+09	1.2E+09	1.1E+09
5	0	9.446	0.000024	9.446024	0.09446	0.085014	0.08407	0.075568
7	0	1.065	1.3E-09	1.065	0.01065	0.009585	0.009479	0.00852
9.5	0	0.1209	8.5E-11	0.1209	0.001209	0.001088	0.001076	0.000967
TOTALS	1.4E+14	1.0E+13	5.5E+15	5.7E+15	5.7E+13	5.1E+13	5.0E+13	4.5E+13

G+gas(H)	H+gas(H)	I+gas(H)
4.2E+13	4.2E+13	4.1E+13
3.6E+12	3.5E+12	3.2E+12
2.7E+14	4.7E+12	4.2E+12
1.8E+12	1.8E+12	1.6E+12
2.0E+14	2.9E+12	2.6E+12
4.9E+12	4.3E+12	3.9E+12
5.2E+12	3.0E+12	2.7E+12
2.0E+14	3.1E+12	2.8E+12
3.4E+14	7.7E+12	6.9E+12
2.0E+14	6.5E+12	5.8E+12
5.9E+13	4.5E+11	4.1E+11
3.5E+13	4.0E+12	3.6E+12
6.6E+12	7.8E+10	7.0E+10
1.5E+11	1.5E+11	1.4E+11
1.3E+09	1.2E+09	1.1E+09
0.085014	0.08407	0.075568
0.009585	0.009479	0.00852
0.001088	0.001076	0.000967
1.4E+15	8.4E+13	7.9E+13

ADSORBER		COMPRESSOR		DRYER		FILTER	
0.01	3.4E+13	0.01	4.2E+13	0.01	4.2E+13	0.01	4.1E+13
0.025	318465.8	0.025	3.6E+12	0.025	3.5E+12	0.025	3.2E+12
0.0375	2.7E+14	0.0375	2.7E+14	0.0375	4.7E+12	0.0375	4.2E+12
0.0575	160363.1	0.0575	1.8E+12	0.0575	1.8E+12	0.0575	1.6E+12
0.085	1.9E+14	0.085	2.0E+14	0.085	2.9E+12	0.085	2.6E+12
0.125	5.2E+11	0.125	4.9E+12	0.125	4.3E+12	0.125	3.9E+12
0.225	2.2E+12	0.225	5.2E+12	0.225	3.0E+12	0.225	2.7E+12
0.375	2.0E+14	0.375	2.0E+14	0.375	3.1E+12	0.375	2.8E+12
0.575	3.3E+14	0.575	3.4E+14	0.575	7.7E+12	0.575	6.9E+12
0.85	1.9E+14	0.85	2.0E+14	0.85	6.5E+12	0.85	5.8E+12
1.25	5.8E+13	1.25	5.9E+13	1.25	4.5E+11	1.25	4.1E+11
1.75	3.1E+13	1.75	3.5E+13	1.75	4.0E+12	1.75	3.6E+12
2.25	6.5E+12	2.25	6.6E+12	2.25	7.8E+10	2.25	7.0E+10
2.75	13624	2.75	1.5E+11	2.75	1.5E+11	2.75	1.4E+11
3.5	111.52	3.5	1.3E+09	3.5	1.2E+09	3.5	1.1E+09
5	7.6E-09	5	0.085014	5	0.08407	5	0.075568
7	8.5E-10	7	0.009585	7	0.009479	7	0.00852
9.5	9.7E-11	9.5	0.001088	9.5	0.001076	9.5	0.000967

Figure 4-2
Calculations Used to Define Source Terms -Water Treatment/Recycle System

QUENCH CHAMBER/DEBRIS TRAP

ENERGY	ACTIV.	ACTIN + D	FISSION	TOTALS	x0.01	GAS, 1wk
0.01	2.6E+15	2.6E+14	6.1E+17	6.1E+17	6.1E+15	3.4E+13
0.025	3.4E+14	2.5E+13	1.4E+17	1.4E+17	1.4E+15	0
0.0375	2.2E+14	4.3E+13	1.1E+17	1.1E+17	1.1E+15	2.7E+14
0.0575	3.5E+15	2.3E+13	1.3E+17	1.3E+17	1.3E+15	0
0.085	1.3E+15	2.4E+14	9.2E+16	9.4E+16	9.4E+14	1.9E+14
0.125	1.2E+15	2.6E+13	8.0E+16	8.2E+16	8.2E+14	5.2E+11
0.225	1.4E+14	2.1E+13	2.3E+17	2.3E+17	2.3E+15	2.2E+12
0.375	2.7E+13	4.3E+12	1.5E+17	1.5E+17	1.5E+15	2.0E+14
0.575	7.7E+15	3.0E+12	1.9E+17	1.9E+17	1.9E+15	3.3E+14
0.85	5.4E+14	4.5E+12	2.4E+17	2.4E+17	2.4E+15	1.9E+14
1.25	2.4E+11	5.3E+10	1.7E+17	1.7E+17	1.7E+15	5.1E+13
1.75	3.8E+09	9235000	4.8E+16	4.8E+16	4.8E+14	3.1E+13
2.25	1.1E+09	44.65	3.6E+16	3.6E+16	3.6E+14	6.5E+12
2.75	1.3E+09	26	1.6E+16	1.6E+16	1.6E+14	0
3.5	1.0E+09	22.45	1.0E+16	1.0E+16	1.0E+14	0
5	3.8E+08	9.445	5.7E+15	5.7E+15	5.7E+13	0
7	6.0E+10	1.065	4.6E+13	4.6E+13	4.6E+11	0
9.5	62010000	0.1209	9.1E+09	9.1E+09	91210100	0
TOTALS	1.8E+16	6.6E+14	2.2E+18	2.3E+18	2.3E+16	1.3E+15

ONE WK. DECAY

ENERGy	ACTIV.	ACTIN. +	FISSION	TOTALS	- GAS	PUMP	x0.001
0.01	2.1E+13	4.7E+12	9.0E+14	9.2E+14	8.9E+14	2.7E+13	2.7E+10
0.025	2.9E+12	6.4E+10	4.0E+14	4.0E+14	4.0E+14	1.2E+13	1.2E+10
0.0375	1.8E+12	4.1E+10	5.2E+14	5.3E+14	2.6E+14	7.9E+12	7.9E+09
0.0575	2.8E+13	1.4E+11	1.7E+14	2.0E+14	2.0E+14	6.1E+12	6.1E+09
0.085	1.0E+13	8.4E+11	3.2E+14	3.3E+14	1.4E+14	4.1E+12	4.1E+09
0.125	9.5E+12	2.4E+12	4.7E+14	4.8E+14	4.8E+14	1.5E+13	1.5E+10
0.225	1.1E+12	1.7E+12	3.3E+14	3.4E+14	3.3E+14	1.0E+13	1.0E+10
0.375	2.1E+11	1.6E+11	3.5E+14	3.5E+14	1.5E+14	4.6E+12	4.6E+09
0.575	5.9E+13	6.8E+08	8.1E+14	8.7E+14	5.4E+14	1.6E+13	1.6E+10
0.85	4.1E+12	1196000	7.2E+14	7.3E+14	5.4E+14	1.6E+13	1.6E+10
1.25	1.8E+09	696700	5.1E+13	5.1E+13	1.8E+09	55990809	55990.81
1.75	25010000	63000	4.5E+14	4.5E+14	4.2E+14	1.3E+13	1.3E+10
2.25	203700	44.69	8.7E+12	8.7E+12	2.2E+12	6.7E+10	67303036
2.75	0	26.76	1.7E+13	1.7E+13	1.7E+13	5.2E+11	5.2E+08
3.5	0	22.45	1.4E+11	1.4E+11	1.4E+11	4.2E+09	4224242
5	0	9.446	0.000024	9.446024	9.446024	0.286243	0.000286
7	0	1.065	1.3E-09	1.065	1.065	0.032273	0.000032
9.5	0	0.1209	8.5E-11	0.1209	0.1209	0.003664	3.7E-06
TOTALS	1.4E+14	1.0E+13	5.5E+15	5.7E+15	4.4E+15	1.3E+14	1.3E+11

Cs, Sr

ENERGy	Cs, Sr	H+Cs+Sr	Bx0.999	FILT. #2	Rest
0.01	1.5E+10	4.2E+10	1.5E+10	2.7E+10	2.7E+08
0.025		1.2E+10	0	1.2E+10	1.2E+08
0.0375	9.8E+10	1.1E+11	9.8E+10	8.0E+09	79975318
0.0575		6.1E+09	0	6.1E+09	60743606
0.085		4.1E+09	0	4.1E+09	41330758
0.125		1.5E+10	0	1.5E+10	1.5E+08
0.225		1.0E+10	0	1.0E+10	1.0E+08
0.375	5.5E+08	5.1E+09	5.5E+08	4.6E+09	45753647
0.575	1.2E+12	1.3E+12	1.2E+12	1.8E+10	1.8E+08
0.85	7.5E+09	2.4E+10	7.5E+09	1.6E+10	1.6E+08
1.25	1.6E+11	1.6E+11	1.6E+11	1.6E+08	1573560
1.75	7.4E+08	1.3E+10	7.4E+08	1.3E+10	1.3E+08
2.25		67303036	0	67303036	673030.4
2.75		5.2E+08	0	5.2E+08	5160606
3.5		4224242	0	4224242	42242.42
5		0.000286	0	0.000286	2.9E-06
7		0.000032	0	0.000032	3.2E-07
9.5		3.7E-06	0	3.7E-06	3.7E-08
TOTALS	1.5E+12	1.6E+12	1.5E+12	1.3E+11	1.3E+09

Figure 4-3
Dose Rate Behind a Steel Shield Around the Quench Tank
(Dose Point is 21 ft from Tank Center.)

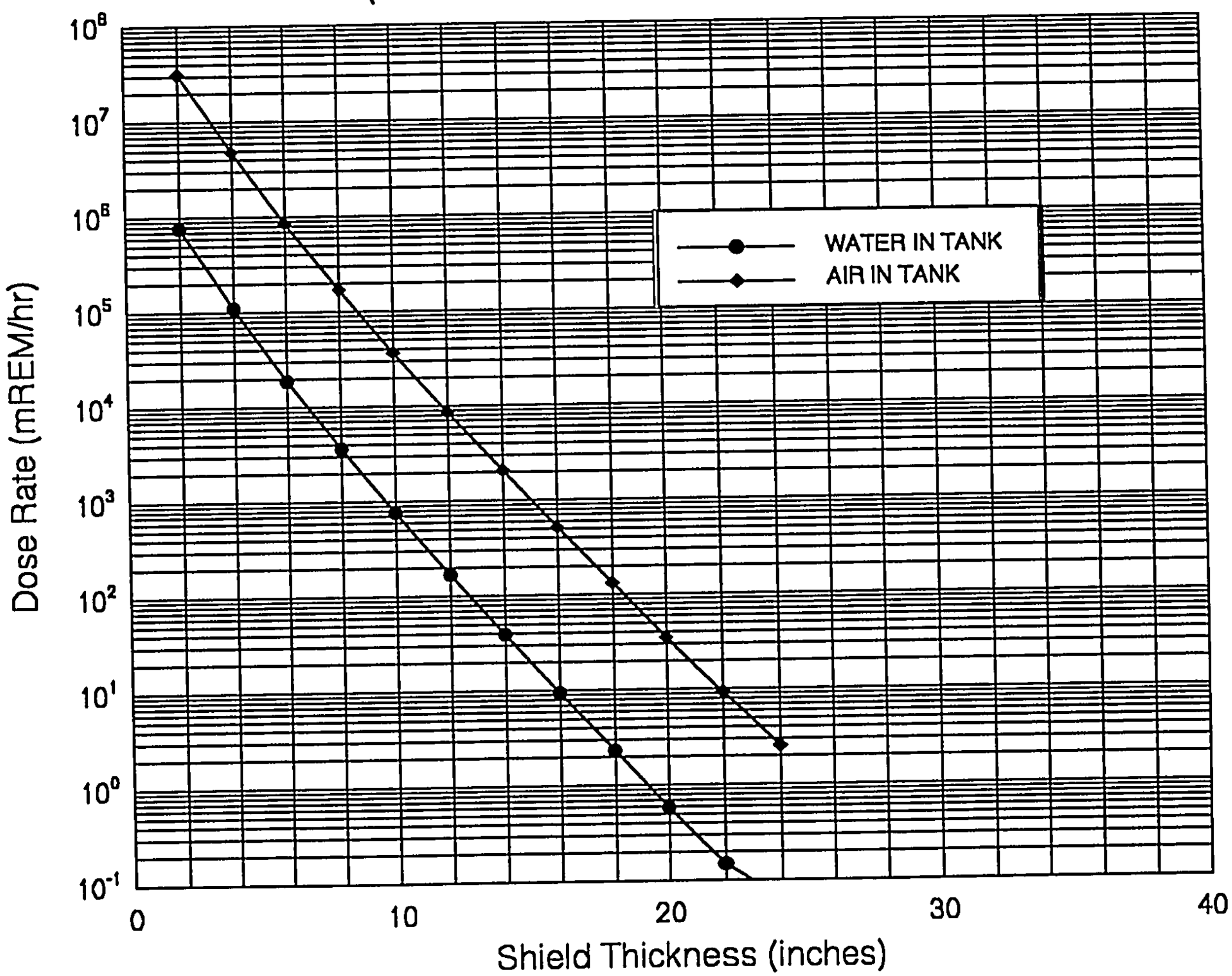

Figure 4-4
Dose Rate Behind a Concrete Shield Around the Quench Tank
(Dose Point is 40 ft from Tank Center.)

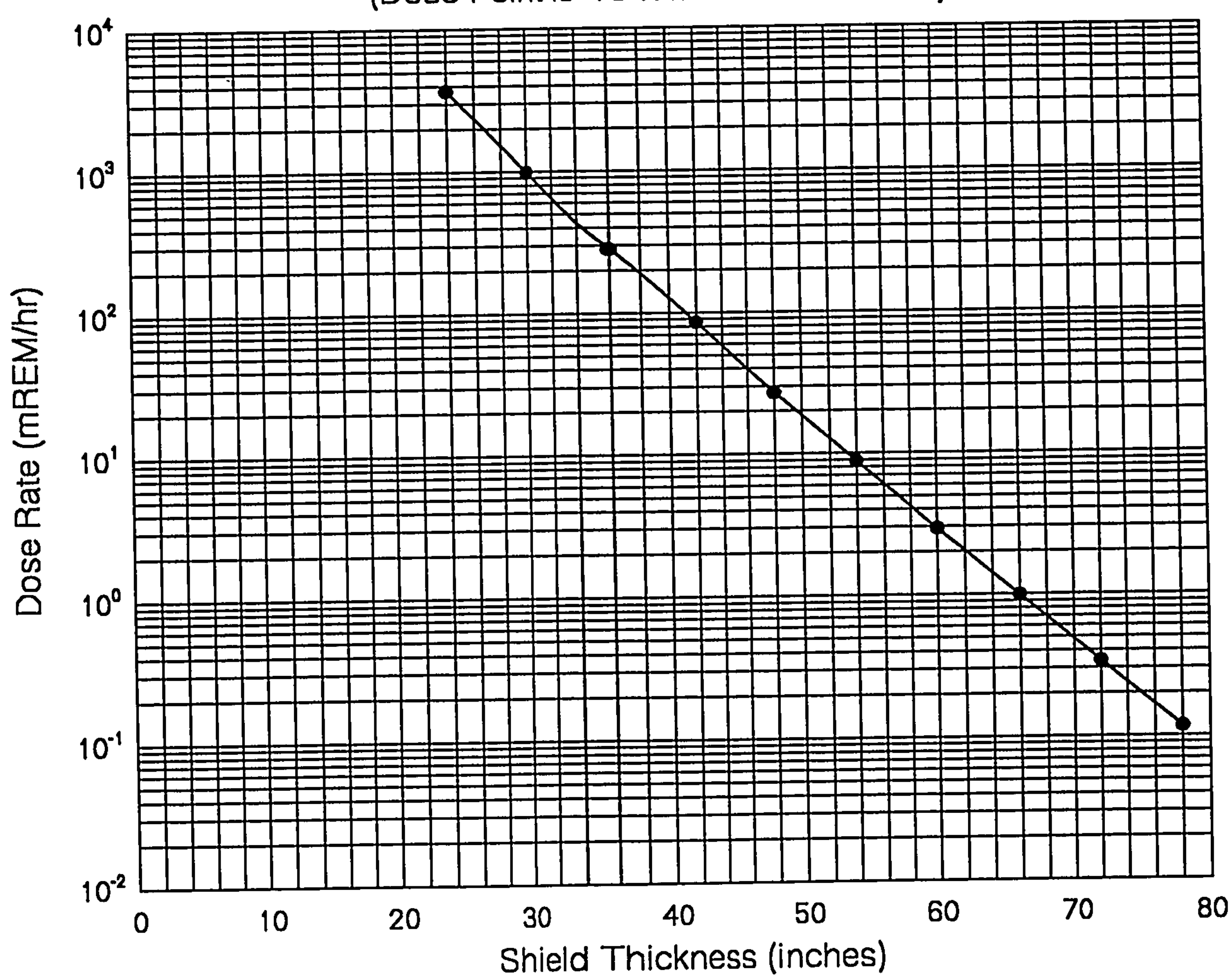

Figure 4-5
Dose Rate Behind a Steel Shield Around the Gas Storage Sphere
(Dose Point is 55 ft from Sphere Center.)

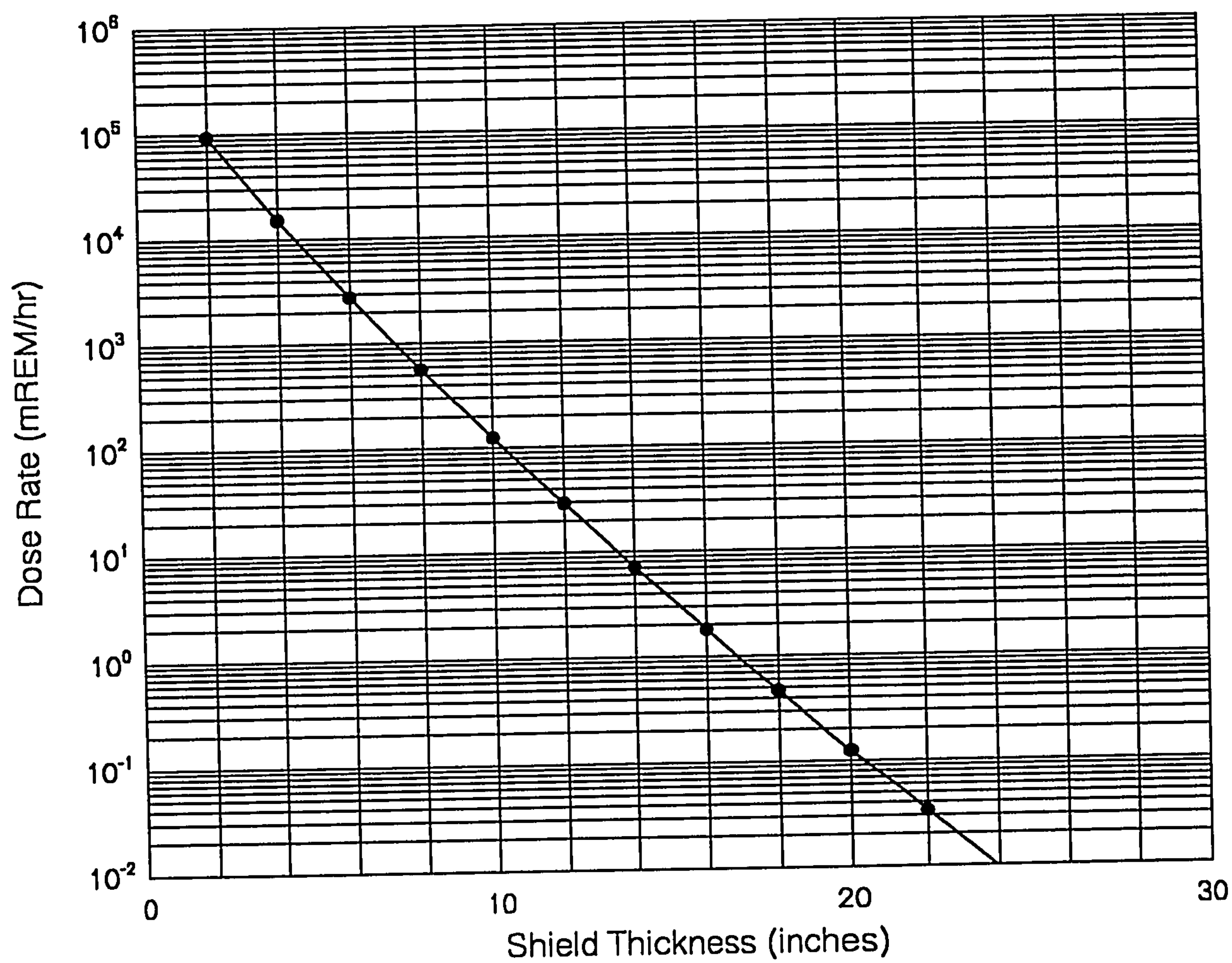

Figure 4-6

Dose Rate Behind a Concrete Shield Around the Gas Storage Sphere
(Dose Point is 55 ft from Sphere Center.)

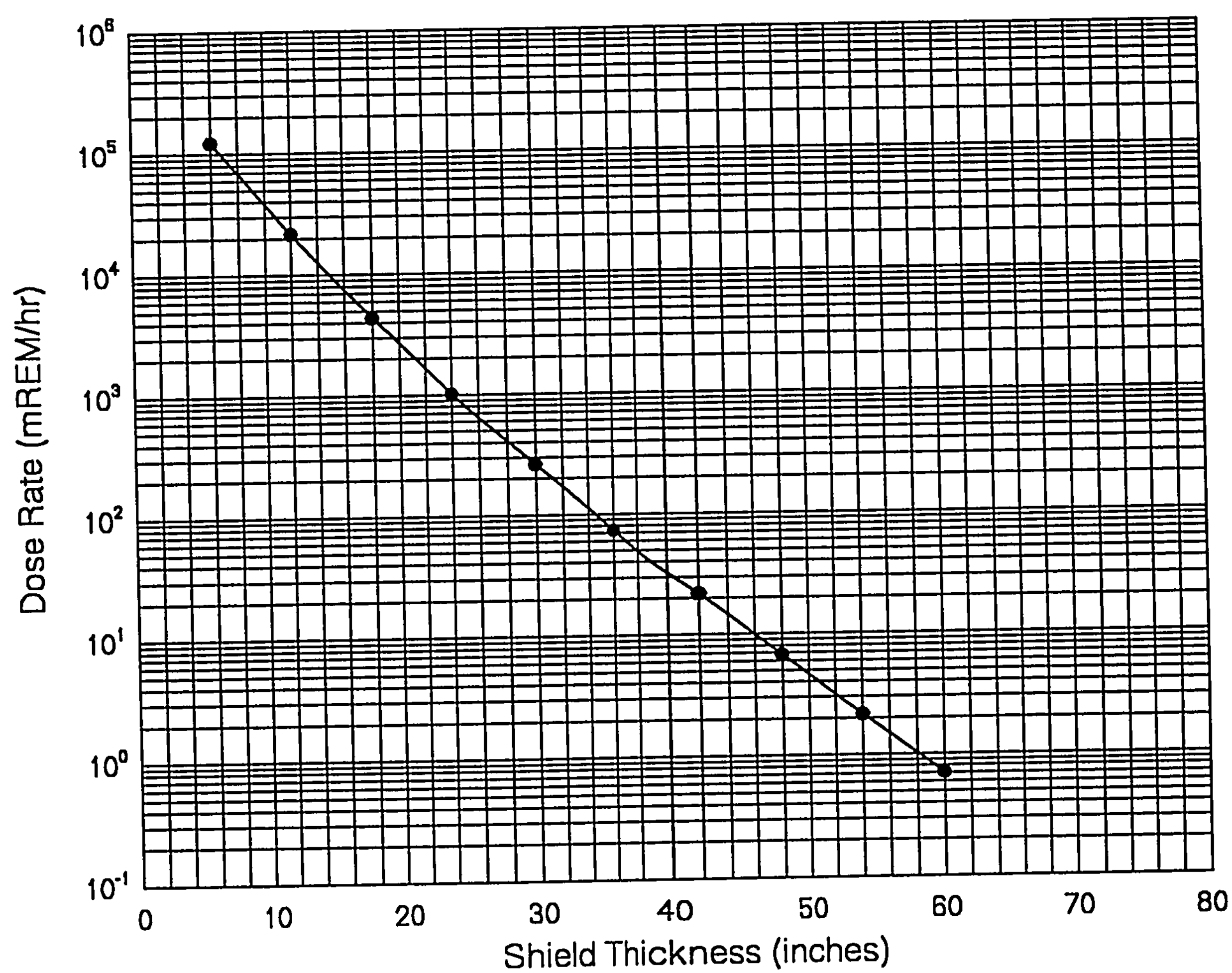

Figure 4-7
Dose Rate Behind a Steel Shield Around the Compressor
(Dose Point is 2 ft 8 in from Face of a 3ftx3ftx3ft Compressor.)

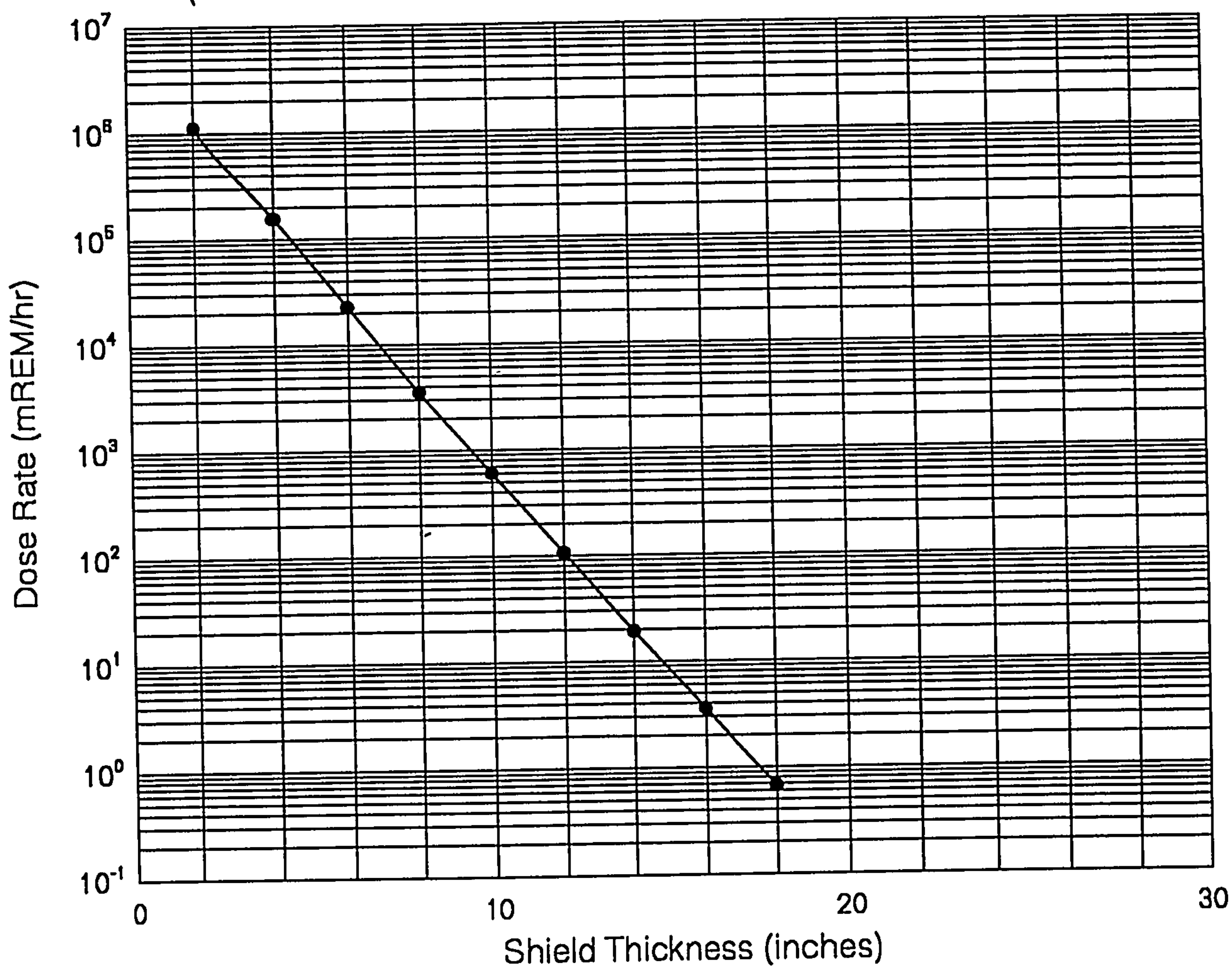

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Figure 4-8
Dose Rate Behind a Concrete Wall Shielding the Compressor
(Dose Point is 4 ft 2 in from Face of a 3ftx3ftx3ft Compressor.)

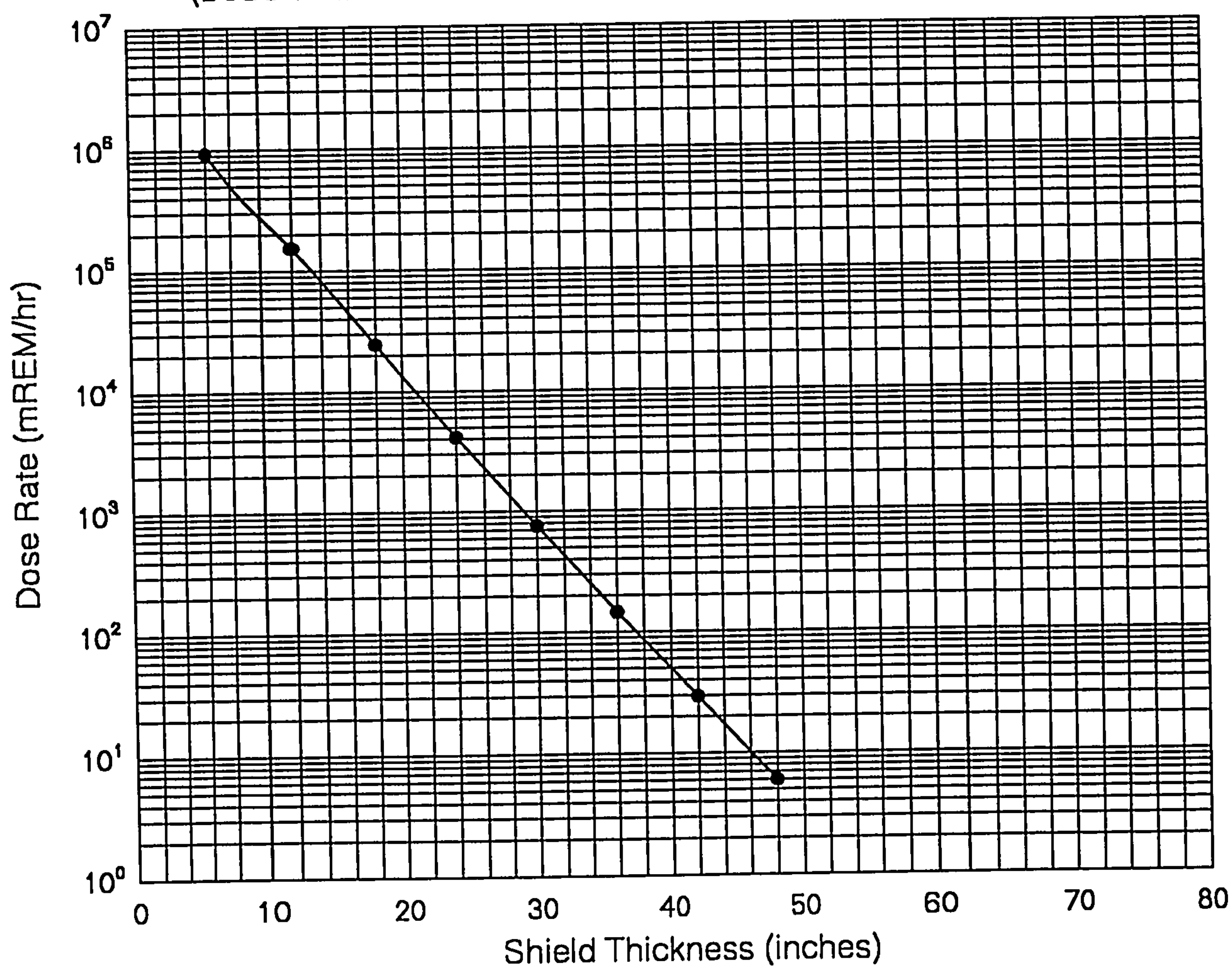

Figure 4-9
Dose Rate Behind a Steel Shield Around the Dryer
(Dose Point is 2 ft from Dryer Center.)

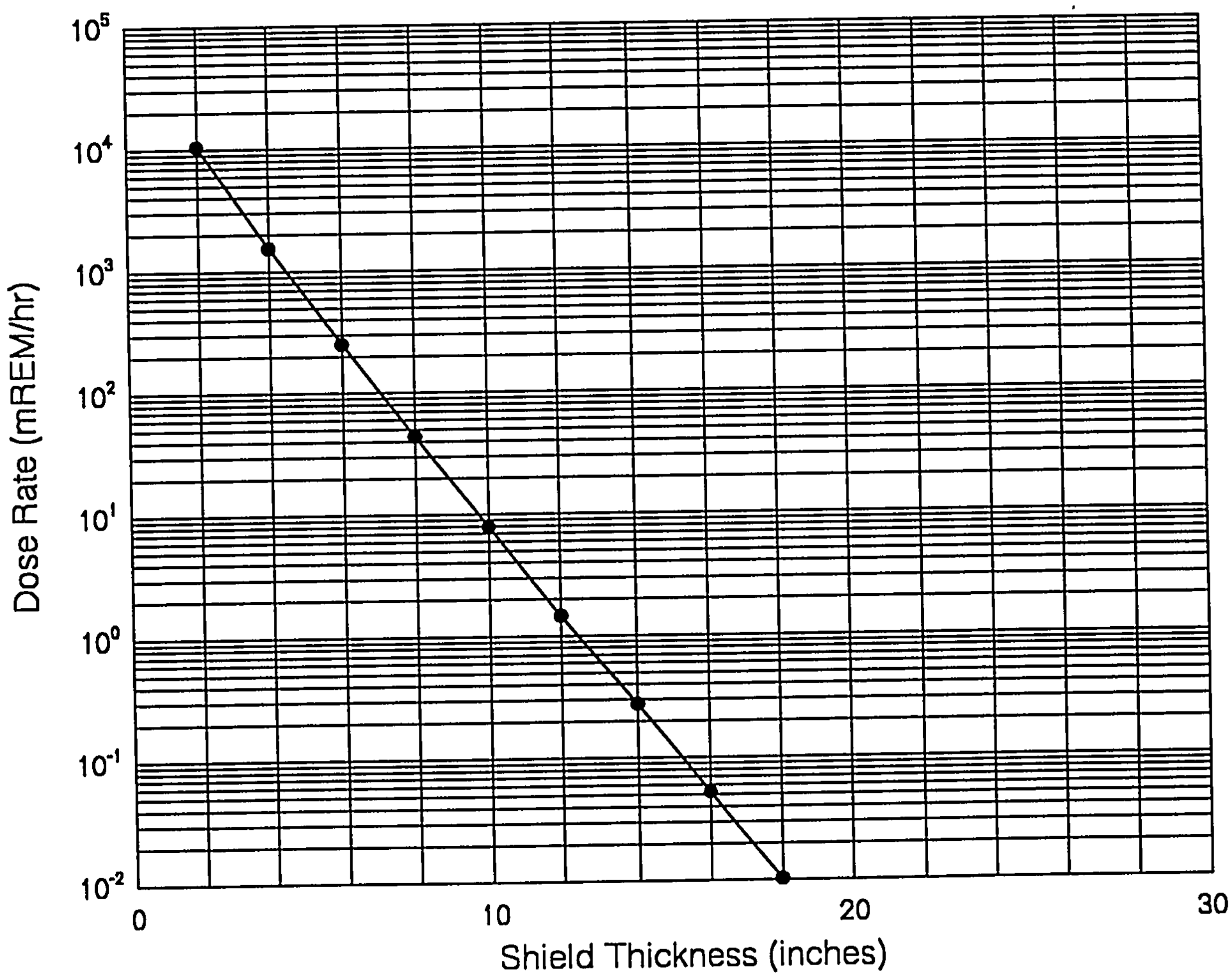

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Figure 4-10
Dose Rate Behind a Concrete Shield Around the Dryer
(Dose Point is 9 ft 2 in from Dryer Center.)

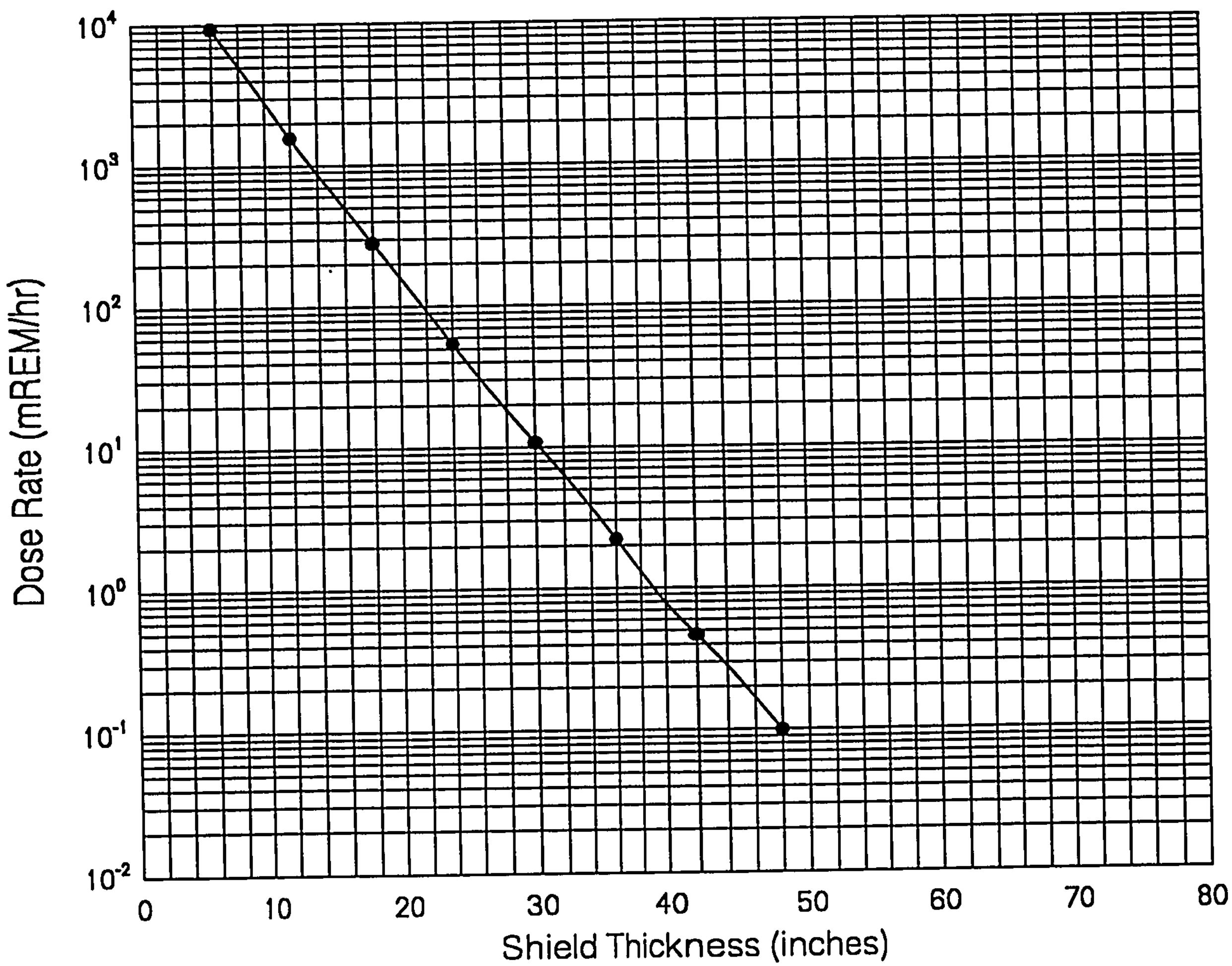

Figure 4-11
Dose Rate Behind a Steel Shield Around the Filter
(Dose Point is 2 ft from Filter Center.)

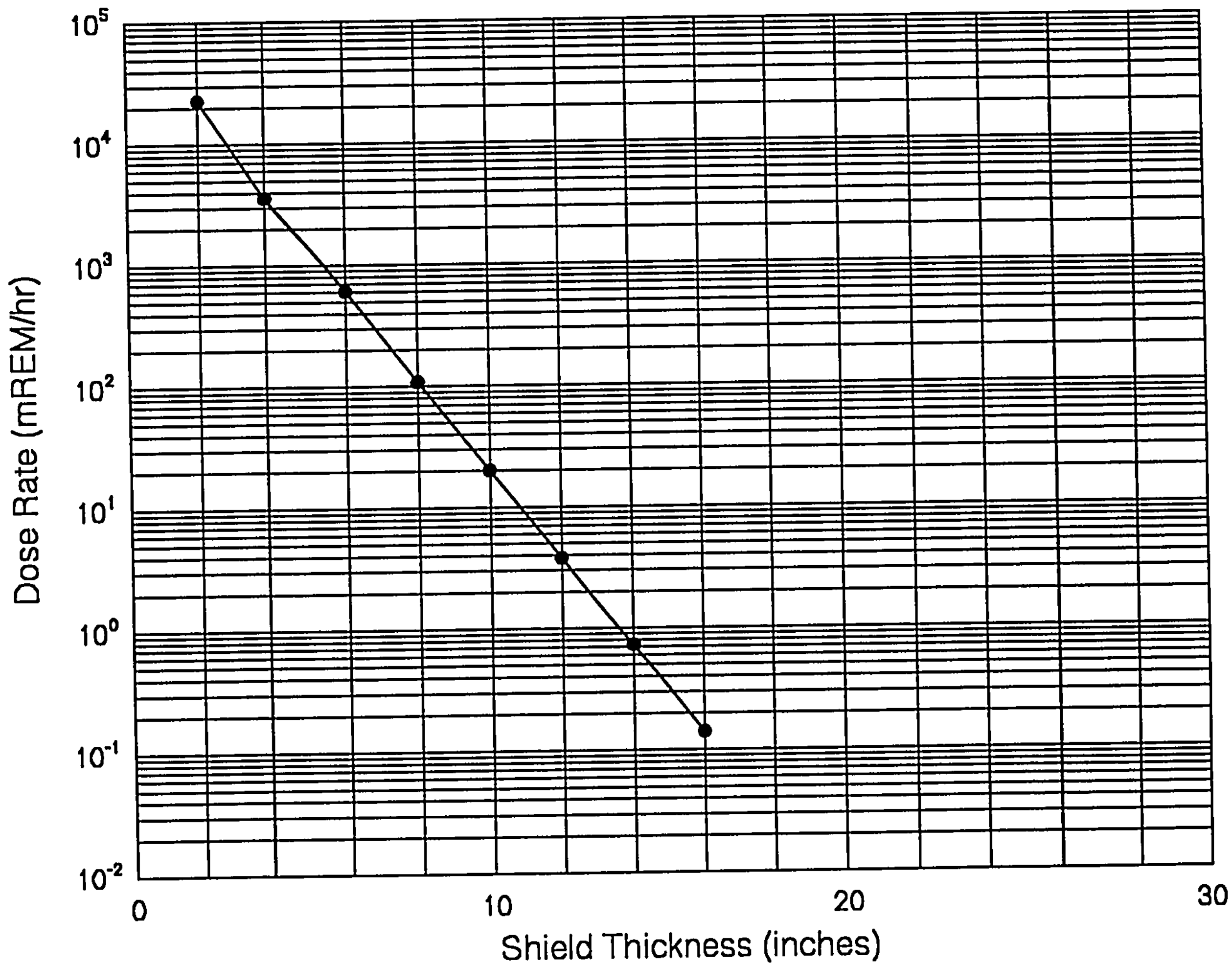

Figure 4-12
Dose Rate Behind a Concrete Shield Around the Filter
(Dose Point is 7 ft 2 in from Filter Center.)

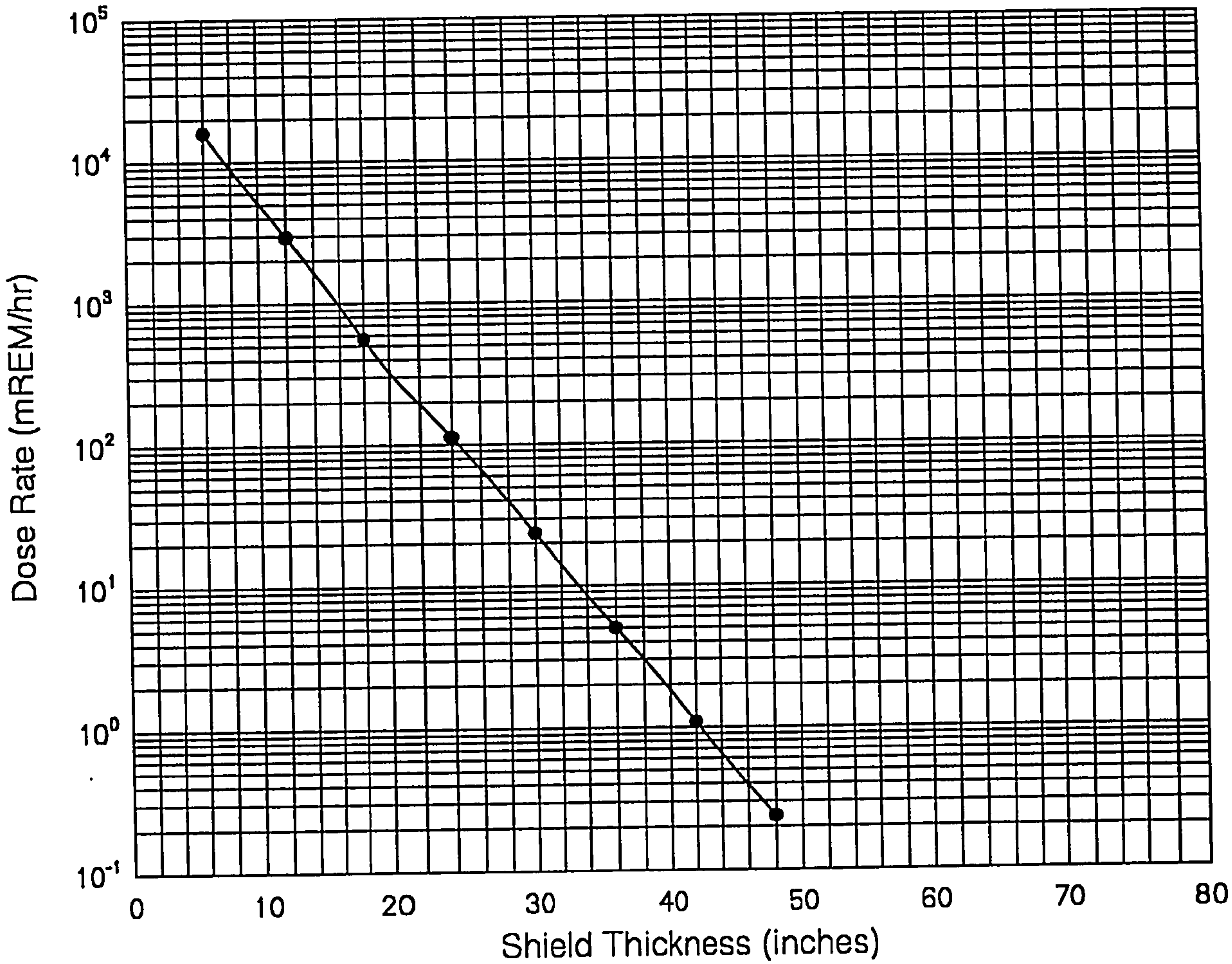

Figure 4-13
Dose Rate Behind a Steel Shield Around the Adsorber
(Dose Point is 2 ft from Adsorber Center.)

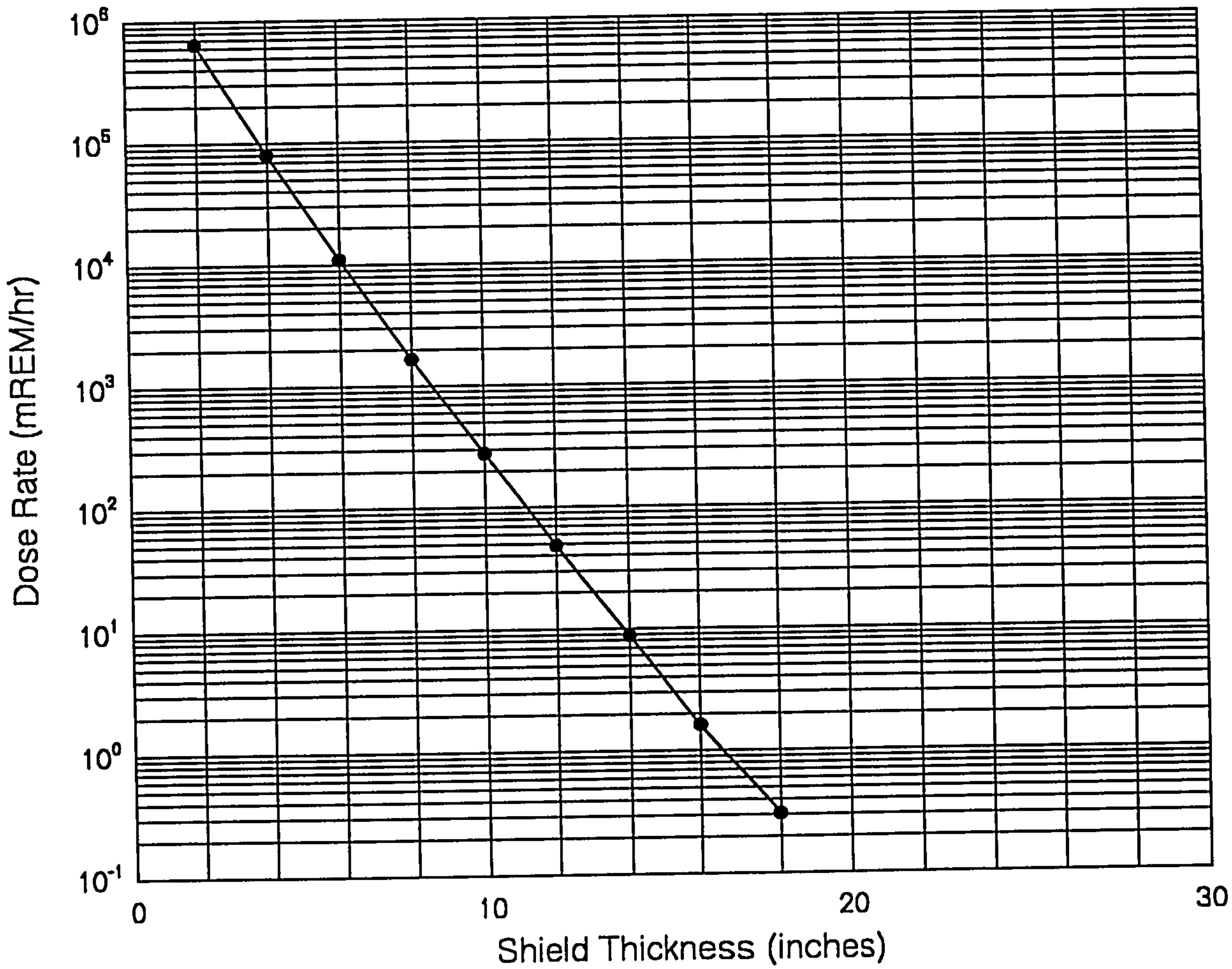

Figure 4-14
Dose Rate Behind a Concrete Shield Around the Adsorber
(Dose Point is 8 ft 2 in from Center of Adsorber.)

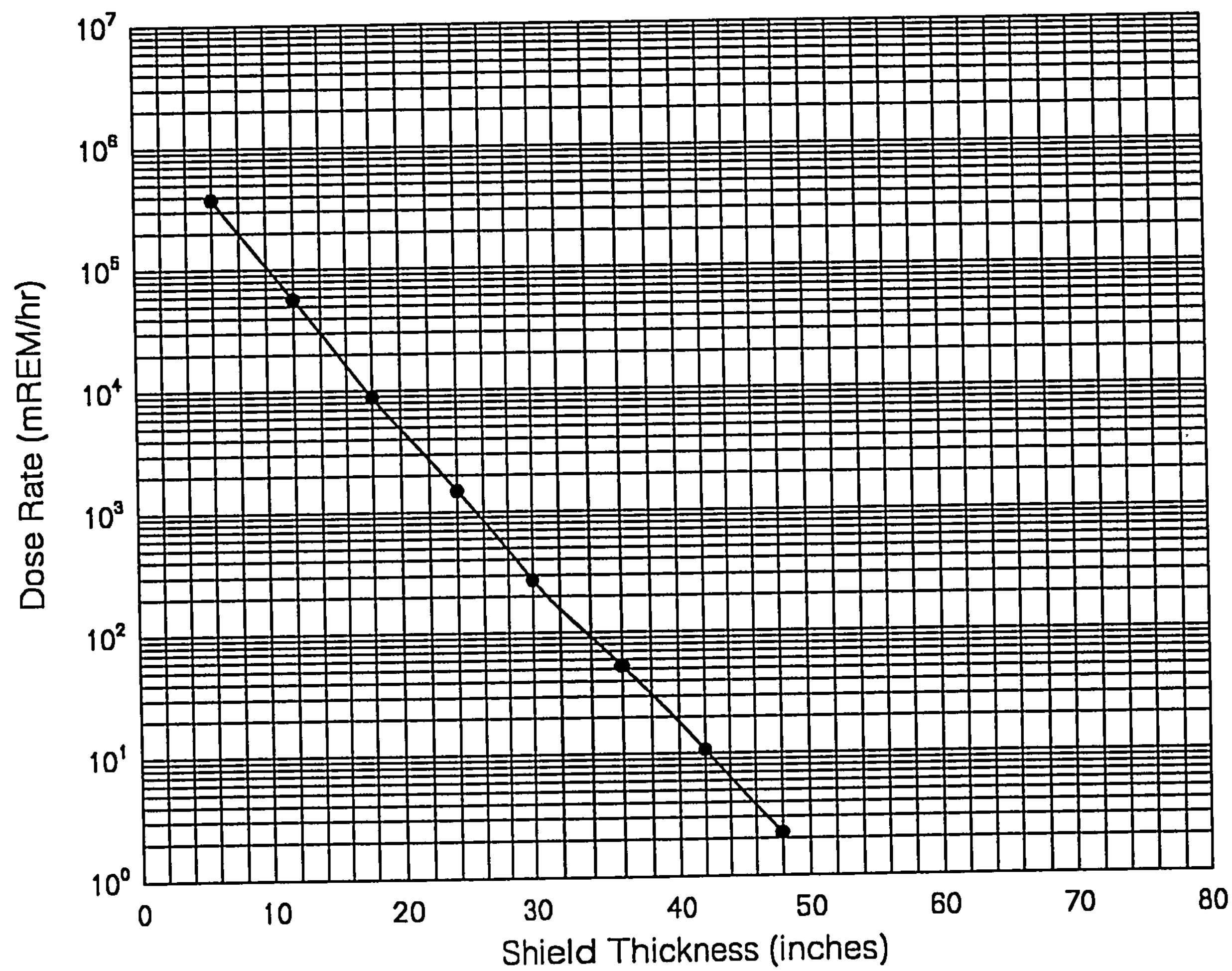

Figure 4-15

Dose Rate Behind a Steel Shield Around the Quench Water Treatment Pump
(Dose Point is 2.5 ft from Face of Pump.)

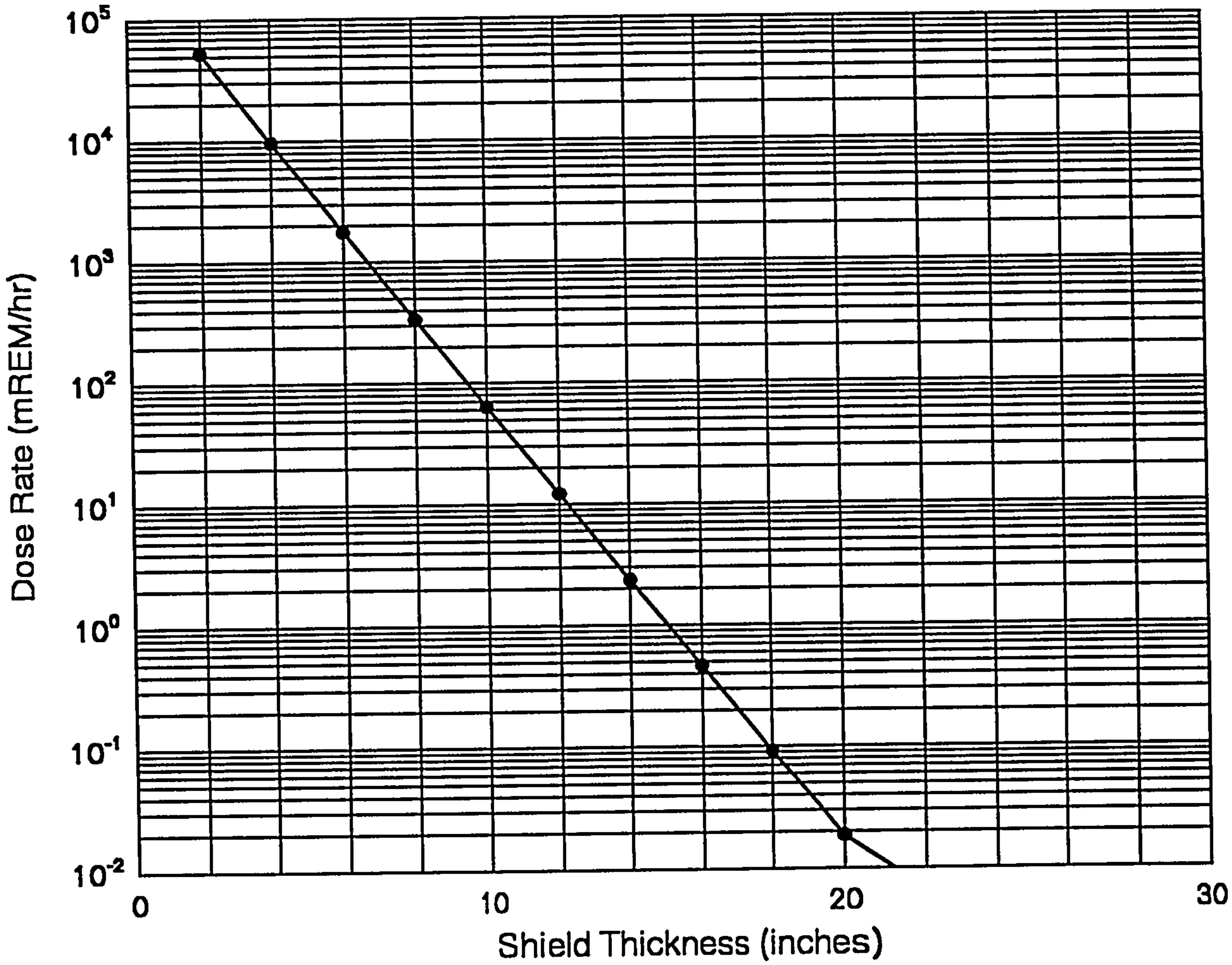

Figure 4-16
Dose Rate Behind a Concrete Shield Around the Quench Water Treatment Pump
(Dose Point is 5.5 ft from Face of Pump.)

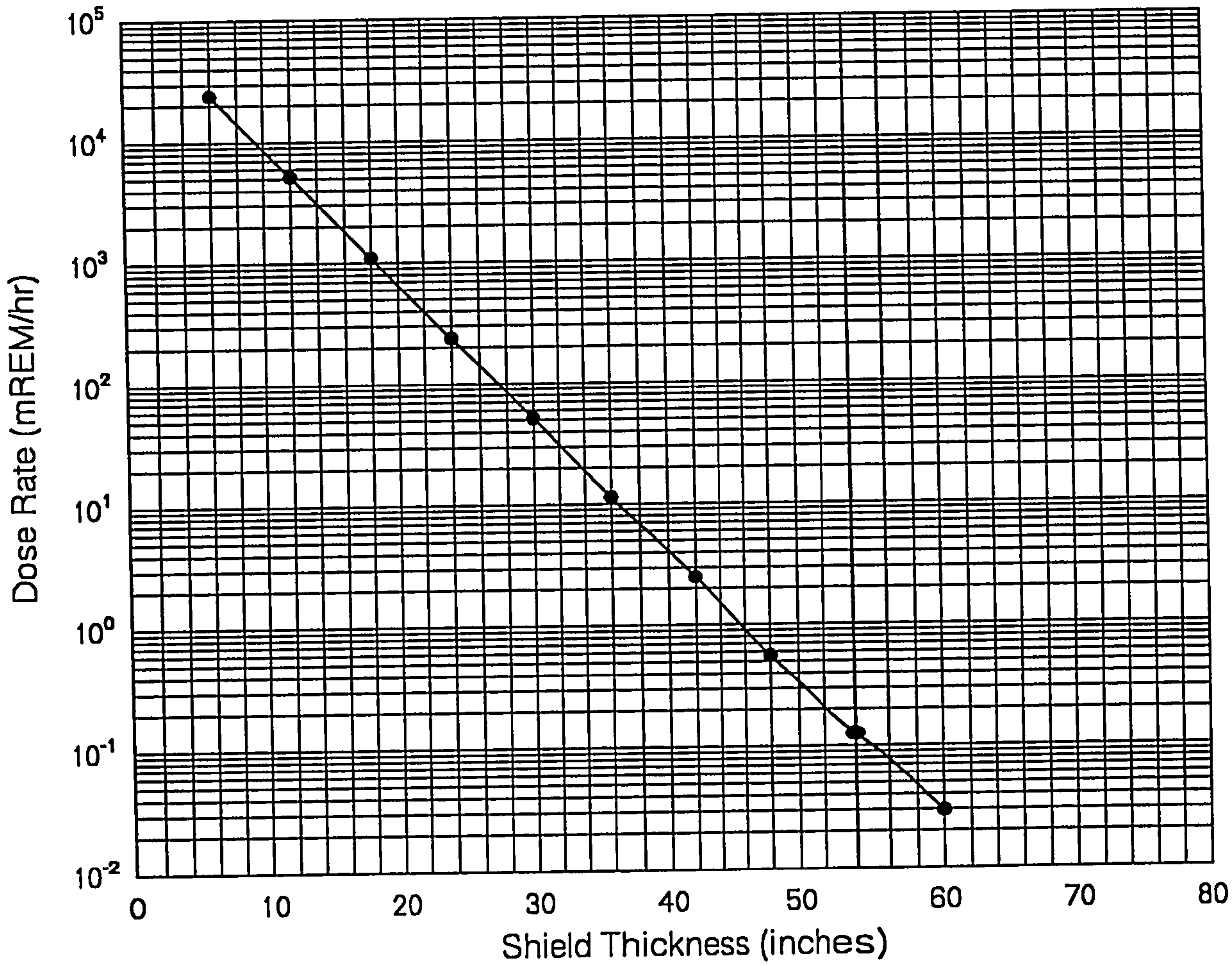

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Figure 4-17
Dose Rate Behind a Steel Shield Around the First Water Filter
(Dose Point is 3 ft from Filter Center.)

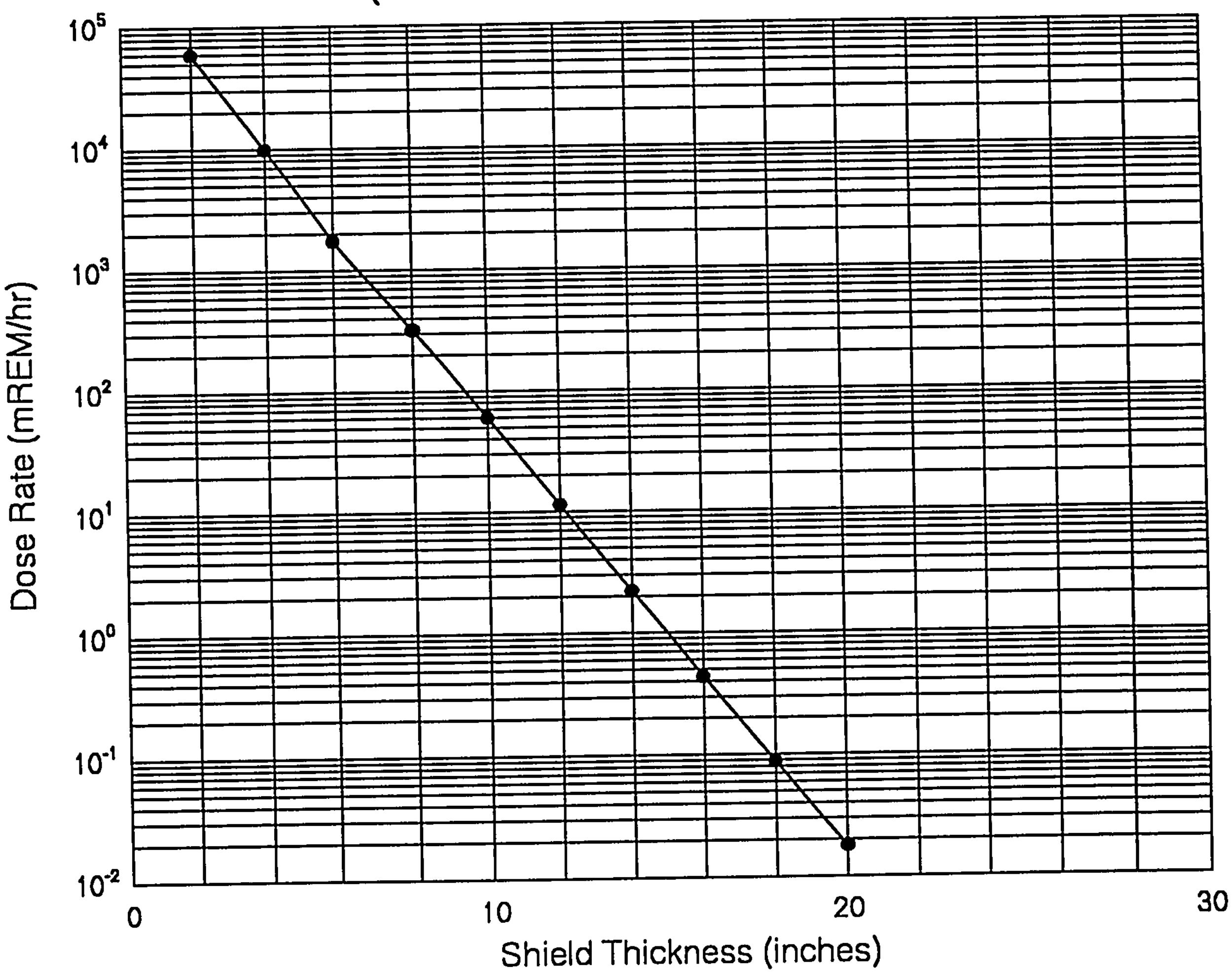

Figure 4-18
Dose Rate Behind a Concrete Shield Around the First Water Filter
(Dose Point is 6.5 ft from Face of Pump.)

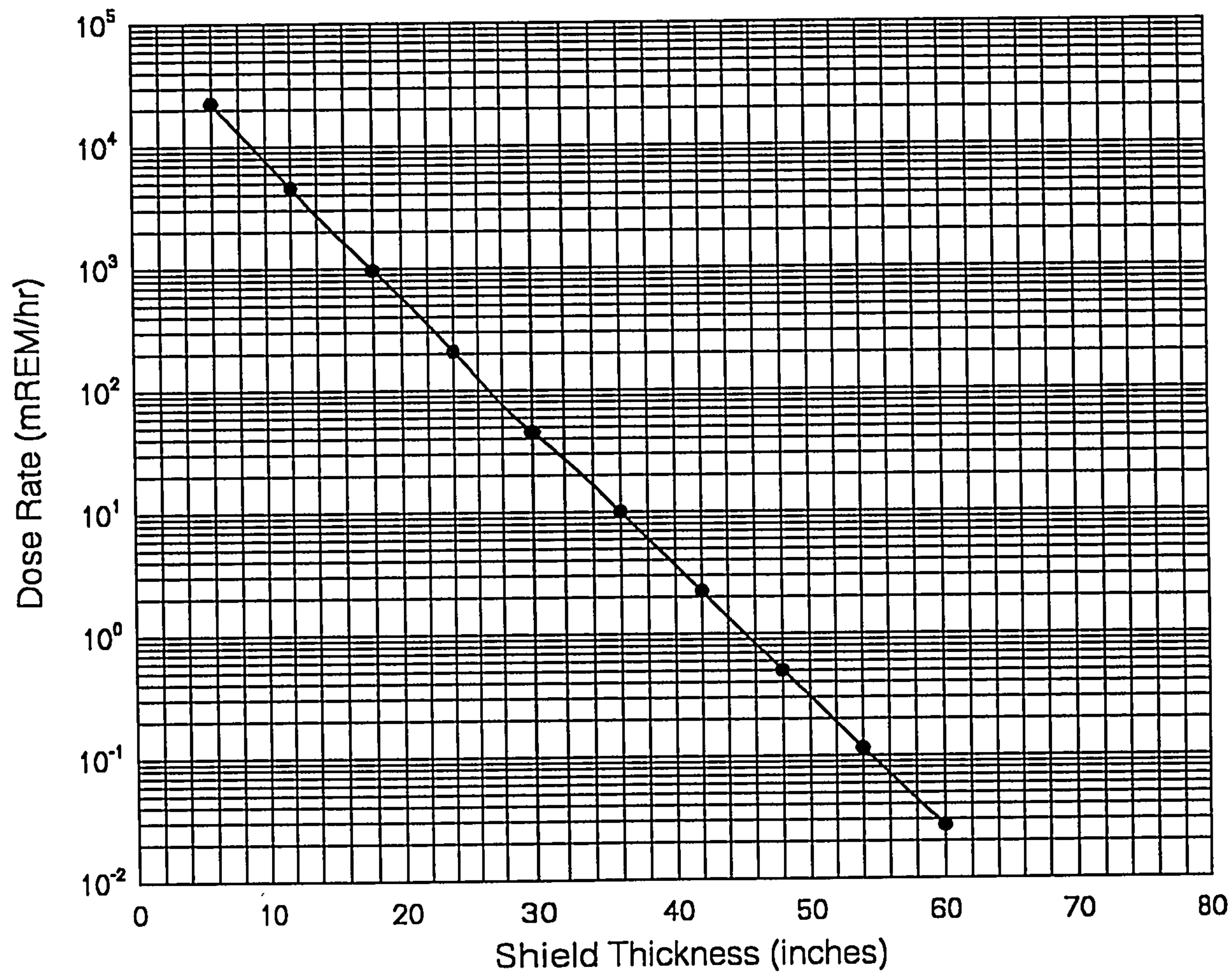

Figure 4-19
Dose Rate Behind a Steel Shield Around the DI Unit
(Dose Point is 4 ft from Unit Center.)

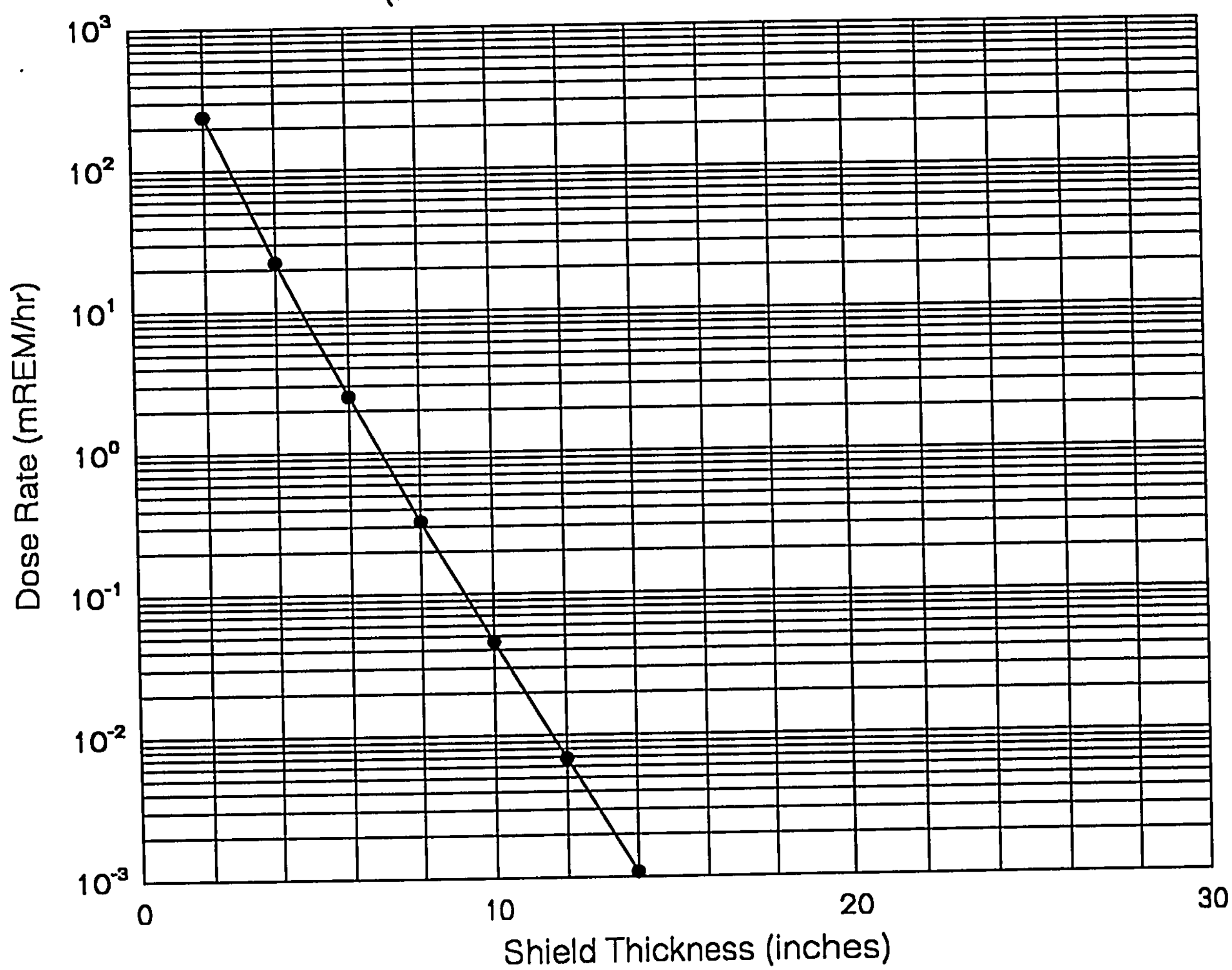

Figure 4-20
Dose Rate Behind a Concrete Shield Around the DI Unit
(Dose Point is 5.5 ft from Unit Center.)

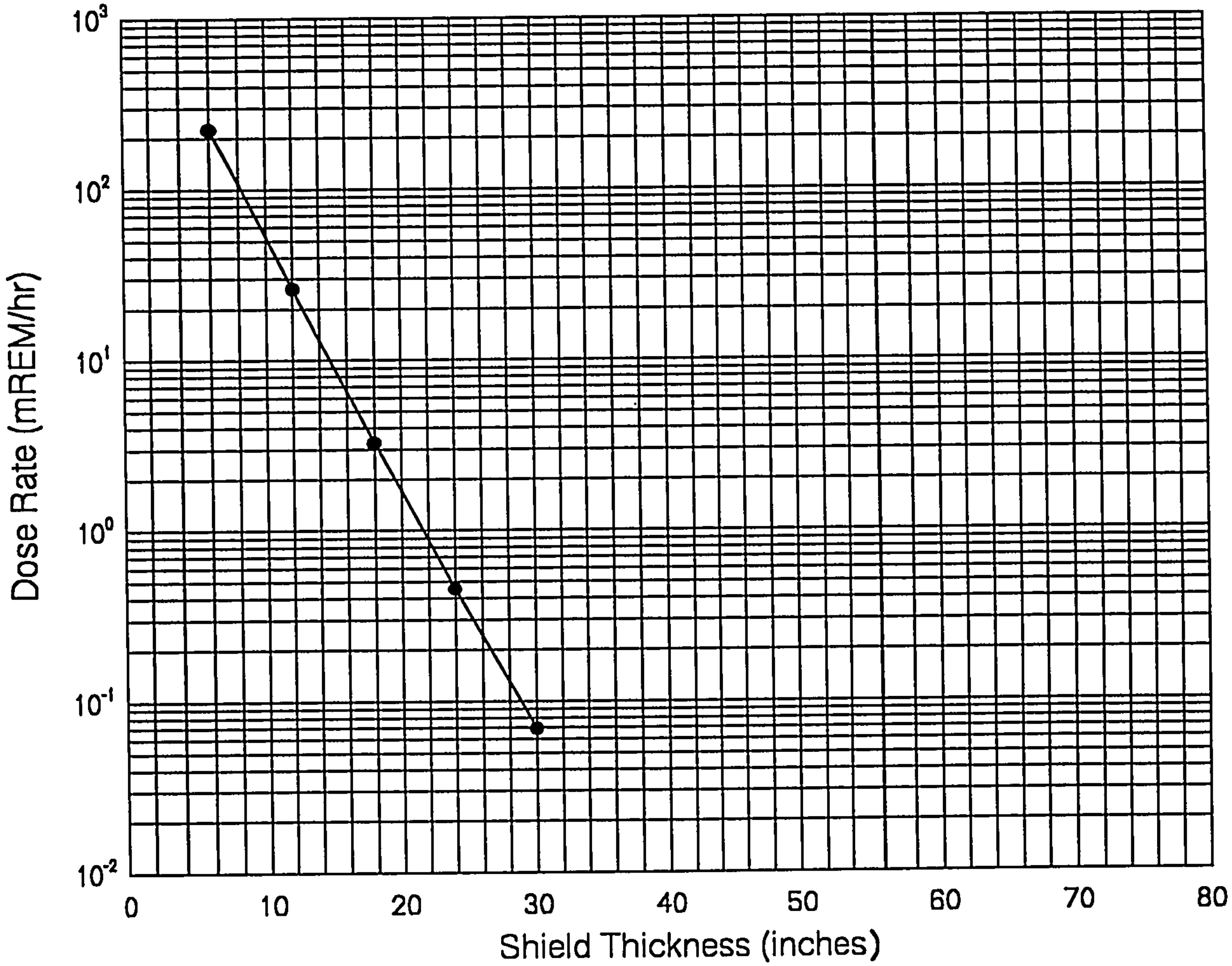

Figure 4-21
Dose Rate Behind a Steel Shield Around the Second Water Filter
(Dose Point is 2 ft from Filter Center.)

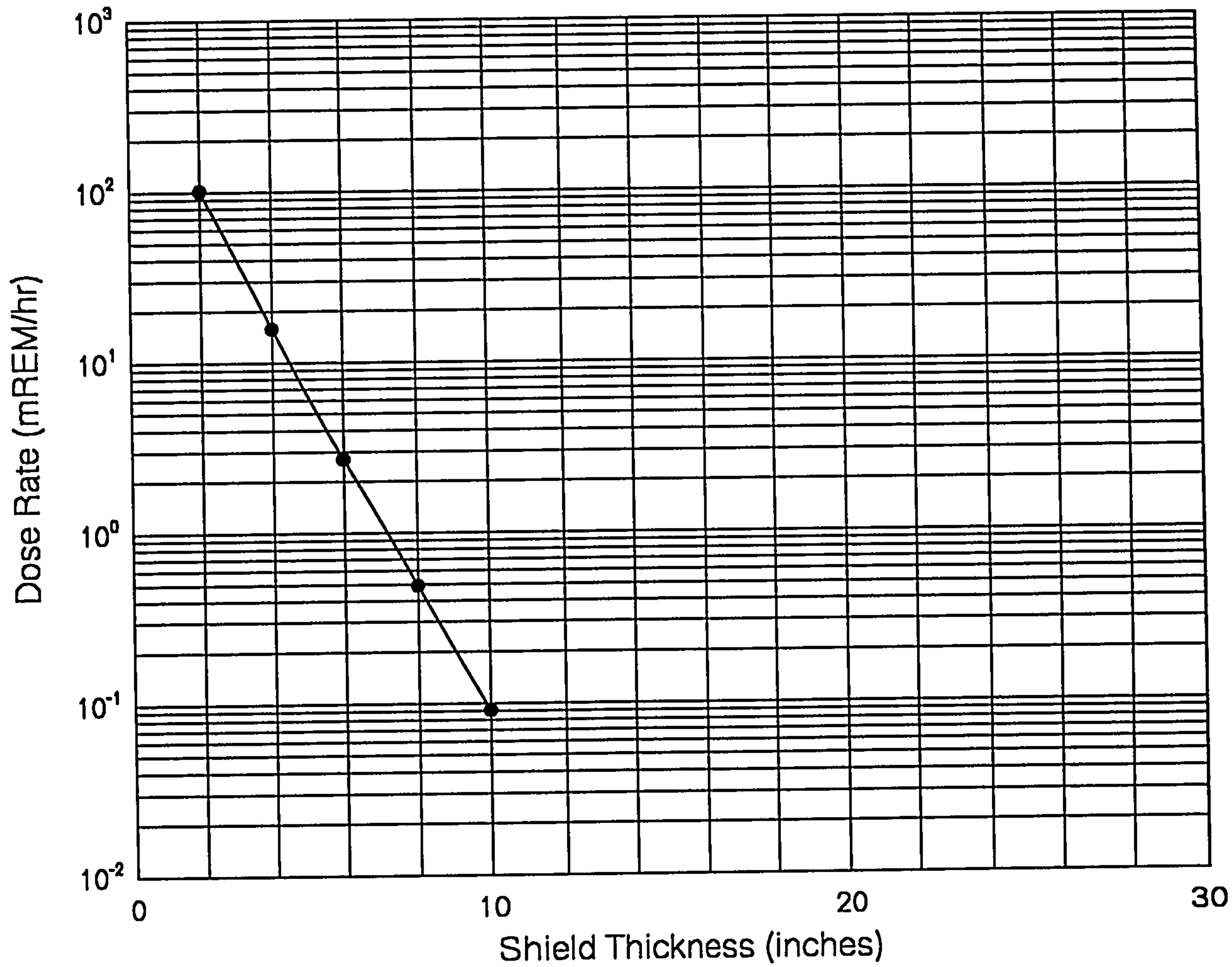

Figure 4-22
Dose Rate Behind a Concrete Shield Around the Second Water Filter
(Dose Point is 4 ft from Filter Center.)

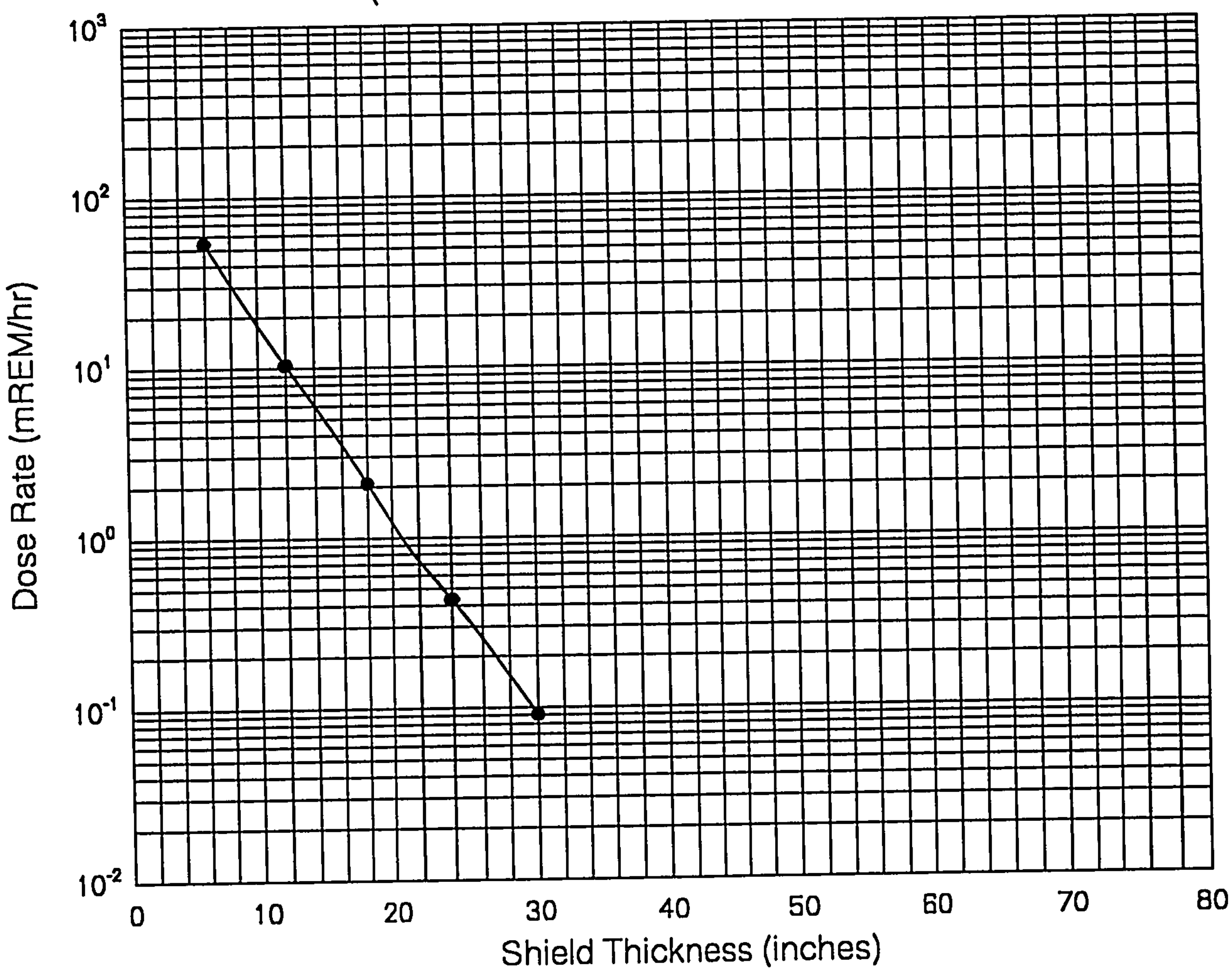

Figure 4-23
Dose Rate Behind a Steel Shield Around the Refrigeration Unit
(Dose Point is 4 in from Source Face.)

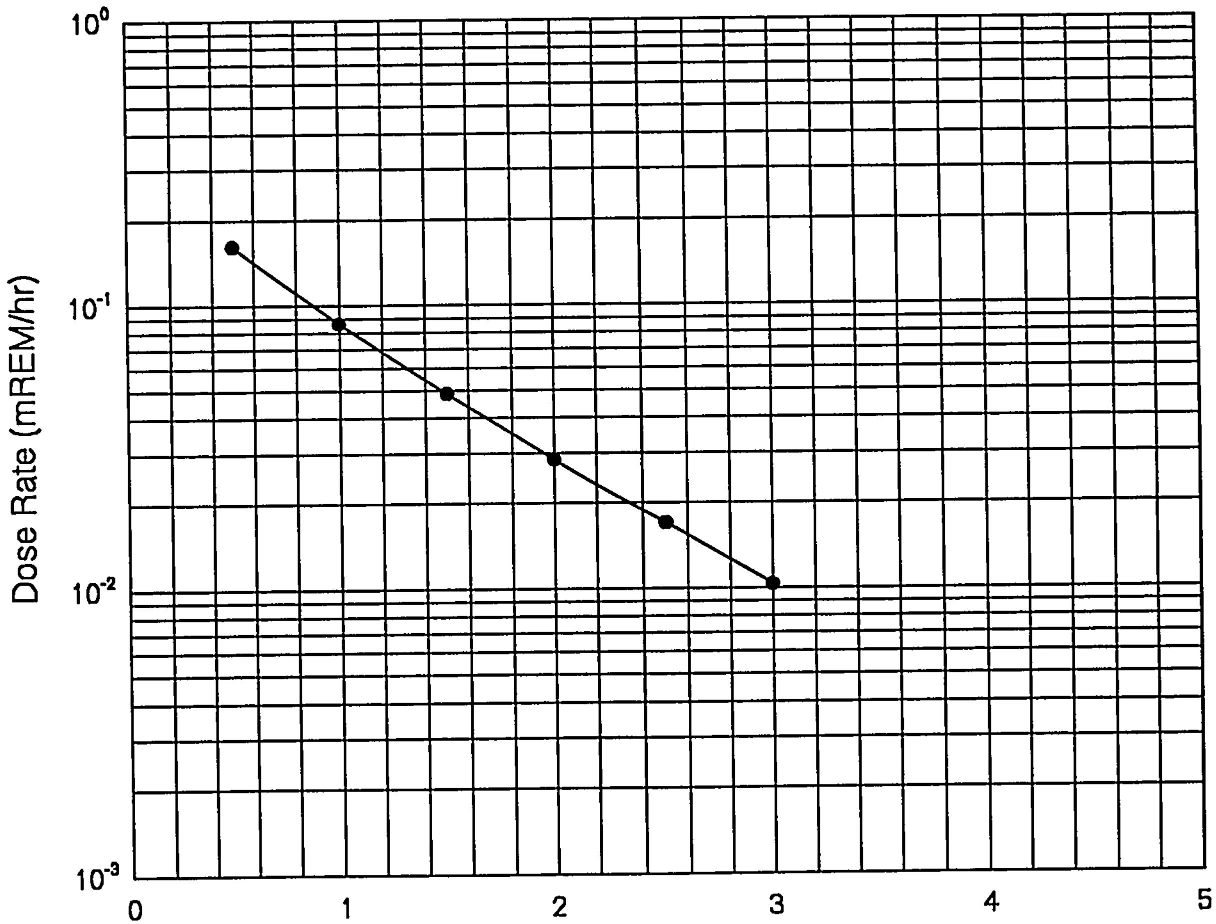

Figure 4-24
Dose Rate as a Function of Distance From the Outside Wall of the Refrigeration Unit
(Wall is 0.125 in Thick Steel.)

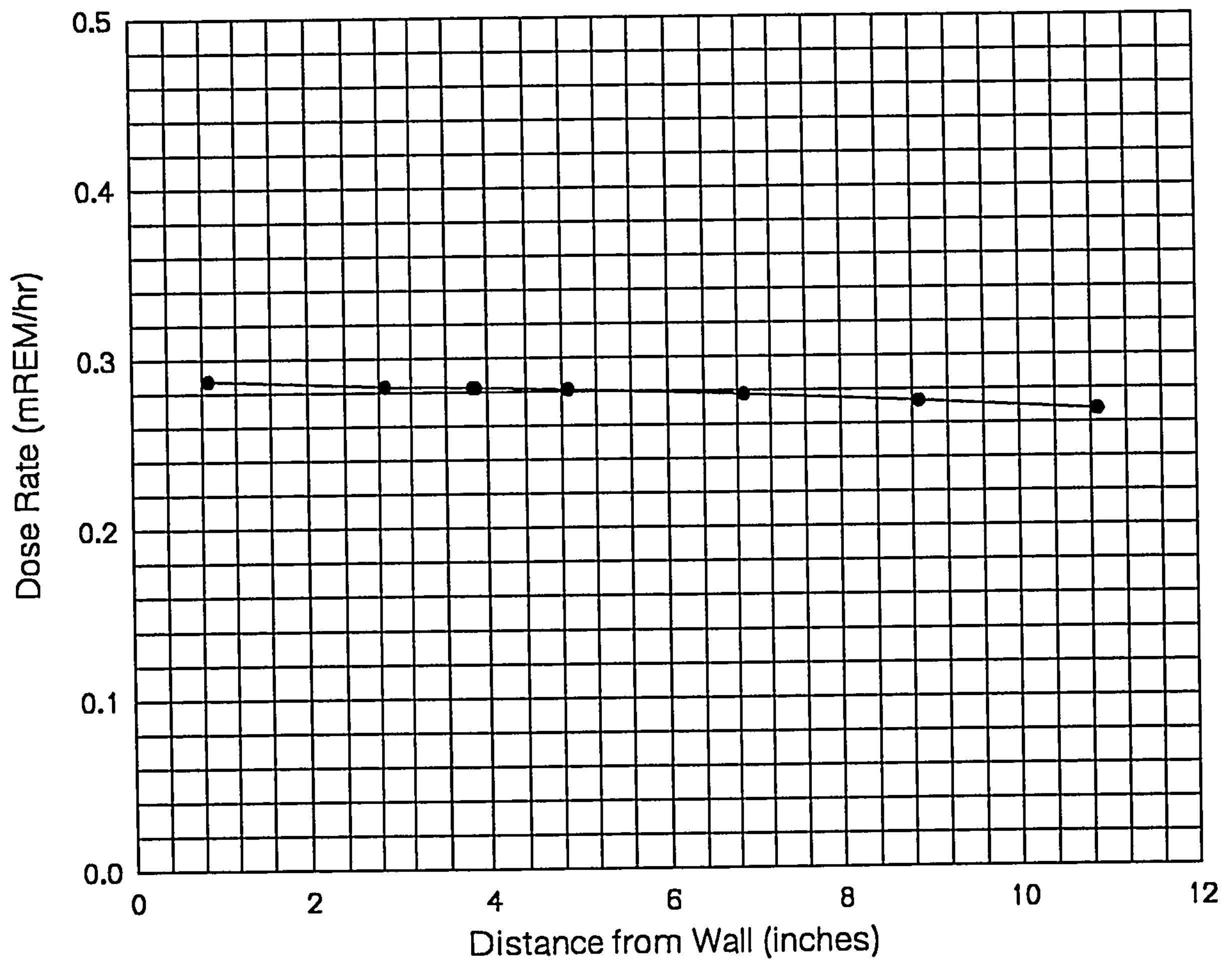

Figure 4-25
Dose Rate as a Function of Distance From the Outside Wall of the Water Feed Pump
(Wall is 0.125 in Thick Steel.)